AN ABSTRACT OF THE THESIS OF

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Title: The Effects of Channel Modification on Characteristics of Streams During Low Flow.

Abstract Approved: ______________________________
Robert L. Beschta

Fluorescent dye was used to assess summer low flow hydraulic retention and transient storage (dead zone) associated with fish habitat structures at Camp Creek, Drift Creek, and the East Fork of Lobster Creek within the central Coast Range of Oregon. Utilizing channel units to stratify stream reaches, the effect of instream structures upon the hydraulic retention of pools was evaluated. The cycling time of water into and out of storage was also estimated by calculating an exchange coefficient.

Camp creek had a pre- and post-treatment design that included unaltered, low, medium, and high levels of coarse woody debris loading. Except for one Camp Creek channel unit (CC21), major alterations to low flow channel unit dimensions did not occur after treatment and the volume of water in transient storage in the other treated channel units was probably not altered. Intensive debris loading increased the length of channel unit CC21 by 6 meters and the average cross-sectional depth by 0.04 meters.

An "additional sums of squares" test was used to evaluate whether there was a statistically significant difference existing between Camp Creek pre- and post-treatment simple linear regressions of transit time versus debris loading and the average cross-sectional area, depth, width, and velocity. The additional sums of squares comparison did show that an increase in post-treatment transit time was statistically significant ($p \leq 0.10$) when compared against debris additions that were located within the low flow wetted perimeter of the stream (wood influence Zone I).

Statistically significant ($p \leq 0.10$) results for dye plume and geomorphic variables for Drift Creek and Lobster Creek are not presented as major conclusions because of a lack of pretreatment control data. Qualitatively, however, one-tailed t-test indicate that during summer discharges, flow velocities and peak concentrations may significantly decrease in treated channel units, compared to the channel units that were assumed to be controls.

Intensive debris loading may enhance low flow channel complexity by increasing turbulent mixing and increasing the transit time of water. However, in this study the largest amount of debris volume was located in the cross-section of channel existing between low flow and bankfull flow (wood influence Zone II). Thus, hydraulic interaction with debris primarily occurs during winter flows and storm flows when streampower is at its highest.

The Effects of Channel Modification on Characteristics of Streams During Low Flow

by

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INTRODUCTION

Large woody debris recruitment from riparian areas is an important element affecting fish habitat in the Pacific Northwest. However, harvesting of riparian trees, coupled with short-rotations, even-aged management, and removal of residual tree biomass from stream channels has resulted in changes in the source, delivery, and distribution of coarse woody debris in forest streams. Bisson et al. (1987) indicate that there is a crucial need for long-term studies that focus on the recruitment of woody debris from streamside forests.

Potential impacts on salmonid production due to logging include increased water temperature, increased sedimentation (logging roads), structural diversity reduction, and habitat alteration due to debris torrents. These impacts may alter channel and bank structure, spawning gravel quality, water quality, and riparian vegetation. Consequently, salmonid habitat diversity and complexity has generally been decreased (Bottom et al., 1985). Streamside management practices that effectively protect aquatic diversity are increasingly needed. Such practices will not only require an analysis of aquatic diversity, but additional research and new approaches to synthesizing existing information (Franklin, 1988).

Habitat manipulations have the potential to alter hydraulic components of streamflow such as velocity, eddying, scouring, and pooling. These hydraulic alterations may aid in the vertical and horizontal sequestering of food sources for a variety of fish species and age classes. Sullivan et al. (1987) found that streamflow hydraulic and morphometric characteristics, including shape, gradient, channel roughness, and flow volume, all play a role in determining salmonid rearing space. However, distinguishing between the biotic and physical control mechanisms for aquatic systems continues to represent an important research question (Ray 1988).

The geomorphic and habitat effects of insufficient amounts of instream large organic debris along a channel reach can often be observed in the field. For example, streams may show a lack of pools, decreased spatial variability in stream velocities, and lack of cover protection for fish. There is also recognition of excessive large organic debris levels including blockage of spawning migration, impaired water quality, plugged culverts, and others (Bisson et al., 1987).

Large organic debris, channel morphology, stream velocity aspects, and slack water associated with instream fishery habitat structures, can be characterized at the channel unit scale as defined by Grant et al., (1990). Using channel units as a basis for stratification, it was hoped that the instream morphologic and hydraulic characteristics influenced by large wood and rock structures could be quantitatively evaluated for this project.

OBJECTIVES

The emphasis of this study is on assessing relationships between the hydraulic and morphologic characteristics associated with the structural alteration of streams for fish habitat.

Specific objectives of this research were to:

1. Using tracer dyes, examine the extent of slack water and/or eddying associated with different configurations of wood, rock, and gabion structures (dye concentrations versus time provided the basis for evaluating changes in hydraulic characteristics).
2. Examine spatial variation in channel width, depth, and velocity associated with different structure classes (i.e, wood, rock, and gabion).

LITERATURE REVIEW--LARGE ORGANIC DEBRIS AND FLUVIAL MORPHOLOGY

In small steep western Oregon streams, 30 to 80 percent of the elevation loss of the stream is influenced by natural debris of some type and large woody debris will comprise 20 to 35 percent of the stream area (Keller and Swanson, 1979). In steep stream channels, such as those prevalent in the Oregon Coast Range, large woody debris plays an important role in dissipating streampower because floodplain and channel terrace aggradation are often constrained by steep valley sideslopes. Bilby and Likens (1980) also found large woody debris dams retained organic material within the system, allowing decompositional processes to break this material into smaller size fractions that are more available for nutrient cycling. In addition, the resultant pooling and/or hydraulic eddies associated with instream debris locally decreases stream velocity and delays downstream transport of nutrients.

The River Continuum Concept (Vannote et al., 1980) indicates biological subsystems for each reach are in general equilibrium with the physical system at that point in the continuum. In "natural" river systems, the temporal change of a species is a slow process of physical and genetic evolutionary drift. However, the aquatic community structure can gain and lose species in response to low probability cataclysmic events and/or slow processes of channel development (Vannote et al., 1980). Harvesting riparian forests every 80 to 100 years, or less, can hardly be considered low probability events within the context of the time required for late successional stand developments. Similarly, the potential for streams to undergo increased sedimentation and temperature, due to land use activities which reduce streamside cover and structural complexity, cannot be considered low probability events. The amount and arrangement of woody debris in a particular stream reach (a point in the continuum) provides an indication of the balance between debris input and output processes (Keller and Swanson, 1979).

Sediment, flow obstructions, and stream discharge comprise three major factors influencing channel morphology. Sediment load increases above background have frequently resulted in channel disturbance (Bisson et al., 1987). For example, potential spawning sites may be degraded if stored sediment should be scoured from streambeds. Furthermore, sediment can accumulate directly upstream of debris accumulations while pools form directly downstream (Beschta, 1979). Thus, with the addition or maintenance of large organic debris, streampower can be locally decreased with sediment being deposited and stored. Bed material transport and downstream delivery processes become slower. Depending on the size of sediment deposited, spawning habitat and water quality may be enhanced.

SPIRALLING

Hydraulic information pertaining to large organic debris, including instream habitat structures, may provide aquatic biologists with additional information pertaining to nutrient spiralling. The stream spiralling concept is viewed as the downstream "looping" of a limited nutrient. The average downstream distance associated with one loop of the nutrient represents the "spiralling length" (Newbold et al., 1981; Newbold et al., 1982a; Newbold et al., 1982b; Elwood et al., 1983; Minshall et al., 1983). If the spiralling length is compressed, the nutrient is more efficiently utilized by the aquatic and riparian ecosystem. Efficiency is enhanced because the particle can complete more cycles before it is adsorbed, precipitates, or exits the system. Spiralling concepts may provide a means of describing (indexing) nutrient downstream transport and recycling potential relative to upstream input (Newbold et al., 1981; Newbold et al., 1982a).

A steady state assumption is generally used in the quantification of spiralling (Newbold et al., 1981;

Newbold et al., 1982a; Elwood et al., 1983) and represents the continuous looping of a nutrient through the flow, streambed, and consumer compartments while being conveyed downstream. Although spiralling length is a function of climate, hydrology, biology, and chemistry; instream physical and biological factors will influence the amount of spiralling and compression along various reaches of a stream.

Increased retention from large debris may enhance biotic assimilation of dissolved or limited nutrients because large organic debris influences pooling, eddying, scouring, and sediment aggradation (Keller and Swanson., 1979; Bilby and Likens., 1980; Newbold et al., 1982a; Minshall et al., 1983; Robison and Beschta, 1990). Large organic and abiotic debris could be expected to provide additional sites for biotic adsorption of a limited nutrient. A decrease in the transport potential may result in faster nutrient uptake, utilization, and cycling back into the system. Subsurface flow may also enhance biotic assimilation of limited nutrients because the intergravel flow velocity is presumably slower.

From another perspective, Bencala and Walters (1983) found solute to be temporarily stored by turbulent eddies created by large-scale bed roughness, large slow recirculating regions along the periphery of pools, mixing zones associated with flow obstructions, side pockets of slack water, and intergravel flow. Likewise, Bencala et al. (1990) found the increased residence time of a lithium tracer in a Colorado mountain stream to be attributed to transient storage of solutes during which contact with a reactive environment was expected to increase.

From headwaters to downstream there is a continuous gradient of site conditions and biotic adjustments (Vannote et al., 1980). Downstream nutrients will depend on upstream input and retention mechanisms. However, spiralling length is apparently independent of reach length and can be used to compare different sized streams. Thus, spiralling characteristics provide a non-dimensional way of comparing reaches of different sizes and water velocities (Elwood et al., 1983).

CHANNEL UNITS

Grant et al. (1990) identified various channel units, (Table 1) which are generally one or more channel widths in length. Groups of macro-bedforms of organized bed particle subunits (steps) comprised of eddies and backwater make up a channel unit. Channel unit bedforms can be identified on the basis of bed slope, degree of step development, and hydraulic characteristics.

Other researchers have also attempted to define steep mountain stream bedforms at a scale of 10^0 to 10^1

Table 1. Summary of channel unit descriptions (adapted from Grant et al., 1990).

Channel unit	Description
Pool	The water surface is tranquil with submerged bed particles.
Riffle	Slight water surface roughness with some hydraulic jumps.
Rapid	The water surface is very rough. The channel width is comprised of large stream spanning steps.
Cascade	A very rough water surface with well developed step-pools.
Boulder step	Single channel spanning steps that are comprised of bedrock, boulders, or large coarse woody debris.

channel widths (Whittaker and Jaeggi, 1982; Whittaker, 1987). For the most part, they have generalized "pool" and "riffle" sequences based on boulder steps, riffle steps, or rock steps.

SALMONID HABITAT

Pacific Northwest salmonids have adapted to reproduce and rear in response to the local hydraulic characteristics of streamflow. Thus, the channel shape, gradient, roughness, and volume of flow play a part in determining the availability and quality of salmonid habitat (Sullivan et al., 1987). Bisson et al. (1981) devised a system (Table 2) that is useful in assessing the spatial segregation of coexisting fish populations. Likewise, Bisson et al. (1981) generalized habitat utilization related to certain species of fish and age classes (Table 3).

A series of habitat patches within a stream could be characterized as an archipelago (Angermeier et al., 1989). Moreover, a variety of channel units may conceivably comprise this archipelago. Because channel units vary in velocity, depth, and bed material, they may differ in species or age group suitability (Sullivan et al., 1987). The available habitat (usable area within a stream) indicated in Table 3 can usually be associated with

Table 2. Summary of low flow habitat types (adapted from Bisson et al., 1981).

Habitat types	Description
Plunge pool	Formed when streamflow passes over a large channel obstruction, drops vertically, and scours the streambed. The depth is often greater than 1 m.
Dammed pool	Impounded water resulting from stream channel blockage (i.e., log jam).
Backwater pool	Caused by eddies behind channel obstructions. The water depth is greater than 30 cm. Substrate is fine-grained.
Trench pool	A long deep "slot" scoured into a coarse stable substrate or bedrock.
Lateral scour pool	Flow is directed to one side of the stream by a partial obstruction where a pool is scoured. Often occurs as an undercut bank.
Low gradient riffle	Streamflow is less than 20 cm deep with a current velocity of 20 to 50 cms^{-1}. Substrate consists of gravel, pebble, and cobble particles.
Rapid	Stream gradient and velocity is greater than 4 % and 50 cms^{-1}, respectively. Substrate is coarser than the low gradient riffle substrate.
Cascade	An alternating series of small waterfall and shallow pool steps primarily constructed of bedrock or boulder. Often found downstream of debris jams.
Glide	Distinguished by attributes of both riffles and pools. Depths are 10 to 30 cm with even "uniform" flow. Substrate is gravel and cobble.
Secondary channel	Water existing as residual pools following a freshet or the high flow season. Often located on gravel bars or along the channel periphery.

Table 3. Summary of low flow habitat utilization by Pacific Northwest salmonids (Bisson et al., 1981).

Habitat type	Coho	Steelhead	Cutthroat
Plunge pool	all	yearling	all
Dammed pool	all	age 1+	age 1+
Backwater pool	age 0+	sometimes	sometimes
Trench pool	all	yearling	1+/2+ if vacant
Lateral scour	n/a	older ages	older ages
Riffle	n/a	under yearling	under yearling
Rapid/cascade	dislike	all ages	dislike
Glide	none	all	under yearling
Secondary channel	few	few	few

specific hydraulics and substrate that are within a species tolerance range. Thus, species or age groups will tend to use channel units with preferred hydraulic conditions, given the available distribution of conditions. According to Sullivan et al. (1987), competition also has an important role in regulating fish distributions throughout the usable habitat of a stream.

USING TRACERS TO MEASURE STREAMFLOW HYDRAULICS

Fluorescent dyes have been used by various researchers to measure time of travel and dispersion (Hubbard et al., 1982; Kaufmann, 1987). Transient storage mechanisms of hydraulic systems have also been studied (Thackston and Schnelle, 1970; Valentine and Wood, 1977; Sabol and Nordin, 1978; Valentine and Wood, 1979a, 1979b; Sabol and Nordin, 1981; Bencala and Walters, 1983; Kaufmann, 1987).

Most studies of river dispersion theory are based on a one-dimensional Fickian process with a convective diffusion term (Sabol and Nordin, 1978). This theory indicates that molecular motion and turbulent fluctuations enable a particle to occur at different flow depths over time and that velocity gradients enable the particle to travel with varying velocity. If a large number of particles are introduced into a flowing stream, some will travel at above average velocity and others at below average velocity. This situation results in a cluster of particles that are moving downstream and undergoing continuous spreading.

Particles that are neutrally buoyant, such as fluorescent dye molecules (rhodamine WT has a specific gravity of 1.19), can be used to trace the characteristics of streamflow. The dye must also be chemically and biologically conservative, otherwise it gets involved in spiralling or retention that is other than by physical processes. Assuming the dye is conservative, its path will be expected to follow the various stream lines that comprise water movement in a reach. Consequently, dyes are excellent for determining the transit time of streamflow through a particular reach. Similarly, dyes can be used to predict or estimate the behavior of contaminants that are introduced into a stream (Hubbard et al., 1982).

Valentine and Wood (1977), Sabol and Nordin (1978), and Sabol and Nordin (1981) indicate that concentration-time relationships tend toward a non-Gaussian distribution with respect to channel position; these relationships become less Gaussian with increasing time. Dye curve distributions are skewed with a tail of low concentration extending upstream, becoming increasingly longer as the dispersant moves downstream. Such skewed distributions are most likely due to the irregular dimensions of natural streams which provide many places for particles (such as dye molecules) to be temporarily stored. A variety of researchers including Hays (1966), Thackston and Schnelle (1970), Valentine and Wood (1977), Sabol and Nordin (1978), Valentine and Wood (1979a, and 1979b), and Sabol and Nordin (1981) have evaluated the effect of channel storage on dispersion by including a storage element in their dispersion models. Many researchers use the term "dead zone" for the transient storage mechanisms that function in stream channels.

LITERATURE REVIEW SUMMARY

Large woody debris often enhances the quality of fish habitat (Bisson et al., 1987). Moreover, Bisson et al. (1987) indicate that by providing physical obstructions to water flow, woody debris can increase the complexity of stream habitat. Bencala and Walters (1983) describe solute as being stored in turbulent eddies resulting from irregular channel bottoms, slow recirculating zones along pool edges, recirculating zones behind obstructions, channel side pockets, and intergravel flow. Based on these considerations it appears that hydraulic retention and dead zones may be important indicators of habitat complexity (Kaufmann, 1987).

Evaluation of instream habitat alteration will require research from a variety of disciplines. Dye methodologies may provide a quantifiable characterization of streamflow hydraulics and their interaction with instream habitat structures. Hopefully, this study will provide additional understanding of streamflow hydraulics associated with structural habitat alterations in streams.

METHODS

GENERAL DESCRIPTION OF STUDY AREAS

The central Oregon Coast Range provided the general setting for this study (Figure 1). Study sites included upper Drift Creek, the East Fork of Lobster Creek, and Camp Creek.

Both Drift and Camp Creeks are located approximately 19 km northeast and 26 km southeast of Waldport, Oregon, respectively, and within the Siuslaw National Forest. Drift Creek has a latitude of 44° 30′ 30″ and longitude of 123° 50′ 00″. Camp Creek is found at a latitude of 44° 18′ 35″ and longitude of 123° 45′ 30″. Lobster Creek is located on Bureau of Land Management grounds approximately 38 km southeast of Waldport, Oregon, at a latitude and longitude of 44° 14′ 50″ and 123° 37′ 35″, respectively. Basin characteristics pertaining to the study streams are presented in Table 4.

Codes were used to represent the various channel units. Camp Creek codes are CC42, CC27, CC23, and CC21 for unaltered, low, medium, and high complexity, respectively. A Camp Creek beaver pond was given the code CCBP. Drift Creek treatment channel unit codes are labeled DCA, DCB, DCC, DCD, DCE, and DCF. Similarly, Drift Creek comparison (control) channel units are

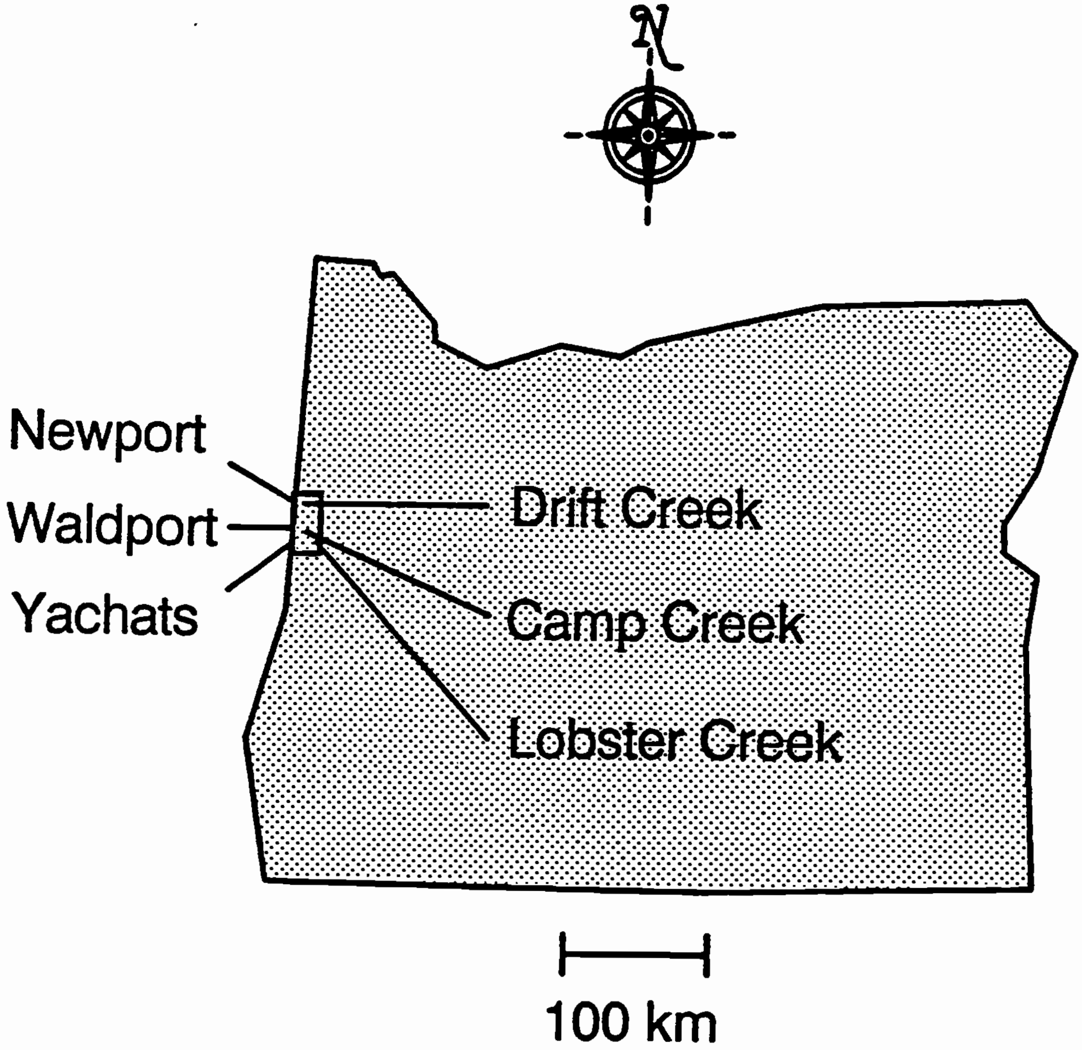

Figure 1. Location of study areas.

Table 4. Site characteristics of study streams.

Characteristic	Camp Creek	Drift Creek	Lobster Creek
Watershed area (km^2)[a]	11.4	180	14.8
Channel gradient (%)[b]	1.2	0.9	1.3
Strahler order at mouth of watershed[c]	2	5[d]	3

[a] Total basin from headwater to mouth
[b] Along the reach of stream being sampled
[c] USGS 1:62000 scale for Drift Creek and USGS 1:24000 scale for Camp and Lobster Creeks
[d] Strahler order 3 at the study site

labeled DC1, DC2, and DC3. Lobster Creek treatment channel unit codes will be labeled LCA, LCB, LCC, and LCD. LC1 and LC2 will designate Lobster Creek comparison controls. Channel unit codes and their respective habitat structures are presented in Table 5.

CLIMATE

The Coast Range is characterized by a maritime climate with mild temperatures and abundant winter rain. Average annual temperatures range between -1°C and 30°C. Most of the precipitation occurs during the winter months when Pacific storms move inland. Summers are dry and warm with frequent morning fog. Thus, streamflows are usually highest during the winter and lowest during early fall. Average annual precipitation generally ranges between 200 and 250 cm, depending on elevation (NOAA, 1990).

GEOLOGY AND SOILS

Camp, Drift, and Lobster Creeks are all underlain by the Tyee and Burpee formation. These bedded sandstones and siltstones formed via estuarine and marine depositional processes (Wells and Peck, 1983). Valley side slopes are steep and have been generally subjected to forest harvesting operations. The logged areas range from recent clearcuts to old second-growth.

Table 5. Habitat structures or natural debris (control) associated with each channel unit (control debris denoted by •).

Channel Unit	Structure/Debris Form	Pool Length (m)
Camp Creek[a]		
CC21	wood	32
CC23	wood	31
CC27	wood	17
CC42	wood	13
CCBP[b]	none	52
Camp Creek[c]		
CC21	wood	38
CC23	wood	31
CC27	wood	17
CC42	wood	13
Drift Creek		
DCA	wood/rock	69
DCB	wood/rock	32
DCC	wood/rock	42
DCD	wood/rock/boulder weir[d]	144
DCE	wood/rock	9
DCF	wood/rock	106
• DC1	bedrock channel	13
• DC2	wood/rock	43
• DC3	wood/rock	36
Lobster Creek		
LCA	wood/gabion	59
LCB	transverse wood jam/rock[d]	22
LCC	wood/rock	14
LCD	gabion	26
• LC1	wood/rock	10
• LC2	wood/rock	22

[a] Camp Creek pretreatment

[b] Beaver pond measurements were obtained during the Camp Creek pretreatment measurements.

[c] Camp Creek post-treatment

[d] Weirs and jams provided slackwater and scour upstream and downstream of their position, respectively

In general, soil for Camp, Drift, and Lobster Creeks are lumped together as the Digger-Bohannon-Preacher series (Soil Conservation Service Map, 1986). These are Udic Mesic soils associated with forested uplands of Oregon.

STATISTICAL DESIGN

An underlying hypothesis for this study was that a channel unit would be physically altered when large debris of wood or rock was placed in the stream. An increase in the transit time of a conservative tracer (dye) is expected following debris loading. Potential alterations on channel morphology and hydraulics include increases or decreases in channel pool dimensions, bed aggradation, and intergravel flow. Debris additions may also contribute to complete stream blockage, or the "sieve" effect where habitat structures catch floating and saltating debris.

The null hypothesis was that instream debris loading would not alter ($\mu_1 = \mu_2$) one or more of the following physical stream parameters: average cross-sectional width, depth, area, or velocity. Similarly, instream debris loading will also not alter one or more of the following concentration-time plot statistics: transit time, transient storage (dead zone), exchange coefficient (average number of times a dye molecule enters a storage compartment per unit time), dye plume peak concentration, centroid velocity, leading edge velocity, time to concentration from the initial release, and the skew of the concentration-time plot. The alternative hypothesis was that one or more of the above mentioned physical stream parameters and dye concentration-time plot statistics will significantly change ($\mu_1 \neq \mu_2$) as a result of instream debris loading of large wood and rock structures.

Statistical methods used to analyze stream data included Student's t-tests, simple linear regressions, and in the case of Camp Creek, an "additional sums of squares" test (Draper and Smith, 1966). One-tailed t-tests were used to evaluate the statistical significance between differences in means for physical channel measurements and the dye statistics calculated from concentration-time plots for Drift and Lobster Creeks. One-tailed t-tests for Camp Creek were not used because of a very low sample size. Simple linear regression in this study primarily served a descriptive purpose because the statistical relations were not intended to be used in predicting any specific change the different types of habitat structures may have on stream morphometric parameters. Simple linear regressions were beneficial because it is assumed that the dependent variables (concentration-time plot results) will vary with the independent variables (physical channel parameters). For instance, an increase in the cross-sectional area may decrease the centroid velocity of the dye plume indicating a potential increase in transit time, dye plume dispersion, and dead zone. Thus, the regression model postulates that for each independent variable, there is a probability distribution for the dependent variable that may vary systematically with the independent variable.

The dependent variables used in the regression analyses were calculated from plotted curves showing the dye concentration versus time in seconds. Curve recession limbs were truncated, or projected (Garstka et al., 1958), to a position with time equivalent to 1 % of the peak concentration. Although the dye curve is continuous and can be considered a probability density function, the curve also requires a "frozen cloud" assumption (Valentine and Wood, 1979a) which means that during the passage of the dye plume past a sampling location, the dye cloud does not disperse. The "frozen cloud" approximation allows the data to be converted from a spatial domain into a temporal domain. The independent variables were acquired from field measurements, or, calculated from measured channel parameters (e.g., average cross-sectional velocity was calculated from discharge and average cross-sectional area).

An "additional sums of squares" test (Draper and Smith, 1966) was used to test whether there was a statistically significant difference existing between Camp Creek pre- and post-treatment simple linear regressions of transit time versus debris loading and the average cross-sectional area, depth, width, and velocity. This test evaluated whether the pretreatment regression intercept and slope is equal to, or significantly different from, the post-treatment regression intercept and slope, at a desired level of confidence.

STATISTICAL LIMITATIONS

Sample sizes in this study are small. Thus, the degrees of freedom are minimal and limit statistical power for discerning differences. Ideally, sample sizes for Camp Creek, Drift Creek, and Lobster Creek should have been on the order of 30 to 40 channel units for each stream.

Another limitation involved a lack in replicating the levels of woody debris complexity (unaltered, low, medium, and high) treatments in Camp Creek, although eight replicates of each level of complexity were available. Thus, discretion may be warranted when interpreting the study results.

Habitat structures in Drift and Lobster Creeks had not been designed to represent various levels of pre- and post-treatment complexity. Thus, channel units that were considered to best represent the pretreatment stream conditions were selected for use as "controls".

EXPERIMENTAL DESIGN

Hydraulic variables that were measured in this study included transient storage, and the average cross-sectional velocity, area, depth, and width. Transient storage pertains to any backwater or channel margin dead zone characteristics associated with channel morphology and/or habitat structures.

Hydraulic Tracer Field Methodology

Rhodamine WT is a liquid fluorescent red dye that was selected for use as a "conservative" tracer in the analysis of transient storage (Table 6). A mass of dye was injected as a solution of dye and water into the stream. Grab samples were obtained at downstream locations and retained for fluorometric analysis. By utilizing slug injections, and retrieving grab samples, a relatively large number of channel units could be assessed, thus minimizing setup and transport of equipment and power sources in the field. Only one site (Lobster Creek) could be reached via automobile with relative ease.

The concentration of dye released (7.9e+07 μgL^{-1}) was held constant throughout the study. Depending on

Table 6. Selected characteristics of rhodamine WT (Keystone Aniline Corporation, 1990).

Category	Characteristic
Color index name	Acid Red 388
Chemical family	Xanthene
Specific gravity	1.19
pH	0.8 (+/- 0.7)
Hazardous ingredients	Sodium Hydroxide (<1 %)
Hazardous burning by-products	C & N Oxides
Carcinogenic listings	None
Lc50 rainbow trout @ 96 & 48 Hr	>3.2e+05 μgL^{-1}
Lc50 daphnia @ 72 Hr	1.7e+05 μgL^{-1}
Lc50 oyster @ 48 Hr	1.0e+04 μgL^{-1}

discharge and location, measured peak dye concentrations at Camp, Drift, and Lobster Creeks ranged between 1 and 73 μgL^{-1}. The overall average peak concentration was 14 μgL^{-1}. The equation used to calculate field injection concentrations is shown below (from Wilson et al., 1986).

$$C_f = C_s S_g \frac{Vd}{(V_w + V_d)}$$

where: C_f = final concentration $[ML^{-3}]$
C_s = concentration of manufacturers dye dye solution (see Appendix A for C_s computation) $[ML^{-3}]$
S_g = dye's specific gravity [non-dimensional]
V_d = volume of dye used $[L^3]$
V_w = volume of distilled water $[L^3]$

The volume of dye solution added to the various reaches ranged from 3 to 18 mL. At the downstream sampling location, the dye was often barely visible. Thus, for relatively large channel units, the volume of the mixture added was sometimes increased to 18 mL of a 1:2 ratio (dye:water) to assist in visually tracking the dye as it moved downstream toward sampling locations (concentration held constant at 7.9e+07 μgL^{-1}). Although the laboratory fluorometer can detect dye concentrations that are 10 to 30 times lower than any encountered in this study, the injection concentration provided enough color to the water to enable visual tracking of the dye during and after initial mixing.

The general procedures used to perform the slug injections in the field include the following:

1. Depending on the size of the stream, either 3, 9, or 18 mL of a 1:2 ratio dye solution were mixed in the laboratory and transported into the field. The majority of the injections consisted of 9 mL dye solutions.
2. Slug releases were performed in constricted and/or turbulent portions of the channel cross-section in order to initiate both vertical and horizontal mixing as quickly as possible.
3. Release locations were generally selected approximately 20 channel widths upstream of the uppermost sampling location (Figure 2). However, this distance was highly site specific. Other factors affecting the release location included tributaries flowing into the stream (these were avoided), the number of pools the dye had to travel through to reach the sampling locations (often the dye was detained in a pool), and the ability to see and follow the dye plume downstream to the first sampling location.

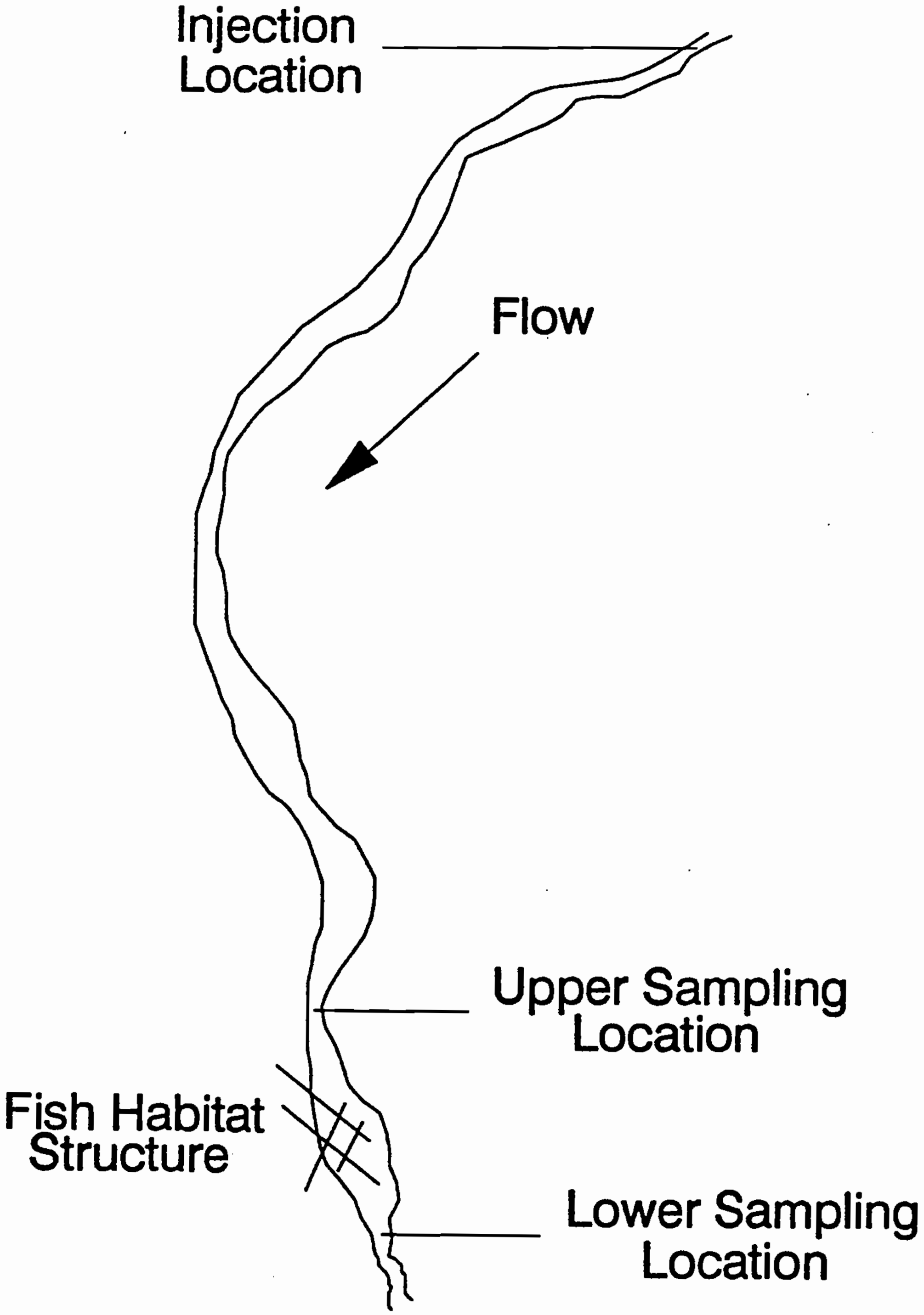

Figure 2. Illustration of the slug injection methodology.

4. Two researchers would concurrently collect grab samples; one sampling location would be immediately above the channel unit being evaluated, and the second location immediately downstream of the channel unit.
5. Typically, 20 to 30 grab samples were collected in 25 mL disposable borosilicate glass vials and taken back to the laboratory for analysis.

Fluvial Geomorphic Variables

The fluvial geomorphic variables that were measured included interpool distances, gradient, width, and depth. Because only one person was usually in the field, an Abney Level was selected to measure the water surface slope rather than a transit level. For each control and treated channel unit, width and depth measurements were systematically obtained at approximately 10 cross-sections. The pool was divided into tenths and the first measured cross-section was randomly located somewhere within the beginning of the pool. From these measurements average cross-sectional area, velocity, depth, and width were calculated for each channel unit.

Velocities were attained by dividing each cross-sectional area value into the discharge, which was assumed to be constant through the channel unit. Discharge was measured according to U.S. Geological Survey methodology (Buchanan et al., 1986) using a Pygmy current meter. Because stream depths at discharge measurement locations were less than 0.5 m, velocity was measured at 0.6 of the stream depth (measured from the water surface downward).

Large Woody Debris and Rock Structures

The instream habitat structures were sketched and, whenever possible, identified as upstream V, downstream V, transverse jam, or boulder weir. However, many structures had been installed in a manner that did not allow them to be simply categorized. Most structures were a conglomeration of several major components. Instream wood structure designs pertaining to habitat alteration have been compiled by Crispin et al. (1989).

Large woody debris and rock comprising fish habitat structures were measured for length, diameter, and volume percentage residing in one of four channel/riparian influence zones. The measurement of large woody debris was performed in a manner similar to that of Veldhuisen (1990). Both large and small diameters along a log were measured as was the log length in order to estimate total volume. The large diameter was acquired at the piece end, or, at diameter breast height (1.4 meters above the ground line) if the rootwad was attached. The small diameter was acquired at the log's end or at a diameter of 0.1 meter.

The estimated percentage of a log's volume that is interacting, or is not interacting with the stream and riparian environment was described utilizing influence zones (Robison and Beschta, 1990). In Figure 3, Zone I is comprised of the low flow active channel. Zone II includes woody debris that is submerged during bankfull discharges. Zone III debris is that suspended vertically above Zone II. Zone IV is the final zone to be estimated and includes the proportion of debris volume in the streamside flood plain and riparian region.

Large rock structure within the channel unit was also measured and sketched. Similar to wood structure classes, rock structure classes were identified as single boulder, boulder cluster, boulder weir, or gabion (Crispin et al., 1989). The influence zone methodology was also applied to the rock structure. However, single rock volumes were estimated assuming the rock was spherical in shape. Rock cluster volumes were estimated assuming the cluster was cylindrical in shape. Gabion dimensions were measured and sketched. Sediment deposition had occurred around most gabions and they were primarily influencing Zone I flows.

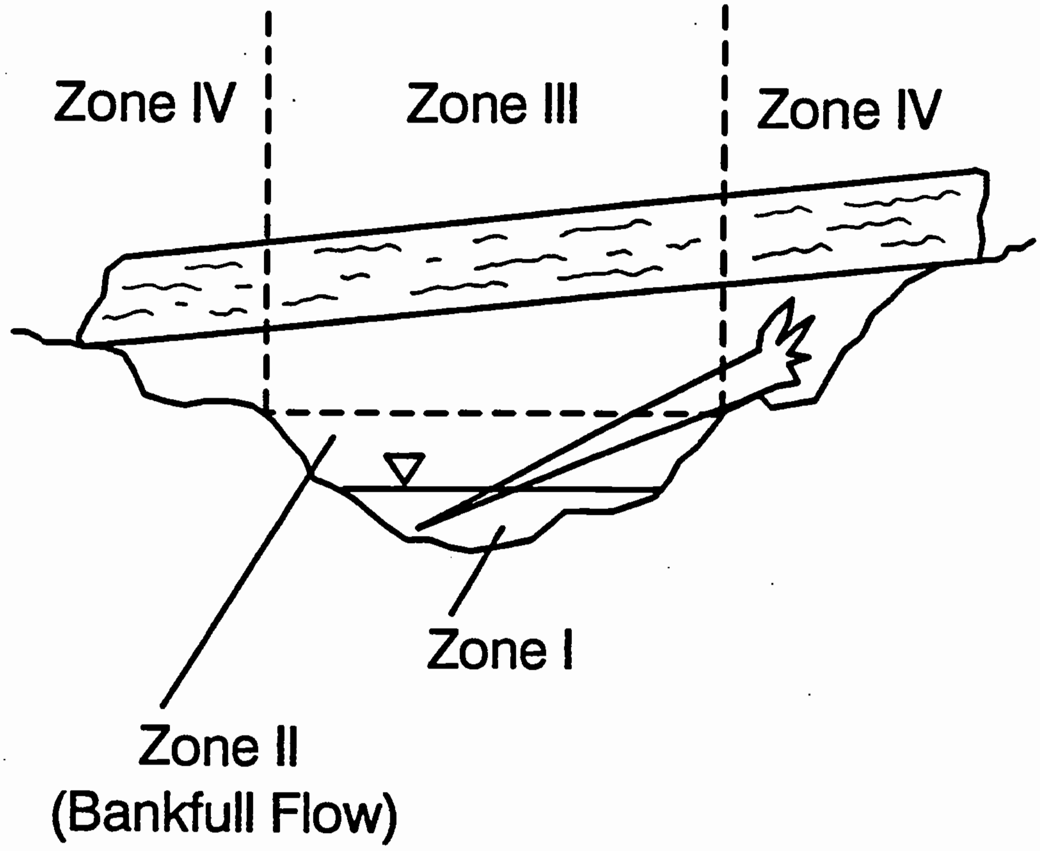

Figure 3. Coarse woody debris influence zones.

LABORATORY ANALYSIS

After the dye/water samples had been acquired in the field, they were returned to the laboratory for fluorometric analysis. Samples were returned to the lab on the same day of acquisition and allowed to equilibrate throughout the night to the ambient room temperature. This allowed the samples to reach the same approximate temperature of the reference standards. The following morning the samples were analyzed for fluorescence with a Turner Model 111 fluorometer. Each field sample was split into thirds and placed in a separate 12 by 75 mL disposable borosilicate glass culture tube. Thus, three replicates of each sample could be analyzed.

The Turner Model 111 fluorometer utilizes an ultraviolet lamp to emit light through a sample containing a fluorescent substance such as rhodamine WT. Upon irradiation, the fluorescent substance begins to emit light. In general, a fluorescent substance behaves as follows (Wilson et al., 1986):

1. The absorption of radiant energy from an outside source such as an ultraviolet lamp or the sun.
2. The excitation of some of the electrons comprising the fluorescent substance, resulting in enlarged electron orbits. This is known as the "excited state".

3. The emission of energy from the fluorescent substance in the form of photons as the excited electrons return to their normal position known as the "ground state".

The emitted (fluorescent) energy always has longer wavelengths and lower frequencies than the absorbed energy because energy is used in the process of emission. The situation conforms to Stoke's Law (not to be confused with particle settling velocity) which states that the emitted photons carry off less energy than energy brought in by the exciting photons (Weast et al. 1984). According to Wilson et al. (1986), most substances are at least mildly fluorescent in the ultraviolet to visible spectrum (200 to 800 nm).

Because more than just dye may fluoresce at any particular site, the fluorometer utilizes a filter combination that isolates the individual fluorescence characteristics of the dye. Similarly, a light source has individual emission spectra and also requires filtering. Rhodamine WT has a peak excitation spectrum (absorption wavelength) of 558 nm and a peak emission spectrum of 582 nm (Smart and Laidlaw, 1977). These are the two important values to consider in the selection of light source and filter combinations.

A General Electric (GE) G4T4/1 far-UV lamp was used to provide a 546 nm peak excitation spectrum. This is close to the 558 nm peak of rhodamine WT. The far-UV bulb is a low pressure mercury-vapor lamp that emits high-intensity monochromatic lines. The monochromatic lines aid in a manner that allows the desired spectra to be isolated with a filter combination (Wilson et al., 1986). For example, the GE bulb also emits useful light outputs of 254 nm, 297 nm, 313 nm, 405 nm, and 436 nm.

As for filter selection, the goal is to isolate light reaching the photomultiplier to the same spectra of light that is being fluoresced by the dye (peak emission spectrum). A primary filter combination was used to pass the peak excitation light (546 nm) and a secondary filter combination allowed a window for the desired peak emission spectrum (590 nm). This primary and secondary filter combination was suggested by Wilson et al. (1986) for use with rhodamine WT and the GE far-UV light source. Specifically, the primary filters were a gel Wratten 61 green filter inserted between two glass Corning 1-60 gray filters. The secondary combination was an orange glass Corning 3-66 filter and a blue glass Corning 4-97 filter. The blue filter is placed closest to the sample in order to filter out any fluorescence from the filters themselves (Wilson et al., 1986). In general, the bulb emits light through the primary filters, through the water sample, through the secondary filters, and finally into the photomultiplier where emitted fluorescence is detected.

The type of dye used is influenced by factors such as cost, availability, and ease of field application. Fluorescent dyes can be attained in a variety of colors including orange, green and blue. However, different colors may have different behaviors in regards to temperature, sorption, photochemical decay, quenching, and pH. According to Wilson et al. (1986) the most significant factor affecting fluorescence, aside from concentration, was temperature. For example, if a sample is left in the fluorometer for an increasing length of time, its concentration will decrease rapidly as temperature increases. Hence, reading values from the fluorometer must be made quickly. Similarly, it is important that calibration standards and field samples are at a common temperature before analyzing.

Fluorescent dye methodology involves the assumption that the dye behaves as a conservative tracer. However, it may not (Smart and Laidlaw, 1977; Bencala et al., 1983; Wilson et al., 1986). Utilizing chloride as a conservative tracer, and lithium as a sorptive tracer, Bencala et al. (1983) found rhodamine WT to sorb to suspended sediment. However, they also indicate that the interaction of rhodamine WT with solids is not well understood and may be dependent on site specific conditions. Despite the possibility of sorption, rhodamine WT is often recommended for use in water studies because it is moderately resistant to adsorption and economical (Smart and Laidlaw, 1977; Wilson et al., 1986).

Bright sunlight can affect the stability of rhodamine dyes. However, photochemical decay is usually only a problem where dye is exposed to sunlight for several days (Smart and Laidlaw, 1977). These authors also report that orange dyes (e.g., rhodamine WT) have relatively low decay rates.

Quenching is another concern in fluorescent dye methodology. True quenching occurs when dye molecules interact with other chemicals in the water and fluorescence is reduced. Wilson et al. (1986) indicate chlorine to be a quenching agent. Because of the threat of quenching, laboratory standards and dilutions were not mixed with tap water because of the potential for true quenching. Concentration quenching is another form of quenching. Concentration quenching may occur when very high concentrations of dye "screen" the emitting light. Dilutions must be performed in order to overcome this.

The fluorescence of rhodamine WT decreases outside the pH range of 5 to 10. Stream water pH was assumed to be within this range throughout the study and was not measured.

Table 7 lists dye recommendations for tracer application and is based on the work of Smart and Laidlaw, (1977). When selecting a dye for this study, the

Table 7. A general overview of common fluorescent dyes (adapted from Smart and Laidlaw, 1977).

- The presence of significant fluorescent background at blue and green wavelengths is probably the most important factor influencing dye selection.

- Temperature affects orange dyes (i.e, rhodamine WT).

- Salinity does not affect a dyes fluorescence unless the exposure to salinity is for long periods.

- Photine CU (blue), fluorescein (green) and pyranine (green) dyes have high photochemical decay rates in both natural and artificial light.

- For orange dyes, photodecay is only a concern for tests lasting several days in length.

- Rhodamine WT is moderately resistant to adsorption.

sorption, photochemical decay, and background fluorescence characteristics were major considerations. Rhodamine WT was selected based on the overview in Table 7, Wilson et al. (1986), and "word-of-mouth" from scientists who have worked with fluorescent dye tracers.

If rhodamine WT is used where human consumption of water is likely the maximum permissible concentration is 10 μgL^{-1} (USDI Geological Survey). When experimenting with release concentrations, 10 μgL^{-1} was used as the target peak concentration to attain in the stream. Another concern was the influence rhodamine WT may have on stream biology. Table 8 is a brief listing of selected biological effects known to result from rhodamine WT.

ANALYSIS OF TRACER CURVES

A total of 52 concentration-time graphs were prepared and digitized. The concentration versus time plot represents a probability density function of tracer travel time for each channel unit. The tracer is assumed to be conservative and the probability density function can be applied to the stream flowing through the channel unit. The area under the concentration-time curves and the first four moments about the origin of each curve were calculated using a spreadsheet.

Table 8. Published biological statistics pertaining to rhodamine WT (adapted from Wilson et al., 1986).

Species	Exposure[a]	μgL^{-1}
Pacific oyster eggs[b,f]	48 hr	1-10,000
Pacific oyster larvae[b,f] (Crassostrea gigas)	48 hr	1-10,000
Silver salmon[b,g]	17.5 hr	10,000
Silver salmon[b,g]	additional 3.2 hr	375,000
Donaldson trout[b,g]	17.5 hr	10,000
Donaldson trout[b,g]	additional 3.2 hr	375,000
Water flea[c,h] (Daphnia magna)	≤ one week	2,000,000
Shrimp[c,h] (Gammarus zaddachi)	≤ one week	2,000,000
Log louse[c,h] (Asellus aquaticus)	≤ one week	2,000,000
May fly[c,h] (Cloeon dipterum)	≤ one week	2,000,000
Pea mussel[c,h] (sp. pisidium)	≤ one week	2,000,000
Laboratory rats[d,i]	not available	10
Laboratory rats[e,j]	56+ days	50

[a] It is not known if exposures pertain to Lc50's.

[b] G.G. Parker (1973) as cited by Wilson et al. (1986).

[c] J.S. Worttley and T.C. Atkinson (1975) as cited by Smart and Laidlaw (1977).

[d] D.E. Donaldson (unpublished, 1971) as cited by Smart and Laidlaw (1977).

[e] Smart and Laidlaw (1977).

[f] There were no abnormalities eggs or 12 day old larvae.

[g] No problems or mortality were cited. The additional 3.2 hours is not included in the initial 17.5 hours.

[h] No mortality disparity was between test and control.

[i] A drinking water test resulting in decreased body weight as well as some effect on the liver with prolonged use.

[j] Dye injections resulted in no traumatic ill effects.

Calculations used to acquire the area under the concentration-time curves and the first four moments about the origin of each curve are as follows:

μ_o = the area under the concentration-time curve

$$\mu_o=\int_0^\infty C_t t dt \approx \sum_0^\infty C_t \Delta t$$

μ_1 = the mean transit time which is approximately equal to the transit time of the dye mass centroid

$$\mu_1=\frac{\int_0^\infty tC_t dt}{\mu_o} \approx \frac{\sum_0^\infty tC_t \Delta t}{\mu_o}$$

μ_2 = the variance of the concentration-time curve

$$\mu_2=\frac{\int_0^\infty (t_1-\mu_1)^2 C_t dt}{\mu_o} \approx \frac{\sum_0^\infty (t_1-\mu_1)^2 C_t \Delta t}{\mu_o}$$

μ_3 = the third central moment

$$\mu_3=\frac{\int_0^\infty (t_1-\mu_1)^3 C_t dt}{\mu_o} \approx \frac{\sum_0^\infty (t_1-\mu_1)^3 C_t \Delta t}{\mu_o}$$

μ_4 = the fourth central moment

$$\mu_4 = \frac{\int_0^\infty (t_i-\mu_1)^4 C_t dt}{\mu_o} \approx \frac{\sum_0^\infty (t_i-\mu_1)^4 C_t \Delta t}{\mu_o}$$

where: t = time [T]

C_t = concentration at t [ML^{-3}]

The coefficient of skew and coefficient of kurtosis were calculated as $\mu_3/\mu_2^{1.5}$ and μ_4/μ_2^2, respectively. Three other important parameters determined from concentration-time curves are the transient storage (dead zone) volume fraction, dead zone exchange coefficient, and stream discharge.

The dead zone volume fraction describes the probability of a dye (water) molecule being in storage at any given instant. The model was developed by Sabol and Nordin (1978). However, Kaufmann (1987) derived an equivalent, intuitive concept (Appendix B) that links Sabol and Nordins model to a spatial representation of slackwater in stream channels. In both models the dead zone volume fraction (a_L) is calculated as $1-(T_L/T_C)$. T_L is the initial time to leading edge of the dye plume at the location of sampling. And, T_C is the time to concentration of the dye plume from the initial time to the plume centroid at the sampling location.

The Sabol and Nordin (1978) volume-based dead zone exchange rate coefficient (δ) is calculated as: $\delta = (2 \cdot a_L \cdot X_i) / (u_c \cdot a_u \cdot \sigma^2)$. The variable X_i is the distance downstream from the injection point to the sample location. The variable u_c is the average convective velocity. The value a_u is equal to T_L/T_C. Lastly, the variance in transit time (T) at the sampling point equals σ^2 and is determined from μ_2. The Sabol and Nordin (1978) dead zone model is presented in Appendix C.

Stream discharge can be calculated with the following equation (Hubbard et al., 1982):

$$W_d = Q \int_0^{\infty} C dt = Q A_c$$

where:
W_d = weight of the dye injected [M]
Q = volumetric discharge rate $[L^3T^{-1}]$
$\int_0^{\infty} C dt = A_c$ = area under the dye curve $[ML^{-3}T]$

This equation can be rearranged into a simpler expression: $Q = W_d/A_c = W_d/\mu_o$. The validity of these equations will depend on the faithfulness of the conservative tracer and complete mixing assumptions.

RESULTS AND DISCUSSION

CAMP CREEK CHANNEL UNITS

The Camp Creek site represented a reach with proposed fish habitat alterations and is associated with a study being undertaken by Steve Fieth from the Department of Fisheries and Wildlife, Oregon State University. Dye releases were undertaken on four channel units prior to the woody debris loading and following the treatment.

The Camp Creek channel units consisted of sites anticipated to represent "unaltered", "low complexity" (minimal addition of wood debris), "medium complexity", and "high complexity" (visually, the stream appears to be choked with wood) habitat. The channel units will be referred to as CC21, CC23, CC27, and CC42 for high, medium, low, and unaltered locations, respectively. A beaver pond (CCBP) was also sampled on Camp Creek for an additional comparison.

Longitudinal Profile

Figure 4 is the longitudinal profile for Camp Creek. The average water surface slope was 1.2 percent and the stream channel dissected valley sideslopes that averaged 44 percent.

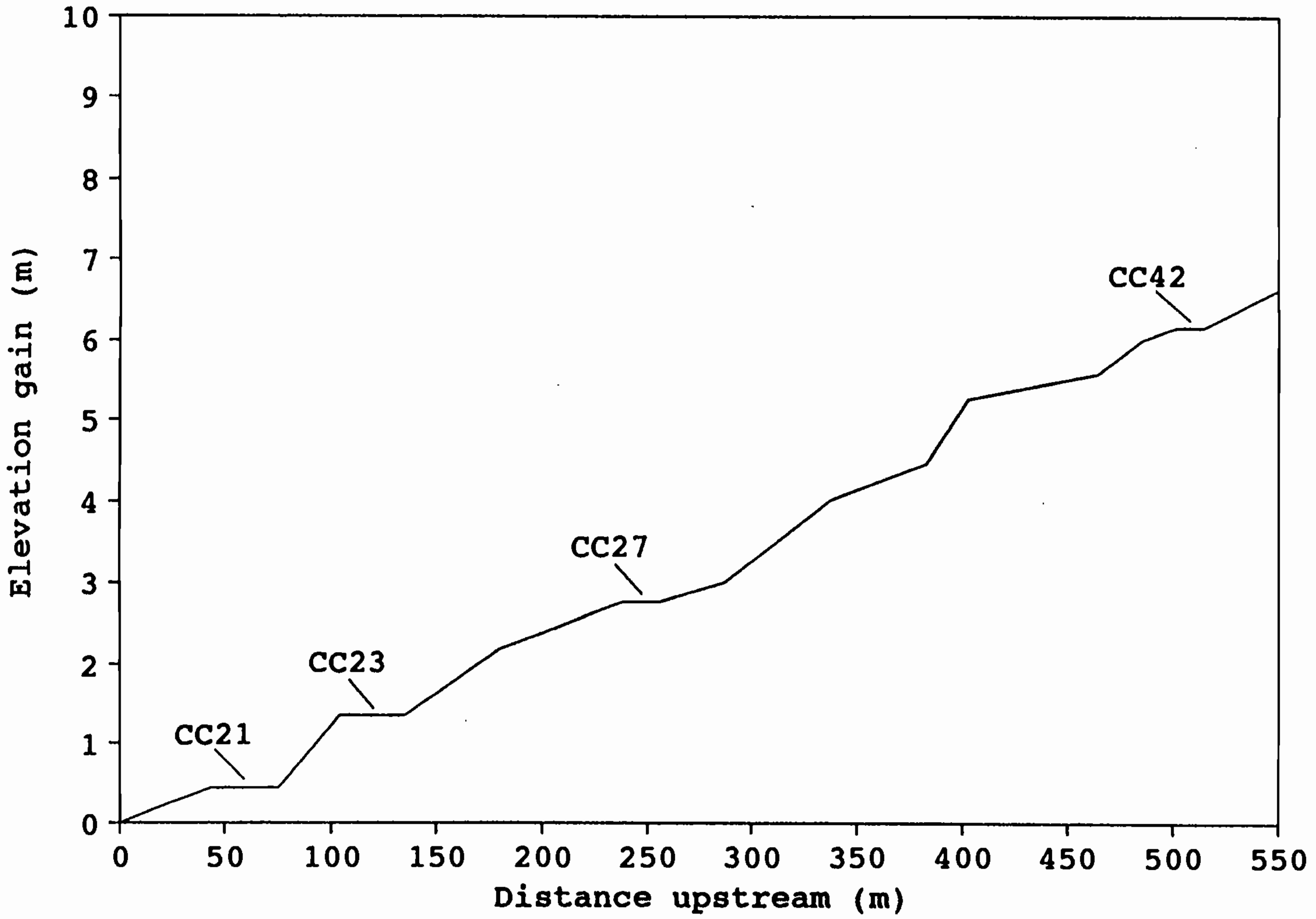

Figure 4. Camp Creek longitudinal profile.

Large Woody Debris

Various levels of woody debris were added to Camp Creek during the summer of 1991 (Appendix D). The volume of wood that was measured or estimated to exist in influence zone I (low flow) and influence zone II (bankfull flow) for each treatment is shown in Figure 5. Overall, total post-treatment wood volumes for zones I and II were 14.2, 4.1, 3.9, and 0.7 m^3 for channel units CC21, CC23, CC27, and CC42, respectively.

Pre- and Post-treatment Statistical Analyses

The use of a pre- and post-treatment experimental design is a relatively rigorous approach for identifying cause-and-effect relationships. A change in response variable is usually expected following treatment and statistics are used to test whether the change is significant at a specified level of confidence. This section presents summary statistics and the results of significance testing at the 90 percent confidence level.

An underlying hypothesis of this study was that the installation of large debris to a stream would physically and hydraulically alter a channel unit. That is, any change in the transit time of water flowing through a channel unit was the expected result of alteration on channel geomorphology or hydraulic complexity. Figure 6

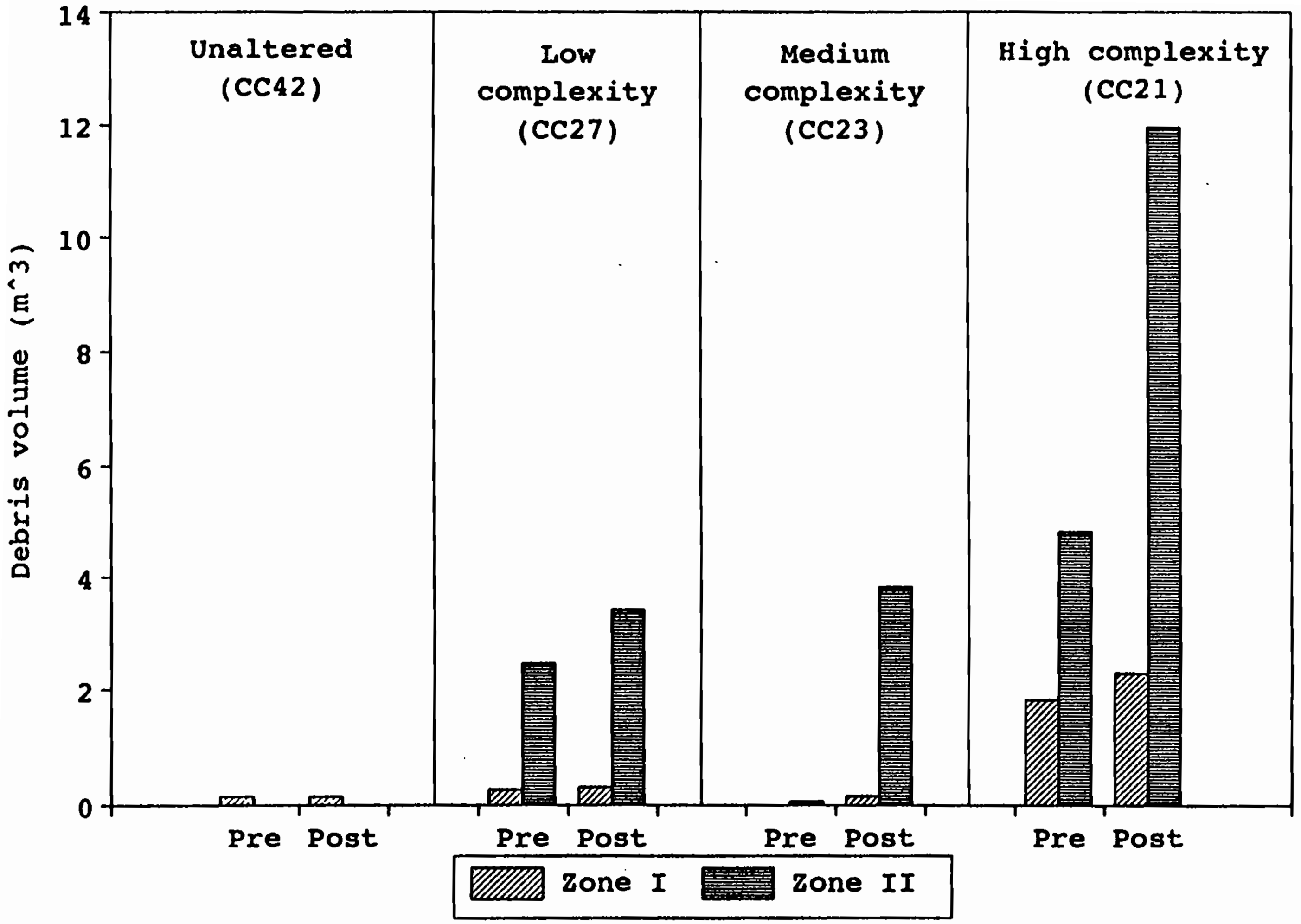

Figure 5. Pre- and post-treatment volume of wood in Camp Creek (CC) channel units.

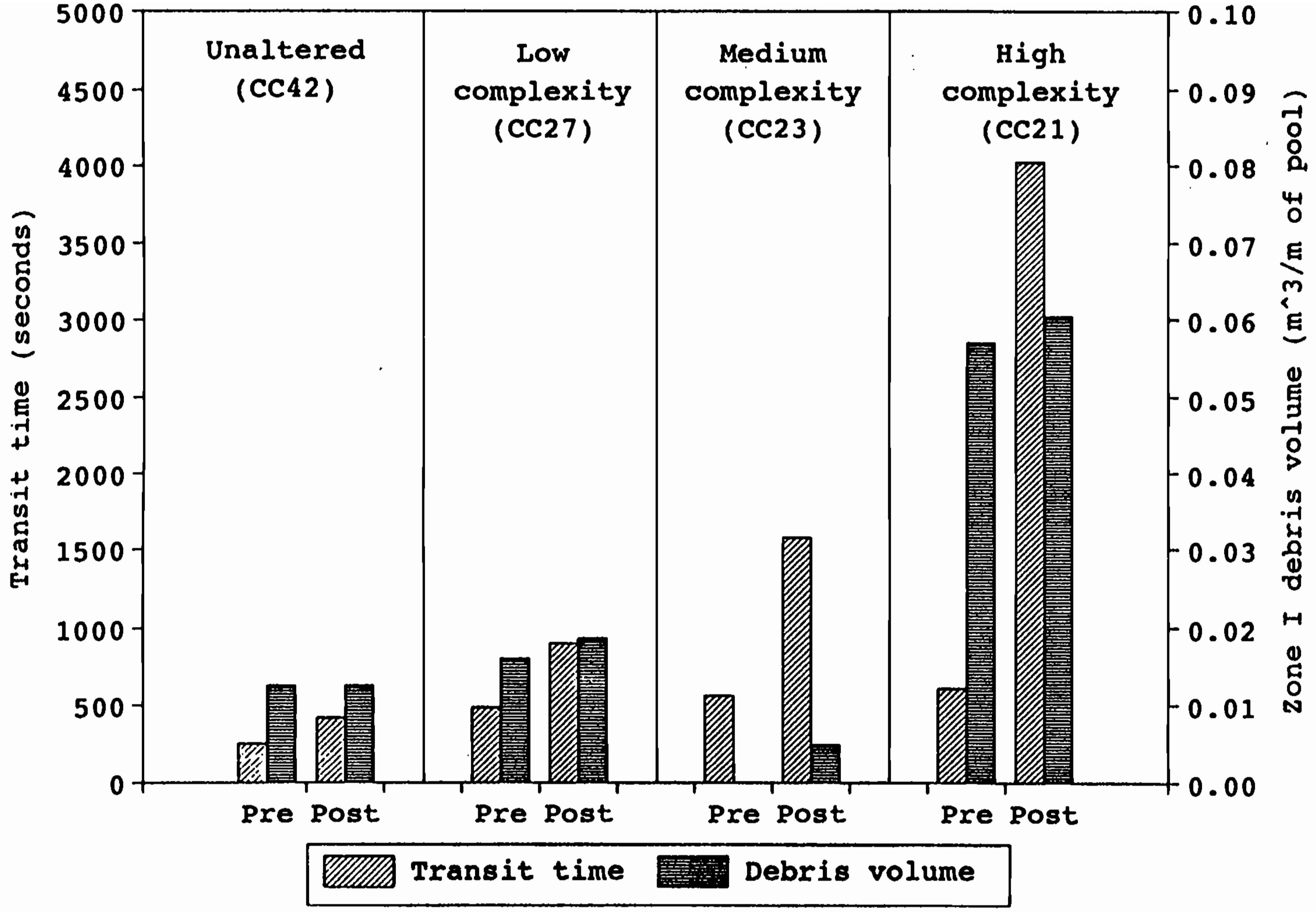

Figure 6. Camp Creek (CC) channel unit transit times and debris volume per unit length of stream.

illustrates the change in transit time and normalized wood volume per meter of channel unit. These results indicate an increase in transit time at the high complexity site, although there is a very small change in Zone I debris loading. However, on-site observations indicated additional CC21 Zone I wood to be ponding more water than during pretreatment.

Because of the minimal addition of Zone I debris, the large increase in CC21 transit time cannot be attributed to debris loading alone. Although post-treatment CC21 pool length and depth increased by 6 m and 0.04 m, respectively, the stream discharge was lower during the post-treatment measurements resulting in lower stream velocities, greater relative roughness, and increased transit time. Lisle (1986) found that debris can minimize reductions in flow depth during low discharges. As channel discharge decreases, the lowering of stream depth may be minimized through increased channel roughness or via a debris dam. Debris additions are most likely increasing post-treatment channel roughness in CC21. Although not as large, post-treatment transit time increases are also apparent in the unaltered, low, and medium complexity sites. However, unless one could define the relationship between transit time changes and discharge over a range of channel roughnesses, transit time data from the unaltered channel unit cannot be used to adjust for any changes in transit times that are occurring in response to the decreased post-treatment discharge.

Simple linear regression analyses, and "additional sums of squares" evaluations were used to ascertain if statistically significant differences ($p \leq 0.10$) in hydraulic variables occurred in response to treatment. If channel units were being altered by the placement of instream structures, the increase in pooling or scour, associated with the debris, should result in changes in average cross-sectional area, depth, velocity, and width. Conceptually, the more complex the treatment, the greater the change in transient storage and channel morphologic characteristics. The physical characteristics of the Camp Creek channel units are provided in Table 9.

Figure 7 illustrates the concentration-time plot of pre- and post-treatment CC21, the high complexity site. When comparing non-treated to treated conditions, post-treatment CC21 was the only Camp Creek concentration-time plot showing a lower peak concentration at the downstream sampling point following treatment. In contrast, the peak concentrations for both upstream and downstream curves of the remaining three post-treatment channel units were higher than the pretreatment. The CC21 curve differences appear to be consistent with the measured changes in morphometric variables. Although the same concentration

Table 9. Summary statistics of channel measurements for Camp Creek.

Statistic	Pre CC21	Post CC21	Pre CC23	Post CC23	Pre CC27	Post CC27	Pre CC42	Post CC42	Beaver Pond
Discharge (m^3/s)	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.04
Pool Length (m)	32	38	31	31	17	17	13	13	52
Sample Size	10	12	11	11	10	10	9	9	11
Velocity									
Average (m/s)	0.04	0.02	0.03	0.02	0.07	0.05	0.04	0.02	0.02
Median	0.03	0.01	0.03	0.02	0.07	0.05	0.04	0.02	0.02
Standard Dev.	0.016	0.010	0.020	0.005	0.040	0.027	0.022	0.013	0.007
Minimum (m/s)	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01
Maximum (m/s)	0.07	0.04	0.08	0.03	0.14	0.09	0.09	0.05	0.03
Area									
Average (m^2)	0.89	1.25	0.96	0.92	0.66	0.49	0.79	0.75	2.12
Median	0.86	1.42	1.01	0.86	0.43	0.29	0.82	0.66	1.74
Standard Dev.	0.30	0.49	0.32	0.25	0.54	0.45	0.34	0.35	0.77
Minimum (m^2)	0.39	0.39	0.38	0.59	0.21	0.17	0.33	0.28	1.16
Maximum (m^2)	1.32	1.96	1.56	1.31	1.93	1.56	1.37	1.30	3.25
Depth*									
Average (m)	0.16	0.20	0.15	0.15	0.10	0.08	0.16	0.16	0.25
Median	0.16	0.23	0.16	0.16	0.09	0.06	0.16	0.18	0.21
Standard Dev.	0.052	0.072	0.057	0.044	0.074	0.057	0.038	0.050	0.086
Minimum (m)	0.09	0.08	0.05	0.08	0.03	0.03	0.08	0.07	0.16
Maximum (m)	0.24	0.29	0.24	0.21	0.25	0.20	0.20	0.22	0.39
Width*									
Average (m)	5.39	6.10	6.44	6.39	6.60	5.70	5.00	4.64	8.38
Median	5.50	5.95	6.40	6.50	6.65	5.00	4.50	4.10	8.20
Standard Dev.	0.47	0.83	1.01	1.02	1.71	1.90	1.34	1.62	0.75
Minimum (m)	4.50	4.50	4.85	4.60	4.40	3.90	2.70	2.60	7.00
Maximum (m)	6.00	7.50	8.30	8.00	9.50	9.50	6.80	6.65	10.00

* Obtained from cross sectional measurements

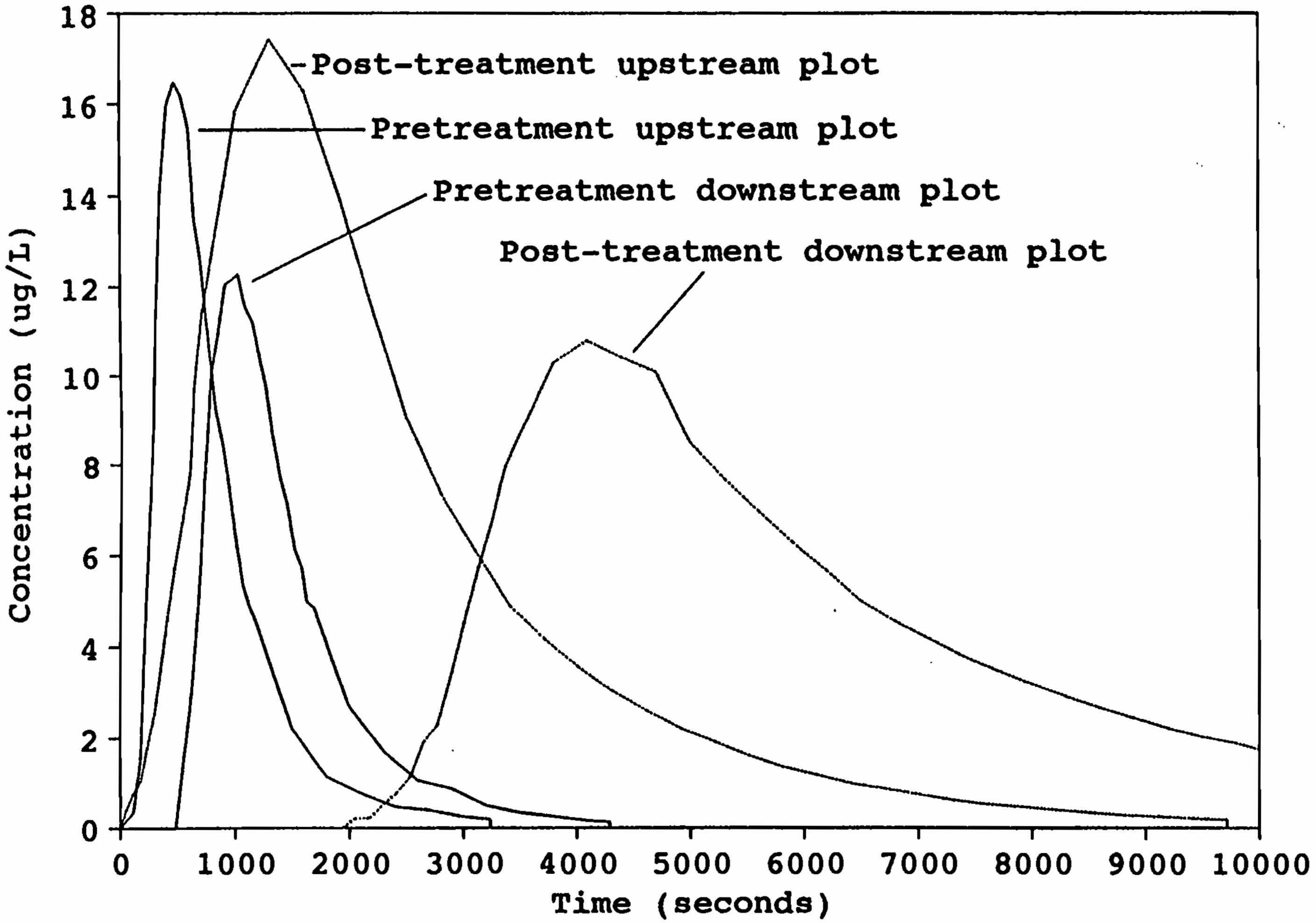

Figure 7. Camp Creek concentration-time plot showing pre- and post-treatment dye curves for CC21.

(and mass) of dye was used for both pre- and post-treatments, the curves differ in curve area, peak height, and skew. Differences between concentration-time plot areas are largely a function of the relationship between discharge and tracer mass. The curve peak height is affected by discharge and slackwater. And, differences in curve skewness are largely due to changes in slackwater. When discharge decreases, the concentration of the tracer increases because of less instream dilution. Thus, post-treatment channel units will probably have larger peak concentrations (due to lower discharge), unless this effect is overcome by the curve attenuation that results from increased slackwater. A concentration-time curve for the upper and lower end of a channel unit was constructed so that the pool area could be "isolated" from the upstream mixing length. Thus, downstream:upstream ratios for the variables calculated from concentration-time plots could be used as dependent variables (assuming the adequate mixing length in the reach was exceeded).

Although the area under both downstream and upstream curves should be equivalent, this was not always true. If the area under the downstream and upstream curves differ, then error may be attributed to incomplete mixing of the dye plume throughout the vertical and lateral water profile of the stream, or, dye adsorption onto organic debris and sediment. Because the potential for dye loss increases as the plume travels downstream, the downstream concentration-time plot may have a smaller area under the curve than the upstream curve. In contrast, the downstream curve should never have a larger area under the curve than the upstream curve. Sampling error resulting from different release masses was not a problem because both curves were obtained from the same dye plume. Appendix E shows downstream:upstream ratios of the areas under each curve in addition to the percent difference between each curve. Utilizing a Student's two-tailed t-test, differences between concentration-time curve areas for downstream samples and upstream samples acquired from each channel unit were not found to be statistically significant (Appendix E).

Utilizing dependent variables obtained from dye concentration-time curves, regression analyses were performed with independent variables of Zone I debris and the average cross-sectional values for velocity, area, width, and depth. The regression results are presented in Table 10. Having acquired concentration-time curves at upstream and downstream ends of the channel unit, individual transit times could be calculated for each channel unit by assessing time differences between dye curve centroids. Although there was a noticeable change in transit time after wood installation (Figure 6), the

Table 10. Regression results from Camp Creek pre- and post-treatments (• denotes statistically significant at $p \leq 0.10$; n = 4).

Dependent Variables[a] Independent Variables[b]		Pre r	Pre p-value	Post r	Post p-value
Transit time (s)					
Debris	(m^3m^{-1})	+0.41	0.59	+0.89	0.11
Velocity	(ms^{-1})	-0.19	0.81	-0.54	0.46
Area	(m^2)	+0.40	0.60	+0.87	0.13
Depth	(m)	+0.02	0.98	+0.66	0.34
Width	(m)	+0.34	0.66	+0.38	0.62
Transient storage					
Debris	(m^3m^{-1})	-0.50	0.50	+0.82	0.18
Velocity	(ms^{-1})	+0.77	0.23	+0.07	0.93
Area	(m^2)	-0.57	0.43	+0.27	0.73
Depth	(m)	-0.92	0.08•	+0.34	0.66
Width	(m)	+0.98	0.02•	-0.14	0.86
Exchange coefficient					
Debris	(m^3m^{-1})	+0.14	0.85	-0.34	0.66
Velocity	(ms^{-1})	+0.22	0.78	-0.57	0.43
Area	(m^2)	-0.48	0.52	+0.18	0.82
Depth	(m)	+0.06	0.94	+0.50	0.50
Width	(m)	-0.50	0.50	-0.90	0.10•
Leading edge velocity					
Debris	(m^3m^{-1})	-0.20	0.80	-0.34	0.66
Velocity	(ms^{-1})	-0.06	0.94	+0.02	0.98
Area	(m^2)	-0.19	0.81	-0.31	0.69
Depth	(m)	+0.27	0.73	+0.10	0.90
Width	(m)	-0.62	0.38	-0.94	0.06•
Time of concentration					
Debris	(m^3m^{-1})	-0.41	0.59	+0.51	0.49
Velocity	(ms^{-1})	+0.25	0.75	-0.18	0.82
Area	(m^2)	+0.04	0.96	+0.50	0.50
Depth	(m)	-0.51	0.48	+0.11	0.89
Width	(m)	+0.84	0.16	+0.86	0.14

[a] Dependent variables are downstream:upstream ratios.

[b] Independent variables are Zone I debris and average cross-sectional velocity, area, depth, and width.

Table 10 Continued. (• denotes statistically significant at $p \leq 0.10$; $n = 4$).

Dependent variables[a]			Pre		Post
Independent variables[b]		r	p-value	r	p-value
Dye centroid velocity					
Debris	(m^{3}m^{-1})	+0.28	0.72	-0.58	0.42
Velocity	(ms^{-1})	-0.55	0.45	-0.03	0.97
Area	(m^2)	+0.29	0.71	-0.36	0.64
Depth	(m)	+0.76	0.24	+0.02	0.98
Width	(m)	-0.97	0.03•	-0.91	0.09•
Concentration-time curve area					
Debris	(m^{3}m^{-1})	+0.04	0.96	+0.79	0.21
Velocity	(ms^{-1})	-0.96	0.04•	-0.81	0.19
Area	(m^2)	+1.00	0.00•	+0.96	0.04•
Depth	(m)	+0.83	0.17	+0.95	0.05•
Width	(m)	-0.50	0.50	-0.15	0.85
Peak concentration					
Debris	(m^{3}m^{-1})	+0.02	0.98	-0.39	0.61
Velocity	(ms^{-1})	+0.12	0.88	-0.33	0.67
Area	(m^2)	-0.39	0.61	-0.05	0.95
Depth	(m)	+0.14	0.86	+0.33	0.67
Width	(m)	-0.55	0.45	-0.97	0.03•
Skew coefficient					
Debris	(m^{3}m^{-1})	-0.56	0.44	+0.50	0.50
Velocity	(ms^{-1})	-0.45	0.55	+0.21	0.79
Area	(m^2)	+0.65	0.35	-0.03	0.97
Depth	(m)	+0.18	0.82	+0.19	0.81
Width	(m)	+0.22	0.78	-0.46	0.54

[a] Dependent variables are downstream:upstream ratios.

[b] Independent variables are Zone I debris and average cross-sectional velocity, area, depth, and width.

relationship between transit times and wood volumes was not statistically significant utilizing simple linear regression.

Dispersion affects the leading edge, trailing edge, and peak concentration travel times of a dye plume. Consider for example, a vertically and laterally mixed slug of dye that is approaching the pool of a channel unit. As the plume enters the pool, it undergoes additional dispersion due to molecular motion and turbulent fluctuations. The leading edge velocity and trailing edge velocity will decrease and/or enter a "dead zone" (zero velocity), increasing the hydraulic retention. Hence, it is important to use centroid differences when evaluating changes in travel times. Because peak concentration travel time between two successive sites is similar to the centroid travel time (Wilson et al., 1986), the times of travel for peak concentrations were not calculated. However, for post-treatment Camp Creek it appears that peak concentrations significantly decrease with increasing width (Table 10). Similarly, ratios of leading edge velocity and centroid velocity were also significantly correlated with width (Figure 8). The decreases in peak concentration, leading edge velocity, and centroid velocity ratios indicate that the stream velocity is decreasing through the channel unit and the dye plume may be undergoing additional dispersion because

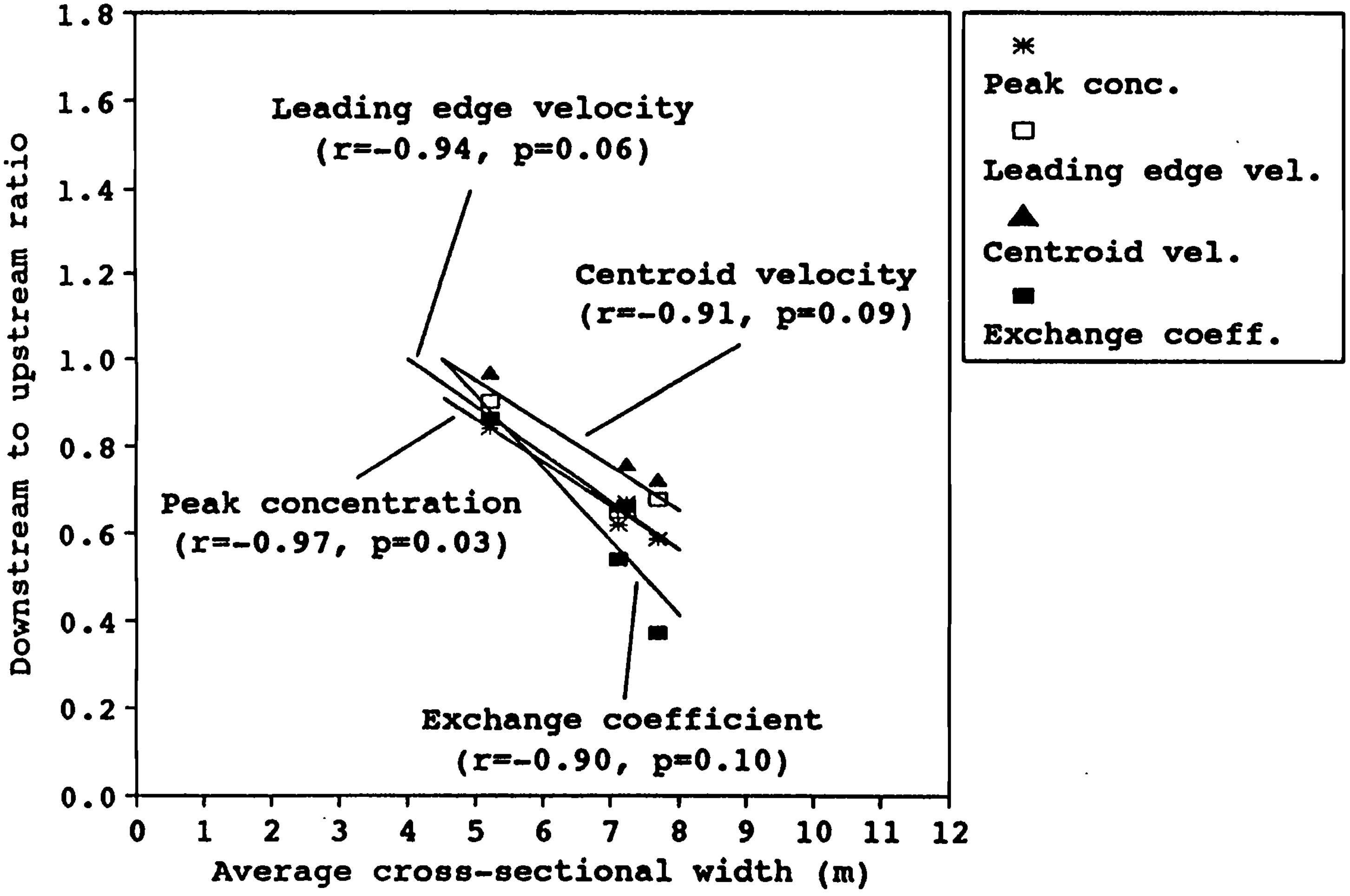

Figure 8. Regression of post-treatment Camp Creek concentration-time plot variables on average cross-sectional width.

the average cross-sectional stream volume has enlarged and storage is enhanced, indicating an increase in the dead zone. Although the post-treatment Camp Creek peak concentrations and dye plume velocities decreased with increasing channel width, dead zone volume fraction regressions were not statistically significant with various independent variables (Table 10).

The exchange coefficient (δ) ratios (Figure 8) of downstream:upstream also had a significantly negative correlation with width. The negative correlation indicates that the fraction of total channel unit stream volume (high flow velocity compartment plus near zero velocity compartment) moving into or out of storage per unit time is decreasing with increasing width. Dispersion is probably increasing with increasing stream width, provided there is enough instream structural complexity (bed roughness and large debris) to enhance dispersion; thus, indicating potential lateral dead zone.

The dispersion reasoning is based on the exchange coefficient equation $\delta=(2\cdot a_L\cdot X_i)/(u_c\cdot a_u\cdot \sigma^2)$. The variable σ^2 is the second moment (variance) of the concentration-time plot and is representative of the dye plume dispersion. As dispersion increases, σ^2 increases, and δ will decrease. Physically, however, not all cases of increased dispersion will result in decreased δ, because what also happens is that dead zone (a_L) increases and the average convective velocity (u_c) decreases, resulting in either an increase or decrease in δ, depending on relative magnitude. Although the post-treatment Camp Creek exchange coefficient decreased with increasing channel width, dead zone volume fraction regressions were not statistically significant with various independent variables (Table 10).

Because the exchange coefficient is inversely related to dead zone (transient storage), it aids in describing whether dead zone is increasing. Assuming constant discharge, when the dead zone increases, the exchange coefficient will decrease, assuming dispersion is becoming increasingly large. When dead zone (a_L) increases, the average convective velocity (u_c) should decrease because the average cross-sectional volume (near zero velocity compartment plus flowing velocity compartment) becomes large, enhancing storage. Thus, the amount of time a particle spends in a dead zone, once it has entered, may increase (longer transient storage) because the particle, on average, is not cycling into and out of storage as rapidly (Thackston and Schnelle, 1970). Contrastingly, if the stream channel is blocked (i.e., transverse log jam) and retains a large amount of slackwater, the dye plume may slow down, but not actually disperse throughout the channel unit because the dye plume is behaving as plug flow. This kind of situation would not result in an increase in the dead zone parameter a_L.

On an individual channel unit basis dead zone did increase in post-treatment CC21 (high complexity) and CC42 (unaltered), along with an expected decrease in the exchange coefficient. The increase in dead zone in CC21 is probably a response to debris additions. Following debris loading, CC21 depth and length increased, further suggesting an increase in transient storage. However, the lower post-treatment discharge is also influencing CC21 via a decrease in dye dilution and a lower average convective velocity of the dye plume. In view of the fact that the relative and absolute changes in both morphometric and hydraulic parameters were much larger in CC21 than in the other reaches, it is likely that the changes can be attributed to debris volume enhancement, as all reaches experienced the same discharge decline. CC42 dead zone is also being influenced by the lower discharge because the increased dye plume concentrations and lower convective velocities are increasing dispersion and dye residence time. Dead zone was not enhanced in CC23 and CC27 following debris additions. Thus, transient storage only appears to have increased in post-treatment CC21. Despite a lower discharge during the post-treatment period, CC21 transit time increased, pool dimensions enlarged, and dye dispersion was able to increase (based on an increase in dead zone and subsequent decrease in exchange coefficient between pre- and post-treatment).

Camp Creek transit time appears to increase following debris loading, especially when a large amount of wood is used (CC21). But, is there a change between pre- and post-treatment relationships of transit time versus channel characteristics? Specifically, is there a difference resulting from the addition of wood? An "additional sums of squares" test (Draper and Smith, 1966) was used to evaluate whether transit time differs significantly between pre- and post-treatment. Results indicate that post-treatment transit time is significantly greater than pretreatment when regressed on Zone I debris volumes (Table 11). The "additional sums of squares" method compared the pretreatment regression (slope and intercept) of transit time on Zone I woody debris with the post-treatment regression. However, when pre- and post-treatment transit times were compared with average cross-sectional velocity, area, depth, and width, no significant differences were detected (Table 11).

Table 11. Additional sums of squares test results for Camp Creek pre- and post-treatment transit times (• denotes statistically significant at $p \leq 0.10$; ns denotes nonsignificant).

Variable[a]		Calculated F Value[b]	Significant
Transit Time on[a]:			
Debris	(m^3m^{-1})	11.4	•
Velocity	(ms^{-1})	1.1	ns
Area	(m^2)	3.4	ns
Depth	(m)	1.3	ns
Width	(m)	1.3	ns

[a] The debris is Zone I and the other variables are average cross-sectional values.

[b] v_1 and v_2 values of 2 and 4, respectively.

DRIFT CREEK AND LOBSTER CREEK CHANNEL UNITS

Drift and Lobster Creeks provided an opportunity to study wood, rock, and gabion structures. Instream structures for Drift Creek included wood and boulder, whereas structures for Lobster Creek were comprised of wood and gabions. Habitat alteration structures for both streams were in place and functional prior to this study. Consequently, there was a problem in selection of a control to use as a comparison site. Thus, non-treated control channel units can only serve as comparison sites for the treated channel units.

Longitudinal Profiles

The average water surface slopes of Drift Creek and Lobster Creek were 0.9 and 1.3 percent, respectively (Figure 9). Drift Creek is also the largest and most sinuous of the three channel units. Valley sideslopes averaged 33 percent for Drift Creek and 50 percent for Lobster Creek. At the Lobster Creek site, aggradation has been occurring and many of the gabions have a large amount of gravel deposition occurring directly upstream of their position. Moreover, some of the gabion structures have been completely covered with gravel.

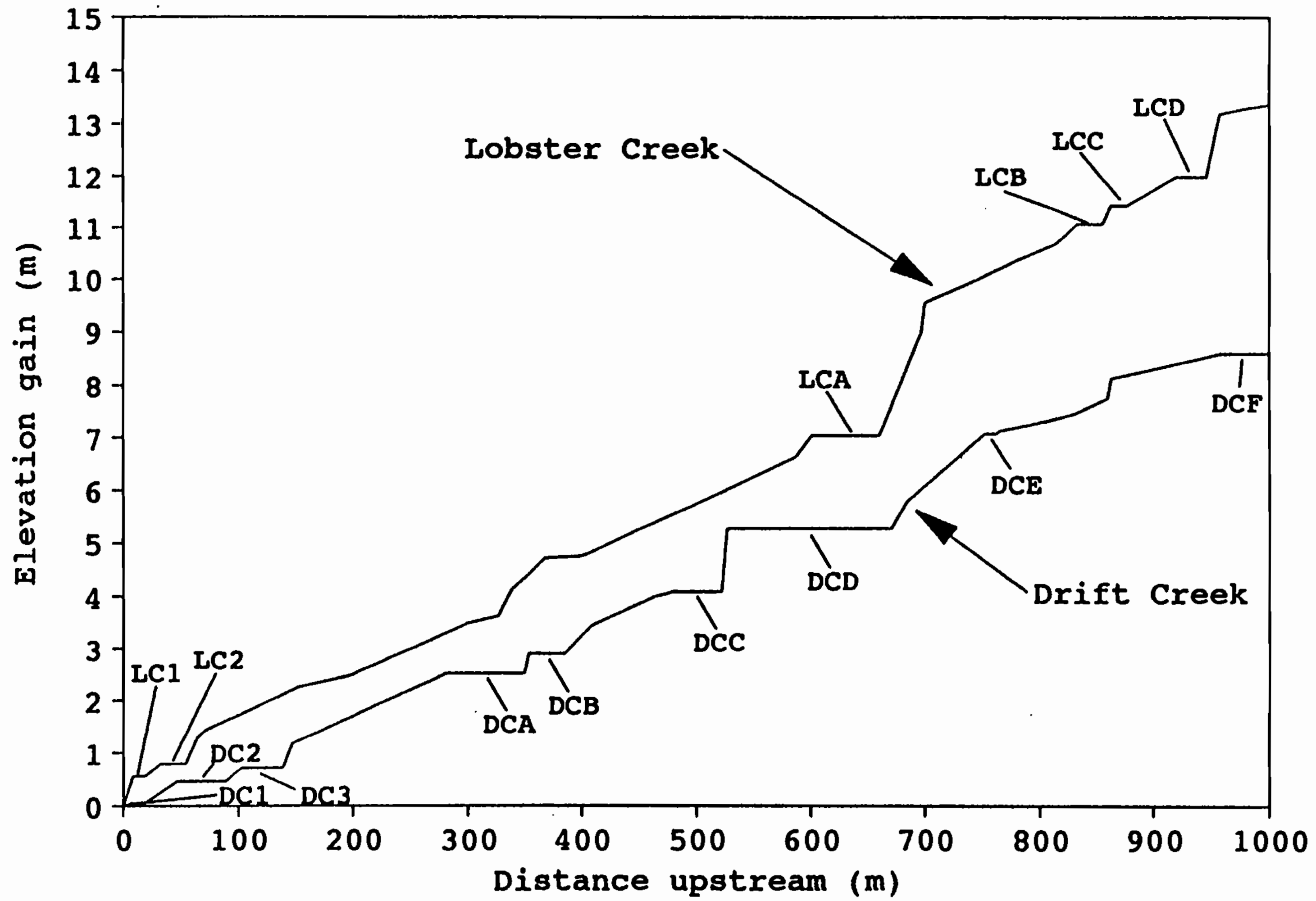

Figure 9. Drift Creek and Lobster Creek longitudinal profiles.

Large Woody Debris and Rock

Wood and rock volumes were combined because they jointly influence stream hydraulics and it would be difficult to separate their individual effects. The total wood and rock volume determined in each of the four influence zones for Drift Creek and Lobster Creek are tabulated in Appendix D. Zone II had the largest quantity of debris per meter of channel unit pools for Drift Creek and Lobster Creek, respectively (Figure 10). From a geomorphic standpoint, the combination of Zones I and II are the most important because of their interactions with the streamflow when streampower is at its highest (excluding episodic flood flows when stream banks are overtopped). The largest amount of scour, sediment transport, and debris accumulation would occur when Zones I and II are operating together. In both Drift and Lobster Creeks, Zone IV had the second largest amount of debris, followed by Zone III, and Zone I.

During summer low flows the total pool volume decreases (but relative dead zone may increase). Consequently, sufficient summer pool depth may be a concern in some streams. While studying the effects of woody debris on salmonid habitat in southeast Alaska, Lisle (1986) reported that debris dams effectively maintain stream depth at low flow. Moreover, relatively

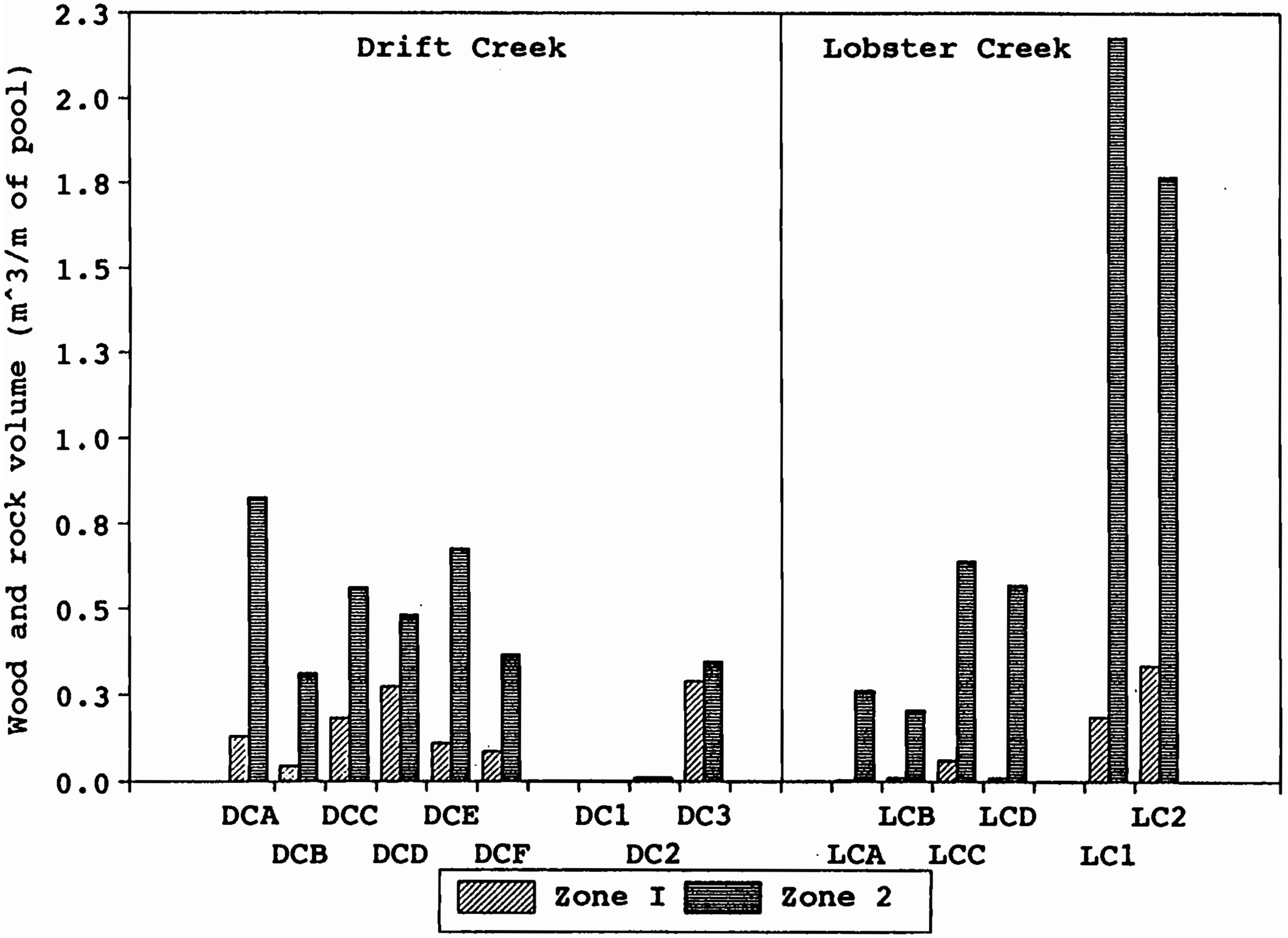

Figure 10. Wood and rock volume per meter of channel unit for influence Zones I and II.

small debris in shallows and constrictions may greatly increase roughness (not necessarily in the form of a dam) as discharge drops during the summer, thereby retarding the decrease in stream depth (Lisle, 1986). Debris comprising habitat alterations in the Drift/Lobster study often does not appear to provide low flow structural diversity (complexity) because the stream is flowing around or under the obstruction with minimal eddying or slackwater.

Several channel units may have hydraulic regimes that might exhibit patterns similar to Lisle's (1986) findings pertaining to low flow dams. Treatment channel units DCD, DCF, and LCB had a large portion of slackwater comprising a section of their pool volume throughout the summer months. DCD and LCB provided deep pooling because they were associated with structures designed to operate as weirs. Similarly, DCD and DCF had pooling associated with downstream V configured wood that was cabled in a manner to allow the debris to fluctuate with discharge, thus maintaining an element of channel roughness at various flows. On the other hand, bedrock pools found in controls DC2, DC3, LC1, and LC2 have natural pooling at low flow without a lot of debris accumulation.

Figure 11 illustrates the concentration-time plots for channel units DCD and LCA and is a good example of the attenuation of peak dye concentration that occurs as a dye

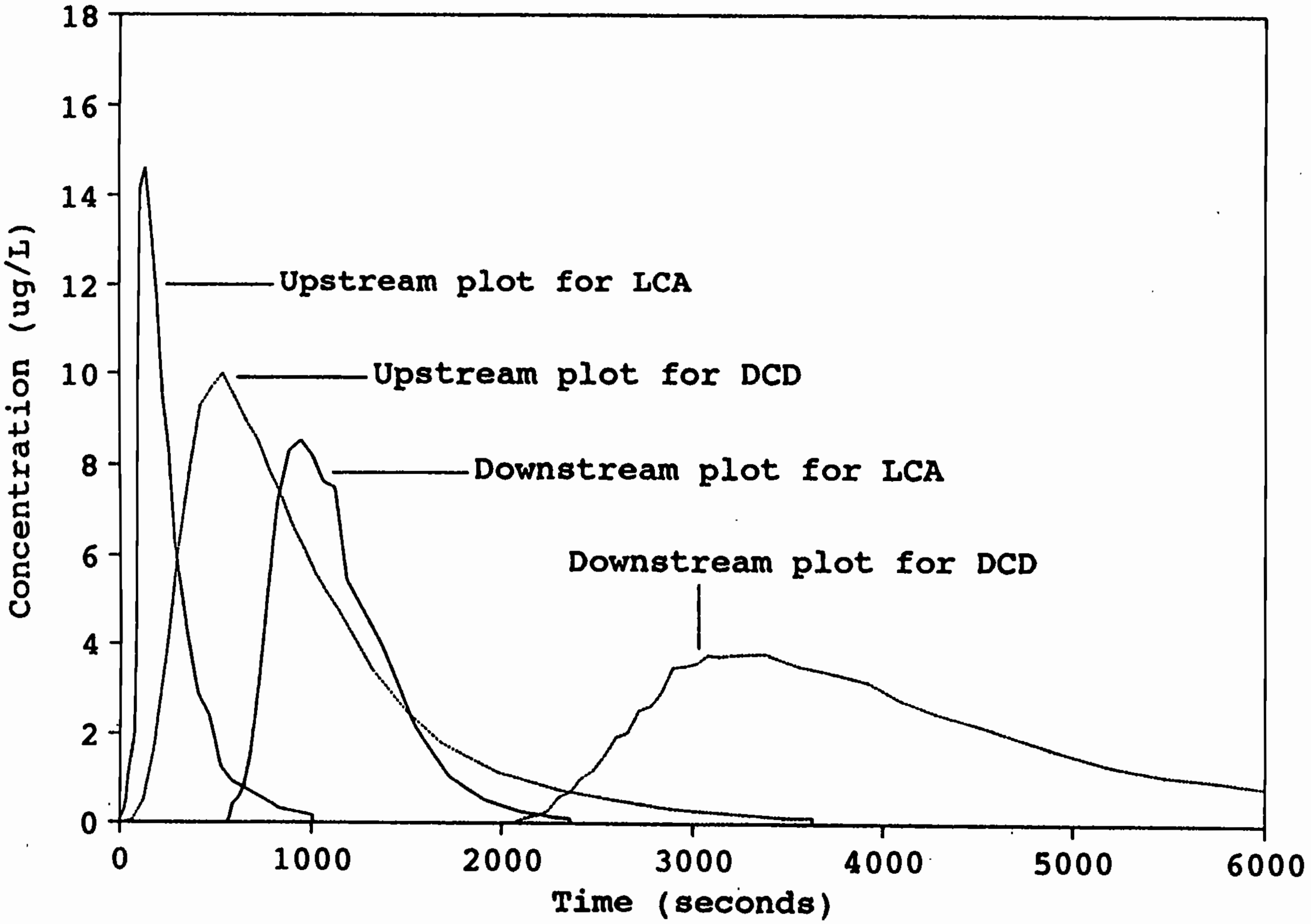

Figure 11. Example of ideal concentration-time plots for pooling associated with complex debris loading and gabion structure in Drift Creek (DCD) and Lobster Creek (LCC), respectively.

plume travels through a channel unit. Although the attenuation of peak concentrations varied between channel units, the curves in Figure 11 are a good generalization of what most of the other channel unit curves looked like. Drift Creek DCD is complex (high debris loading) and had the longest transit time. Lobster Creek LCA is comprised of three gabions and is not very complex in terms of wood volume. Although DCD and LCA have different levels of complexity, the downstream attenuation of their peak concentrations indicate that the dye plume has decreased in velocity and is dispersing throughout the channel unit.

The area under both upstream and downstream curves should be equivalent, however, as shown in Appendix E this is not always the outcome. Error may be attributed to incomplete mixing throughout the vertical and lateral water profile of the stream, or dye adsorption onto organic debris and sediment. Because dye loss potential increases as the plume travels downstream, the downstream concentration-time plot curve cannot have a larger area under the curve than the upstream curve. Appendix E shows downstream:upstream ratios of the areas under each curve in addition to the percent difference between each curve. Utilizing a Student's two-tailed t-test, differences between the areas of downstream and upstream concentration-time curves for each channel unit were not found to be statistically significant (Appendix E), indicating that virtually all of the dye tracer was recovered, a condition necessary for successful implementation of conservative tracer experiments.

Figure 12 is an example of what an undesirable (bad) concentration-time plot looks like. The downstream curve has a larger area under the curve as well as a higher peak concentration (no downstream attenuation). It is hard to "guess" why, however, a possible explanation is that the dye plume underwent incomplete lateral or vertical mixing prior to reaching the upstream sampling location. Sabol and Nordin (1981) obtained similar results when they calculated a ratio of the mass of tracer acquired at a downstream sampling location to the mass injected and found that in some instances the recovery ratio was larger than one. Table 12 also shows LCC to have an anomalous average cross-sectional velocity (this velocity was not calculated from dye plume parameters). Nonetheless, the dye plume in Figure 12 is not dispersing and hydraulic retention due to instream debris (wood structure) is minimal. This situation suggests that instream structural complexity is low. Transit times calculated for Drift and Lobster Creeks are shown in Figure 13.

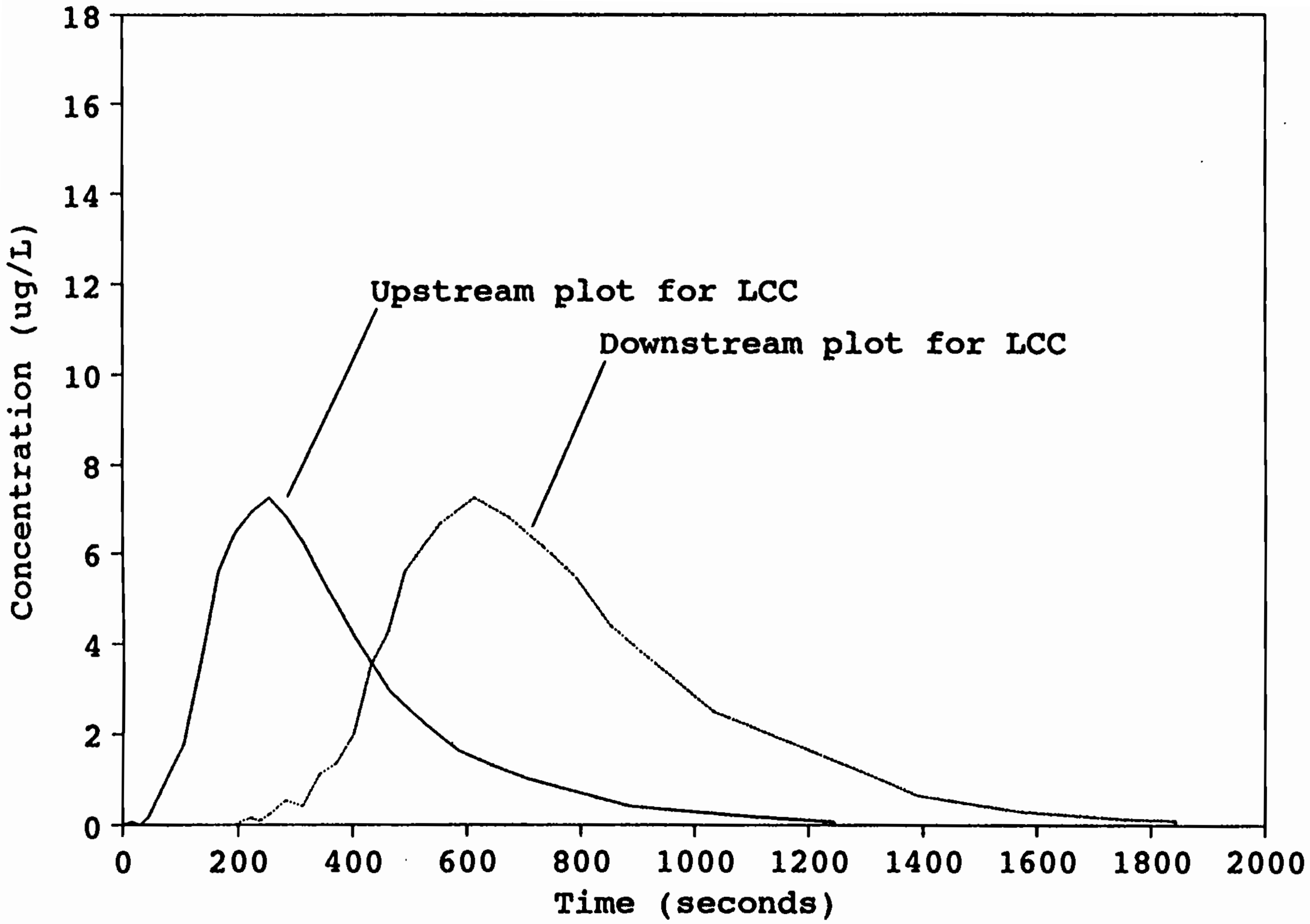

Figure 12. Example of a concentration-time plot for a channel unit expected to have a minimal level of complexity.

Table 12. Summary statistics of channel measurements for Drift and Lobster Creeks.

Statistic	Treatments = A,B,C,D,E, & F						Controls = 1,2, & 3		
	DCA	DCB	DCC	DCD	DCE	DCF	DC1	DC2	DC3
Discharge (m^3/s)	0.45	0.45	0.23	0.19	0.20	0.17	0.29	0.20	0.20
Pool Length (m)	68	32	42	143	9	106	12	43	36
Sample Size	27	7	13	10	9	14	9	11	10
Velocity									
Average (m/s)	0.17	0.08	0.13	0.07	0.10	0.10	0.10	0.07	0.06
Median	0.17	0.07	0.13	0.06	0.08	0.06	0.09	0.08	0.05
Standard Dev.	0.080	0.032	0.068	0.041	0.082	0.072	0.029	0.020	0.038
Minimum (m/s)	0.07	0.04	0.05	0.02	0.05	0.04	0.08	0.05	0.02
Maximum (m/s)	0.36	0.12	0.26	0.15	0.31	0.29	0.17	0.12	0.16
Area									
Average (m^2)	3.28	3.40	2.23	3.86	2.70	2.62	2.34	3.19	4.74
Median	3.72	3.27	1.70	3.14	2.64	3.17	2.54	2.88	4.55
Standard Dev.	1.54	1.44	1.15	2.46	1.07	1.36	0.53	0.81	2.77
Minimum (m^2)	1.26	1.87	0.87	1.31	0.65	0.59	1.36	1.85	1.43
Maximum (m^2)	6.65	5.45	4.18	9.51	3.97	4.81	2.93	4.68	11.69
Depth*									
Average (m)	0.24	0.33	0.19	0.33	0.30	0.25	0.29	0.33	0.42
Median	0.20	0.35	0.17	0.28	0.31	0.28	0.30	0.29	0.39
Standard Dev.	0.103	0.143	0.083	0.190	0.100	0.122	0.096	0.114	0.234
Minimum (m)	0.10	0.18	0.08	0.16	0.13	0.08	0.17	0.14	0.16
Maximum (m)	0.49	0.57	0.32	0.77	0.42	0.44	0.41	0.51	0.93
Width*									
Average (m)	13.46	10.38	11.40	11.63	8.83	10.75	8.29	10.06	11.46
Median	13.40	10.00	11.50	12.20	9.80	11.00	8.40	9.56	11.75
Standard Dev.	1.89	1.54	1.82	2.52	1.89	2.46	1.25	1.62	2.06
Minimum (m)	10.00	8.10	8.35	7.00	4.95	6.30	6.48	7.50	7.45
Maximum (m)	17.00	12.00	14.30	15.20	10.90	15.80	10.25	13.35	14.00

* Obtained from cross sectional measurements

Table 12 Continued.

Statistic	Treatments = A,B,C, & D				Controls = 1 & 2	
	LCA	LCB	LCC	LCD	LC1	LC2
Discharge (m^3/s)	0.03	0.03	0.09	0.09	0.04	0.04
Pool Length (m)	59	22	14	26	10	22
Sample Size	15	10	10	9	10	10
Velocity						
Average (m/s)	0.07	0.07	0.33	0.15	0.07	0.05
Median	0.04	0.07	0.19	0.13	0.07	0.03
Standard Dev.	0.063	0.043	0.308	0.056	0.030	0.031
Minimum (m/s)	0.02	0.01	0.05	0.06	0.02	0.02
Maximum (m/s)	0.26	0.15	0.96	0.24	0.13	0.11
Area						
Average (m^2)	0.60	1.05	0.66	0.70	0.65	1.05
Median	0.70	0.43	0.50	0.71	0.52	1.06
Standard Dev.	0.29	1.43	0.58	0.31	0.38	0.56
Minimum (m^2)	0.12	0.20	0.10	0.39	0.26	0.33
Maximum (m^2)	1.24	4.27	1.70	1.42	1.61	2.13
Depth*						
Average (m)	0.11	0.16	0.10	0.13	0.15	0.22
Median	0.11	0.09	0.09	0.11	0.12	0.22
Standard Dev.	0.050	0.179	0.069	0.045	0.090	0.101
Minimum (m)	0.04	0.03	0.01	0.06	0.07	0.07
Maximum (m)	0.20	0.55	0.23	0.20	0.38	0.41
Width*						
Average (m)	5.49	5.73	6.43	5.99	4.29	4.73
Median	4.60	5.20	6.60	5.00	4.32	4.55
Standard Dev.	1.73	1.90	3.28	2.52	0.56	1.32
Minimum (m)	3.36	3.90	2.85	3.55	3.25	2.60
Maximum (m)	8.90	9.95	11.45	10.70	5.03	6.50

* Obtained from cross sectional measurements

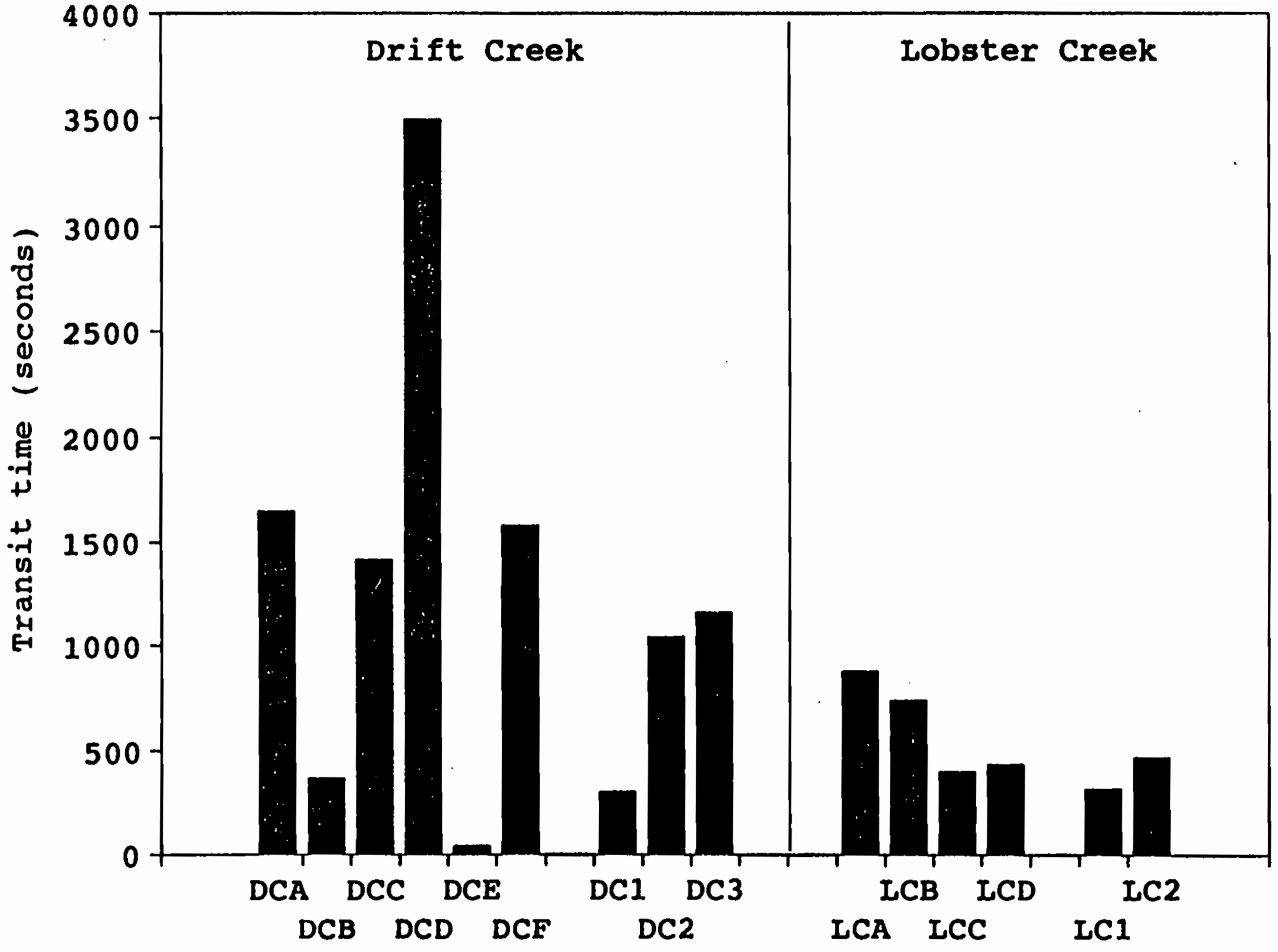

Figure 13. Drift Creek (DC) and Lobster Creek (LC) channel unit transit times.

Control and Treatment Statistical Analyses

Summary statistics of channel measurements for Drift Creek and Lobster Creek are presented in Table 12. If instream structures increase in size or create backwater, plunge, and scour pools, then, a change in the average cross-sectional velocity, area, depth, and width can be expected. Student's t-tests were used to compare the mean values of channel measurements as well as dye plume statistics (Table 13). Results of the t-tests did not show any significant differences between treatment and control physical measurements or channel parameters. On the other hand, t-tests showed significant differences for several dye plume parameters (e.g., downstream:upstream ratios of peak concentration, times of concentration, centroid velocities, and leading edge velocities). In the case of centroid and leading edge velocities, the one-tailed tests showed treatment velocities to be significantly less than the control velocities. A significant difference between transit time, dead zone and exchange coefficients was expected, although t-tests for these differences were not significant ($p > 0.10$).

It is not known whether, or to what extent, habitat alterations changed the average cross-sectional areas of the Drift Creek and Lobster Creek channel units. Thus, discretion is warranted when assessing the following

Table 13. One-tailed t-test results for Drift and Lobster Creeks (• denotes statistically significant at $p \leq 0.10$; n = 5 and 10 for control and treatment, respectively).

Variables[a]		Test[b]	P-value
Debris	(m^3m^{-1})	treatment > control	0.43
Velocity	(ms^{-1})	treatment < control	0.86
Area	(m^2)	treatment > control	0.64
Depth	(m)	treatment > control	0.91
Width	(m)	treatment > control	0.11
Transit time	(s)	treatment > control	0.18
Dead zone	Ratio	treatment > control	0.72
Exchange Coefficient	"	treatment > control	0.71
Peak concentration	"	treatment < control	0.06•
Time of concentration	"	treatment > control	0.04•
Skew	"	treatment > control	0.94
Centroid velocity	"	treatment < control	0.08•
Leading edge velocity	"	treatment < control	0.06•
Concentration-time curve area	"	treatment < control	0.62

[a] Debris is Zone I and velocity, area, depth, and width are average cross-sectional values. Except for transit time, all other variables are downstream: upstream ratios.

[b] H_o: treatment = control versus
H_a: treatment ≠ control

results because it is not known whether the statistically significant correlations are a direct result of channel alteration due to debris loading, changing discharge, or no change in treatments.

The regression results are presented in Table 14. Individual transit times were calculated for each channel unit by assessing time differences between dye curve centroids. Transit time significantly correlated with average cross-sectional area for control and treatment reaches (Figure 14).

Dye plume centroid velocities within the control and treatment reaches were statistically significant and correlated with average cross-sectional areas (Figure 15). However, these correlations were positive and negative for the treatment and control reaches, respectively. It is not clear why the centroid velocities for the treatments had a positive correlation with average cross-sectional areas. One reason may be that the Drift Creek treatment units often contained a large amount of channel that was scoured to bedrock, with sediment aggradation only occurring in the deeper pooled sections. On the other hand, Lobster Creek treatments were highly aggraded with a greater bed roughness than the controls. Moreover, Zone I wood debris was not heavily distributed within the treatment units at either Drift Creek or Lobster Creek and did not appear to play a primary role in altering flows in

Table 14. Regression results from Drift and Lobster Creeks (• denotes statistically significant at $p \leq 0.10$; $n = 5$ and 10 for control and treatment, respectively).

Dependent Variables[a]		Treatment		Control	
Independent Variables[b]		r	p-value	r	p-value
Transit time (s)					
Debris	(m^{3}m^{-1})	+0.01	0.98	+0.10	0.87
Velocity	(ms^{-1})	+0.09	0.80	-0.23	0.71
Area	(m^2)	+0.55	0.10•	+0.86	0.06•
Depth	(m)	+0.37	0.30	+0.83	0.08•
Width	(m)	+0.53	0.11	+0.87	0.05•
Transient storage					
Debris	(m^{3}m^{-1})	-0.24	0.50	+0.26	0.68
Velocity	(ms^{-1})	-0.20	0.58	-0.03	0.96
Area	(m^2)	+0.46	0.18	+0.69	0.19
Depth	(m)	+0.47	0.17	+0.59	0.30
Width	(m)	+0.48	0.16	+0.68	0.21
Exchange coefficient					
Debris	(m^{3}m^{-1})	-0.21	0.56	+0.80	0.10•
Velocity	(ms^{-1})	+0.23	0.52	-0.62	0.26
Area	(m^2)	-0.10	0.79	-0.35	0.56
Depth	(m)	+0.10	0.79	-0.41	0.49
Width	(m)	-0.09	0.80	-0.39	0.52
Leading edge velocity					
Debris	(m^{3}m^{-1})	-0.28	0.43	+0.69	0.19
Velocity	(ms^{-1})	+0.17	0.64	-0.64	0.25
Area	(m^2)	+0.81	0.00•	-0.71	0.18
Depth	(m)	+0.87	0.00•	-0.64	0.24
Width	(m)	+0.49	0.15	-0.75	0.14
Time of concentration					
Debris	(m^{3}m^{-1})	+0.14	0.69	+0.35	0.57
Velocity	(ms^{-1})	-0.17	0.64	-0.44	0.45
Area	(m^2)	-0.36	0.31	+0.79	0.11
Depth	(m)	-0.44	0.20	+0.77	0.12
Width	(m)	-0.38	0.28	+0.78	0.12

[a] Dependent variables are downstream:upstream ratios.

[b] Independent variables are Zone I debris and average cross-sectional velocity, area, depth, and width.

Table 14 Continued. (• denotes statistically significant at $p \leq 0.10$; $n = 5$ and 10 for control and treatment, respectively).

Dependent Variables[a] Independent Variables[b]		Treatment r	 p-value	Control r	 p-value
Dye centroid velocity					
Debris	(m^3m^{-1})	-0.18	0.63	+0.23	0.71
Velocity	(ms^{-1})	+0.47	0.17	-0.33	0.59
Area	(m^2)	+0.75	0.01•	-0.85	0.07•
Depth	(m)	+0.81	0.00•	-0.75	0.15
Width	(m)	+0.42	0.23	-0.86	0.06•
Concentration-time curve area					
Debris	(m^3m^{-1})	+0.17	0.65	+0.19	0.75
Velocity	(ms^{-1})	-0.32	0.37	-0.01	0.98
Area	(m^2)	-0.60	0.07•	+0.63	0.25
Depth	(m)	-0.69	0.03•	+0.51	0.38
Width	(m)	-0.36	0.31	+0.62	0.26
Peak concentration					
Debris	(m^3m^{-1})	+0.14	0.69	-0.50	0.40
Velocity	(ms^{-1})	+0.16	0.66	+0.73	0.16
Area	(m^2)	-0.32	0.37	-0.39	0.51
Depth	(m)	-0.29	0.41	-0.43	0.47
Width	(m)	-0.21	0.57	-0.38	0.52
Skew coefficient					
Debris	(m^3m^{-1})	+0.05	0.90	-0.10	0.87
Velocity	(ms^{-1})	+0.09	0.80	+0.45	0.45
Area	(m^2)	+0.72	0.02•	+0.81	0.09•
Depth	(m)	+0.56	0.09•	+0.80	0.11
Width	(m)	+0.62	0.06•	+0.80	0.11

[a] Dependent variables are downstream:upstream ratios.

[b] Independent variables are Zone I debris and average cross-sectional velocity, area, depth, and width.

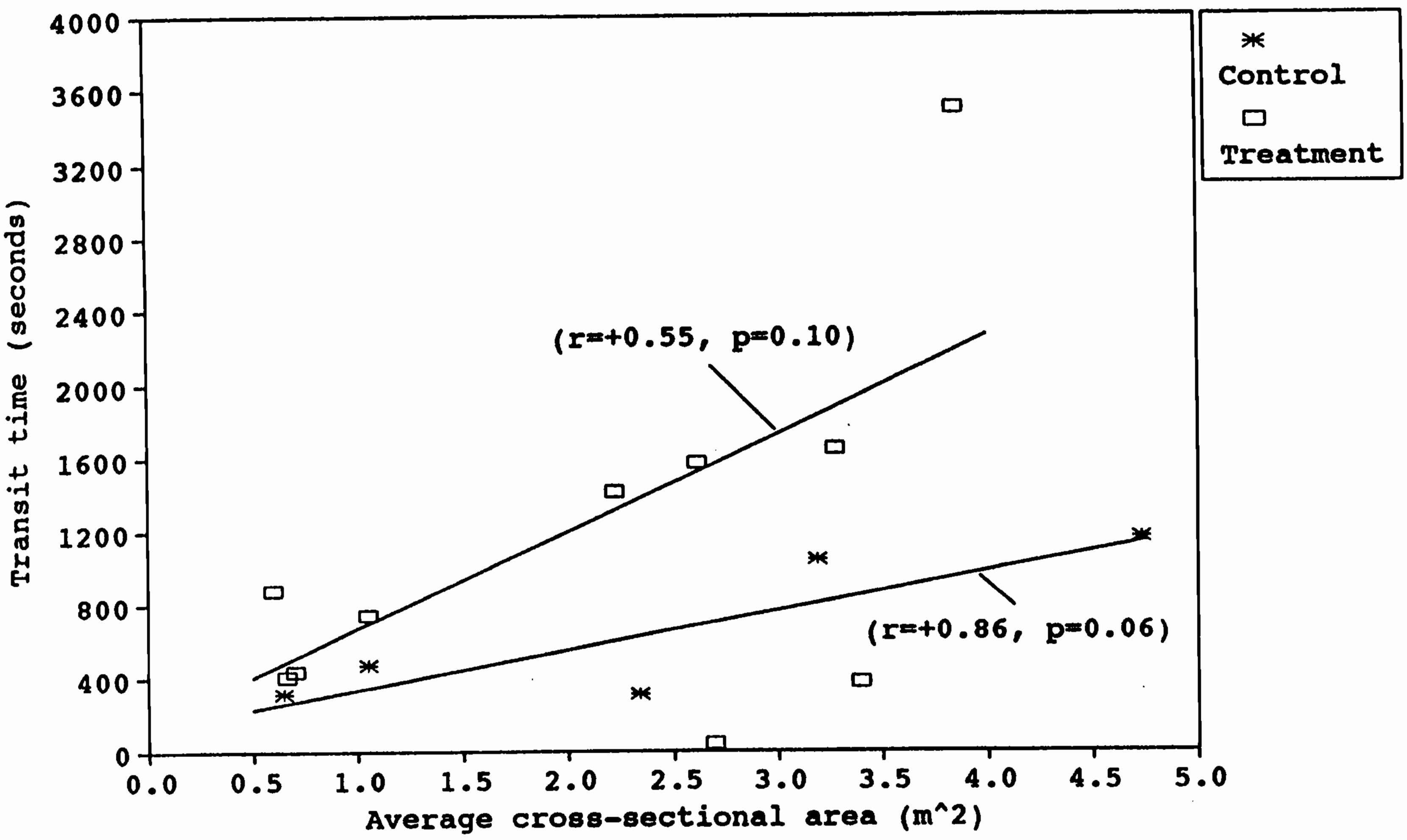

Figure 14. Regression of Drift Creek and Lobster Creek transit times on average cross-sectional area.

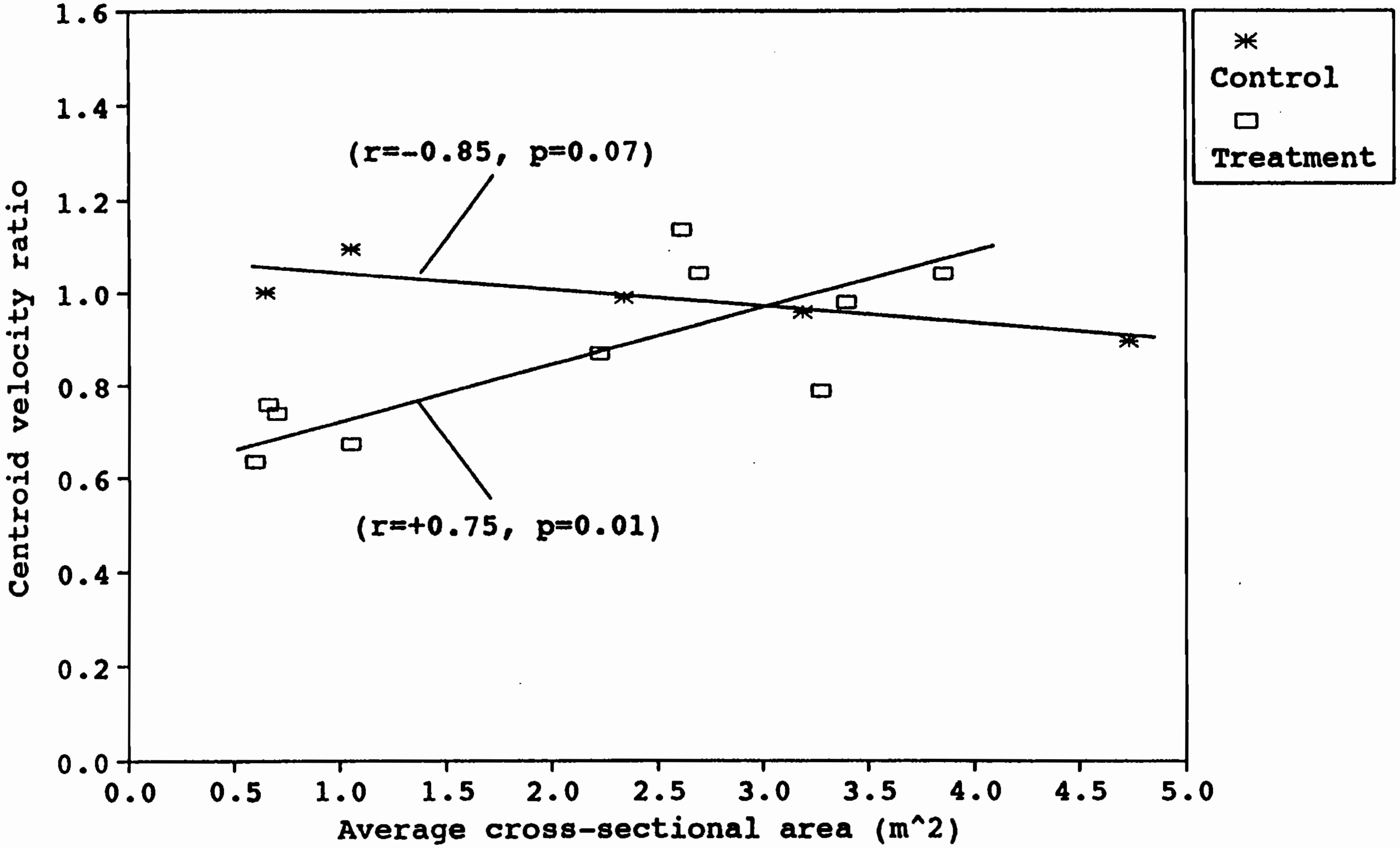

Figure 15. Regression of Drift Creek and Lobster Creek centroid velocity ratios on average cross-sectional area.

the control reaches. The large rock and boulder in the controls may aid in the lowering of stream velocities.

The exchange coefficient (the average number of times a dye molecule goes into storage per unit time) was significantly and positively correlated with debris volume in the control channel units (Table 14). Based on regression results, the intensity of turbulent exchange (cycling time) between the flowing water compartment and the dead zone volume fraction compartment (Sabol & Nordin model, 1978) appears to increase with increasing debris volume in the control reaches. However, wood in the control channel units is primarily in the shallower sections where it has a less direct interaction with streamflow and dye plume dispersion. Drift Creek controls DC2 and DC3 are deep, with scattered large boulders. However, because large coarse structural complexity is slight, a dye plume travelling through these channel units probably travels as plug flow. Thus, the dye plume average convective velocity and leading edge velocity will slow down and dispersion of the dye will not be as extensive as if large debris were interacting (mixing) with the main flow portion of the channel. Consequently, with an increasing exchange coefficient, dead zone would be expected to decrease. Lobster Creek controls were shallower than Drift Creek controls. However, they existed as bedrock pools without any coarse debris interacting with the stream flow. Thus, plug flow was probably the primary form of advection through these channel units and the volume fraction of dead zone was probably minimal.

Ratios of downstream:upstream dead zone volume fraction for Drift Creek and Lobster Creek controls and treatments ranged from 0.79 to 1.23. Dead zone would be expected to increase in a downstream direction and the ratio should be larger than 1 if transient storage is increasing. However, the ratio only exceeded 1 for two controls (DC3 and LC1) and four channel units comprised of woody debris (DCB, DCD, LCB, and LCC). In addition to DC3 and LC1, plug flow is expected to be occurring in DCD and LCB because of the slack water and scour pools associated with a transverse boulder weir and log jam in DCD and LCB, respectively. Thus, the debris weir and jam may be creating several small reservoirs instead of a diversity of dead zone storage pockets that are located throughout the stream.

Although differences in dead zone volume fraction was a major interest in this study, regression analysis using dead zone as a dependent variable did not yield any significant relationships. Thackston and Schnelle (1970) tested variables such as friction factor, velocity, depth, and slope with dead zone volume fraction. Their results indicated only the friction factor to have any significant effect on dead zone volume fraction. Moreover, the non-significant variables tabulated by Thackston and Schnelle (1970) did not show the dead zone to have any potential trends with increasing average velocity, depth, or slope.

Skew coefficients were found to be significantly correlated with average cross-sectional area for control and treatment reaches (Figure 16). Skew, being in the form of a long tail with lower concentration suggests a storage and release mechanism (Sabol and Nordin, 1978). Similarly, Thackston and Schnelle (1970) observed tracer concentrations to become trapped in stream pockets and to have a long tail during their work with dead zones. Based on Drift Creek and Lobster Creek regression analyses, dye probably is being stored in dead zone associated with large scale roughness, deep pools, or in backwater areas (DCD and LCB). On the other hand, skew may be less pronounced when there are dye losses in response to decay or the adsorption of the tracer on bed and bank sediment particles (Nordin and Troutman, 1980). However, dye losses resulting from decay or adsorption are assumed to not be a problem in this study. Dye plume decay was not assumed to be a problem because the dye samples acquired from the stream were collected within five hours of the release. Moreover, the dye plume was never exposed to continual sunlight. Adsorption was not assumed to be a

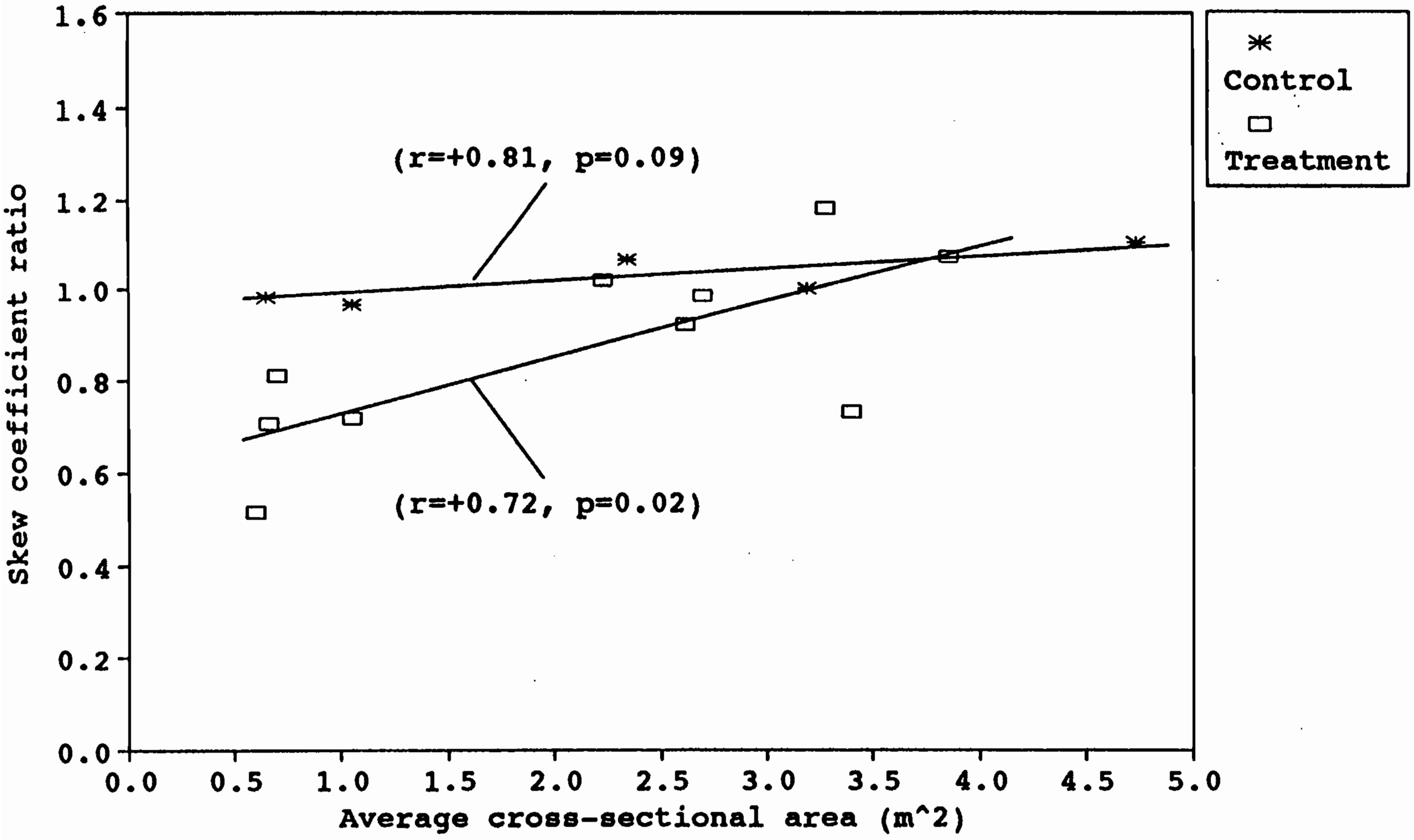

Figure 16. Regression of Drift Creek and Lobster Creek skew coefficient ratios on average cross-sectional area.

problem because of the underlying assumption that rhodamine WT is primarily non-adsorptive and can be utilized as a conservative tracer.

ADDITIONAL COMPARISONS

Gwynn Creek and Little Cummins Creek

Kaufmann (1987) completed a project incorporating fluorescent dye and the Sabol and Nordin (1978) dead zone model. During 1984 and 1985 he evaluated dead zone characteristics associated with stream recovery following debris torrents. The torrent affected sites were of varying age and located in the central Coast Range of Oregon. Included in his study were Gwynn Creek (1982 debris torrent) and Little Cummins Creek (undisturbed by debris torrent for 100 to 120 years). Gwynn Creek, following the torrent, underwent large woody debris habitat alteration. On the other hand, Little Cummins Creek is considered to be an old-growth system. During the late summer of 1991, dye releases were undertaken in both of these streams.

Methodologies between this study and the Gwynn Creek and Little Cummins Creek study by Kaufmann (1987) are different (i.e., Gwynn and Little Cummins were performed on a reach scale, among others). Nonetheless, methodologies for calculating dead zones and exchange coefficients are identical. Hydraulic tracer results for 1984, 1985, and 1991 are presented in Table 15.

The Gwynn Creek habitat alteration project is now approximately eight years old. Similar to Camp Creek, large woody debris additions (utilizing volume as a surrogate for "complexity") ranged from a control (GC5) to medium (GC2) and high (GC1) loadings. Of interest is that the Gwynn Creek (GC1) high wood volume site had a decrease in dead zone compared with values for a year after treatment, whereas the Gwynn Creek (GC2 and GC5) and Little Cummins Creek (LK1) sites all had an increase in dead zone. If the addition of wood in the high complexity site had enhanced scour, pooling, and aggradation (Gwynn Creek had been scoured via debris flow), it is conceivable that the dead zone volume fraction of the stream did increase at some point because a larger portion of streamflow would have interacted with wood and gravel. However, the main change in GC1 that may have aided in decreasing dead zone is the filling of one large deep pool that had been excavated during the habitat alteration, thus decreasing total reach pool volume.

The exchange coefficient (δ) decreased in all of the study sites. With the Sabol and Nordin (1978) model, a decrease in the exchange coefficient would be expected with an increase in the dead zone volume fraction. The exchange coefficient is always sensitive to discharge and

Table 15. Summary of 1984, 1985, and 1991 hydraulic tracer results for Gwynn (GC) and Little Cummins (LK) Creeks.

	Dead zone		Exchange coefficient (s^-1)		Centroid velocity (m/s)		Stream discharge (m^3/s)	
Site*	**1984/85**	**1991**	**1984/85**	**1991**	**1984/85**	**1991**	**1984/85**	**1991**
LK1	0.4519	0.5789	0.0164	0.0053	0.0932	0.0407	0.02	0.01
GC1	0.5804	0.4765	0.0145	0.0109	0.0768	0.0623	0.04	0.02
GC2	0.3985	0.5520	0.0335	0.0096	0.1432	0.0878	0.03	0.03
GC5	0.3883	0.4397	0.0255	0.0129	0.1338	0.0667	0.04	0.03

* The 1984 dye releases pertain to LK1.

the decrease in exchange coefficients is also attributed to the lower 1991 discharge, and associated lower stream velocities. Dead zone is very sensitive to discharge (e.g., dead zone goes to 100 % if Q=0). Thus, in most cases, a decrease in discharge would indicate an increase in dead zone.

Bencala et al. (1983) found dead zone to be approximately twice as large as the measured stream cross-sectional area, thus, indicating intergravel and interbank flow. Albeit, they were using a different model, the conceptual dead zone model (Kaufmann, 1987) is essentially the same--it is what makes up dead zone that differs. For instance, in Bencala's case, a lot of intergravel flow. In other cases, a lot of pools and slackwater. Bencala and others used continuous dye injection to acquire a dilution-based discharge measurement and compared this measurement with the channel cross-section. Because a lot of dye mass (time integral of concentration times the cross-section) is missing downstream, they conclude that a large part of the flow cross-section is subsurface.

Interaction with streambed gravel has also been found to be an important factor in rhodamine WT loss in mountain stream environments (Bencala et al., 1983). Thus, streambed gravel may be undesirably influencing the use of dye dispersion to measure channel structure and pools. Intergravel flow is most likely a factor in the

Lobster Creek channel units. However, many of the Drift Creek channel units have a bedrock streambed and intergravel flow may not be a concern in this stream.

Beaver Pond

A beaver pond (CCBP) exists several hundred meters upstream from the uppermost Camp Creek channel unit (CC42). The stream valley has increased in width here and the channel gradient has decreased somewhat. Within this reach of channel, beaver have performed additional channel modification via a low head "stick" dam.

Additional dye releases and measurement of the physical parameters were also performed on this channel unit. The beaver pond was relatively devoid of large wood and rock, yet, out of all the Camp Creek sites used in this study, the beaver pond had the lowest average cross-sectional velocity and the largest average cross-sectional areas, depths, and widths (Table 8). Thus, a large amount of hydraulic retention is occurring in the beaver pond (Figure 17). To illustrate, the transit time of the beaver pond was 86 percent greater than pretreatment CC21. Even post-treatment CC21 (recall this unit as being the most complex) transit time was still 5 percent lower than the beaver pond. Thus, beaver are very efficient at creating large regions of slackwater. However, the pond

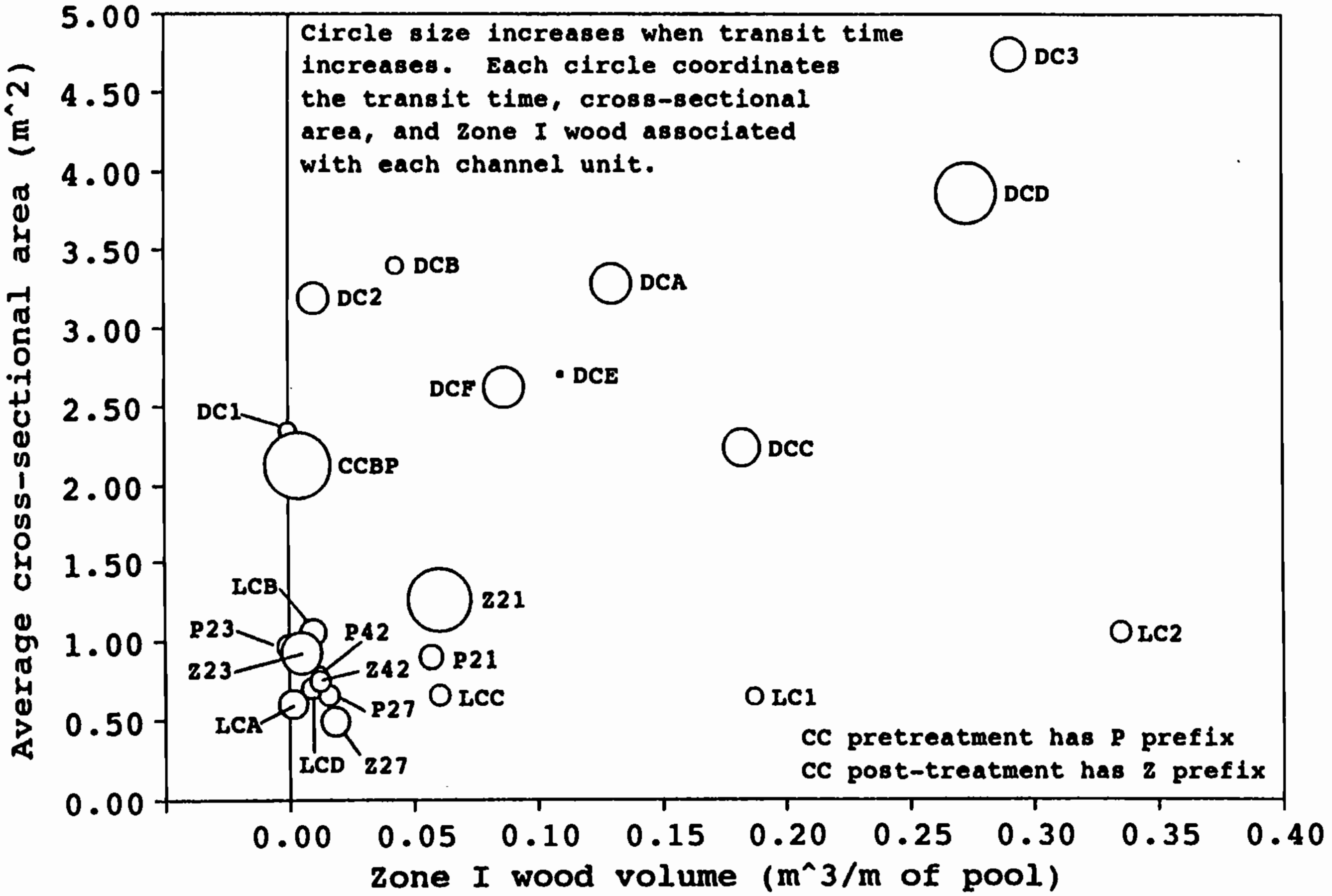

Figure 17. Transit time, average cross-sectional area, and influence Zone I wood volume associated with each channel unit for Camp (CC), Drift (DC), and Lobster (LC) Creeks.

is probably behaving as one large dead zone and diversity in dead zone size and location may be minimal. Thus, the beaver pond may not provide hydraulic complexity in terms of velocity and transient storage diversity.

SUMMARY AND CONCLUSIONS

This study has attempted to quantify and compare the hydraulic retention of instream habitat alterations on a channel unit scale as defined by Grant et al. (1990). Fluorescent dye was used to calculate hydraulic retention through each study channel unit. A second method of assessing hydraulic retention utilized the transient storage model developed by Sabol and Nordin (1978) and conceptually modified by Kaufmann (1987). This model allowed a specific transient storage (dead zone) parameter to be calculated. In addition, the cycling time into and out of the dead zone could be calculated as an exchange coefficient. The model takes into account any features of the channel that have relatively slow velocity compared with the mainstream flow, be they intergravel flow, pools, or lateral backwaters. Thus, if a large amount of dead zone is intergravel, then it is hard to interpret dead zone as pool volume. Calculated results for the transient storage model variables can be found in Appendix F.

Differences between Camp Creek pre- and post-treatment regressions of transit time increases (hydraulic retention) versus Zone I woody debris were found to be significant ($p \leq 0.10$). Yet, increased transit time was also being influenced by a lower discharge during the post-treatment measurements.

Drift Creek and Lobster Creek were studied with controls that could not be used to validate changes in hydraulic variables. Drift Creek and Lobster Creek do, however, provide good qualitative assessment of how the habitat alterations are currently interacting with the streamflow because the instream structures have had approximately 2 and 9 years, respectively to equilibrate with local flow conditions. However, direct changes in the cross-sectional areas of Drift Creek and Lobster Creek channel units, that are the result of changes in the width or depth following debris loading, cannot be ascertained because pretreatment data measurement was not undertaken prior to the stream rehabilitation.

Channel bed and bank scouring did not appear to be prevalent in most channel units. In contrast, channel units that contained debris weirs or transverse log jams did increase upstream slackwater as well as scour immediately below the structures. Thus, an assumption will be made that average cross-sectional area probably did increase in channel units containing large debris weirs or jams (DCD and LCB). Gabions are not intended to be used specifically as a scouring device, however, Lobster Creek gabions did accomplish the management objective of stream gravel aggradation. Several gabion structures had even been buried by gravel. Nonetheless, the extent to which structures altered the cross-sectional area or increased aggradation is not certain without pretreatment data.

Figure 17 attempts to summarize the effects of channel modification on the hydraulic characteristics of all three streams. Transit time is influenced by the length of the pool, cross-sectional area, bed and bank roughness, discharge, flow obstructions, and transient storage (dead zone). The use of dye enabled transit time, transient storage, cycling time into and out of transient storage, and average dye plume velocities to be calculated. Results of the dye analyses could then be compared to debris and geomorphic measurements. Figure 17 combines width, depth, wood volume, and the average convective velocity of the dye with geomorphic measurements, then utilizes three "primary" variables that are expected to change following instream alteration. The circles (transit times) are matched with their respective average cross-sectional areas and Zone I debris volumes. The size of the circles represent the proportion of channel unit transit time relative to other channel unit transit times. Thus, the longer the transit time, the larger the circle. This can be seen by locating DCE and DCD, both of which had the shortest and longest transit times, respectively.

Figure 17 shows a large amount of variability in average cross-sectional area, Zone I debris volume, and transit time. However, all of the channel units vary in length and the longer the channel unit, the longer the potential transit time may be. Although Zone I wood volumes have been scaled, the placement or grouping of wood and its interaction with channel unit length will vary, thus yielding different transit times and average cross-sectional areas. Consequently, if any major trends exist in Drift Creek and Lobster Creek, they are masked by the variability in channel unit length and debris placement.

CAMP CREEK CONCLUSIONS

Except for CC21, major alterations to channel unit dimensions did not occur after treatment, thus, the volume of water in transient storage (dead zone) would not be expected to change in channel units CC23, CC27, and CC42. Alterations to channel unit average cross-sectional dimensions occurred only in CC21 (high complexity site). The channel unit lengthened by approximately 6 m and increased in average cross-sectional depth by about 0.04 m.

An increase in transit time between pre- and post-treatments was statistically significant when tested against Zone I woody debris utilizing an "additional sums of squares" (Draper and Smith, 1966) comparison of pre- and post-treatment regressions. The difference between regressions is assumed to be a response to treatment.

DRIFT AND LOBSTER CREEKS CONCLUSIONS

Based on the results of one-tailed t-tests, flow velocities and peak concentrations were found to decrease significantly in treatment channel units when compared to comparison (control) channel units. The placement of debris in channels may enhance low flow channel complexity by altering flow hydraulics, enhancing dispersion, and increasing the transit time of water.

Statistically significant results of simple linear regressions for dye statistics on geomorphic variables will not be presented as major conclusions because of a lack of pretreatment control data. At best Drift and Lobster Creeks provide a qualitative representation of how treatments may alter morphometric and hydraulic aspects of stream habitat.

ADDITIONAL RESEARCH AND DYE METHODOLOGY

1. There is a definite need for pre- and post-treatment comparisons pertaining to instream habitat structures. But, they should be monitored over a lengthy time period to better ascertain changes in channel morphology associated with these structures.
2. Fluorescent tracer methodology might be better utilized at the reach scale. If the reach is long enough, this would eliminate the need to develop the upstream concentration-time curve that was required in this methodology to "isolate" a particular channel unit. Secondly, channel reaches of equal length should be selected to aid in making reach comparisons as well as comparing with previous research.
3. Studies are needed that better define the interaction between influence Zone I flows and debris structures. Most wood used for habitat alteration is large, existing in several influence zones. At low flow, they are seldom topped by water. It is conceivable that pristine systems had an annual input of floatable, or, small woody debris only operating in Zone I. Even if such inputs last for one year, they never the less might have a significant effect on local channel hydraulics.

4. Because pristine systems suitable for use as research controls are diminishing, additional comparisons of streamflow hydraulics between beaver ponds and habitat alteration structures may be useful. Prior to large scale human land use, beaver were most likely an active component in stream and riparian ecosystems. For example, between 1769 and 1868 the Hudson's Bay Company auctioned 4,708,702 beaver pelts. During the same time span, both the North West and Canada Companies were trading beaver pelts in numbers just as large (Lopez, 1986). It is likely that beaver were widely distributed throughout the Oregon Coast Range prior to large scale settlement by Anglo-Americans. Thus, in terms of pools, natural beaver ponds may be of value as surrogates for previous (historical) stream, pool, and riparian interactions.

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APPENDICES

APPENDIX A

Equations and Calculations Used With Rhodamine WT

1. The serial dilution equation for preparing standard curves:

$$C_f = C_s S_g \frac{V_d}{(V_w+V_d)_1} \times \frac{V_d}{(V_w+V_d)_2} \times \frac{V_d}{(V_w+V_d)_3} \times \frac{V_d}{(V_w+V_d)_4}$$

where: C_f = final concentration [ML^{-3}]

C_s = concentration of dye solution obtained from the manufacturer (see page 101) [ML^{-3}]

S_g = specific gravity of rhodamine WT (which is 1.19)

V_d = volume of dye solution [L^3]

V_w = volume of distilled water [L^3]

1,2,3 & 4 = initial steps for the serial dilution procedures (Wilson et al., 1986)

2. Because rhodamine WT is 20% by weight, the value used for C_s is 20e+07 μgL^{-1}. The derivation is:

$$\frac{0.20g}{g}\times\frac{10^3g}{kg}\times\frac{10^6\mu g}{g}=20e{+}07\,\mu gkg^{-1}$$

Note: 1 μgkg^{-1} = 1μgL^{-1}, so C_s = 20e+07 μgL^{-1}

3. Field "injection" concentration calculated from:

$$C_f=C_sS_g\frac{V_d}{(V_w+V_d)}$$

In addition: 1 mL pure water = 1 g at 4°C

1 mL water = 1 cm^3

1 μgL^{-1} = 1 μgkg^{-1}

1 mgL^{-1} = 1 $mgkg^{-1}$

APPENDIX B

The Kaufmann Conceptual Dead Zone Model (1987)

$$U_t = Q/A_t = [(U_m \cdot A_m) + (U_d \cdot A_d)] / A_t$$

where:

Q = volumetric reach discharge [L^3T-1]

U_t = mean reach velocity of total water mass [LT^{-1}]

U_m = mean velocity in the actively flowing mainstream (upper compartment) of the stream channel [LT^{-1}]

U_d = mean downstream velocity in the transient storage (dead zone) compartments [LT^{-1}]

A_t = mean channel flow cross-sectional area including active flow portions and transient storage (dead zone) portions [L^2]

A_m = mean flow cross-sectional area of mainstream compartment portion of stream channel [L^2]

A_d = mean cross-sectional area of transient storage (dead zone) compartment portion of stream channel [L^2]

* ASSUMING all longitudinal movement is in the upper mainstream compartment and there is no net longitudinal movement in the dead zone

then: $U_d = 0$ (by definition)

$U_t = (U_m \cdot A_m)/At$

$(U_t/U_m) = (A_m/A_t)$ = mainstream flow portion.

* ASSUMING $U_t = U_c$ = the dye plume centroid velocity, and ASSUMING $U_m = U_L$ = the dye plume leading edge velocity

then: $(U_c/U_L) = (A_m/A_t)$ = mainstream flow portion.

* Because $A_m + A_d = A_t$, and $[(A_m/A_t) + (A_d/A_t)] = (A_t/A_t) = 1$

then: $(A_d/A_t) = [1-(A_m/A_t)] = [1-U_c/U_L]$ = the dead zone proportion.

* THEN $[1-U_c/U_L] = a_L$ = the dead zone proportion as defined by Sabol and Nordin (1978).

APPENDIX C

The Sabol and Nordin Dead Zone Dispersion Model (1978)

Sabol and Nordin (1978) developed a two compartment dead zone storage model. Water in the upper compartment moves uniformly at a velocity equal to the advective velocity in the mainstream. Velocity in the lower compartment is near zero.

$$f_{(t,x_i)}=\pi_2 e^{-\pi_1-\pi_2(t-\pi_3)}\sum_{n=1}^{\infty}\left[\frac{\pi_1{}^{n}}{n!\,(n-1)}\,[\pi_2(t-\pi_3)]^{n-1}\right]$$

$$C_{(t,x_i)}=f_{(t,x_i)}\frac{W}{\gamma Q}$$

where:

$$\pi_1=\frac{a_l a_u \delta x_i}{U}$$

$$\pi_2=a_u\delta$$

$$\pi_3=\frac{a_u x_i}{U}$$

and:

U = convective velocity = dye centroid velocity [LT^{-1}]

a_u = probability that a particle is in the upper layer at that instant = t_l/t_c = time from injection to the leading edge of tracer cloud at x_i divided by the centroid (time to concentration) of the dye plume

a_L = $1-a_u$ = dead zone = probability that a particle is in the lower streamflow compartment (zero velocity) at that point in time

δ = exchange coefficient = $(2 \cdot a_l \cdot x_i)/(U \cdot a_u \cdot \sigma^2{}_t)$ = average number of times a particle goes into storage per unit time $[T^{-1}]$

$\sigma^2{}_t$ = $(2\pi_1)/(\pi^2{}_2)$ = $Var[T_{(x)}]$, frozen cloud assumption

W = weight of the tracer released [M]

γ = specific weight of the dispersant

Q = discharge rate $[LT^3]$

n = number of times a particle enters the upper layer

$\sigma^2{}_t$ = variance of the concentration-time data

$var[T_{(x)}]$ = variance of the transit time

APPENDIX D

Camp Creek, Drift Creek, and Lobster Creek Total Debris Loading by Influence Zones

Table D1. Camp Creek pre- and post-treatment total debris loading volumes by influence zones.

		Influence Zones			
		I	II	III	IV
Channel Unit		(m^3)	(m^3)	(m^3)	(m^3)
CC21	Pre	1.8	4.8	0.0	2.9
	Post	0.5	7.1	3.8	2.6
	Total	2.3	11.9	3.8	5.5
CC23	Pre	0.0	0.1	0.0	0.0
	Post	0.2	3.8	3.9	0.6
	Total	0.2	3.9	3.9	0.6
CC27	Pre	0.3	2.5	2.8	2.0
	Post	0.1	1.0	1.5	0.7
	Total	0.4	3.5	4.3	2.7
CC42	Pre	0.7	0.0	0.0	0.0
	Post	0.0	0.0	0.0	0.0
	Total	0.7	0.0	0.0	0.0

Table D2. Debris volumes measured in Drift Creek by influence zones (treatments).

Channel Unit		Influence Zones I (m^3)	II (m^3)	III (m^3)	IV (m^3)
DCA	Wood	3.6	48.6	12.9	38.5
	Rock	5.2	7.7	0.0	0.0
	Total	8.8	56.3	12.9	38.5
DCB	Wood	1.0	4.6	0.0	0.0
	Rock	0.4	5.4	0.0	0.0
	Total	1.4	10.0	0.0	0.0
DCC	Wood	2.3	6.2	16.5	18.5
	Rock	5.3	17.4	0.0	0.0
	Total	7.6	23.6	16.5	18.5
DCD	Wood	5.1	54.7	31.2	19.4
	Rock	34.1	14.2	0.0	7.0
	Total	39.2	68.9	31.2	26.4
DCE	Wood	0.4	6.1	0.6	1.9
	Rock	0.6	0.0	0.0	0.0
	Total	1.0	6.1	0.6	1.9
DCF	Wood	5.8	31.3	22.1	32.4
	Rock	3.4	7.5	0.0	0.0
	Total	9.2	38.8	22.1	32.4

Table D2 Continued. Debris volumes measured in Drift Creek by influence zones (comparative controls).

Channel Unit		Influence Zones I (m^3)	 II (m^3)	 III (m^3)	 IV (m^3)
DC1	Wood	0.0	0.0	0.0	5.9
	Rock	0.0	0.0	0.0	0.0
	Total	0.0	0.0	0.0	0.0
DC2	Wood	0.0	0.0	0.0	3.4
	Rock	0.5	0.5	0.0	0.0
	Total	0.5	0.5	0.0	3.4
DC3	Wood	0.1	0.2	4.8	16.0
	Rock	10.4	12.2	0.0	0.0
	Total	10.5	12.4	4.8	16.0

Table D3. Debris volumes measured in Lobster Creek by influence zones (treatments).

Channel Unit		Influence Zones I (m^3)	II (m^3)	III (m^3)	IV (m^3)
LCA	Wood	0.0	2.4	0.8	0.7
	Rock	0.0	13.2	0.0	0.0
	Total	0.0	15.6	0.8	0.7
LCB	Wood	0.2	4.0	4.8	26.0
	Rock	0.0	0.0	0.0	0.0
	Total	0.2	4.0	4.8	26.0
LCC	Wood	0.6	8.2	1.8	19.6
	Rock	0.3	0.7	0.0	0.0
	Total	0.9	8.9	1.8	19.6
LCD	Wood	0.0	0.0	0.0	12.9
	Rock	0.2	14.8	0.0	0.0
	Total	0.2	14.8	0.0	12.9

Table D3 Continued. Debris volumes measured in Lobster Creek by influence zones (comparative controls).

Channel Unit		Influence Zones I (m^3)	II (m^3)	III (m^3)	IV (m^3)
LC1	Wood	0.1	4.1	4.1	23.3
	Rock	1.8	17.7	0.0	0.0
	Total	1.9	21.8	4.1	23.3
LC2	Wood	0.0	8.5	29.0	26.6
	Rock	7.4	30.4	0.0	0.0
	Total	7.4	38.9	29.0	26.6

APPENDIX E

The Differences Between Downstream and Upstream Curve Areas of Concentration-time Plots

Table E1. Areas under the concentration-time curves, the percent differences, and ratios between downstream and upstream curves.

Channel unit	Ratio[a]	Percent Difference
CC21 (pretreatment)	1.006	1
CC23 (pretreatment)	1.034	3
CC27 (pretreatment)	0.923	8
CC42 (pretreatment)	0.975	3
CCBP (pretreatment)	0.947	5
CC21 (post-treatment)	1.028	3
CC23 (post-treatment)	0.981	2
CC27 (post-treatment)	0.952	5
CC42 (post-treatment)	0.983	2
DCA	1.113	10
DCB	0.914	9
DCC	1.044	4
DCD	0.993	1
DCE	0.930	7
DCF	0.749	25
DC1	0.989	1
DC2	1.007	1
DC3	1.149	13
LCA	1.331	25
LCB	0.911	9
LCC	1.463	32
LCD	1.143	13
LC1	1.059	6
LC2	0.934	7

[a] Downstream:upstream ratios

Table E2. Two-tailed t-test results for the differences between downstream and upstream areas under the concentration-time curves ($p \leq 0.10$; n = 4 for Camp Creek pre- and post-treatments; n = 5 for Drift Creek and Lobster Creek controls; n = 10 for Drift Creek and Lobster Creek treatments).

Concentration-time curve area ($\mu gL^{-1} \cdot s$)	Test[a]	P-value
Pre Camp Creek	upstream = downstream	0.19
Post Camp Creek	upstream = downstream	0.21
Drift and Lobster Creeks (treatments)	upstream = downstream	0.24
Drift and Lobster Creeks (control)	upstream = downstream	0.28

[a] H_o: upstream curve area = downstream curve area
H_a: upstream curve area ≠ downstream curve area

APPENDIX F

The Concentration-time Results for Upstream and Downstream Sampling Locations

Table F1. Upstream sampling location results for concentration-time curves.

a Site	b Area (s*ug/L)	c Centroid Time (s)	d Leading Edge (s)	e Time of Conc. c+d (s)	f Dist. to Leading E. (m)	g Variance	h Skew
PRECC21	13069.18	820.38	750.00	1570.38	152	283649	1.7371
PRECC23	11751.49	399.97	390.00	789.97	92	42083	1.1262
PRECC27	14545.78	277.18	465.00	742.18	83	36710	1.6841
PRECC42	14573.76	598.89	550.20	1149.09	84	215085	1.7175
BEAVER	25484.07	2550.03	2700.00	5250.03	203	3061991	1.6020
POSTCC21	45559.10	2426.13	2080.20	4506.33	152	3113572	1.5238
POSTCC23	39913.58	1139.72	900.00	2039.72	92	548827	1.7246
POSTCC27	41432.14	686.49	660.00	1346.49	83	140416	1.7030
POSTCC42	39359.85	1192.63	960.00	2152.63	84	654619	1.6532
LCA	4117.95	230.19	195.00	425.19	59	26266	1.8792
LCB	13125.52	596.88	690.00	1286.88	125	141251	1.5346
LCC	2719.87	362.39	420.00	782.39	94	47797	1.3718
LCD	3186.04	350.19	274.80	624.99	102	53308	1.0679
LC1	5590.33	1393.48	1980.00	3373.48	113	781334	1.0409
LC2	12723.89	1300.94	1320.00	2620.94	77	730183	1.0463
DCA	9617.38	1195.79	1167.00	2362.79	206	539517	1.3423
DCB	5320.04	795.43	895.20	1690.63	166	327218	1.5936
DCC	5095.31	1690.65	1729.20	3419.85	181	1565920	1.3926
DC1	12461.92	2331.57	1830.00	4161.57	203	3322680	1.3337
DC2	10502.45	2155.98	1939.80	4095.78	213	2402153	1.3255
DC3	11948.72	2000.52	1590.00	3590.52	200	2494847	1.3549
DCD	9982.04	975.53	2497.80	3473.33	132	412312	1.4672
DCE	1662.38	1096.19	1960.20	3056.39	170	541511	1.3035
DCF	13186.92	1992.93	1275.00	3267.93	155	2786654	1.5781

Table F1 Continued.

Site	i Kurtosis	j Leading Edge f/d (m/s)	k Centroid Velocity f/e (m/s)	l Q (m^3/s)	m Au d/e	n Al 1-m	o Cap Sigma (2*n*f)/(k*m*g (s^-1)
PRECC21	6.4418	0.2020	0.0965	0.0544	0.4776	0.5224	0.0121
PRECC23	4.2787	0.2346	0.1158	0.0605	0.4937	0.5063	0.0385
PRECC27	6.5448	0.1785	0.1118	0.0489	0.6265	0.3735	0.0241
PRECC42	6.3422	0.1519	0.0728	0.0488	0.4788	0.5212	0.0116
BEAVER	5.8573	0.0752	0.0387	0.0279	0.5143	0.4857	0.0032
POSTCC21	5.2899	0.0728	0.0336	0.0156	0.4616	0.5384	0.0034
POSTCC23	6.7077	0.1017	0.0449	0.0178	0.4412	0.5588	0.0094
POSTCC27	6.2619	0.1258	0.0616	0.0172	0.4902	0.5098	0.0199
POSTCC42	6.0324	0.0871	0.0388	0.0181	0.4460	0.5540	0.0082
LCA	6.9054	0.3046	0.1397	0.0576	0.4586	0.5414	0.0382
LCB	5.5563	0.1812	0.0971	0.0361	0.5362	0.4638	0.0158
LCC	4.8687	0.2238	0.1201	0.0871	0.5368	0.4632	0.0282
LCD	3.8226	0.3697	0.1626	0.0744	0.4397	0.5603	0.0299
LC1	3.9040	0.0569	0.0334	0.0424	0.5869	0.4131	0.0061
LC2	3.8371	0.0583	0.0293	0.0373	0.5036	0.4964	0.0071
DCA	4.8533	0.1761	0.0870	0.1479	0.4939	0.5061	0.0090
DCB	5.4645	0.1854	0.0982	0.1336	0.5295	0.4705	0.0092
DCC	4.8106	0.1044	0.0528	0.1395	0.5056	0.4944	0.0043
DC1	4.3591	0.1109	0.0488	0.1141	0.4397	0.5603	0.0032
DC2	4.5039	0.1098	0.0520	0.1354	0.4736	0.5264	0.0038
DC3	4.4758	0.1258	0.0557	0.1190	0.4428	0.5572	0.0036
DCD	5.2095	0.0528	0.0380	0.1425	0.7191	0.2809	0.0066
DCE	4.7529	0.0867	0.0556	0.1426	0.6413	0.3587	0.0063
DCF	5.2890	0.1216	0.0474	0.1078	0.3902	0.6098	0.0037

Table F2. Downstream sampling location results for concentration-time curves.

a Site	b Area (s*ug/L)	c Centroid Time (s)	d Leading Edge (s)	e Time of Conc. c+d (s)	f Dist. to Leading E. (m)	g Variance	h Skew
PRECC21	13150.03	930.83	1245.00	2175.83	184	424321	1.4804
PRECC23	12152.30	626.97	720.00	1346.97	123	162206	1.4147
PRECC27	13427.90	465.34	765.00	1230.34	100	97330	1.4533
PRECC42	14204.75	608.07	790.20	1398.27	96	193730	1.4259
BEAVER	24131.31	4126.51	5340.00	9466.51	255	9909869	1.8490
POSTCC21	46830.74	4514.20	4020.00	8534.20	190	10604430	1.5126
POSTCC23	39144.33	1754.20	1860.00	3614.20	123	1096941	1.3566
POSTCC27	39441.47	1075.48	1170.00	2245.48	100	556136	1.6282
POSTCC42	38708.08	1344.57	1230.00	2574.57	96	801278	1.6813
LCA	5481.04	554.90	750.00	1304.90	116	91045	0.9686
LCB	11952.36	976.19	1050.00	2026.19	133	301094	1.1016
LCC	3978.55	569.73	615.00	1184.73	108	77408	0.9709
LCD	3643.07	501.28	555.00	1056.28	127	80391	0.8662
LC1	5921.37	1527.51	2160.00	3687.51	123	943027	1.0220
LC2	11887.39	1466.44	1620.00	3086.44	99	899231	1.0087
DCA	10705.81	1835.77	2175.00	4010.77	274	1672097	1.5837
DCB	4859.88	1056.15	1005.00	2061.15	198	360117	1.1659
DCC	5319.07	2161.61	2670.00	4831.61	222	2694514	1.4170
DC1	12328.92	2453.05	2010.00	4463.05	216	4204668	1.4209
DC2	10579.38	2654.00	2479.80	5133.80	256	3672658	1.3253
DC3	13731.41	2798.66	1950.00	4748.66	236	4275492	1.4955
DCD	9910.38	2407.47	4560.00	6967.47	276	3086458	1.5691
DCE	1546.36	961.66	2130.00	3091.66	179	486371	1.2832
DCF	9882.02	2611.13	2235.00	4846.13	261	3324318	1.4528

Table F2 Continued.

Site	i Kurtosis	j Leading Edge f/d (m/s)	k Centroid Velocity f/e (m/s)	l Q (m^3/s)	m Au d/e	n Al 1-m	o Cap Sigma (2*n*f)/(k*m*g (s^-1)
PRECC21	5.3000	0.1474	0.0843	0.0541	0.5722	0.4278	0.0077
PRECC23	4.8026	0.1701	0.0909	0.0585	0.5345	0.4655	0.0145
PRECC27	5.1260	0.1301	0.0809	0.0529	0.6218	0.3782	0.0154
PRECC42	5.0826	0.1219	0.0689	0.0501	0.5651	0.4349	0.0111
BEAVER	6.7619	0.0478	0.0269	0.0295	0.5641	0.4359	0.0015
POSTCC21	5.1816	0.0471	0.0222	0.0152	0.4710	0.5290	0.0018
POSTCC23	4.8662	0.0659	0.0339	0.0182	0.5146	0.4854	0.0062
POSTCC27	5.4367	0.0850	0.0443	0.0180	0.5210	0.4790	0.0074
POSTCC42	6.3269	0.0783	0.0374	0.0184	0.4778	0.5222	0.0070
LCA	3.8615	0.1547	0.0889	0.0432	0.5748	0.4252	0.0212
LCB	4.0412	0.1262	0.0654	0.0397	0.5182	0.4818	0.0125
LCC	3.8287	0.1756	0.0912	0.0596	0.5191	0.4809	0.0284
LCD	3.4661	0.2294	0.1205	0.0651	0.5254	0.4746	0.0237
LC1	3.7518	0.0569	0.0334	0.0400	0.5858	0.4142	0.0055
LC2	3.7619	0.0612	0.0321	0.0399	0.5249	0.4751	0.0062
DCA	5.5536	0.1260	0.0683	0.1328	0.5423	0.4577	0.0040
DCB	4.5123	0.1970	0.0961	0.1463	0.4876	0.5124	0.0120
DCC	4.9168	0.0831	0.0459	0.1337	0.5526	0.4474	0.0029
DC1	4.6488	0.1072	0.0483	0.1153	0.4504	0.5496	0.0026
DC2	4.4627	0.1032	0.0498	0.1344	0.4830	0.5170	0.0030
DC3	4.9995	0.1211	0.0497	0.1036	0.4106	0.5894	0.0032
DCD	5.5656	0.0604	0.0395	0.1435	0.6545	0.3455	0.0024
DCE	4.7197	0.0840	0.0579	0.1533	0.6890	0.3110	0.0057
DCF	5.0235	0.1167	0.0538	0.1439	0.4612	0.5388	0.0034