Channel Morphology and Hydraulic Characteristics of Torrent-Impacted Forest Streams in the Oregon Coast Range, U.S.A.

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Tracer-derived estimates of hydraulic resistance and transient hydraulic storage were related to measures of pool volume and channel morphometric variability in small streams of the Oregon coast, U.S.A. Fourteen 100 m study reaches in 3 streams were selected to compare channel and hydraulic characteristics in streams representing a time series of recovery since major torrent scour or deposition (2, 12 and 120 years). Transient storage ("dead zone") volume fractions, ranging from 0.3 to 0.6 in the study reaches, were significantly ($p < .01$) correlated with aggregate residual pool volume ($r = +0.94$) and the standard deviation of thalweg depth ($r = +0.95$). Darcy-Weisbach friction factors (f) ranging from 2 to 90 were correlated (r values from +0.95 to +0.98) with the standard deviation of thalweg depth (SDD) within restricted ranges of summer low flow and elevated springtime discharge. Regressions of f versus SDD for combined data collected over a range of discharges (0.019 to 0.11 m^3/s) showed increased scatter. A semi-logarithmic relationship ($r^2 = 0.60$, $n = 40$) between dimensionless velocity $(8/f)^{0.5}$ and a dimensionless measure

indexing relative submergence of large scale bed features (mean thalweg depth/SDD) was significant at $p < .01$.

Measures and indices of pool volume and transient storage were positively correlated ($r = +0.78$ to $+0.89$) with volumetric loadings of woody debris. High total pool and dead zone volumes in reaches were largely due to plunge pools formed by scouring downstream of woody debris accumulations. Among the study streams, the greatest reach pool volume and channel complexity occurred in torrent deposit reaches of the intermediate (12 yr.) recovery stage stream. Reaches scoured recently (2 yr.) by a debris torrent had the lowest pool volume and channel complexity. The stream experiencing the longest period of "recovery" (120 yr) had characteristics between those of the 2- and 12-year recovery streams. Torrent scouring reduced pool volume, dead zone fraction and channel morphometric variability. Torrent deposition and subsequent local reworking of sediments by the stream increased values of these variables, especially when torrent deposits contained woody debris and boulders.

The relative importance of pool-forming agents varied with recovery time and amount of torrent deposits. Bedrock, cobbles, log clusters, and single logs contributed about equally to the small residual pool volume in reaches recently scoured by a torrent. Log clusters and boulders dominated in two reaches of the intermediate recovery class stream where logs and sediment were deposited by a torrent, and in two reaches where boulders were left as lag deposits. Bedrock and log clusters contributed about equally to pool formation in the relatively undisturbed stream.

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In the fall of 1981, I walked with my major professor, Bob Beschta, down a six-mile stretch of Deer Creek, a small stream on the east slope of the Oregon Cascades. This stream was considered an example of high quality salmonid habitat. We marveled at the complexity of debris jams, falls, backwaters and pools in this stream. Jokingly, I suggested that the time it takes to walk a given length of stream might serve as a much-needed index of fish habitat quality and diversity of stream channel morphology. After walking several dozen other streams and completing some coursework in hydraulics and fisheries, I concluded that the flow of water might provide a more objective "measuring stick" and proposed the study and the concept which this dissertation describes.

Bob Beschta allowed me a great deal of intellectual freedom during my graduate studies. While often encouraging unorthodox ways of looking at a research problem, he continually challenged me to explicitly identify the practical management significance of my work.

Many individuals provided me with insights, ideas and encouragement throughout this project. The enthusiasm of Jim Sedell and Ken Cummins was inspirational. These stream ecologists also helped me to define the applicability of my research to other areas. Fred Swanson helped me to see that the terrestrial part of the landscape is as dynamic as that composed of water; he also displayed a certain measure of skepticism which forced me to reexamine this project at every stage. Dave Bella and George Brown introduced me to the beauties of mathematical modeling, as well as the importance of realizing the simplification that such models impose upon our thinking about the world's complexity.

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Finally, I would like to thank my wife, Denise, for her unfailing confidence--never doubting for a minute that I could complete the task I undertook.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure		Page

CHANNEL MORPHOLOGY AND HYDRAULIC CHARACTERISTICS OF TORRENT-IMPACTED FOREST STREAMS IN THE OREGON COAST RANGE, U.S.A.

I. INTRODUCTION

A. Problem Statement

Watersheds of the Pacific slope of North America are important not only for their timber but also their fishery resources (Hall and Lantz, 1969; Everest and Harr, 1982). For example, Everest and Summers (in press) estimate that anadromous salmonids reproducing in Pacific Northwest National Forests alone provided approximately 5 million angler days of recreation in 1977. In addition, these same forests provided a commercial harvest of 76 million pounds of anadromous salmonids that year (Everest and Harr, 1982). Despite these impressive statistics, the size of this fishery resource continues to be eroded by the direct and indirect effects of resource management. The fishery now represents only a small fraction of its historic levels (Everest and Harr, 1982; Sedell and Luchessa, 1982). Excessive ocean harvests, a "fishing-up" effect, and, in particular, the mixed harvest of wild and hatchery stocks of differing production potential have likely played a large part in the decline of fishery resources in Oregon (Larkin, 1972; ODFW, 1981; Brown, 1982). Furthermore, management activities in stream basins, such as impoundment, snagging, road building and logging also had major effects (Sedell et al., 1981; Brown, 1982; Sedell and Luchessa, 1982; Shields and Nunnally, 1983; Sedell and Duval, 1985).

An important area of human impact is the change in stream channel morphology which may result when land use-related debris torrents or debris floods alter the amount of in-channel sediment and large woody debris. It should be recognized that while the frequency and magnitude of such events may be affected by human activity, debris torrents and debris floods are a normal component of the natural disturbance regime in small upland streams of the Pacific Northwest (Swanston and Swanson, 1976; Dietrich and Dunne, 1978; Swanson, 1979; Cummins et al., 1983). As such, their scouring effects constitute a "resetting" mechanism for the general trend of wood and sediment accumulation in natural streams (Cummins et al., 1983). Where debris torrents cause massive deposition of wood and sediment, this material may increase the structural complexity of the stream channel, enhancing some aspects of fish habitat (Swanson et al., 1976; Swanson and Lienkaemper, 1978) and increasing the nutrient retentivity of the stream ecosystem.

This study quantifies changes in channel morphology that have occurred in small streams in the Oregon Coast Range as a result of debris torrents and debris floods. Study reaches were selected to allow comparison of various stages of recovery following disturbance. A distinction was made between the effects of scouring and those of deposition. Emphasis was placed on quantification of the size, abundance, and morphology of slackwater features such as pools and backwaters. These elements of channel structure are critical both for fish and as features which enhance the retention of organic matter and nutrients essential for fish productivity.

There is a general lack of standardized, practical, and meaningful methods of fish habitat assessment which are applicable in a wide variety of streams (Armantrout, 1981; Platts et al., 1983). The methods used often do not have predictive power. Using such methods, one cannot make quantitative judgments about whether the habitat is likely to improve or deteriorate over time. Similarly, because most fish habitat assessments are not based upon a quantitative, functional understanding of stream channel morphology and hydraulics, they do not index the habitat potential of a given stream over a range of flows--nor do they allow clear comparisons between streams. A lack of predictive power in estimating the direction and rate of change in habitat quality of small streams stems from the fact that: 1) quantitative morphologic/hydraulic methods are not often employed in describing "habitat," 2) complex hydraulic processes that form the channels of small upland streams are not quantitatively understood, and 3) linkages among land use, mass wasting and channel form have not been defined.

The purpose of this study is to describe, hydraulically and morphometrically, one aspect of the habitat changes resulting from debris torrents. Before this could be done, it was necessary to develop and adapt quantitative "tools" from other disciplines with which to describe "habitat." An understanding of several channel feature/hydraulic relationships, as well as the effects of debris torrents and organic debris on stream channels, will lend more objective quantification to stream ecology, and provide more ecologic and geomorphic relevance to the contributions of hydraulic science and tracer dispersion theory.

The information gained from this study will, hopefully, aid fishery and forestry managers in assessing the immediate and long-term impacts of debris torrents on the quality and quantity of fish habitat in stream channels. It should also illuminate the reasons for the observed changes, aiding an understanding of the impacts of other types of disturbance on stream morphology and habitat. Elements of channel structure chosen for study control habitat quality for coho salmon and other salmonid fishes (Mundie, 1969; Bustard and Narver, 1975a, 1975b; Tschaplinski and Hartman, 1983; Everest, personal comm.; Reeves, personal comm.; Sedell, personal comm.).

B. Fish Habitat Considerations

Of the eight species of anadromous salmonid fishes in the Pacific Northwest, two species of salmon (Coho and Chinook) and two species of anadromous trout (Steelhead and Coastal Cutthroat) are relatively abundant in Oregon. However, Oregon fishery resources, like those of the Pacific Northwest as a whole, have shown declines over time. For example, Sedell and Luchessa (1982) used old cannery records to estimate annual Chinook and Coho runs on the Siuslaw River of 27,000 and 218,750, respectively, for the period between 1889 and 1896. They contrast these figures with Oregon Department of Fish and Wildlife's Coho Management Plan (ODFW, 1981) annual escapement goal of 200,000 to 250,000 wild Coho adults to *all* coastal Oregon streams after habitat rehabilitation.

The character of large and small streams in the Pacific Northwest has changed drastically from conditions of several hundred years ago. Researchers associated with the USDA, Forest Service (Swanson et al., 1976; Meehan et al., 1977; Swanson and Lienkaemper, 1978; Sedell et al., 1981; Sedell and Froggat, 1984) have undertaken research into a wide range of sources of historical information to illuminate the past character of Pacific Northwest streams. They have found that fast, turbulent streams as well as low gradient streams and rivers contained very large amounts of wood influencing their channels. Most streams, they report, consisted of a complex pattern of main channels, off-channel areas, log jams, and backwater eddies, all highly influenced by large woody debris. Large rivers like the Willamette presented a maze of anastomosing channels in low gradient sections such as the one between Eugene and Corvallis, Oregon. Smaller, high gradient stream channels were often dominated by large woody debris and boulders. Scouring and deposition associated with these obstructions created complex stair-stepping longitudinal profiles with numerous back-eddies and pools. Beaver dams formed ponded areas, added new wood to the stream system, and increased the interaction of streams with their riparian zones (Sedell, personal comm.). Such "pristine" conditions, including an essential element of natural disturbance, generally describe the optimum habitat requirements for various salmonids in the Pacific Northwest (Sedell and Luchessa, 1982). It is within this physical stream setting that the genetic adaptations of Oregon's Pacific Salmon have largely evolved (Sedell and Luchessa, 1982).

Over the past century, streams and rivers have been subjected to debris and boulder removal to improve navigation and to facilitate log drives (Swanson et al., 1976; Sedell et al., 1981; Sedell and Luchessa, 1982; Sedell and Froggat 1984; Triska, 1984; Sedell and Duval, 1985). Streams and rivers alike have been channelized in an effort to improve agricultural land drainage and prevent flooding and bank erosion. Many small and large streams have been impounded for flood control, water supply and hydroelectric power production. The influence of beavers on both small and large streams has been greatly reduced through beaver trapping and alteration of riparian vegetation (Sedell, personal comm.). Small channels, in particular, have been altered in recent decades by the direct effects of logging, road building, silvicultural activities, and stream cleanup operations (Moring and Lantz, 1974; Chamberlin, 1982; Everest and Harr, 1982). As a result of these habitat alterations, streams of today are generally much more uniform in the spatial distribution of physical characteristics such as channel cross-section area, local slope, width, depth and water velocity. These channel changes can adversely affect habitat quality for anadromous salmonids.

Requirements and preferences in rearing habitat of juvenile salmonids have been studied by numerous researchers. A thorough review is presented by Reiser and Bjornn (1979). An important consideration in Pacific Northwest streams is the nearly universal occurrence of territoriality and other space-defensive behavior in stream-dwelling salmonids. A contest for space is apparently substituted for direct competition for food (Chapman, 1966). The number of salmonids in a given stream reach is controlled by the availability of suitable locations for obtaining food in an energetically efficient manner. Salmonids defend these spaces against intruders of the same or different species (Chapman, 1966; Allen, 1969; Chapman and Bjornn, 1969; Waters, 1969). Since food in a stream largely moves past stream salmonids in a way analogous to a "conveyor belt" (Cummins, personal comm.), spatial territories are chosen which offer access to this food, but which also offer refuge from predation and high water velocities. Although recent experimental work by Wilzbach (1985) suggests that food availability can override cover (for Cutthroat trout in Oregon Cascade streams), these experiments were carried out in channel areas of relatively low water velocity. Water velocities were not significantly different between cover and no-cover sites. Salmonids, however, cannot take advantage of food, even in abundance, if favorable water velocity conditions are not available.

Mundie (1969) identifies three basic strategies adopted by different species of emerging salmonid fry for obtaining food while minimizing the energy costs of procuring it. Pink, Chum and Sockeye salmon accomplish this objective by immediately migrating downstream to a lake or to the sea after emerging, where food can be obtained in relatively still water (Hoar, 1953; McFadden, 1969; Mundie, 1969). Steelhead remain in the home stream but hold feeding stations and territories close to the stream bottom away from the highest water velocities. They rise up into swift water to take drifting food items (Kalleberg, 1958). Coho salmon adopt a third strategy. Theirs is to remain in the home stream, living primarily in slackwater, in pools and in marginal back eddies into which food drifts or from which they can venture briefly into swift water where food is more plentiful (Mundie, 1969). As will be discussed later, the type of slackwater habitat desirable for Coho rearing may be closely related to the concept of "dead zone" channel area employed by researchers modeling the hydraulic processes of advection, dispersion, and transient storage of dye tracers in streams and rivers.

Studies of Coho in Oregon, Washington and British Columbia have shown the importance of slackwater space and cover to Coho production. Such studies have found Coho numbers and biomass to be highly correlated with pool size, abundance of pool habitat, and organic debris cover in 2nd to 4th order streams during the summer rearing season (Bustard and Narver, 1975a,b; Li and Schreck, 1982; Bisson et al., 1981; Tschaplinski and Hartman, 1983; Everest, personal comm.). Coho require additional roughness elements such as large boulders or organic debris cover in order to take full advantage of the large amount of slackwater habitat potentially available in pools exceeding 50 cubic meters in volume (Everest, personal comm.).

A primary consideration for salmonids in western streams is to avoid being washed downstream during late fall, winter and spring floods. In snowmelt streams such as the Salmon River in Idaho, Chinook salmon and Steelhead trout retreat into interstices of the bottom substrate at the onset of cold water temperatures (Chapman and Bjornn, 1969) and often make fairly extensive downstream migrations to lower water velocity (see review in Chapman and Bjornn, 1969). Those that remain in high gradient streams avoid being washed downstream during the annual snowmelt period by retreating into substrate crevices if the size of the substrate particles is sufficiently large to resist transport as bedload (Everest, personal comm.).

In the Oregon Coast Range, temperatures are normally high enough to permit feeding throughout the winter season (Everest, personal comm. 1983; Reeves, personal comm.). However, due to the prevalence of freshets from November through April, Coast Range Coho must find slackwater refuge to avoid being washed downstream and out of favorable habitat (Hartman, 1965; Chapman, 1966). Studies in Carnation Creek, British Columbia (Bustard and Narver, 1975a,b; Tschaplinski and Hartman, 1983), in Knowles Creek, Oregon (Everest, personal comm.) and in several western Washington streams (Bisson et al., 1981) have found that juvenile Coho avoid high water velocities by entering stream margin slackwaters or off-channel sloughs during the high flow season. Chapman and Bjornn (1969) indicate that the extensive fall-winter downstream migrations of salmonids observed in Idaho streams are not observed in Pacific coastal streams. However, recent studies in Pacific coastal streams have shown fall-winter movement of juvenile Coho and other salmonids both upstream to small, intermittent head-water streams and downstream to low gradient, off-channel slough areas in larger streams to avoid high water velocities (Bustard and Narver, 1975a,b; Tschaplinski and Hartman, 1983; Everest, personal comm.).

"Winter habitat" for Coho may not simply mean low velocity cover for preventing the fish from being washed out of the stream during floods. The stream margin slackwater areas created by high flow may be equally as important for Coho as winter feeding areas enriched by intimate contact with the terrestrial environment (Everest, personal comm.; Reeves personal comm.). A substantial portion of the annual growth of Coho juveniles in Oregon Coast Range streams takes place between October and April (Everest, personal comm.; Reeves, personal comm.). In contrast, little over-winter feeding occurs in salmon and trout of colder snowmelt streams (Chapman and Bjornn, 1969) or coastal streams in British Columbia (Bustard and Narver, 1975a; Tschaplinski and Hartman, 1983).

Mundie (1969) has enumerated the elements of an "ideal" Coho rearing stream. This description is essentially in agreement with information on Coho habitat utilization and preference reported by Chapman and Bjornn (1969), Moring and Lantz (1974), Bustard and Narver (1975a,b), Reiser and Bjornn (1979), and Tschaplinski and Hartman (1983). The optimum Coho rearing stream, according to Mundie, is relatively narrow (3 to 6 m), shallow (.07 to .60 m), and has fairly swift midstream flow velocities (0.6 m/s). In addition, this stream should have a high proportion of marginal slackwater and back eddies in relation to main channel area (high "dead zone fraction" in hydraulic terminology) so that juvenile Coho can take advantage of drift from high water velocity midstream aquatic macroinvertebrate production areas. Coho habitat quality is enhanced by complex, overhanging banks and organic debris cover which permits hiding. Abundant overhead tree or shrub vegetation prevents heating of the stream water, provides leaf fall and contributes terrestrial insects to macroinvertebrate drift.

The preceding description fits many second to fourth order streams which are important to fisheries in Oregon and elsewhere along the Pacific coast of North America (Sedell et al., 1981; Chamberlin, 1982; Everest and Harr, 1982). It has been estimated (Everest and Harr, 1982) that in forested watersheds of Oregon, Washington, and Alaska, the majority of anadromous salmonid spawning and rearing activity takes place in such small streams. First order stream channels are often inaccessible to salmonid migration because of barriers and steep channel gradients (Everest and Harr, 1982). They can, nevertheless, crucially influence salmonid habitat because retentiveness for nutrients, sediment and organic material largely determines the character of downstream habitat (Hynes, 1975; Beschta, 1978; Everest and Harr, 1982). While the importance of small streams is critical for salmonid production in Oregon, they are, nevertheless, vulnerable to the direct and indirect effects of management practices on commercially valuable timber lands (Hall and Lantz, 1969; Everest and Harr, 1982).

C. Effects of Logging-Related Land Use Activity

Chamberlin (1982) has reviewed the literature concerning the effects of timber harvest on anadromous fish habitat in western North America. Everest and Harr (1982) presented a similar review of the effects of silvicultural treatments. While the effects of silvicultural activities such as site preparation and planting are generally of a similar nature to those caused by timber harvest, effects due to silviculture are usually much smaller (Everest and Harr, 1982). Chamberlin (1982) identified three broad categories of timber harvest impact on salmonid spawning and rearing streams: (1) changes in streamflow quantity and timing, (2) removal of riparian vegetation, and (3) direct effects of harvest activity (including road building) on stream channels.

Recent concern is centering on estimating the probability of debris torrent occurrence as well as the beneficial and adverse impacts of such torrents on salmonid habitat and stream productivity (Benda, 1985; Everest, personal comm.; Sedell, personal comm.; Pyles, personal comm.). Debris torrents, while related in general to the source categories identified by Chamberlin, are natural catastrophic events whose frequency of occurrence can be altered by forest land use activity. A debris torrent is an intense, rapid flow of water, sediment and associated organic debris along a stream channel. Torrents in the Pacific Northwest are usually initiated by headwall slope failures (Swanston and Swanson, 1976; Swanson and Lienkaemper, 1978; Benda, 1985). Whether natural or man-caused, the immediate triggering mechanism in this region is usually a storm of high precipitation intensity which occurs under conditions of high antecedent soil moisture (Swanston and Swanson, 1976).

Timber cutting can increase the incidence of shallow, rapid slope failures through a reduction in the binding of soil to bedrock by tree roots (Swanson and Dyrness, 1975, Swanson and Fredrickson, 1982). Road building is a more frequent cause of slope instability, with failures resulting from the alteration of surface and subsurface drainage patterns as well as from changes in the weighting and gradients of cut and fill slopes (Swanson and Dyrness, 1975, Brown 1980, Swanson and Fredrickson, 1982). A small initial headwall slope failure can produce a large torrent in a stream channel, as the initial slurry of water and debris entrains material in snowball fashion from the streambed and banks (Swanson, personal comm.; Bustard, 1983; Benda, 1985).

The length of torrent tracks is variable. The downstream extent of torrent travel is dependent upon the size and composition of the initial slope failure, the gradient and morphology of the channel, and the shape of the drainage network. Recent studies involving large numbers of debris torrents in the Cascades and the Oregon Coast Range (Benda, 1985) have shown that the higher in the drainage the headwall failure is (the steeper the gradient), and the less the tributary junction angle deflects flow along the torrent track, the longer will be the torrent travel distance. A torrent proceeding down a steep first order channel may stop abruptly if that channel directly enters a lower gradient third or fourth order stream. In such a case, the small channel is often scoured to bedrock while the larger channel receives a massive deposit of sediment and organic debris (Everest personal comm.; Benda, 1985). Water and sediment may be impounded upstream of the point of torrent deposition. Torrents initiated high in the drainage and in drainage network positions that allow downstream movement without severe deflection at tributary junctions can proceed many kilometers downstream (Benda, 1985). Torrent travel commonly stops at a channel gradient of approximately 4 percent in the Oregon Coast Range (Reim, personal comm.). This limitation would be a function of the volumetric discharge, density, viscosity, and momentum of the torrent, in addition to the characteristics of the channel. A long torrent track may leave extensive lengths of stream bottom and banks severely scoured and straightened, terminating in a large deposit of mixed organic debris and sediment.

Beside the initial destruction of salmonid habitat which occurs during the actual event, debris torrents can subsequently affect stream channels and salmonid habitat through the following mechanisms:

1. change in the supply of sediment to the stream channel from upstream,
2. change in the storage of sediment in the channel,
3. change in the supply of large organic debris to the stream channel over time,
4. change in the amount of large organic debris stored in the stream channel, and
5. change in the structure and stability of streambanks and associated vegetation and boulders within the flood channel.

A change in the supply of sediment can create or destroy salmonid spawning habitat. Field and laboratory investigations have demonstrated an inverse relationship between percent fine sediments (<1 mm) in gravels and the survival and emergence of salmonid fry (Reiser and Bjornn, 1979). Though much attention has been given to impacts on spawning habitat

(Reiser and Bjornn, 1979), spawning success is often adequate to seed streams with fry and other habitat factors may limit production in a given stream. Sediment can also affect the Coho salmon rearing potential of streams by altering pool-riffle ratios (Moring and Lantz, 1974; Reiser and Bjornn, 1979; Bryant, 1980; Chamberlin, 1982; Bustard, 1983) and by siltation of backwater areas (Bustard and Narver, 1975a, b). For example, Bustard and Narver (1975b) demonstrated that Coho seeking winter cover in a natural stream in British Columbia preferred simulated backwater habitats that were unsilted over those which were silted.

Pulses of bedload-sized sediment originating from mass failures associated with land use activity have been observed as localized areas of aggradation and channel widening. These pulses of sediment slowly work their way downstream (Kelsey, 1982; Madej, 1982; Reid, 1982). In aggrading sections, pools and backwaters are often "drowned out" by the influx of gravel. Streams often adjust to an increase in bedload sediment supply by increasing channel width (Leopold et al., 1964). A wider channel configuration often reduces pool habitat (Lisle, 1982).

Lyons and Beschta (1983) observed significant increases in channel width on the middle fork of the Willamette River on the western slope of the Cascade Mountains in Oregon. These width changes were measured from sets of aerial photographs taken over 44 years, during which time road-building and timber harvest activity took place. Lyons and Beschta attributed the initial cause of observed width changes to alterations in the rate of sediment input. Such channel width changes can potentially result from increased bedload sediment supply due to mass wasting, destruction of riparian zone vegetation which protects the streambank, removal of large stable woody debris and other roughness elements, or increases in peakflows.

Debris torrents may affect stream channels through alterations in the supply and in-channel storage of large woody debris. The removal of in-channel large woody debris (through harvest, stream cleaning or torrent scouring) can eliminate pools and reduce the stair-stepping structure of stream channels. However, debris avalanches from steep side slopes or debris torrents from tributaries may provide a needed source of both organic debris and sediment to streams (Keller and Swanson, 1979). In such cases, the slope failures may enhance portions of the stream, from the standpoint of juvenile salmonid rearing potential (Everest, personal comm.; Sedell, personal comm.). Active slumps and earthflows may decrease bank stability and cause increases in the number of trees falling into a stream channel (Swanston and Swanson, 1977).

One of the dominant effects of large woody debris in small headwater streams is the creation of pools as a result of the obstruction of water flow past debris dams (Heede, 1976; Swanson et al., 1976; Swanson and Lienkaemper, 1978; Beschta, 1979; Keller and Swanson, 1979; Bilby and Likens, 1980; Bilby, 1981). In small streams, organic debris dams can begin to form when a large piece of woody debris falls into a stream. If the size of the piece is extremely large in relation to the flow of the stream, the debris may remain stable. Otherwise, it can be carried downstream until obstructions protruding from the bed or bank catch and hold the piece against the current (Bilby, 1981). Gradually, smaller sticks begin to collect against the larger piece, providing a framework on which leaves and other smaller debris can accumulate. Ultimately, the structure may become almost water-tight, impounding a pool of deeper water upstream (Bilby and Likens, 1980; Bilby, 1981). Debris dams impounding large ponds are often formed as a result of the deposition of torrent material in a stream, particularly in cases where such torrents move from steep tributaries directly into low gradient channels (Sedell, personal comm.; Benda, 1985). Ponds impounded by organic debris dams are often reported to be of a significantly larger scale than pools produced by scour and deposition of sediment alone (Lisle, in press). During flood flows these pools may offer low velocity refuges for fish and may be instrumental in retaining fine organic detritus.

The presence of large organic debris, boulders, gravel accumulations or bedrock outcrops, particularly in small, steep headwater streams, produces a characteristic "stair-stepping" profile in which stream potential energy is dissipated (Morisawa, 1968; Heede, 1972; Swanson et al., 1976; Meehan et al., 1977; Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Bilby and Likens, 1980; Bilby, 1981). Stair-stepping profile characteristics enhance stream habitat complexity and retention of nutrients by dissipating stream energy which otherwise would be used by the stream to transport bedload and suspended material. Such dissipators provide an abundant variety of water velocities for aquatic biota. In addition, the aggregation of extremely high water velocities in extremely short longitudinal distances both increases the slackwater habitat for fish and facilitates the upstream migration of adult salmonids (Reiser and Bjornn, 1979).

Changes in the storage of sediment in a stream channel are dependent not only upon the sediment supply rate to the stream, as discussed previously, but also upon the sediment retention characteristics of that stream. Large organic debris plays a dominant role in the control of sediment routing and dissipation of energy in Pacific Northwest forest streams. Studies employing removal of organic debris dams have demonstrated the mobilization of large amounts of dissolved and particulate organic materials (Bilby and Likens, 1979, 1980; Bilby, 1981) as well as fine inorganic sediment and gravel (Beschta, 1979), illustrating the importance of woody debris in retaining these materials within the stream system.

Debris torrents, logging activity, or stream cleaning activity may locally decrease or increase the amount and size of woody debris in a stream. Timber harvest and catastrophic torrent scouring of riparian zones may also alter the size and availability of future woody input to streams. Large woody debris, in combination with sediment routing and the kinetic energy of moving water, is highly instrumental in shaping stream channels and determining their pattern of "recovery" following debris torrents. Debris influences channel structure and retention of organic and inorganic materials by the stream, molding fish habitat structure through the processes of ponding, flow convergence, flow deflection and the creation of a stair-stepping longitudinal profile. Excessive concentrations of organic debris, of course, can constitute a barrier to spawning adult salmon (Reiser and Bjornn, 1979; Bryant, 1980; Chamberlin, 1982).

D. Concepts of Stream Recovery

Of interest to managers of forest and fishery resources is the potential for recovery of salmonid rearing streams altered by debris torrents or by land use activities in general. Will these streams recover their structural complexity by natural processes? How long will it take? Will riparian zone management policies which alter the size or availability of woody debris and sediment hasten or delay that recovery? Is intervention necessary to rehabilitate salmonid production potential in streams to that which apparently existed in the past? If such intervention or habitat restoration is necessary, how should it be designed in order to yield positive, lasting results? While we may be able to offer conceptual answers to some of these questions, quantitative answers and methodologies for addressing these questions continue to be elusive.

Relationships between the structural complexity of stream ecosystems and physical "laws" regarding the nature of change in entropy production over time may remain sufficiently obscure to thwart attempts at estimating the rate of change in recovery towards some future state. These relationships may, however, elucidate the direction and endpoint of change. Yang's theory of minimum rate of potential energy dissipation states that a stream system is at equilibrium when its rate of potential energy dissipation per unit weight of water ("unit stream power" = mean velocity X water surface slope) is at the minimum value allowed by constraints (Yang, 1971a,b,c; Yang et al., 1981). "Constraints" include discharge, average slope of the stream valley, suspended sediment load, and character of bedrock (Yang, 1971a). Adjustments made by streams in minimizing stream power include meandering (Yang, 1971b), formation of riffles and pools (Yang, 1971c), adjustment of gradient through aggradation and scour (Yang, 1971a; Leopold et al., 1964; Yang, 1972), and convergence of channels in drainage patterns (Yang et al., 1981). Yang and others (1981) have demonstrated that the long-term adjustments in the functional relationships between discharge and stream width, depth and mean velocity are generally in agreement with the theory of minimum rate of potential energy expenditure.

If logging or natural disturbance to a stream channel causes an increase in stream power over a reach, that stream would be expected, under Yang's hypothesis, to make adjustments in width, depth and longitudinal profile to reduce stream power. Langbein and Leopold (1964) argued that the most probable, or equilibrium state, is represented by a compromise between minimum stream power possible (given the imposed external constraints) and a uniform distribution of energy expenditure over the stream network. While energy dissipation may tend towards uniformity among portions of a network, it appears to tend towards non-uniformity on the scale of channel units within the stream reaches. This apparent dichotomy in predictions of Yang's stream power model may stem from differences in "distance" from equilibrium at different spatial scales. Historical information on streams reveals a high degree of structural complexity presumably characteristic of streams left undisturbed for centuries. Interpretation of the role of structural complexity in the provision of a diversity of paths for energy dissipation might lead to a hypothesis that at points very far from ultimate equilibrium, local maxima of structural complexity are associated with semi-stable sub-equilibrium conditions (Prigogine, 1978; Johnson, 1981). A high degree of channel complexity offers the maximum opportunity for dissipation of the potential energy available to a stream flow due to its elevation (leading to local maximization of stream power but minimization over the scale of whole reaches). The amount of complexity obtainable is, of course, subject to such boundary constraints as parent material, sediment load, discharge regime and availability of large organic debris in the channel.

Davies and Sutherland (1980, 1982) support an alternate hypothesis for stream adjustment from that of Yang (1971a), citing field and laboratory evidence regarding channel bed forms, meander geometry and channel armoring. Their hypothesis is that streamflow in channels with deformable boundaries will alter those boundaries in such a way as to increase their resistance to water flow. An implication of that hypothesis is that a channel will adjust to move sediment as efficiently as possible, in agreement with Kirkby's (1977) hypothesis of maximum sediment efficiency. Davies and Sutherland (1980, p. 178) argue:

> ...that maximum sediment efficiency implies that with a given water input and unlimited sediment supply the channel will adjust its boundaries to carry the largest possible amount of sediment. This would occur if the channel adopted a shape offering maximum hydraulic resistance.

In an intriguing series of arguments, Davies and Sutherland (1982) contrast their Maximum Friction Factor Hypothesis (MFF) and Yang's (1971a) Minimum Potential Energy Dissipation Rate Hypothesis (MEDR). They demonstrate that in the case of *long-term* river adjustment, where the water and sediment discharge rates can be considered independent variables, both hypotheses predict minimization of slope and maximization of flow depth. For intermediate time scales, where discharge and slope can be considered independent, Davies and Sutherland (1982) state that Yang's MEDR hypothesis cannot be used, because the slope-discharge product is not free to adjust. Under these constraints, the MFF hypothesis predicts, in agreement with field and laboratory findings, channel adjustment producing maximum depth and sediment transport rate. Under flume conditions where discharge and depth are independent, data showed that MFF correctly predicted equilibrium adjustments involving an *increase* in slope and bed shear stress (Davies and Sutherland, 1982). MEDR would have incorrectly predicted a minimization of slope and sediment discharge rate.

Flow resistance, as measured by friction factor, increases with an increase in channel boundary roughness, including large scale form roughness caused by channel cross-section irregularities. Therefore, under the Maximum Friction Factor Hypothesis, channel adjustments over time should make maximum use of available boundary materials to increase channel resistance, for example by scouring pools, meandering, and dissipating energy in plunges and cascades.

The complex physical structure which dissipates potential energy in a stream provides a diverse array of habitat conditions for aquatic communities. This array includes variation in cover, space, water velocity, depth, and substrate size. In addition, physical and hydraulic stream features which dissipate potential energy tend to promote retention of organic material and other nutrients within the stream. This retention allows recycling or spiraling (*sensu* Webster, 1975), which promotes community stability and increases the conversion efficiency of secondary production (insects and fish) in a stream reach, given a limited input or production of organic material (Cummins, 1974; Triska and Sedell, 1975; Sedell et al., 1978; Naiman and Sedell, 1979a,b, 1980; Moeller et al., 1979).

A physically diverse system should support a diverse array of organisms from the microorganism level to the level of larger organisms such as fishes. This hypothesis, unfortunately, has not been extensively tested in stream systems. Gorman and Karr (1978), however, in a study of Indiana streams subject to a range in degree of disturbance, found that in most cases fish diversity was linearly related to diversity in physical habitat. Habitat diversity was evaluated using the Shannon-Weiner index calculated from multiple measurements of stream depth, substrate type and current velocity. Watershed disturbances, including stream channelization, dredging, removal of riparian vegetation, and deforestation of drainage areas, were accompanied by decreases in stream channel diversity. The seasonal instability of fish communities Gorman and Karr observed in disturbed stream systems led these researchers to suggest that such streams lack the structural complexity which lends temporal stability to fish communities in undisturbed streams. In the less disturbed streams of their study, meanders moderated the scouring effect of floods, pools supplied low flow refuge for fishes, and tree canopy coverage ameliorated the oxygen-depleting effects of summer algal blooms. In the Pacific Northwest, channel structural diversity in the form of pools and debris accumulations provide conditions favorable to the growth and survival of many types of salmonid fishes (Sedell et al., 1981; Sedell and Luchessa, 1982). In one recent preliminary study in a coastal stream in British Columbia, Coho abundance was found to be positively correlated with an index measuring the complexity of woody debris accumulations (Forward, 1984).

The general trend in streams then, may be that diversity or complexity in the physical stream channel lends temporal stability to the resident aquatic community. Complex stream channels, because of the shear multitude of physical, chemical, and biological linkages which regulate the flow of matter and energy through these systems, may tend to resist seasonal and yearly changes in their biological components. Johnson (1981) maintains that temporal stability in energy availability to an ecosystem generally allows increased diversity of organisms. The relationship is not at all simple however, as evidenced by the observations of Vannote et al. (1980), whereby predictable seasonal changes in stream conditions (water temperature and food quality) may have allowed the coexistence of a greater number of aquatic macroinvertebrate species than would have been be possible without the seasonal variation. Temporal habitat partitioning apparently allowed "species-packing" within an otherwise equivalent space.

A distinction made by Webster et al. (1975) between the stability concepts of *resistance* and *resilience* was evoked by Naiman and Sedell (1979a) in an evaluation of the general community stability of Oregon streams. *Resistance* was termed the ability of an ecosystem to resist any shift away from an equilibrium or reference state. By *resilience* was meant the capacity of an ecosystem to return to equilibrium once disturbed. Resistance is the result of the structural complexity of an ecosystem while resilience reflects inherent dissipative forces, rapid turnover rates and rapid recycling rates. Naiman and Sedell (1979a) described small, head-water forested streams with abundant large organic debris as quite *resistant* because of large standing crops of detritus and long turnover times. Large streams with nutrient input from headwater areas and significant in-stream primary production tend to be less retentive than lower order streams because of greater stream power and lesser influence of large woody debris. They were, however, described by Naiman and Sedell (1979a) as more *resilient* than the smaller streams.

It is possible that this difference in resilience between large and small streams in Oregon may be an artifact related to the designation of equilibrium position. Surely the structural complexity and associated biological community that once characterized the larger streams (Sedell and Froggat, 1984) would take *longer* to redevelop than the equivalent state of complexity in small streams. The period of recovery is controlled by the relationship between the woody debris and sediment supplies and the hydraulic forces which affect their transport or retention. The resilience observed in the larger streams may be a tenacity towards a new sub-equilibrium state of lesser structural complexity, lesser resistance to change in state, and lesser entropy production. Adjustments of the abiotic and biotic components of the larger stream communities toward a state of maximum entropy production now take place in a context which lacks the large woody debris that controlled stream adjustments in the past.

E. Streamflow Hydraulics

Water velocity, water volume, and channel dimensions are extremely important physical components of fish habitat. They are also interrelated in a somewhat predictable manner. The concept of flow resistance is central to an understanding of the relationship between water flow and stream channel characteristics. This understanding is essential if one is to attempt to understand and ultimately predict the response of streams to disturbance and their subsequent pattern of "recovery." An initial point of departure for quantitatively describing flow resistance is to assume that (for a given discharge) flow depth and velocity at any given point in a stream channel are constant over time, and that they remain constant along a given flow line. These two simplifications are, respectively, the steady and uniform flow assumptions. The flow resistance equations currently in popular use for predicting mean water velocity through a stream reach (the Chezy, Manning, and Darcy-Weisbach equations) were developed using these simplifying assumptions. These equations, semi-empirical in nature, describe an experimentally-derived relationship between measured mean water velocity and channel physical characteristics such as water depth, wetted perimeter and water surface slope. The three common flow resistance equations that have been derived for steady, uniform flow through prismatic reaches in open channels (Chow, 1959; Dingman, 1985) are as follows:

Chezy Equation: $U = m_c\ CR^{(0.5)}Se^{(0.5)}$,

Manning Equation: $U = m_m\ (1/n)R^{(2/3)}Se^{(0.5)}$,

Darcy-Weisbach Equation: $U = [(8gRSe)/f]^{(0.5)}$;

where

U = mean velocity of water mass through reach = $[LT^{(-1)}]$;

R = hydraulic radius = (mean channel cross-section)/(wetted perimeter) = $[L]$;

Se = energy slope = water surface slope in uniform flow;

g = gravitational acceleration = $[LT^{(-2)}]$;

C = Chezy's "C", a coefficient of channel roughness;

n = Manning's "n", a coefficient of channel roughness;

f = Darcy-Weisbach friction factor, a dimensionless coefficient of hydraulic resistance;

m_c = constant with dimensions $[L^{(0.5)}T^{(-1)}]$, whose value depends upon the system of units used;

m_m = constant with dimensions $[TL^{(-1/3)}]$, whose value depends upon the system of units used.

The proportionality factors C, n, and f above are an expression of the flow resistance imparted by the channel. Of the three coefficients, only the Darcy-Weisbach friction factor is dimensionless. As such it holds considerable advantage in scientific study. It should be noted, however, that the all three resistance coefficients can be readily interrelated through the following equation taken from Thorne and Zevenbergen (1985):

$$(8/f)^{(0.5)} = C/g^{(0.5)} = R^{(1/6)}/ng^{(0.5)}.$$

As expressed in the Chezy, Manning, and Darcy-Weisbach equations, flow resistance appears at first to be a straightforward physical parameter. However, as pointed out by Chow (1959) and Dingman (1984), any attempt to fully understand flow resistance leads quickly to the realization that it is almost impossible to separate cause and effect. Changes in either channel boundary roughness or slope cause changes in depth, for example. The components of the equations are not, therefore, independent. Any statement describing a particular flow, for example its mean velocity, mean depth and slope, is an implicit statement about flow resistance as well. However, in spite of the complexities associated with the concept of flow resistance, all the factors which contribute to flow resistance within a stream reach can be specified (Dingman, 1984). These factors are skin friction, form resistance, and such intense energy dissipation mechanisms as plunges, breaking waves and hydraulic jumps.

Skin friction arises from the effect of flow shear stresses derived from the channel boundary material itself. Skin friction increases as the grain size of this material increases as, for example, from sand to cobbles. It is also affected by grain shape and spacing. Form resistance derives from channel roughness of a larger scale which distorts flow streamlines, causing local velocity accelerations and decelerations. Form resistance in streams is due to flow deformation associated with bedforms, obstructions, channel bends and abrupt changes in cross-section geometry such as alternating riffle/pool structure. The separation into skin resistance and form resistance is somewhat artificial; the differences being more in degree than in type of resistance. All roughness features cause eddies that are driven by energy from the main flow, hence detracting from the energy available to that flow (Dingman, 1984). Energy of the main flow is eventually dissipated in heat as well as the scouring and transport of substrate particles. Energy of the main flow is also dissipated by intense turbulence in such flow features as plunges, breaking waves and hydraulic jumps which result from abrupt changes in cross-section geometry (Chow, 1959; Simons and Senturk, 1977; Dingman, 1984; Simons and Richardson, 1966).

The Chezy, Manning and Darcy-Weisbach flow resistance equations provide relatively satisfactory estimates of flow resistance or mean velocity for the comparatively uniform flow conditions found in many large rivers. The "steady flow" assumptions of these uniform flow equations can be stretched somewhat to allow variation in depth and velocity from moment to moment at a given point in a stream channel, as long as the time-averaged velocity and depth are constant at that point (Chow, 1959; Simons and Senturk, 1977; Dingman, 1984). It is not clear exactly how far one can stretch the assumption of spatially uniform flow. Engineering experience has shown that these equations accurately predict (cross sectional velocity and mean time of travel through short river and stream reaches where velocity accelerations and decelerations occur on the spatial scale of substrate particle sizes, or where temporal accelerations in velocity occur because of moving eddies of relatively small size (Chow, 1959; Dingman, 1984). Correction factors have been used with varying success to modify semi-subjective estimations of the flow resistance coefficient that take into account channel bends and other aspects of large scale form roughness in rivers (see Chow, 1959, p. 109).

In order to use the flow resistance equations to calculate mean velocity of flow in channels, it is necessary to estimate the flow resistance factor from information about the morphology of the channel and its substrate. There are two approaches to this problem: one is a largely subjective empirical approach and the other is an attempt at incorporating knowledge about the flow processes involved.

Common engineering practice in the design of artificial channels has for many decades relied on the first approach with reasonable success. It is an empirical one which employs descriptive and pictorial representations of channel characteristics associated with measured values of a flow resistance coefficient (see, for example the photographs and tables on pages 109 through 123 in Chow, 1959). An appropriate resistance coefficient is subjectively chosen for the design situation at hand. In addition to inaccuracies stemming from the subjective choice of a value for channel resistance, this method suffers potentially large errors because the resistance coefficients are erroneously assumed to remain constant with changes in discharge (Bathurst et al., 1979). This method, nevertheless, has been and continues to be used extensively for flow computations in natural stream and river channels because of its simplicity and minimal requirement for quantitative channel and substrate data. The more complex the natural channel and the larger its relative roughness (roughness size in relation to flow depth), the less reliable are flow computations employing descriptions and photographs to assign a value of channel resistance.

In the second approach to estimation of channel resistance, the flow resistance coefficient is calculated by an equation based largely on a theoretical description of the flow processes involved. The potential accuracy of such an approach is greater, but at present only simple flows can be described (Bathurst et al., 1979, Thorne and Zevenbergen, 1985). The conceptual approaches to describing flow differ with the scale of roughness in the stream channel.

Stream channel roughness is described as small scale (Bathurst et al., 1979) when it is less than one tenth to one fourth the flow depth. Small scale roughness is assumed to act as an homogeneous surface which imparts a frictional shear on the flow above the boundary. This boundary shear produces a predictable velocity profile whose slope is determined by the size, shape and spacing of roughness elements and by the geometry of the channel (Chow, 1959; Simons and Senturk, 1977; Bathurst et al., 1979). Equations for calculating the flow resistance coefficient for a given channel cross section take the following general form, as discussed by Bathurst et al. (1979) and the American Society of Civil Engineers (1963):

$$U/(gRS)^{0.5} = (8/f)^{0.5} = A + B\log(R/k) \; ;$$

where:
- k = roughness height;
- R = hydraulic radius;
- R/k = relative submergence = 1/relative roughness;
- A and B = constants with precise theoretical meanings, but which in practice are often derived empirically for a given stream.

Boundary layer theory cannot be used in the case of large scale roughness, where bed material height is of the same order of magnitude as flow depth (Bathurst et al., 1979) and velocity profiles cannot be assumed to be logarithmically shaped (Bathurst, 1985). Hydraulicians and engineers have traditionally avoided systematic, quantitative study of flow resistance in streams with large scale roughness. This avoidance was natural, stemming in part from the complexity of the problem and in part because of a perception that the most important human management and impacts were on lowland rivers and streams. Hydraulicians simply did not have to contend with small upland streams to any great extent

(Bathurst et al., 1979; Dingman 1984; Thorne & Zevenbergen 1985). Recent decades, however, have sparked increased interest in small upland streams as human management and impact in upland regions have intensified through such activities as forestry, road construction, fishery management, and recreation.

Small upland streams are characterized by high slope (> 1%), intermediate ($0.25 < k/R < 1$) to large scale roughness ($k/R > 1$), complex channel morphology and often markedly non-uniform flow, in contrast to most lowland rivers from which the majority of flow resistance theory was developed. At present, little is known about the hydraulic properties (or even the morphology) of such streams. Until such knowledge is developed, it will be difficult to quantitatively predict their response to management impacts. Bathurst (1978), Bathurst et al. (1979) and Thompson and Campbell (1979) have made important advances in the understanding of flow resistance in mountain streams with high relative roughness. Excellent analyses and reviews of the present "state of the art" in predicting flow resistance in mountain streams are presented by Bathurst (1985) and Thorne and Zevenbergen (1985).

The research equations developed by Bathurst and co-workers, and by Thompson and Campbell, are semi-empirical in nature and are not as yet suitable for general engineering use (Bathurst, 1985). The fixed-bed flow resistance equation of Bathurst et al. (1979), for example, describes flow resistance from large scale roughness as being due to the sum of the form drags of individual roughness elements. Because wall effects dominate the flow, these authors state that roughness geometry and distortions of the free water surface around roughness elements account for most of the channel flow resistance. Channel geometry is thought to be secondary in that it has only an indirect influence through its effect on the flow around roughness elements. Bathurst's equation, developed from steep flume studies at Colorado State University, is stated as follows:

$$U/(gRS)^{0.5} = (8/f)^{0.5} = \{(0.28/b)Fr\}^{\log(0.755/b)}$$
$$\times \ (13.4(W/Y50)^{0.492})(b^{1.025(w/Y50)^{0.118}})$$
$$\times \ (Aw/Wd') \ ;$$

where $b = \{1.175(Y50/W)^{0.557}\ (D/S50)\}^{0.648\sigma^{-0.134}}$;

Fr = Froude number $U/(gD)^{0.5}$;

W = surface width at a section;

Y50 = size of cross-stream axis of a roughness element which is greater than or equal to 50 % of the cross-stream axes of a sample of elements;

S50 = size of vertical axis of a roughness element which is greater than or equal to 50 % of the vertical axes of a sample of elements;

D = mean depth of flow;

U = mean velocity of flow;

σ = standard deviation of a particle size distribution;

A = flow cross sectional area;

Aw = wetted roughness cross sectional area;

Wd' = A + Aw;

Aw/Wd' = relative roughness area, approximately equal to $(W/D)^{-b}$ for channel flows.

Bathurst et al. (1979) indicate that term (1) accounts for the free surface drag of roughness elements, term (2) accounts for roughness geometry, and term (3) accounts for the portion of the channel flow cross section occupied by roughness elements.

The Bathurst et al. (1979) flow resistance equation above is applicable for steady, uniform flow (broadly defined) in wide channels ($13 < W/D < 150$) with intermediate to large scale roughness ($0.40 < D/S50 < 12$), Froude numbers between 0.2 and 1.9, and Reynolds numbers between 1,000 and 44,000. These conditions generally describe steep, riffly, boulder and cobble-bedded mountain streams and rivers flowing at gradients from 1 to 5 percent. Despite their contribution to the understanding of flow resistance in mountain streams, such research equations as the one described above have not provided a sufficient improvement in accuracy to justify their additional data requirements and cumbersomeness in application (Thorne & Zevenbergen 1985). Both Thorne and Zevenbergen (1985) and Bathurst (1985) found the relatively simple equation of Hey (1979) to be the most successful in tests involving a wide range of cobble and boulder bedded channels. The Hey (1979) equation,

$$(8/f)^{0.5} = 5.62\log\{(a'R)/(3.5D_{84})\} ,$$

is based on a semi-logarithmic relationship between dimensionless velocity, $U/U_* = U/(gRS)^{0.5} = (8/f)^{0.5}$, and relative submergence, R/D_{84}. The factor a' is a function of channel shape and varies between 11.2 and 13.5. The success of this equation is surprising, since it was not intended for use in boulder-bedded channels with low relative submergence (Thorne & Zevenbergen, 1985).

The flow resistance equations discussed above and a number of others evaluated by Thorne and Zevenbergen (1985) and Bathurst (1985) are intended to provide estimates of channel flow resistance in stream reaches where resistance is due to channel controls. They can greatly underestimate flow resistance in reaches where a significant amount of resistance results from downstream controls, such as occur as a result of channel constrictions and typical pool-riffle morphology (Bathurst, 1985). Current practice for estimating time-of-travel over longer reaches showing significant variations in width, depth and elevation profile is restricted to complex, data-intensive hydraulic routing procedures or coarse empirical methods based on measured relationships between mean transit velocity and slope, drainage area, and approximate discharge.

There have been few attempts at deriving flow resistance equations to estimate total resistance over long reaches, or that component of flow resistance due to factors other than "skin" or grain resistance (see for example Parker and Peterson 1980). Bathurst (1981) suggested that the ratio of measured discharge to discharge calculated by a grain resistance equation such as that of Hey (1979) should be an inverse measure of "bar resistance," which is primarily due to ponding effects (expansion losses, impoundment, etc.). This ratio should be proportional to the ratio of (D-Do)/D, mean depth minus mean depth at zero discharge divided by mean depth, which Bathurst used as an inverse measure of the degree of ponding. Bathurst (1981) stated that:

> ...There seems to be a good possibility that bar resistance could be calculated directly from the residual depth (the primary source of the resistance), which would be more satisfactory than deriving it from shear stress criteria which are less directly related to the process involved. Considerably more experimental data, though, will be needed to bring this idea to fruition....

F. Use of Flow Tracers to Explore Channel Morphology

1. The Profile of Dye Concentration Versus Time

The importance of understanding the relationships between hydraulic flow resistance and channel morphology was discussed in the preceding section. A related, but conceptually divergent approach to relating water flow to stream channel characteristics can be based on hydraulic tracer dispersion theory. A profile of concentration versus time for a dye tracer slug release experiment in a stream reach is a statistical measure of the frequencies of dye molecules which have taken flow pathways differing in transit time (Hays, 1972). If it is assumed that the dye is thoroughly mixed at the instant of dumping and that the dye molecules do not affect the flow characteristics of the stream water, then the dye molecules can be used as tracers to observe and measure the different pathways taken by water as it courses through a stream reach. Because of the relationships between flow characteristics and channel morphology, dye tracer methods show some promise for evaluating channel characteristics. In particular, such methods may offer a relatively simple and meaningful way of quantifying hydraulically detentive features which constitute slackwater habitat for fishes and which enhance nutrient retention in streams.

Although water paths may differ both in length and velocity within the same stream reach, dye concentration profiles are measures only of the aggregate frequencies of water molecules passing through that reach with different transit times. There can therefore be alternate paths which yield the same time of arrival for a molecule at the point of observation. Consider a situation with simple advective transport (no dispersion) of dye tracer from upstream point 1 to point 2 in a stream reach. An expression of Bernoulli's Equation states that the total energy upstream (expressed as hydraulic head, or energy per unit weight of water) minus the frictional losses within the reach equals the total energy downstream. For simplicity, I have written a one-dimensional expression and am assuming no suspended or bedload movement within the reach:

$$(p_1/\rho g) + [(u_1^2)/2g] + z_1 - h_L = (p_2/\rho g) + [(u_2^2)/2g] + z_2$$

where: subscripts 1 and 2 denote upstream and downstream values,

z_1 and z_2 are fluid surface elevations,

p_1 and p_2 are fluid pressures,

u_1 and u_2 are mean flow velocities,

h_L is the frictional head loss within the reach due to skin friction, turbulence, and internal shear,

ρ is the mass density of the fluid, and

g is the acceleration due to gravity.

If reference points 1 and 2 are both at the water surface and at equal depths, p1 and p2 can be considered equal and will cancel out in the expression. Similarly, if the average velocities at points 1 and 2 are equal, the velocity head components of the expression will cancel. For a sufficiently long stream reach, most differences in velocity or pressure head will be relatively insignificant compared to the difference in elevation. The energy loss through the stream reach will simply equal z_1 minus z_2, the difference in elevation over the reach. If one measures, for a stream reach, the dye concentration change at point 2 after releasing dye uniformly through the cross-section at point 1, the transit time of the dye mass and the corresponding change in elevation allow calculation of the time rate of potential energy expenditure in the reach.

The simplistic explanation above illustrates that the mean velocity of a dye tracer cloud evaluates hydraulic pathways in terms of their energy equivalency, rather than their exact spatial equivalency. The mean rate of movement of water through a meander might be the same as that produced by a debris dam pool or a wide, low gradient riffle. Because of differences in turbulence, vertical and horizontal velocity profiles, and transient storage of water through each type of reach section, however, one would expect the shape of the profile of dye concentration versus time to differ even though the mean transit time of the dye mass itself (reflecting the total energy expenditure within the reach section) may be the same. Actual dye concentration profiles for natural stream channels normally show an increased variance in transit time as roughness increases, and a skewness (or elongation of the "tail" of the profile in the direction of increasing transit time) which becomes more marked as roughness and slackwater volume increase in the bottom and the sides of the channels (Hays, 1966; Fischer, 1967; Sayre, 1967; Thackston & Schnelle, 1970; Chatwin, 1971, 1980; Day, 1975; Day & Wood, 1976; McQuivey & Keefer, 1976; Valentine and Wood, 1977, 1979a,b; Sabol & Nordin, 1978; Beltaos, 1980a,b; Bencala & Walters, 1983).

2. Tracer Dispersion Modeling Approach

If some of the paths which can be taken by water between the upstream dye release point and the downstream point of measurement differ in their amounts of energy dissipation, the dye mass will disperse as it moves downstream. The shape of the dye concentration curve produced is controlled by the elapsed time, the downstream distance from the point of release, and the flow characteristics (and therefore the morphology) of the stream channel.

Some researchers have suggested that information gained from dye concentration profiles could be used to characterize natural stream channels (Valentine & Wood, 1979b; Chatwin, 1980). To date, the theoretical and practical potentials of this idea have not been systematically developed. The procedure for accomplishing such a characterization would be to first develop a model describing the dye concentration change with respect to time at a fixed downstream point and then attempt to "back-calculate" model parameters from the dye concentration-time curve and other known channel and flow information.

A model was developed by Fischer (1966) which described transport of a conservative, neutrally buoyant dye used as a tracer of water movement. The model describes transport resulting from advection plus "Fickian" dispersion, i.e., the longitudinal dispersion caused by turbulent transport of dye molecules across horizontal and vertical gradients of velocity within the stream channel. Fischer's model is summarized in Appendix A. This type of model suffers from the inability to describe certain skewness and tailing characteristics which are typical in concentration-time curves (Hays, 1966; Thackston & Schnelle, 1970; Chatwin, 1971; Day & Wood, 1976; Sabol & Nordin, 1978).

Models have since been developed which additionally take into account transient storage areas or "dead zones" in the channel sides and bottom which trap and detain dye molecules (see for example: Hays, 1966; Sayre, 1967; Valentine & Wood 1977, 1979b; Sabol & Nordin, 1978; Beltaos, 1980a, 1982; Nordin & Troutman 1980; Bencala & Walters, 1983;

LeGrand-Marqu & Laudelout 1985). With some variation, most of the "dead zone" dispersion models are quite similar to the model developed by Hays (1966), where two simultaneous equations comprise a general expression for dye transport in a channel by the processes of advection, velocity-gradient dispersion and transient storage in peripheral dead zones:

$$\partial Ca \partial t = Da(\partial^2 Ca/\partial x^2) - U(\partial Ca/\partial x) + Ka(Ca-Cd)$$

$$\partial Cd/\partial t = Kd(Ca-Cd)$$

where: Ca = average cross-sectional dye concentration in the main stream $[ML^{(-3)}T^{(-1)}]$,

Cd = average cross-sectional dye concentration in the dead zone $[ML^{(-3)}T^{(-1)}]$,

Da = longitudinal dispersion coefficient in the main stream $[L^2T^{(-1)}]$,

Ka = volume-based mass transfer coefficient in the main stream $[T^{(-1)}]$,

Kd = volume-based mass transfer coefficient in the dead zone $[T^{(-1)}]$,

U = average velocity in the main stream $[LT^{(-1)}]$,

t = elapsed time since dye release [T], and

x = distance downstream from point of dye release [L].

Hays (1967) derived an analytical solution for the above equations, assuming the release of a known mass of tracer to the stream. This solution, shown in Appendix A, employs a LaPlace transformation, allowing the calculation of a profile of mainstream concentration versus time at a fixed downstream position. Calculation of this simulated profile requires that the values of four model parameters be known in addition to the tracer mass (M) and the reach length (L):

T = L/Ua = travel time of tracer mass

Pe = LU/Da = Peclet Number

Td = 1/Kd = Dead Zone residence time ratio

β = Ad / (Aa + Ad) = Dead Zone volume (or cross-sectional area) ratio

where: Aa = cross-sectional area of mainstream,

Ad = cross-sectional area of dead zone, and

α = Aa/(Aa + Ad), and (note that $\alpha + \beta = 1$)

Ua = velocity of the center of mass of the tracer cloud.

Thackston and Schnelle (1970) discuss methods for predicting the values of the four model parameters T, Pe, Td, and β in the Hays model.

When variable T is divided by the reach length, it yields the mean velocity (convective velocity) of the tracer cloud. It can be estimated from a dye release experiment as the centroid of the concentration-time curve (after making the "frozen cloud" approximation that the shape of the cloud in the spatial domain does not change as the cloud passes the point of concentration measurement).

Calculation of the Peclet number Pe requires an estimate of average mainstream velocity U, and the longitudinal dispersion coefficient Da. U can be calculated from the discharge and mean cross-sectional area of the main channel. Fischer (1967) has developed a method employing uniform flow assumptions for the calculation of Da using a measured lateral velocity profile. Thackston and Schnelle (1970) state that Fischer's is the only reasonable method available for predicting Da in most natural streams. Because Fischer's method requires an assumption of uniform flow, it would also be necessary to make these simplifying assumptions regarding velocity field dispersion before using the Hays dead zone model to estimate channel characteristics from tracer curves.

The residence time ratio Td represents the average time spent by dye in the dead zone divided by the average time spent in the entire reach. Thackston and Schnelle (1970) suggest that this parameter should be a function of at least the dead zone size and its mass transfer coefficient.

Preliminary analysis of the dead zone volume fraction β by Thackston and Schnelle (1970) showed that $\beta = c + mf^n$, where c, m, and n are constants determined by non-linear least squares procedures on a regression of measured dead zone volume fraction on channel friction factor ($f = (8gRSe)/U^2$). The standard error for this regression was less than 1 percent of the total stream cross section for β ranging from 0.01 to 0.06 and f ranging from 0.04 to 0.26.

The major problem with attempting to infer channel structure by back-calculating model parameters from concentration-time data is that the existence of more than one model parameter makes it difficult to "fit" model parameters with confidence. Ideally, all but one parameter should be estimated by other methods, such as those partially illustrated above. Hays (1966) has, however, used non-linear least squares procedures to calculate, from actual concentration-time curves, the most probable set of four dead zone model parameters for a given dye release experiment. Hays (1966) has also analyzed the effect of the various model parameters on the first three central moments of concentration-time curves simulated by the dead zone model. The first moment about the mean is T, the average residence time of dye in the reach. The second moment about the mean of the concentration-time curve is the variance in transit time. It increases with corresponding increases in the dead zone fraction β, the dead zone residence time (Td), and the dispersion coefficient. The third moment shows a strong positive dependence upon the dead zone residence time (Td), illustrating the association of dead zone storage with the marked skewness observed in experimental data (Hays, 1966). Chatwin (1980) has suggested that different types of stream flow can be distinguished and classified by the downstream evolution of the third and fourth central moments of the concentration-time profile.

A major departure from the dead zone dispersion modeling approach by Hays (1966) was first proposed by Kaijser (1971) and later modified and tested by Sabol and Nordin (1978). This approach considers dispersion in a natural channel to be caused by periodic random transfers between two velocity compartments in the stream channel. One compartment is assumed to be moving uniformly at a velocity equal to the velocity of the leading edge of the dye tracer cloud. The second compartment is defined as a zero down-stream velocity compartment which represents all detentive features of the channel, including marginal and bottom dead zones. Individual tracer molecules are exchanged back and forth between the two compartments in a random way, affected by the degree of turbulence and the size of the storage zone. Tracer molecules are assumed to be completely mixed within both zones (but not between zones). Their exchange is assumed, therefore, to be a first order kinetic process whose rate depends on the difference in cross sectional average concentration between the two compartments and also on an exchange coefficient. The exchange coefficient is volume-based and reflects the intensity of turbulent transport of water between the two compartments. A more detailed outline of Sabol and Nordin's model is contained in Appendix A. This model achieves good fit to actual river data, considering the remarkable simplicity of its concept. The Sabol and Nordin model can be shown to be a special case of the general dead zone dispersion model of Hays (1966) in which the effect of longitudinal dispersion within the velocity field is ignored and dispersion is due only to transient storage (Sabol & Nordin 1978). The advection term remains in the model. Solution of Sabol and Nordin's model requires values for the four model parameters Uc, au, a_L, and δ. The definitions and methods for estimation of these parameters are listed below, as paraphrased from Sabol and Nordin (1978):

Uc = convective velocity. This parameter can be determined from the centroid of the C vs. t curve. It is the time rate of travel of the dispersing cloud of tracer.

au = TL/Tc = time from zero to the leading edge of the tracer cloud at the downstream point of measurement divided by the centroid of the concentration-time distribution. This parameter is equal to the probability that at a given instant, a dye molecule is in the main stream (moving) water compartment.

a_L = (1 - au) = the probability that a dye molecule is in the transient storage (zero velocity) compartment at any given instant.

δ = $(2\ a_L\ \chi_i)\ /\ (Uc\ au\ \sigma^2)$; where χ_i is the distance downstream to the point of dye measurement, and σ^2 = var[T(x)] = the variance in transit time at a given downstream point (χ_i). δ is equal to the average number of times a dye molecule goes into storage per unit time. (This may also be interpreted as the portion of the total stream volume moving into or out of storage per unit of time.)

3. Application of Tracer Dispersion Modeling

In this study, Sabol and Nordin's (1978) tracer modeling approach was chosen to analyze hydraulic tracer data. All of Sabol and Nordin's model parameters can be back-calculated unambiguously from an empirical profile of dye concentration versus time. It remains to be seen, however, whether or not these model parameters are correlated with elements of channel morphology or have physical meanings which are associated with channel characteristics.

The following derivation produces an expression exactly equivalent to the formulation derived by Sabol and Nordin (1978) but with a somewhat different conceptual basis. This derivation, admittedly intuitive, serves to demonstrate the equivalency of the *stochastic* concept of the probability of a molecule being in the dead zone (in transient storage) with the *spatial* concept of dead zone volume or cross-sectional area fraction. I have borrowed from the assumptions of Sabol and Nordin's (1978) transient storage model and from the ideas of Hays (1966) and Valentine and Wood (1979b) in their definition of dead zone volume fraction. I employ the flow continuity equation as a starting point:

$$Ut = Q/At = [(Um \times Am) + (Ud \times Ad)] / At$$

where:
- Q = volumetric discharge rate in a reach $[L^3T^{-1}]$
- Ut = mean velocity of the total water mass in a reach $[LT^{-1}]$
- Um = mean velocity in the actively flowing "mainstream" of the stream channel $[LT^{-1}]$
- Ud = mean downstream velocity in the stagnant "dead zones" of the channel $[LT^{-1}]$

At = mean channel flow cross sectional area including active flow portion plus dead zones [L^2]

Am = mean flow cross sectional area of actively flowing portion of stream channel [L^2]

Ad = mean cross sectional area of dead zone portion of stream channel [L^2]

If Ud = 0, by definition, assuming no net longitudinal movement in dead zones and all longitudinal movement in the mainstream, then Ut = (Um × Am)/At. Therefore, the mainstream flow portion (Am/At) = Ut/Um. Now, assuming that Ut = Uc = the centroid velocity of a curve of tracer concentration versus time, and assuming Um = U_L = velocity of the leading edge of the tracer curve (as assumed by Sabol and Nordin, 1978); then Am/At = Uc/U_L. Since Am + Ad = At, and (Am/At) + (Ad/At) = At/At = 1, then the dead zone proportion (Ad/At) = 1 - (Am/At) = 1 - (Uc/U_L).

The final expression of this derivation [1 - (Uc/U_L)] is the same as the formulation given by Sabol and Nordin (1978) for a_L, which is the probability that a water molecule is in transient storage at any given time. The extent to which the total channel water velocity Uc lags the mainstream velocity (estimated by U_L) is a measure of the proportion of relatively quiescent water in the reach exchanging with the mainstream or active flow of the channel.

The value of Sabol and Nordin's variable a_L is therefore equivalent to the relative portion of channel cross section area comprising the dead zone (Ad/At). This statement is true only within the confines of the conceptual flow description restricting flow to two distinct portions within the channel. The moving layer flows uniformly at a velocity equal to the discharge divided by the cross sectional area of this moving portion, the "mainstream." The dead zone portion of the channel has no net movement up- or downstream. Both of these conceptual restrictions are artificial--we know that this is not exactly how streams "behave." However, these simplifying assumptions do eliminate the need for estimating longitudinal dispersion resulting from the turbulent exchange of water across vertical and especially horizontal gradients of velocity. They therefore eliminate the requirement for measuring such velocity gradients before back-calculating dead zone volume fraction from tracer data.

In extremely complex channels alternating among narrow chutes, deep pools, and wide, shallow riffles, it is difficult to conceive of a mean velocity gradient in the horizontal or vertical direction which would adequately represent such flow complexity. It seems conceptually more satisfying, in fact, to drop back to the more general representation by Kaijser (1971) and Sabol and Nordin (1978) of a rapidly moving "mainstream" adjacent to a "dead zone" of relatively quiescent water. It is important to remember that this dead zone concept is one of *effective* dead zone portion. The calculated dead zone proportion of the mean channel cross section represents all the detentive features within the given stream reach. The more the exchange process between regions of relatively swift and relatively still water dominates over "velocity gradient dispersion," the more accurately the model represents the real-world stream. It can be seen, however, that there is ultimately no fundamental difference between the process by which water and momentum are exchanged by turbulence across a velocity gradient (as represented by the "Fickian" dispersion term of the Hays model) and that through which the exchange is by turbulence across a region in which there is an abrupt change in velocity (as in the Sabol and Nordin model or the dead zone portion of the Hays model).

There is in reality a continuous velocity gradient in both cases. The processes differ only in the steepness of the gradient and the uniformity of its rate of change over vertical or lateral distance. For this reason the Fickian dispersion term describing velocity field dispersion is somewhat redundant, at least for complex channels where transient storage in dead zones is the primary cause of longitudinal dispersion.

One can readily see a parallel here between dispersion theory and hydraulic theory. Equations using velocity gradient considerations adequately describe flow resistance or mean velocity as long as values of substrate relative roughness and variance in channel cross sectional dimensions are low. When relative roughness values are very high, or when there is a great deal of flow separation due to channel variation, equations based on the assumption of a predictable vertical or horizontal velocity profile become inadequate. At that point, we are forced to drop back to a more general level of sophistication in modeling, relating flow resistance and dispersion to the geometry of flow obstructions or impoundments, without making any specific assumptions about the detailed nature of the velocity field surrounding those features. The definition of dead zone volume, depth or cross sectional area fraction is conceptually very similar to the concept of the residual pool depth ratio advanced by Bathurst (1981), and which was discussed in the previous section of this dissertation. Bathurst suggested that "bar resistance" (due mostly to expansion losses) might be directly calculated from residual pool depth. An understanding of the channel morphology associated with measured values of dead zone fraction will undoubtedly lead to a greater understanding of flow resistance due to expansion losses.

Since the initial studies of Thackston and Schnelle (1970), there has been considerable recent interest in analyzing correlations between tracer dispersion model parameters and various channel and streamflow characteristics (including morphometric measures of dead zone fraction, bed roughness, Froude number, Reynolds number and fluid shear velocity), as evidenced in the work of Pederson (1977), Valentine and Wood (1979a,b), Abd El-Hadi and Davar (1976), Bencala and Walters (1983), and LeGrand-Marcqu and Laudelout (1985). This work is primarily aimed at developing ways of estimating model parameters for use in predicting concentration-time profiles in pollution studies. However, such research may indirectly aid in assessing stream channel and flow characteristics from known concentration-time data. A major portion of my study is aimed at exploring the relationships between field measurements of stream channel morphology and model estimates of channel dead zone fraction and storage-exchange intensity derived from tracer data. I shall also demonstrate the potential utility of dispersion model parameters in the study of stream nutrient dynamics and fish habitat assessment.

II. OBJECTIVES

The primary emphasis of this study is on determining the relationships between channel morphology and hydraulic characteristics. In doing so, changes in stream channel morphology of third order Oregon Coast Range streams were evaluated following channel scour and deposition by debris torrents. The size, morphology and abundance of channel features such as main channel pools, channel margin backwaters, and stair-stepping features of the longitudinal stream profile were quantified. These channel characteristics were then related to measures of flow resistance and dispersion calculated from tracer data. The size and abundance of main channel pools and marginal backwaters are of particular importance in the provision of summer and winter rearing habitat for coho salmon. These channel slackwater features are also important for the retention and cycling of nutrients and organic material within any given reach of stream. "Stair-stepping" channel profiles enhance nutrient retention and provide a diversity of physical habitat.

The purpose of my twin-pronged approach is to describe the habitat changes resulting from debris torrents in a quantitative way that is hydraulically meaningful. It is an attempt to express these habitat changes in terms of their quantitative morphologic and hydraulic characteristics and to gain, furthermore, an insight into their possible morphological trends over time. Finally, it is hoped that this study can lend more objective quantification to one aspect of the science of stream ecology while at the same time providing more ecological and geomorphological relevance to the contributions of hydraulic and dispersion theory.

Specific research objectives were as follows:

1) To examine the relationship between channel form and hydraulic characteristics in small Oregon Coast Range streams and to evaluate the influence of large organic debris on both form and flow.

2) To determine whether hydraulic properties of these streams can be used to describe channel characteristics. Of special interest were those characteristics such as pools and channel complexity which are important for fish habitat and nutrient retention.

3) To examine the effects of severe scour and massive deposition from debris torrents on channel form and its attendant hydraulic properties. The pattern of recovery following such channel disturbances was considered, as were the implications of observed channel changes and inferred recovery tendencies on fish habitat quality and nutrient dynamics.

4) To examine the effects of experimental debris placement on channel form and hydraulics in a recently torrent-impacted stream.

III. METHODS

A. General Study Design

In order to accomplish my dual objective of exploring the influence of debris torrents on channel morphology and analyzing the effects of channel morphology on hydraulic characteristics, small streams of like geology, climate, basin vegetation type, drainage area, and channel gradient were required. Therefore, I chose study streams in the central Coast Range of Oregon, a region were numerous small streams are (or are at least potentially) important as spawning and rearing habitat for Pacific salmon species and Steelhead Trout. These streams differed primarily in the amount of time elapsed since they had been impacted by a debris torrent or a debris flood. Inferences were based upon an assumption that these different streams approximately describe the disturbance and recovery pattern that might occur on a single stream over a long period of time.

The field study consisted of a stratified sample design employing collection of systematic longitudinal data from random starting points. Three streams (Figure 1) were selected as case studies to represent three disturbance classes, based upon the time since major debris torrent impact: recent disturbance (2 to 3 years), intermediate time of disturbance (10 to 20 years) and relatively undisturbed (100 to 150 years since torrent impact). The streams selected were Gwynn Creek (2 yr.), Cape Creek (12 yr.), and Little Cummins Creek (117 yr.). All three streams

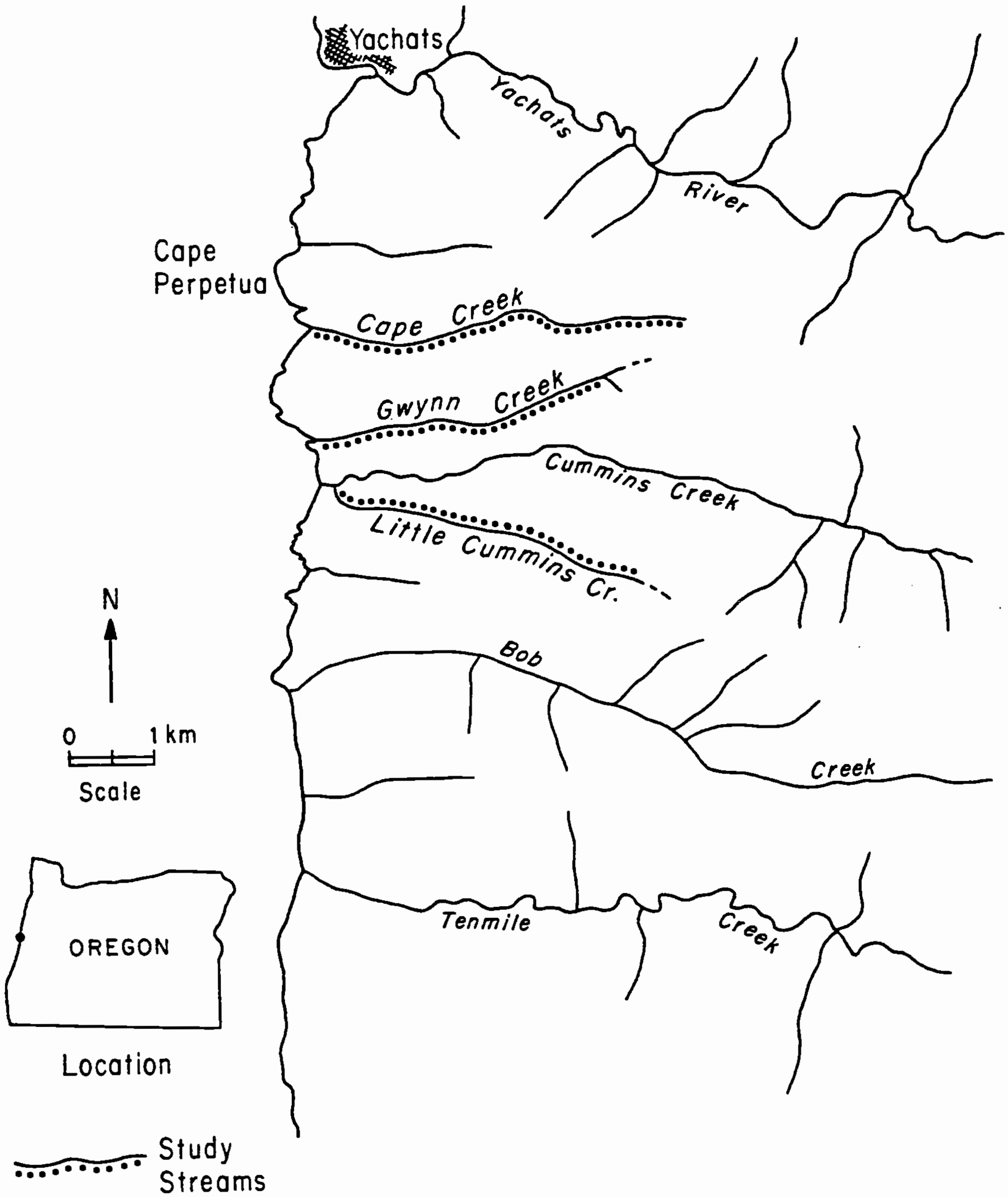


Figure 1. Location of Study Streams in the Oregon Coast Range

are third order (*sensu* Strahler, 1957) Oregon Coast Range Streams with total drainage areas ranging from 3.1 to 4.8 square kilometers (Table 1). Within each stream, channel gradient and contributing watershed area were used as criteria to select a suitable length of stream on which to locate sample reaches. It was necessary that these stream reaches approximately match each other in order to reduce unwanted variability in discharge and morphology. At the same time, these selected reaches had to have been impacted by a torrent or debris flood which had travelled at least 800 meters in the channel. This restriction eliminated sections of channel impacted only by deposition of debris from small side tributary torrents.

Table 1. Basin Characteristics of Study Streams in the Oregon Coast Range[a].

Characteristic	Gwynn Creek	Cape Creek	Little Cummins Creek
Watershed Area (km^2)	3.17	4.84	3.07
Vertical Relief (m)	524	573	585
Strahler Order	3	3	3
Basin Shape Factor $(length)^2/area$	6.2	4.4	6.2
Land Type[b]	Igneous Uplands	Igneous Uplands	Igneous Uplands
Geology	Yachats Basalt	Yachats Basalt	Yachats Basalt
Vegetation Type	Sitka Spruce-W. Hemlock	Sitka Spruce-W. Hemlock	Sitka Spruce-W. Hemlock
Date Whole Basin Last Burned	1868	1868	1868
Date of Torrent Disturbance Within Study Section	1982	1972	≃1870

[a]Total basin from headwater to mouth
[b]U.S.D.A. Forest Service, Siuslaw National Forest Land Type designation

Within each of the three selected sections of the study streams, a starting point was established from which to initiate systematic sampling of width, depth and other physical characteristics along the channel. These starting points were chosen by proceeding random distances upstream from the downstream end of a selected stream section. At least three 100 meter reaches were located in each stream. Additional reaches were added to encompass the variability of reach types found within the selected study section of a stream, or, in the case of Gwynn Creek, to establish matched treatment and control reaches for a woody debris placement experiment. The stream reaches and their sampling dates were coded as shown in Table 2.

Table 2. Stream Reach Identification Codes and Dates of Measurements.

Stream	Flow/Date of Measurement	Reach/Sample Code[a]
Little Cummins Creek	Summer low, 7/84-9/84	L1,L2,L3
Little Cummins Creek	Spring high, 4/2/85	L1w,L2w,L3w
Little Cummins Creek	Spring base, 4/24/85	L1s,L2s,L3s
Little Cummins Creek	Stormflows, 4/11/85	L1sta,L2stb
Cape Creek	Summer low, 7/84-9/84	C1,C2,C3,C4
Cape Creek	Spring base, 5/1,2/85	C1s,C2s,C3s,C4s
Gwynn Creek (Pre-trt)	Summer low, 7/84-8/84	g1,g2,g3,g4,g5,g6,g7
Gwynn Creek (Post-trt)	Summer low, 9/84	p1,p2,p3,p4,p5
Gwynn Creek (Post-trt)	Sring base, 4/29,30/85	p1s,p2s,p3s,p4s
Gwynn Creek (Post-trt)	Spring base, 4/29,30/85	p5s,p6s,p7s
Gwynn Creek (Post-trt)	Summer low, 7/85-8/85	gs1,gs2,gs3,gs4
Gwynn Creek (Post-trt)	Summer low, 7/85-8/85	gs5,gs6,gs7

[a]Numbers denote location of 100 m reaches on study stream--lower numbers are father downstream. Note that Gwynn Creek Treatment Reaches are numbered 1 to 4, Control Reaches 5 to 7.

Detailed longitudinal profiles of bottom elevation, depth, width, water velocity, pool volume, and organic debris volume were obtained on fourteen 100 meter long study reaches. Qualitative descriptions of channel features and semi-quantitative measurements of substrate size in these reaches were also obtained. These measurements were made primarily during the summer low flow period from July through September 1984. Selected channel measurements were made during high flow periods in the winter and spring of 1985 as well as during specific storms, in order to match hydraulic data collected at those times.

Fluorescent dye tracers were used to explore the relationship between measured channel morphology and the characteristics of water flow in the fourteen 100 meter study reaches. Using curves of dye concentration versus time, the discharge, apparent flow resistance and "dead zone volume fraction" were calculated for stream discharges ranging from summer low flows of 0.019 m^3/s to winter storms up to 0.38 m^3/s.

River dispersion models employing dead zone storage terms and advection with and without a term for "Fickian" dispersion have been quite successful in simulating concentration-time curves in rivers with and without slackwater areas. However, quantitative information about how dead zone fraction and transfer coefficients are related to bulk flow and channel form in other than the simplest of channels is almost non-existent. A large part of this study was therefore aimed at illuminating the relationships among pool volume, depth variance and dead zone volume fraction calculated from concentration-time data. Similarly, a quantification of the relationship of overall reach flow resistance to measures of large scale roughness and dead zone volume fraction was addressed. Such overall measures of flow resistance incorporate the effects of pools, bends and backwaters on the travel time of water through a length of non-homogeneous stream reach. The at-a-section channel information normally obtained in flow resistance studies is not appropriate for evaluating resistance over a reach where channel cross-section dimensions vary greatly along the length of that reach.

A fish habitat management project undertaken by the U.S. Forest service in August 1984 on Gwynn Creek afforded a unique opportunity not only to measure resulting changes in channel morphology, but to perform an experiment to test my hypotheses regarding the relationships among channel complexity measures and dead zone volume. The Forest Service placed large organic debris in Gwynn Creek in order to create pools through scour and impoundment. Changes in hydraulic characteristics directly resulting from the induced channel changes were measured. Initially, channel morphology measurements and tracer studies were undertaken at summer low flow on seven 100 meter reaches before the treatment. The measurements were repeated on four treatment reaches and one control reach at approximately the same discharge immediately after the treatment and then again at a higher discharge in the spring of 1985, following winter storms. In the August of 1985, one year after treatment, measurements were again repeated on all seven of the study reaches. The timing of measurements allowed an assessment of the role of winter and spring floods in sculpting the channel over the year following debris additions.

In order to test the geographical generality of my hypothesis concerning the influence of large organic debris on stream flow hydraulic characteristics, hydraulic tracer studies were conducted on 17 reaches in addition to those used in the intensive portion of my study. These 100 meter reaches were distributed among 9 streams in the Oregon Coast Range shown in Figure 2 where Heimann (1986) had measured large woody debris volume and distribution, as well as various channel characteristics. Characteristics of the stream reaches associated with Heimann's study match mine fairly closely, with forested basin areas ranging from 1.5 to 5.7 square kilometers, stream gradients from 2.8 to 5.8 percent, and summer low flow mean widths ranging from 2.5 to 5.4 meters (Heimann, 1986). Large woody debris volumes ranged from 6.3 to 105 m^3 for 9 meter wide zones along 100 meters of stream length in these 17 reaches; the number of pieces of large woody debris ranged from 32 to 201. For both studies, large woody debris was defined as pieces greater than or equal to 0.10 m in diameter and 1.0 m in length. Hydraulic tracer measurements were made on the 17 reaches between July 23 and September 3, 1985. My intention was to match flows among the streams as closely as possible during the summer low flow period. The dead zone properties of any given channel are sensitive to discharge, although much less so than measures of flow resistance such as Manning's "n" and the Darcy-Weisbach friction factor.

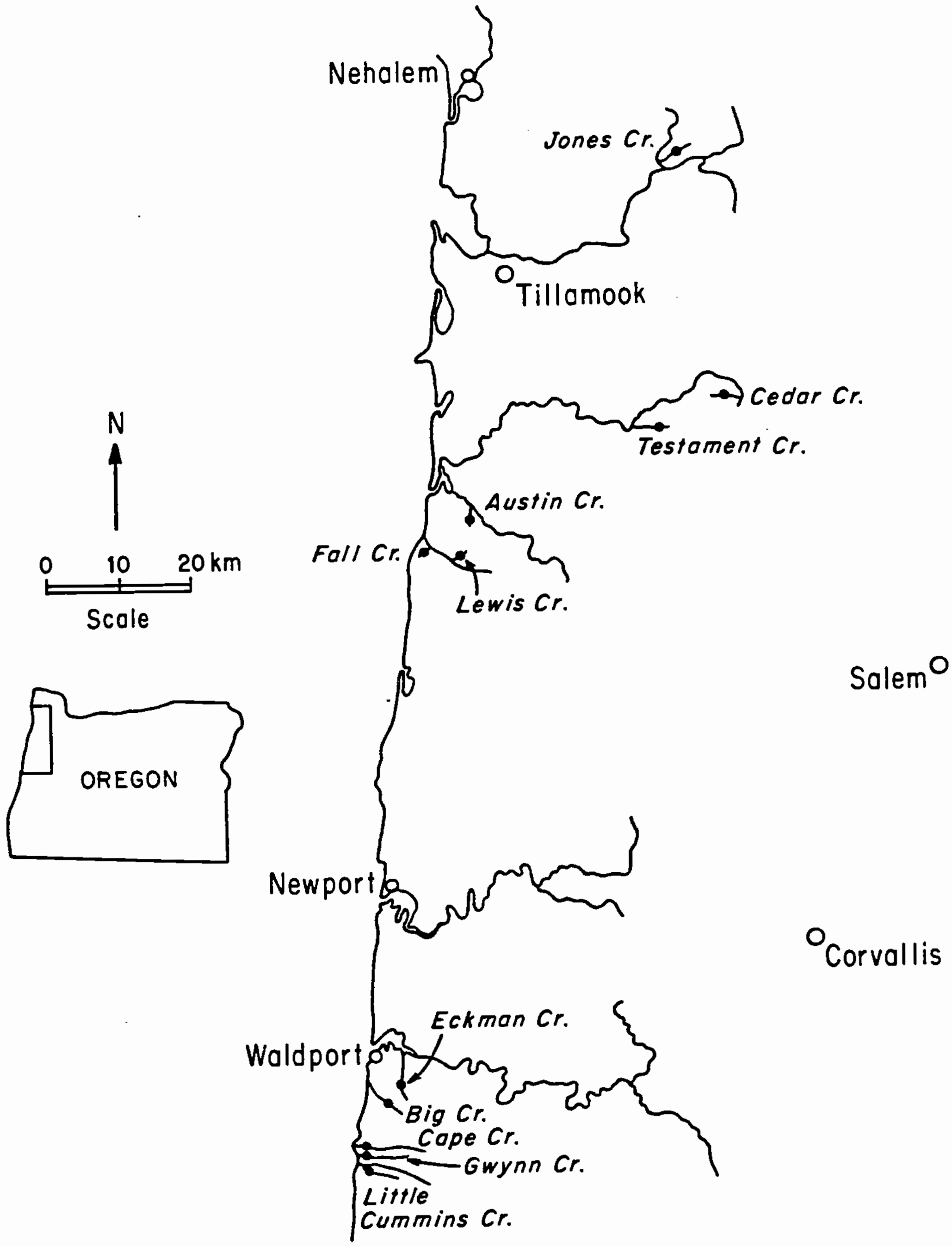


Figure 2. Streams Where Both Woody Debris and Tracer Studies were Undertaken (adapted from Heimann, 1987).

B. Site Description

For intensive study, I chose reaches distributed among 3 streams differing mainly in the number of years since a major debris torrent passed through the stream section under consideration. The three study streams: Little Cummins Creek, Cape Creek and Gwynn Creek, are shown on the map in Figure 1. More detailed maps showing the location of each study reach on the streams are contained in Appendix B. These streams have nearly contiguous drainages all located within the Siuslaw National Forest in the vicinity of Cape Perpetua south of Waldport on the central Oregon Coast. The three drainages are long and narrow, 3.1 to 4.8 km^2 in area, and are oriented approximately East-West (Figure 1 and Table 1). Like many small streams in the Igneous Uplands of the Oregon Coast (U.S.F.S. Landtype designation), their relatively straight valleys follow faults in the underlying Yachats Basalt (Franklin and Dyrness, 1973; Rosenfeld, 1979; Marston, 1980). Cape Creek and Gwynn Creek flow directly into the Pacific Ocean. Little Cummins Creek formerly flowed directly into the ocean but was re-routed into the larger Cummins Creek a short distance from its mouth when U.S. Highway 101 was constructed.

The thin residual soils overlying steep, basalt-underlain hillslopes of the study basins support lush coniferous forest vegetation but are subject to debris avalanches and torrents (Marston, 1980), particularly when vegetation is removed or when soil is disturbed by road building. Thicker colluvial soils developed on gentler terrain in the basins also have a high potential for sliding because they are often near the angle of repose (Schlicker and Deacon, 1974; Marston, 1980).

The climate of the study basins is temperate, wet and mild; extremes of temperature and moisture are moderated by proximity to the Pacific Ocean. Approximately 80 percent of the 180 cm average annual precipitation falls between October and March (U.S. Weather Bureau 1960a,b; as presented in Franklin & Dyrness, 1973). Precipitation is almost entirely in the form of rainfall in storms of moderate intensity typically lasting for several days (Schlicker and Deacon, 1974; Schlicker et al., 1973). Frequent fog and low clouds during the relatively drier summer months augment precipitation through fog drip (Ruth, 1954). Annual streamflow hydrographs reflect the timing of precipitation, showing a general rise beginning in October, a general maximum in winter, and a gradual decrease through the spring and summer. Minimum flows are normally observed in September. The pattern of peak flows is erratic. Major peaks usually occur in January or February, with secondary peaks occurring anytime from mid-October to May.

Franklin and Dyrness (1973) classified the narrow, fog-influenced coastal band of the Western Hemlock (*Tsuga heterophylla*) Vegetation Zone as the Sitka Spruce (*Picea sitchensis*) Zone. Except for their furthermost inland ridges, the basins of the study streams are within this Sitka Spruce Zone, where Western Hemlock is the climax dominant tree species. A large area of the Oregon Coast Range, including the study basins, was burned during the Yaquina Wildfire of 1868. Some old-growth conifers (many greater than 1.5 m DBH) remain as survivors of that fire. They are located near the actual study stream channels and on a south-facing hillslope of the Gwynn Creek drainage. Dominant overstory vegetation in the study basins now consists mainly of second growth Sitka Spruce and Western Hemlock near the valley bottoms and at locations nearer to the seacoast. Douglas Fir (*Pseudotsuga mensiesii*) and Western Hemlock dominate at greater elevations and at greater distances from the sea. Where disturbance of the canopy and soils has taken place, vegetation is typically very dense and includes salmonberry (*Rubus spectabilus*), red alder (*Alnus rubra*), stink currant (*Ribes bracteosum*), big leaf maple (*Acer macrophyllum*), vine maple (*Acer circinatum*), and swordfern (*Polystichum munitum*).

No management disturbances such as logging or road building have taken place in the drainage of Little Cummins Creek, except for considerable channel modification due to the diversion near its mouth (Marston, 1980). The study reaches on Little Cummins Creek have probably not undergone any massive channel disturbance over the century since the Yaquina Wildfire, as evidenced by examination of riparian vegetation and historic records. On the basis of charcoal found in deposits and the age of trees growing on those deposits, it appears likely that a torrent passed through the study reaches near the time of the fire (117 years ago), scouring upstream portions of the stream and depositing sediment and large woody debris in the furthermost downstream of the study reaches (L1).

Twenty-six percent of the Cape Creek basin had been logged as of 1980 (Marston 1980). Logging upstream of the study reaches occurred primarily in 1965 and 1978, but also in 1959, 1970 and 1974. A major debris torrent passed through the study section in 1972 (see map in Appendix B). It entered the mainstem of Cape Creek from a tributary bordering the 1965 clearcut. Marston (1980, p. 83) wrote:

> ....[the torrent entered] with enough momentum to bank up on opposite sides of the narrow valley bottom as it travelled downstream for one-half mile (0.8 km). The current channel position alternates from one side of the valley bottom to the other side as

> shifted by torrent deposits. Logs protrude from channel banks where the stream has downcut through the torrent deposits. Stream cleanup was undertaken following the torrent, including removal of any pre-existing log steps....

Field evidence and conversations with a U.S. Forest Service employee involved in the cleanup suggested that the cleanup probably proceeded as far upstream as the upper half of my study Reach C1 (see Appendix B).

The basin of Gwynn Creek is largely unlogged except for an area of approximately 0.4 km^2 in its steep headwaters. The logged area comprises approximately 13 percent of the basin. In December, 1981, a debris flood event ("torrent") occurred, scouring the valley of the mainstream of Gwynn Creek and removing riparian vegetation described in 1969 as "dense native brush and trees" by a U.S. Forest Service stream surveyor (U.S.F.S., 1969). U.S. Forest Service files at the Waldport Ranger District (Dwight Barnett, District Soils Scientist, 1984) noted:

> The Gwynn Creek flood event was triggered by failure of sidecast along a spur road. The failure of shallow sidecast below Forest Service spur road 5599 to the north of Gwynn Creek caused a massive slide into the headwaters of Gwynn Creek. This blocked and impounded the flow. When the impoundment burst, a large volume of water and debris surged down over a previous debris jam about 600 feet downstream. The volume of water necessary to enable a debris flood to travel three miles at a 4% gradient could not have accumulated in the absence of the road slide. In addition, two other slides contributing to the first (downstream) jam appear to have been related to roads: one started at a landing, the other just downslope from where a large volume of water, flowing down a spur road east of Gwynn Creek entered the unit....

The Waldport Ranger District undertook a fish habitat improvement project in August 1984. Elizabeth Holmes, Special Resources Biologist, wrote in the project proposal (U.S.F.S., 1984):

> ....a debris flood event...sluiced the entire mainstream to bedrock and rubble. Currently the only fish present...are cutthroat trout. Presumably these fish were not survivors of the torrent but moved into Gwynn Creek from a neighboring stream 2 years after the torrent event.... The habitat condition...is extremely poor.... Rehabilitation would be accomplished by introducing in-stream structure necessary to catch some of the bedload that is currently moving unrestrained through the system. Any in-stream structure would help stabilize the system and would exercise considerable control over the channel morphology, especially in the development of pools and sediment storage sites which are critical fish habitat requirements....

The total cost was approximately $2,000 (180 man-hours) for planning and implementation of the Gwynn Creek fish habitat enhancement project (Holmes, pers. comm.). Salmonid rearing habitat was enhanced over 0.8 kilometer of the stream. The excavator used in the project was owned and operated by the Forest Service. Had it been necessary to rent a comparable bulldozer and operator, the project cost would have been roughly $1,600 greater (Holmes, pers. comm.).

C. Stream Reach Measurements

The procedures described in this section were carried out on each intensive study reach on the dates shown in Table 2.

1. Channel Form, Point Velocity, and Qualitative Measurements

Using a surveyor's level and rod, bed elevations and water depth were measured at 0.5 meter intervals along the thalweg (line connecting deepest points in successive cross-sections). These profiles ran continuously through 320 m in Little Cummins Creek, 550 m in Cape Creek, and 750 m in Gwynn Creek. Markers were placed on the streambank every 5 meters along the thalweg to facilitate orientation in subsequent surveys. The precision of the bed elevation measurements is theoretically ±0.5 cm.

However, due to the difficulties of placing and holding a surveying rod on irregular substrates and viewing that rod through the thick salmonberry brush often found along and over the streams, the precision of individual elevation measurements varies from ±0.5 cm to perhaps ±2 cm in some areas of the profile.

Multiple measurements of wetted width, thalweg water depth, thalweg water velocity, and cross-section maximum velocity were obtained along the channel spaced at 1.0 meter increments. The velocity of flow at the thalweg was measured at six-tenths depth with a Marsh-McBirney Model 201D electromagnetic water velocity meter and a top-setting wading rod. Maximum velocities in each cross-section were measured at whatever depth these maxima occurred. Every 5 meters along the channel a cross-sectional profile of water depth was measured. Discharge was estimated on most field visits using the velocity-area integration method.

In addition to making repetitive measurements of elevation, depth, width, and velocity, I characterized the stream in a qualitative way. This type of survey was done to aid interpretation of more objective, quantitative measurements. The qualitative survey consisted of identification of channel features such as cascades, riffles, glides, pools of various types, and pool formative agents such as bedrock, logs and boulders. This classification was generally according to that of Bisson et al. (1981) with some modification. Dominant and subdominant size classes of bottom substrate at each meter location along the thalweg were also estimated using the sediment size grade scale accepted by the American Society of Civil Engineers (Rouse, 1950). Materials finer than 2 mm were grouped into sand, silt, or clay categories.

The length and two end dimensions were determined for every piece of large woody debris greater than 1.0 m in length and greater than 0.10 m in diameter within each 5 meter segment of stream length. All debris within the bankfull channel was counted, as was any additional debris contained in a swath 9 meters wide if the bankfull channel width was less than 9 meters. The portion of individual debris pieces overtly affecting channel morphology was identified.

2. Residual Pool Measurements

To compare morphological characteristics of pools in different streams, and in the same reach at different flows, it is useful to have a measure of pool dimensions which is independent of stream discharge. Lisle (in press) used a measure he termed "residual pool depth" in which he calculated the depth of pools which would exist if there were no surface flow and pools were filled up to the elevation of their downstream lips. This concept was first introduced in general terms by Bathurst (1981) in a discussion of factors controlling hydraulic resistance due to gravel bars. It is also related to the definition of "low flow stored water volume" employed by fishery biologists (Fred Everest, pers. comm.). Lisle calculated residual pool depth by subtracting the pool bottom elevation from the elevation of the pool lip or downstream control point of the pool on a profile of thalweg elevation along the length of a stream (Figure 3). I have expanded on Lisle's idea by calculating residual pool vertical profile area (RPA) and mean residual depth (Do = RPA/reach length) in addition to the dimensions of residual pool depth and length he identified. I have defined residual pool vertical profile area as the area between the water surface and bottom on a profile of thalweg elevation and residual pool

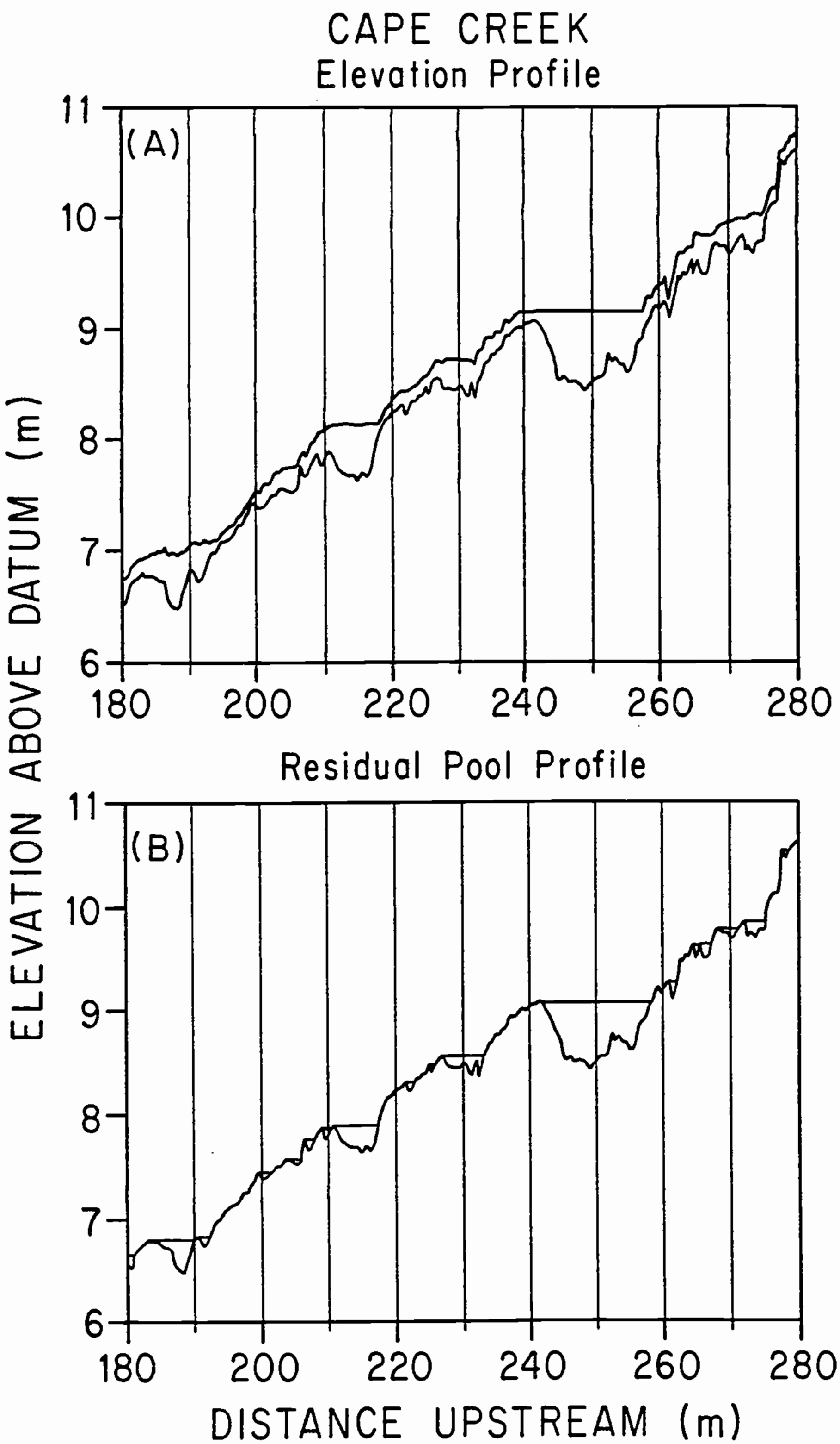


Figure 3. Longitudinal Profile Illustrating (A) Thalweg and Water Surface Elevations and (B) Residual Pool Concept.

surface elevation such as that shown in the lower half of Figure 3. Though the dimensions of residual pool (vertical) profile area are obviously square units of length, the parameter can be used as a rough index of pool volume when comparing streams of nearly equal width. Similarly, it can be considered to be a rough measure of pool volume divided by stream width in any size stream, as long as channel cross-sections are approximately rectangular. I have freely used residual pool profile area as a flow-independent surrogate measure of low flow pool volume in subsequent discussions where pool volumes were compared among streams of very similar width.

The residual pool profile area concept was used to obtain *aggregate* measures of pool volume within reaches and to also obtain flow-independent dimensions of *individual* pools within a reach. In the latter case, individual "residual pools" were identified according to type and formative cause by comparison of long profiles of residual pools in reaches with detailed qualitative field notes. The following types of individual residual pool features (codes in parentheses) were identified, each associated with a formative agent believed to have "caused" the pool: Impoundment pools (I), Cascade Plunge pools (P), Vertical Scour pools (V), Trench pools (T), Backwater pools (B), Step pools (S), Inter-Cobble-Row pools (N), Lateral Scour Trenches (M), Lateral Scour pools (L), and Glides (G). Formative agents (and their codes) were: log clusters (j), rootwads (r), single logs (w), bedrock (g), boulders (b), and cobbles (c). A brief description of these pool and slackwater types is provided in Appendix C.

3. Hydraulic Tracer Procedures

Hydraulic time of travel and tracer dispersion characteristics in study reaches were determined using both continuous in-situ sampling and discrete sampling methods to measure concentrations of a fluorescent dye tracer. Continuous sampling methods yielded curves of dye fluorescence versus time on a chart recorder in the field. These were converted to dye concentration versus time curves using a digitizing process described later in this section. In the discrete sampling method, curves of dye concentration versus time were constructed after laboratory analysis of dye concentration in sample bottles collected in the field.

Continuous sampling methods were used on all 14 study reaches during 1984 summer low flows (August 1 through 16), in Gwynn Creek post-treatment measurements (September 8, 9, 1984, and April 29, 30, 1985), and in Cape Creek Spring high flow measurements (April 1, 2, 1985). Discrete sampling methods were found to yield unbiased results of lower (but acceptable) precision and were used for spring high-flow (April 2, 1985) and spring low-flow measurements (April 11, 1985) in Little Cummins Creek, and for low-flow measurements one year after treatment in Gwynn Creek (August 5 to 7, 1985). Discrete Sampling methods were used as well for sampling during isolated storms and for obtaining tracer data on the 17 additional reaches (with variable large woody debris loadings) whose locations are shown in Figure 2.

For the continuous, in-situ measurement of dye concentration, a measured mass of fluorescein dye tracer was released at a known time in a location of intensive mixing at the upstream end of each reach under consideration. The mass of dye was injected as a 1,000 mg/l solution of dye in water. The actual mass of dye to be used was estimated by experience. It had to be sufficient to generate a plume with a peak concentration between 0.001 and 0.008 mg/l in order to produce a usable curve of concentration versus time for subsequent analysis. Such a plume was usually only barely visible at the sampling point. Fluorescence was measured continuously at the downstream end of each reach using a Turner Model 111 Fluorometer. The peak of the excitation spectrum for fluorescein is 510 nm, producing fluorescence in a spectrum with a peak at about 520 nm. Because the excitation and fluorescence peaks are so close in wavelength, it is desirable to use energy of shorter wavelength within the excitation spectrum to avoid interfering with the sensing of fluorescent emissions. Hence, a "window" of sample excitation centering on 436 nm was used. This discrete band of far U.V. excitation energy was obtained by using a 47B filter (passing 390 to 450 nm) in combination with a 2A filter (passing wavelengths >412 nm) to filter the excitation energy from a 4 watt GE F4T4/1 far U.V. source lamp. Fluorescent emissions at wavelengths greater than 510 nm were passed to the fluorometer's light sensor using a 2A-12 sharp cut secondary filter.

Stream water was continuously sampled at 0.10 to 0.13 liters per second using a 1.15 cm diameter, 500 cm length of Tygon tubing attached to a "Little Giant" Model 1, 1.1 amp submersible electric pump. The sample was pumped through a Turner 110-880 continuous flow-through sample door, which interchanges with the standard sample holding door on the fluorometer. This modification allows continuous movement of the stream water sample through the fluorometer. The sampling tube was darkened to prevent light leakage. The delay time of the sampling assembly was earlier determined in the laboratory at various pumping heads and was normally about 3.5 seconds. No adjustments were made to the concentration-time curves to compensate for this lag time. There were no instances during field sampling where the pumping head was high enough to cause significant errors in the measurement of tracer travel time. The submersible pump was mounted on a metal tripod which positioned the intake midway between the channel bottom and the water surface. Intake positions were chosen at locations of flow convergence.

Fluorescence measurements and elapsed time were recorded on an Esterline Angus Model T171B chart recorder with the chart moving at a constant speed of 20 mm/min. The pump, fluorometer and chart recorder were powered by a 400 volt-amp, 60 Hz Honda alternating current gasoline-powered generator. A surge protector was installed in the circuit to prevent possible damage to the fluorometer in the event of possible generator failure, which never occurred. The fluorometer and chart recorder were contained in a foam-insulated wooden field box which shielded the instruments from rain and direct sunlight (previous measurements indicated that direct sunlight on the fluorometer could cause measurement errors).

Calibration of the fluorescence versus time plots obtained on the chart recorder was accomplished by a field standardization procedure at each site. This procedure, while tricky to develop, was eventually perfected so that it could be accomplished easily when practiced. First a measured volume of streamwater was collected in an 8 liter plastic bucket. After voiding the water from the submersible pump, hose and fluorometer, the pump and both hose ends were placed in the bucket. Recirculation of the water within the bucket was initiated by suction priming and then background fluorescence measurements were obtained. Since fluorescence is somewhat temperature sensitive, it is important to accomplish the standardization procedure rapidly (within about 5 minutes)--before the bucket of water is heated up through pumping and recirculation. After a stable background fluorescence was determined, known quantities of fluorescein were incrementally added to the bucket. Fluorescence was recorded for each stepwise addition of dye. It was therefore possible to obtain a standard curve based on five to seven data points for each standard run. The whole procedure was replicated three times at each site. The replicates were averaged and separate relationships between fluorescence and concentration were obtained for each set of measurements at each stream and date.

When using the discrete tracer sampling technique, on the other hand, water samples were collected at recorded time intervals during dye release experiments and analyzed later in the laboratory. This technique did not require a field standardization procedure. A measured mass of fluorescein dye tracer (either a 1,000 or 10,000 mg/l solution, depending upon the mass required) was released at the upstream end of each study reach. Because sampling times were chosen visually, it was necessary to adjust the tracer dosage to produce a visible plume at the sampling point. Under ideal light conditions, I could detect fluorescein in the stream at concentrations as low as 0.001 mg/l, even though dye was not readily discernible in sample bottles until its concentration reached about 0.03 mg/l. The ideal tracer plume peak concentration for discrete sampling by eye was 0.035 to 0.050 mg/l at the downstream sampling point. This is approximately 20 times the concentration required when continuous automated methods of sampling and analysis of fluorescein were used.

As in the continuous sampling method, the choice of the exact location for releasing the dye was important. The release point was typically a zone in the mainstream flow of the channel where rapid vertical and lateral mixing could occur within a short downstream distance. Such locations were usually found at channel constrictions or narrow points in riffles. Dye was released in these riffle locations to avoid large overestimations of dead zone volume fraction which can occur if dye is added directly to a pool or peripheral slackwater area in a channel.

After dye release, discrete water samples were collected at variable time intervals in 20 ml polypropylene bottles. These samples were taken from the point of highest velocity in the downstream channel cross-section and were never taken within a large pool. The elapsed times between dye release and sample collection were recorded. The sampling frequency was determined visually and was adjusted to detect the time of the leading edge of the dye plume, the height of its peak, and the shape of its trailing end or "tail." Ten to fifteen discrete samples were usually adequate to describe the shape of the concentration versus time curve for an individual dye release experiment. Knowledge gained from continuous sampling runs described earlier allowed me to predict the general shape of the curves with enough confidence that they could later be drawn unambiguously after analysis of the discrete samples taken.

The concentration of fluorescein tracer in the water samples was determined in the laboratory using the same Turner Model 111 Fluorometer and the same excitation and emission wavelengths previously discussed for field determinations. Before fluorometric analysis, water samples were left standing overnight at room temperature (22°C) to allow settling of solid particles and equilibration of temperature. Portions of the samples were placed in 5 ml borosilicate glass cuvettes for the actual determinations. A set of fluorescein solutions in a range of known concentrations was prepared in order to construct a standard curve from which to convert stream sample fluorescence measurements to fluorescein concentrations. Plots of fluorescein dye concentration versus time since dye release were constructed. Smooth curves were fitted by hand through these points and were digitized and analyzed as described in the following section.

4. Tracer Curve Analysis

Dye fluorescence versus time and dye concentration versus time graphs obtained from dye releases employing continuous or discrete sampling methods were electronically digitized. A small computer program was developed to convert the digitizer signals to concentration versus time coordinates and to compute the tracer curve area and the first four moments about its origin (Appendix D). In this application, the concentration-time plot is effectively being treated as a probability density distribution of tracer molecule travel times for the stream reach under consideration. Since the tracer is non-reactive, the probabilities can be ascribed as well to the water flowing in the stream. The transit times of the peak and leading edge of the dye cloud were determined from the curve. The curve area and the first four central moments of the curves were calculated as follows:

μ_o = area under the concentration-time curve

$$= \int_{t=o}^{t=\infty} C_t t \approx \sum_{t=o}^{t=\infty} C_t \Delta t$$

μ_1 = arithmetic mean transit time, approximately equal to transit time of centroid of dye mass

$$= \left\{ \int_{t=o}^{t=\infty} t C_t \right\} / \mu_o \approx \left\{ \sum_{t=o}^{t=\infty} t C_t \Delta t \right\} / \mu_o$$

μ_2 = variance of the concentration-time distribution

$$= \left\{\int_{t=o}^{t=\infty}(t_i - \mu_1)^2 C_t\right\}/\mu_o$$

$$\approx \left\{\sum_{t=o}^{t=\infty}(t_i - \mu_1)^2 C_t \Delta t\right\}/\mu_o$$

$$\mu_3 = \left\{\int_{t=o}^{t=\infty}(t_i - \mu_1)^3 C_t\right\}/\mu_o$$

$$\approx \left\{\sum_{t=o}^{t=\infty}(t_i - \mu_1)^3 C_t \Delta t\right\}/\mu_o$$

$$\mu_4 = \left\{\int_{t=o}^{t=\infty}(t_i - \mu_1)^4 C_t\right\}/\mu_o$$

$$\approx \left\{\sum_{t=o}^{t=\infty}(t_i - \mu_1)^4 C_t \Delta t\right\}/\mu_o$$

(Note: coef. of skewness = $\mu_3/\mu_2{}^{1.5}$ and coef. of kurtosis = $\mu_4/\mu_2{}^2$.)

Dead zone volume fraction is equivalent to the probability of a water or dye molecule being in transient storage at any given moment under the assumptions of the Sabol-Nordin (1978) model (see Ch. I, Introduction). This parameter, designated a_L, was calculated from digitized dye curves according to the formula of Sabol and Nordin (1978): $a_L = 1 - (T_L/T_c)$, where T_L and T_c are respectively the transit times of the leading edge and centroid of the dye cloud.

The volume-based dead zone exchange rate coefficient, δ, was calculated according to the formula of Sabol and Nordin (1978): $\delta = (2a_L X_i)/(u_c \ au \ \sigma^2)$, where χ_i is the downstream distance from the point of dye release to the point of measurement, au = T_L/T_c, and σ^2 = var[T(x)] = μ_2 = the variance in transit time (T) at the downstream point of measurement (χ_i).

Stream discharge rates were not only measured on several sampling occasions by the velocity-area integration method as discussed previously, but were also calculated from each dye concentration-time curve produced as a result of dye release experiments. Assuming that the dye is conservative, the entire mass of dye added upstream will be recovered downstream after sufficient time. Employing the continuity equation to define this relationship yields the following equation (Hubbard et al., 1982):

$$Wd = Q \int_0^{\infty} C dt = QAc,$$

where Wd = the weight of dye added,

Q = the volumetric discharge rate, and

$\int_0^{\infty} C dt = Ac$ = the area under the concentration-time curve.

Rearranging the above equation yields the expression for discharge:

$$Q = Wd/Ac = Wd/\mu_o$$

The accuracy of the above equation depends upon complete mixing of the dye mass in the stream cross section by the time the plume reaches the point of measurement. It also depends upon the applicability of the assumption of a conservative tracer.

Darcy-Weisbach friction factor estimates for entire reaches were calculated according to the following formulations, employing flow-continuity considerations and the wide, rectangular channel approximation:

$$f = (8g\ R\ Se)/U^2 \approx \{8g(Q/UW)Se)\}/U^2 \approx (8g\ Q\ Ss)/WU^3$$

where:

f = Darcy-Weisbach friction factor

g = gravitational acceleration $[LT^{-2}]$

R = hydraulic radius $[L]$

Se = energy gradient

Ss = water surface slope

Q = volumetric discharge rate $[L^3T^{-1}]$

U = mean velocity $[LT^{-1}]$

W = flow width [L]

IV. RESULTS

A. Channel Morphology and Woody Debris Loadings

1. Longitudinal Profiles

Gwynn Creek, illustrative of a stream in the initial stages of recovery following extreme channel scouring by a debris torrent, showed the most uniform thalweg elevation profiles among the three study streams. A representative elevation profile is shown in Figure 4. Example width and depth profiles are contained in Appendix F. Summer low flow profiles in 1984 showed that all seven of the 100 meter study reaches were consistently shallow, with a general lack of large pools. Most of the pools present were small, relatively shallow glides between transverse cobble-rows. The cobble-rows presumably developed as a result of size-sorting of bed material. Typically, there were transverse rows of large cobbles separated by lower gradient reach segments with small cobble and very large gravel substrate (A.S.C.E. grade classification). Most of the channel features that would actually be termed "pools" in fish habitat parlance were shallow lateral scour pools at meander bends (see subsequent section describing Pool Morphology). Many of these lateral scour pools were associated with bedrock as the stream channel reworked shallow cobble deposits left after the recent debris torrent. Although these lateral scour pools generally lacked overhead cover, juvenile steelhead or cutthroat trout were occasionally seen in them. The largest pools in Gwynn Creek were formed by scouring downstream of short, steep cascades of small and

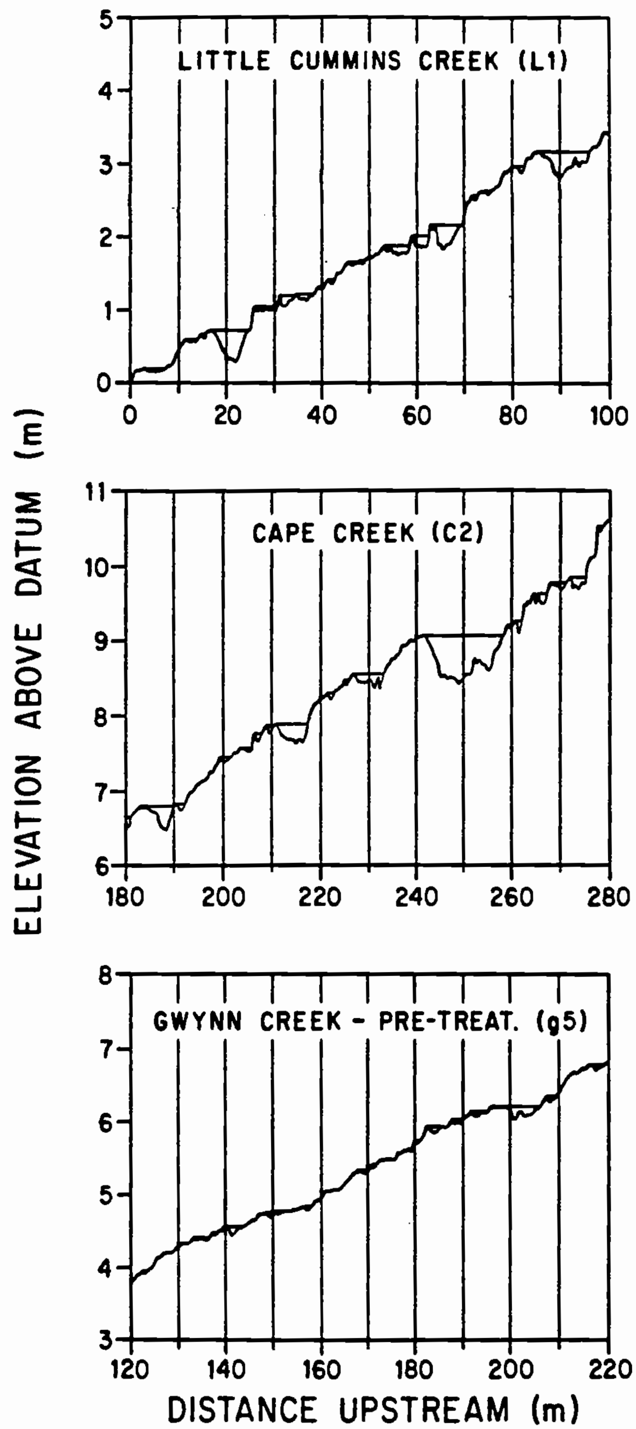


Figure 4. Representative Longitudinal Profiles of Thalweg Elevation and Residual Pools for the Three Study Streams.

large cobbles. These cobble cascades were formed where bedload transport was obstructed by partial dams of organic debris. Though infrequent (0.8 per 100 m), such larger pools (mean residual volume 1.2 m^3) constituted a large fraction of the pool volume in reaches where they occurred. They also constituted the bulk of the available habitat for larger salmonid fishes in the lower half of the Gwynn Creek drainage. Within two years following the debris torrent in Gwynn Creek, fishery scientists observed about one adult cutthroat trout in each of these large pools (Fred Everest, pers. comm.).

Little Cummins Creek, undisturbed by major debris torrent scouring or massive deposition for approximately 120 years, showed a stepped longitudinal profile of thalweg elevation. An illustrative elevation profile showing residual pool surface is shown in Figure 4. Unlike the uniform pattern observed in Gwynn Creek, boulders, cobbles, gravel and fines (less than 1mm diameter) were well sorted in Little Cummins Creek. Sorting of bed material in Little Cummins Creek into accumulations of large cobbles or small boulders accounted for most of the steepened areas observed. Local channel gradients in Little Cummins Creek ranged between 10 and 30 percent in cascade and bedrock chute sections of reaches. Consequently, there were relatively long glides where the gradient was 1 to 2 percent and pools with nearly flat gradients. Pools created by transverse bars in Little Cummins Creek were larger than those observed in Gwynn Creek. The sediments forming transverse bars in Little Cummins tended to be of larger size (large cobbles to small boulders) than those observed in Gwynn Creek, creating higher gradient riffle segments and longer, lower gradient glides.

Stepping of the thalweg elevation profile in Little Cummins Creek was especially pronounced in Reach L1, which showed evidence of massive past deposition of sediment and large woody debris. Examination of vegetation in the riparian area suggested that this deposition probably occurred as a result of a torrent 100 to 120 years ago, likely related to the 1868 Yaquina Wildfire (which swept the region including all three study stream basins). Reach L1 also shows evidence of more recent local deposition of material scoured from a 35-meter length of channel in Reach L2 approximately 50 meters upstream of the head of Reach L1.

A considerable portion of the pool volume in Little Cummins Creek consisted of relatively large pools formed by scouring downstream of short, steep cascades of small boulders and large cobbles. As observed in Gwynn Creek, these cascades appeared to be formed through the obstruction of bedload transport by partial dams of large woody debris. Their locations were frequently at the outsides of meander bends where the stream channel had become constricted between the valley wall and the debris accumulation. Distribution of large woody debris in Gwynn Creek indicated that where such debris accumulations were likely placed by a debris torrent or flood, they tended to occur at valley bends and constrictions pre-determined by bedrock and topography. The location of large Cascade Plunge Pools appears, then, to be at least partially controlled by the interaction of torrent deposition with valley topography and bedrock structure.

There was an average of 1.7 large Cascade Plunge Pool per 100 meters in Little Cummins Creek, more than twice the frequency observed in Gwynn Creek. The frequency of these large pools was greatest in the aggraded downstream third of the study section (Reach L1), where there were 3 of these pools within 100 meters. Such Cascade Plunge Pools in

Little Cummins Creek provided high quality potential habitat for both juvenile and adult salmonids. These pools were characterized by their large size (mean residual volume 3.6 m^3), low water velocities (summer low flow mean water velocity at thalweg = 0.17 $\pm$ 0.069 m/s), and the prevalence of overhead and underwater cover associated with undercut banks, roots, vegetation, and woody debris.

The banks of Little Cummins Creek were reinforced with living tree roots. These riparian tree and shrub roots enabled the formation of deeply undercut banks and a relatively narrow, deeper cross section than that of Gwynn Creek, where roots were largely absent. The large organic debris accumulations associated with large pools and backwaters in Little Cummins Creek increased both the amount of slackwater for fish and the amount of protective cover from fish predators. Dense growth of Salmonberry vegetation overhanging riffle sections of study reaches provided both cover and a food source for aquatic insects.

In torrent-deposit reaches of Cape Creek (Cl, C2, and lower half of C3), the presence of abundant sediment and large woody debris allowed the formation of a markedly stepped profile with large cobble/small boulder cascades and deep Cascade Plunge Pools. An example profile of thalweg elevation and residual pools in Reach C2 is shown in Figure 4. As in Little Cummins Creek, large Cascade Plunge Pools were prevalent at scour locations downstream from where large woody debris accumulation near valley walls had apparently caused cobble/boulder cascades.

Upstream from the reaches of major torrent sediment and debris deposition in Cape Creek were reaches (C4 and upper half of C3) with narrower cross-section, larger average substrate size (frequent small and medium boulders), and relative paucity of large woody debris. The valley floor along these reaches was a flat terrace lacking trees or large woody debris. This terrace appeared to have been formed by the 1972 torrent and was now overgrown with a dense grove of Stink Currant. This pattern of revegetation is in contrast to that seen in Gwynn Creek, where dense growth of Red Alder followed Fire Weed regeneration. These differences may be related to a higher fine sediment content in the material deposited by the Cape Creek torrent in comparison with the Gwynn Creek event. (The valley surface left after the Gwynn Creek torrent, a "debris flood," was largely gravel lacking fine material and organics--a favorable seedbed for regeneration of alder.) In the scoured Cape Creek reaches identified above, the active channel flowed mostly along one side of the valley, where it was in intermittent contact with bedrock. This channel was incised about 1.5 meters into the terrace deposit, but undercut banks were not common because the Stink Currant root systems apparently did not provide sufficient bank cohesion. It appears likely that the active channel was formed after the torrent event and that the many small and medium boulders contained in the channel were apparently left as lag deposits as the stream scoured through the terrace.

In the scoured reaches of Cape Creek described above, the medium and small boulders were instrumental in causing the formation of pools (Step Pools) of quite different character than those associated with woody debris and abundant cobble and gravel deposits (Cascade Plunge Pools and Vertical Scour Pools). Boulders in these reaches have accumulated in a series of minor constrictions caused by bedrock irregularities. These "trapped" boulders form short porous dams that impound water in relatively deep Step Pools upstream and cause local scouring at the head of the next downstream Step Pool.

There appeared to be a consistent spatial pattern of torrent scour and deposition in the three study streams, as evidenced by observations in the intensive study reaches as well as in upstream and downstream reaches not intensively studied. The longitudinal pattern was represented by a repeating series of deposition and scouring reaches in a length ratio of 1:2. Depositional ("Constructional") reaches tended to be about 35 to 50 channel widths in length while scoured ("Degradational") reaches were usually 70 to 100 channel widths in length. This rough pattern has also been observed by Heimann (personal comm.) in streams of similar size in the Oregon Coast Range and by Frissel (personal comm.) in smaller streams of MacDonald Forest near Corvallis, Oregon.

Appendix F illustrates example width-depth profiles for the study streams. Auto-correlation analysis of spatial series data from the three streams revealed only weak periodicity (at a length frequency of 10 to 20 channel widths for width data and 5 to 10 channel widths for depth data). Cycle lengths were longest in scoured reaches and shortest in complex torrent deposit reaches. There was, however, a distinct "memory effect" in both width and depth series data. Series data for thalweg depth in scoured channels were positively correlated until they were 2 channel widths downstream from each other; width data was positively correlated until 3 to 5 channel widths distant. In complex torrent deposit reaches this "memory effect" persisted for only a little over 1 channel width downstream distance in depth data and for about 2.5 channel widths distance in width data. These data suggest the typical lengths of width oscillations and of depth variations like transverse bars and glides in these streams. In scoured reaches, cross-correlation analysis revealed a tendency for deep areas to be associated with channel constrictions during low flow. Torrent deposit reaches showed variable patterns, but there was a tendency for deep locations to be associated with wide areas about 2 to 3 channel widths distance upstream and narrow areas 1 to 2 channel widths distance downstream. This finding agreed with observations regarding the most notable depth deviations in torrent deposit reaches, Cascade Plunge Pools, which were usually located about 2 to 3 channel widths distance downstream of wide, aggraded areas of the channel apparently caused by channel constrictions at the heads of these pools.

2. Comparison of Mean Stream Reach Characteristics

Mean 1984 summer low flow channel characteristics of reaches in the three intensive study streams are listed in Table 3. Hydraulic characteristics at low flow are listed in Table 4. Channel characteristics during higher spring season flows are shown in Table 5. Although the data are reported as arithmetic means and standard deviations, subsequent statistical tests were performed on log-transformed data to stabilize variance. A typical figure for summer low flow discharge was 0.030 cubic meters per second (1.0 c.f.s.), with summer low flows ranging between 0.02 and 0.04 m^3/s between July and September 1984. For the mean basin contributing area of about 2.7 km^2 (1.0 square mile), this corresponds to an a real discharge rate of 0.011 $m^3/s\text{-}km^2$ (1.0 c.s.m.). Near-bankfull discharges of 0.38 m^3/s (0.14 $m^3/s\text{-}km^2$ or 13 c.s.m.) were measured separately within a span of several hours in both Gwynn Creek and Little Cummins Creek during a rain storm on March 27, 1985, showing the hydrologic similarity of these two watersheds. The 100 m study reaches were well-matched with basin contributing areas ranging from 2.14 to 3.26 km^2 and mean water surface slopes ranging from 0.0285 to 0.0389 around

Table 3. Channel Characteristics During Summer Low Flow (arithmetic mean ± 1 standard deviation).

	Gwynn Cr. (Pre-Trt) (n=7)	Cape Creek (n=4)	Little Cummins Creek (n=3)	All Reaches (n=14)
Gradient	0.0325 ± 0.0041	0.0365 ± 0.0021	0.0361 ± 0.0018	0.0344 ± 0.0037
Width (m)	3.00 ± 0.25	3.39 ± 0.63	2.66 ± 0.30	3.04 ± 0.45
Coef. Var. in Width[a]	0.29 ± 0.078	0.35 ± 0.069	0.32 ± 0.012	0.31 ± 0.069
Thalweg Depth (m)	0.144 ± 0.0076	0.197 ± 0.0243	0.156 ± 0.0071	0.162 ± 0.027
S.D. Thalweg Depth (m)	0.0440 ± 0.0066	0.101 ± 0.0353	0.0659 ± 0.0191	
Coef. Var Thalweg Depth[a]	0.30 ± 0.062	0.51 ± 0.11	0.42 ± 0.11	0.38 ± 0.12
Width/Depth Ratio	23.3 ± 3.4	22.4 ± 3.4	20.2 ± 1.6	22.4 ± 3.1
Coef. Var W/D[a]	0.47 ± 0.11	0.71 ± 0.17	0.60 ± 0.043	0.57 ± 0.15
Width*Depth Product (m^2)	0.42 ± 0.03	0.66 ± 0.14	0.41 ± 0.058	0.49 ± 0.14
Coef. Var. W*D[a]	0.37 ± 0.092	0.65 ± 0.26	0.55 ± 0.22	0.49 ± 0.21
RPA per reach, >0.15m^2 (m^2/100m)[b]	1.24 ± 0.672	6.20 ± 2.89	3.98 ± 2.13	3.24 ± 2.79
RPA per reach, total (m^2/100m)[b]	2.13 ± 0.437	7.13 ± 2.85	4.87 ± 1.88	4.15 ± 2.75
RPA per pool (m^2/pool)	0.104 ± 0.034	0.343 ± 0.158	0.220 ± 0.113	0.197 ± 0.140
Woody Debris Vol. (m^3/100m)[c]	3.3 ± 2.5	18.4 ± 7.4	11.3 ± 10.5	9.3 ± 8.9
Woody Debris No. (pieces/100m)[c]	17 ± 14	48 ± 33	28 ± 7.2	28 ± 23
Woody Debris Size (m^3/piece)[c]	0.23 ± 0.20	0.40 ± 0.099	0.36 ± 0.25	0.31 ± 0.19
Drainage Area (range, km^2)	2.14 to 2.64	2.85 to 3.26	2.59 to 2.70	2.14 to 3.26

[a] Standard deviation + mean of 100 seperate measurements at 1 meter intervals of thalweg distance in each 100 meter reach.

[b] Aggregate profile area of residual pools calculated from long profile of elevations at 0.5 meter intervals along the thalweg of each 100 meter reach (RPA >0.15m^2 includes only the larger "pools," RPA total includes all).

[c] Organic debris, pieces ≥ 1.0 m long and ≥ 0.10 m diameter in a swath 9 meters wide (criteria same as used by Heimann, 1987).

Table 4. Hydraulic Characteristics During Summer Low Flow (arithmetic mean ± 1 standard deviation).

	Gwynn Creek (n=7)	Cape Creek (n=4)	Little Cummins Creek (n=3)
Discharge (m^3/s)	0.043	0.027	0.019
U_c = Mean Convective Velocity (m/s)	0.19 ± 0.018	0.094 ± 0.019	0.11 ± 0.012
Mean Thalweg Point Velocity (m/s)	0.38 ± 0.032	0.25 ± 0.058 (n=3)	0.27 ± 0.045
f = Darcy-Weisbach Fricton Factor (dimensionless)	5.7 ± 1.9	38 ± 33	18 ± 5.6
a_L = Dead Zone Volume Fraction (dimensionless)	0.36 ± 0.019	0.51 ± 0.066	0.41 ± 0.39
δ = Volume-Based Storage Exchange Rate Coef (sec^{-1})	0.057 ± 0.0092	0.028 ± 0.014	0.031 ± 0.013
Skewness of Dye Curves (100m reaches)	1.36 ± 0.18	1.10 ± 0.11	1.33 ± 0.31
Kurtosis of Dye Curves (100m reaches)	5.78 ± 0.92	4.14 ± 0.47	5.29 ± 0.98

Table 5. Channel and Hydraulic Characteristics During Springtime Flows (arithmetic mean ± 1 standard deviation).

	Gwynn Creek untreated (n=3)	Cape Creek (n=3)	Little Cummins Creek (n=3)
Channel:			
Gradient	0.0345 ± 0.0039	0.0365 ± 0.0021	0.0361 ± 0.0018
Width (m)	3.27 ± 0.36	4.18 ± 0.345	3.38 ± 0.168
Coef. Var. Width[a]	0.28 ± 0.12	0.29 ± 0.076	0.27 ± 0.023
Thalweg Depth (m)	0.162 ± 0.00304	0.250 ± 0.0227	0.217 ± 0.0106
S.D. Thalweg Depth (m)	0.0455 ± 0.0092	0.104 ± 0.0382	0.0832 ± 0.0258
Coef. Var. Thalweg Depth[a]	0.28 ± 0.055	0.41 ± 0.11	0.38 ± 0.10
Width/Depth Ratio	22.7 ± 2.3	19.8 ± 3.9	19.3 ± 1.6
Coef. Var. W/D[a]	0.53 ± 0.13	0.48 ± 0.089	0.56 ± 0.053
Width*Depth Product (m^2)	0.51 ± 0.066	1.02 ± 0.0902	0.68 ± 0.035
Coef. Var. W*D[a]	0.30 ± 0.062	0.50 ± 0.19	0.41 ± 0.19
Hydraulic:			
Discharge (m^3/s)	0.055	0.079	0.099
U_c = Mean Convective Velocity (m/s)	0.24 ± 0.016	0.19 ± 0.023	0.25 ± 0.041
f = Darcy-Weisbach Friction Factor	3.3 ± 1.1	7.9 ± 3.3	5.8 ± 2.3
a_L = Dead Zone Volume Fraction	0.36 ± 0.030	0.47 ± 0.075	0.47 ± 0.067
δ = Volume-Based Storage Exch. Rate Coef. (sec^{-1})	0.071 ± 0.00075	0.043 ± 0.015	0.054 ± 0.021

[a] Standard deviation + mean of 100 separate measurements at 1 meter intervals along thalweg of each 100 meter reach.

an overall mean of 0.0344. Analysis of variance (ANOVA) in the gradients of the 14 study reaches did not reveal significant differences ($p = 0.10$) among the three streams.

The overall mean summer low flow wetted width for the 14 one-hundred meter study reaches was 3.04 ± 0.45 meters. Gwynn Creek (7 reaches) and Cape Creek (4 reaches) were significantly wider than Little Cummins Creek (3 reaches) at low flow (t-test, $p = 0.10$), but were not significantly different from each other. At higher flows ($\approx 0.08\ m^3/s$) during April and May 1985, Cape Creek was significantly wider (t-test, $p = 0.10$) than either of the other two streams, Gwynn and Little Cummins Creeks, but these two did not differ significantly from each other. The coefficients of variation in sets of 100 width measurements taken over the length of each study reach ranged from 0.19 to 0.41 but significant differences were not discernible among stream means at either summer low flow or higher spring flows (ANOVA, $p = 0.10$).

The summer low flow thalweg depth averaged over 14 study reaches was 0.16 meter. Mean reach depths were greatest in Cape Creek (0.20 m) and shallowest in Gwynn (0.14 m), with Little Cummins intermediate at 0.16 m. These values reflect the general pattern of channel hydraulic resistance and pool volume, with Cape Creek showing high values and Gwynn Creek, with a paucity of large organic debris and sediment in a relatively uniform channel, showing low values, as shall be discussed later in this dissertation. Water depth is, of course, dependent upon discharge as well as hydraulic resistance at a given channel gradient, so comparison of mean thalweg depths at other than closely matched flows can be misleading.

The within-reach variance in thalweg depth showed the same pattern as mean thalweg depth within a given flow range. This correspondence is not surprising in light of an expected positive correlation between depth variance and relative roughness. The standard deviations of thalweg depth measurements within reaches differed significantly among streams at low flow (t-tests, $p = 0.10$). Mean coefficients of thalweg depth variation were 30, 42, and 51 percent for reaches in Gwynn, Little Cummins, and Cape Creek. At spring flows, the difference between Cape Creek and Little Cummins was no longer significant ($p = 0.10$).

Width/depth ratios were calculated as the wetted width at the time of survey divided by the corresponding thalweg depth taken at the same place and time. One hundred values were calculated and averaged to give means for each study reach on a given sampling date. Width/depth ratios averaged 22.4 and 20.6 for the 14 reaches during summer and spring flows, respectively. Reach means ranged from 18.6 to 29.1 at low flow and from 17.1 to 24.8 at the higher spring flows. Grouped by stream, these data showed a slight tendency to narrow over time since disturbance with Gwynn Creek the highest, followed by Cape Creek and then Little Cummins Creek. Analysis of variance, however, showed no significant differences ($p = 0.10$) among the streams during summer low flows or spring flows about 5 times as high. Prevalence of undercut banks was associated with low width/depth ratios in reaches of these three streams, making it surprising that the streams did not differ significantly. A high frequency of undercutting and bank reinforcement by roots was observed in the banks of Little Cummins Creek, undisturbed by major torrents for over a century. Such bank characteristics were evident to a lesser extent in Cape Creek, but were nearly absent in Gwynn Creek.

For stream channels with a width/depth ratio greater than about 20:1 and with channel cross-sections roughly rectangular, the product of thalweg depth and wetted width approximates the channel cross-sectional area. Cross-sectional area indexes flow resistance when discharge and slope are held constant (see introductory discussion of channel flow resistance). Width-depth products were calculated for each 100 paired wetted width and thalweg depth measurements spaced at one meter intervals along 100 meter reaches; mean width-depth products were calculated for each study reach. Like mean thalweg depth, width-depth product is sensitive to discharge. A comparison of mean values at other than exactly matched flows (Table 4) is misleading, as it reflects both the difference in channel resistance and the difference in discharge (assuming equal slopes). The main use of mean depth and width-depth product information was in the calculation of channel flow resistance and in relating hydraulic resistance and dispersion measures to channel morphology or the spatial variance in that morphology.

An important component of these small streams was large organic debris and living vegetation. This material typically formed portions of the channel boundary and influenced channel form both up- and downstream by controlling channel scour and sediment transport. Three main mechanisms: torrent deposition, windthrow, and bank cutting appear to provide most of the large organic debris input to these study streams and others like them in the Oregon Coast Range. Extensive aggregations of large organic debris, many spanning approximately 100 meters of channel length, but typically involving about 50 meters, have been deposited by debris torrents. This debris was mixed with and buried in sediment deposits at points where the slide or torrent momentum decreased with flattening of the channel gradient or where it lost energy in a channel bend or valley constriction. In Gwynn Creek, for instance, valley constrictions below reach g6, and in the lower end of reach g4, appeared to have caught large aggregations of log debris high on and above channel banks. Another constriction in the upper end of reach g7 appears to have influenced the accumulation of large logs into a jam in that reach. The torrent in Gwynn Creek was more like a flood wave than a true debris torrent (Benda, pers. comm.). As such, it did not deposit great masses of inorganic sediment in the gravel, cobble and boulder size ranges. There were, however, reaches which were apparently aggraded by the deposition of cobbles and gravel. Most of the torrent track experienced massive channel and riparian zone scouring with intermittent deposition of loose clusters of large organic debris relatively free of sediment. In the study reaches, these accumulations were generally high up on the bank beyond the reach of normal flood flows. Most of the debris was deposited en-masse on Highway 101 near the mouth of Gwynn Creek and extending approximately 300 meters upstream (Reim, pers. comm.). This debris deposit, containing massive old growth timber, was approximately 300 meters downstream of the lower end of the study section. The deposition was salvage-logged for its commercial value and for the purpose of protecting the highway from possible damage resulting from further movement of the debris (Reim, pers. comm.).

Torrent deposits in Cape Creek and Little Cummins Creek appeared to be of a different nature, causing different types of residual assemblages of large organic debris. The torrents in these streams had apparently contained larger amounts of cobble, small boulder, and fine sediment. Massive deposition of both inorganic and large organic debris was evident in reach L1 of Little Cummins Creek and reaches C1 and C2 of Cape Creek. Scouring with intermittent deposition of logs and boulders was evident in the reaches upstream of these deposits (reaches L2, L3, C3, C4). The scouring may have taken place immediately or over the decades following the original torrent event, as the stream reworked and cut down through a broad plain of sediment deposited by the torrent or by previous gradual or catastrophic events.

In both Cape Creek and Little Cummins Creek, large conifer logs were delivered to the stream channel through windthrow. Windthrow may also become a significant mode of delivery of both hardwood and conifer wood to Gwynn Creek in the future. The windthrow process appears to have produced contagious distributions of debris in Cape and Little Cummins Creeks. Certain areas of these streams were particularly prone to repeated inputs by this mechanism. Because of aspect and topography, some areas of a watershed may be more likely to receive strong and turbulent winds. Once an opening in the forest canopy is formed by windthrow (or by logging or side tributary landslides), trees near the edges of that opening can be thrown more easily because the force of the wind may be better directed against individual trees. To compound this effect, newly exposed trees are often tall and slender, lacking the supportive root strength of trees that grow in open areas.

Bank cutting was a common method of large organic debris delivery in Cape and Little Cummins Creeks. Logs delivered by this method often included rootwads. Bank cutting was particularly effective in delivering single or clustered small to large alders into the streams, as these were more often found near the stream banks than were other tree species. Alders are an important component of riparian vegetation in the Pacific

Northwest, both because they often revegetate flood and torrent scars and because they are fast-growing and relatively hydrophilic. Because of the vigorous alder revegetation of the denuded riparian zone of Gwynn Creek, one would expect, based on the findings of Heimann (1987), significant inputs of sizable alder debris to that stream after 20 or 30 years.

Large organic debris loadings ranged from a low of 6 pieces per 100 m in a highly scoured reach of Gwynn Creek to a high of 97 pieces/100 m in a reach of Cape Creek subjected to torrent deposition and subsequent windthrow (Table 3). Total debris volumes ranged from 0.99 m^3/100 m in a reach of Gwynn Creek to 26.6 m^3/100 m in the aforementioned reach of Cape Creek. Reaches in Cape and Little Cummins Creeks had mean numbers of woody debris pieces significantly greater than those in Gwynn Creek (t-test, $p = 0.10$). The four lower reaches of Gwynn Creek had particularly sparse large woody debris loadings (6 to 9 pieces/100 m) in comparison to the upper 3 reaches (13 to 41 pieces/100 m). If these lower 4 reaches are ignored, the large woody debris numbers of reaches in the three separate streams did not differ significantly (t-tests, $p = 0.10$) from one another. However, because the overall mean piece size was substantially smaller in Gwynn Creek (0.23 m^3) than in the other streams (L. Cummins: 0.36 m^3, Cape: 0.40 m^3), the mean total woody debris volume in reaches of Gwynn Creek was significantly smaller than that in each of the other streams (t-tests $p = 0.10$). Total debris volumes in Cape and Little Cummins Creeks, which included both torrent deposit reaches and reaches apparently scoured by torrents, were not significantly different from each other (t-test, $p = 0.10$).

Typical large woody debris pieces in the study streams were logs 2 to 4 meters long with diameters ranging from 0.3 to 0.4 meter. These

pieces had contagious distributions within reaches, as was also found by Heimann (1987) in his study of 17 third order streams in the Oregon Coast Range. Such distributions suggest that smaller pieces of debris are repositioned near large, relatively stable pieces during storm flows.

3. Pool Studies

a. Comparison of Individual Pool Types

Table 6 shows the average dimensions (arithmetic mean ± 1 standard deviation) of the 10 slackwater types identified in this study. The sample consisted of all those residual pool features with vertical profile areas greater than 0.015 m^2 which could also be visually identified in the field. Out of 288 residual pools defined from thalweg elevation profiles, 259 could be classified from field notes and their dimensions were used to characterize each pool class. No man-made pools were included in the sample. It included all pools in 1300 meters of channel in the three study streams, 300 m in Little Cummins Creek, 400 m in Cape Creek, and 600 m in Gwynn Creek prior to log additions. An effort was made to get an approximately equal sample number of the important pool types in each stream, hence different lengths of stream channel were used. Because the distributions of pool dimensional measurements tended to be approximately log-normal, all tests of means and analyses of variance were performed on log-transformed raw data. At the bottom of Table 6 is a summary of one-way ANOVA contrasts among pool types with respect to Residual Profile Area (RPA), Maximum Residual Depth (Dmax), Residual Pool Length (L), and the form ratio Dmax/L. The Bonferroni method of multiple contrasts was used to yield an overall p-value of < 0.05 for families of simultaneous ANOVA contrast statements listed in the table. Although pool characteristics are reported as arithmetic means in Table 6, statistical tests were performed on log-transformed raw data.

Table 6. Arithmetic Mean Dimensions (± 1 standard deviation) of Residual Pool Types in Gwynn, Cape, and Little Cummins Creeks.

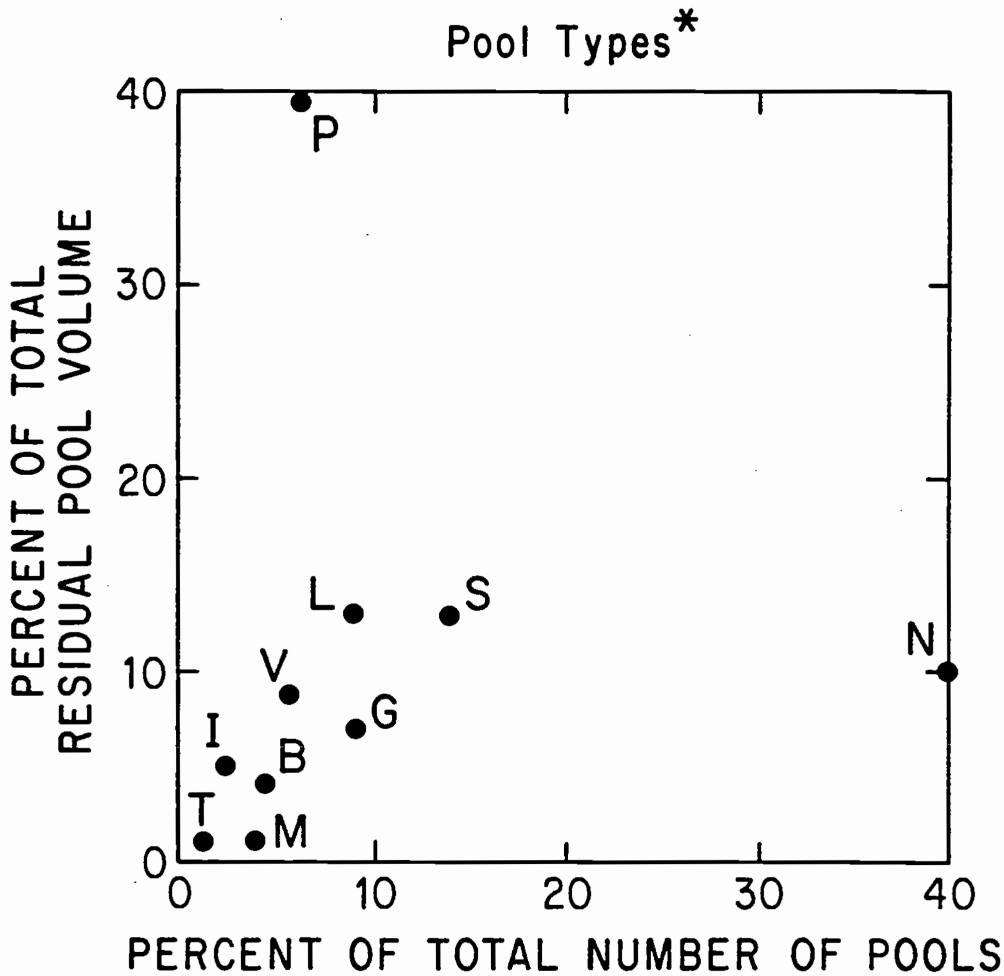
Pool Classification	ERV[a] (m^3)	RPA[b] (m^2)	Dmax (m)	Length (m)	Dmax/Length	F[d]	n[e]
P-Cascade Plunge Pool	3.9	1.3 ± 1.5	0.33 ± 0.12	6.2 ± 3.8	0.067 ± 0.041	1.2	16
V-Vertical Scour Pool	0.90	0.30 ± 0.47	0.14 ± 0.10	2.6 ± 2.5	0.077 ± 0.062	1.2	15
L-Lateral Scour Pool	0.86	0.29 ± 0.30	0.11 ± 0.06	3.5 ± 2.6	0.043 ± 0.031	1.8	24
B-Backwater Pool	0.54	0.18 ± 0.20	0.11 ± 0.06	2.5 ± 1.6	0.055 ± 0.027	0.92	12
S-Step Pool	0.54	0.18 ± 0.16	0.11 ± 0.05	2.4 ± 1.5	0.056 ± 0.028	2.8	37
G-Glide	0.50	0.16 ± 0.12	0.08 ± 0.03	3.0 ± 1.4	0.030 ± 0.016	1.8	24
T-Trench Pool	0.42	0.14 ± 0.08	0.09 ± 0.02	2.2 ± 1.6	0.058 ± 0.042	0.3	4
I-Impoundment Pool	0.29	0.10 ± 0.05	0.09 ± 0.02	1.7 ± 1.0	0.081 ± 0.066	1.0	13
N-Inter-Cobble-Row Pool	0.15	0.05 ± 0.03	0.06 ± 0.02	1.3 ± 0.6	0.055 ± 0.036	8.0	104
M-Lateral Scour Trench	0.14	0.05 ± 0.02	0.05 ± 0.01	1.4 ± 1.0	0.060 ± 0.046	0.77	10
Contrast Statements:		(P>L)*	(P>VBLSTI)*	(P>GL)*	(VIP>BST)n.s.		
		(P>SVTG)*	(VBLSTI>G)*	(GL>BSTV)n.s.	(BST>NM)n.s.		
		(L>SVTG)n.s.	(G>NM)*	(BSTV>INM)*	(NM>L)n.s.		
		(SVTG>BI)n.s.	(N>M)n.s.	(G>L)n.s.	(L>G)n.s.		
		(BI>NM)*			(N>M)n.s.		

[a] Est. Resid. Vol.
[b] Resid. Profile Area
[c] Resid. Max Depth
[d] Frequency (pools/100 m)
[e] Sample Size
* $p < 0.05$ (1 way ANOVA on log transformed raw data, Bonferroni method of multiple contrasts).

Cascade Plunge Pools formed a unique group of pools distinguished by their relatively large volume and depth (Table 6). The geometric mean residual pool maximum depth (Dmax) of Cascade Plunge Pools was 3.2 times the combined mean for Vertical Scour Pools, Backwater Pools, Lateral Scour Pools, Step Pools, Trench Pools, and Impoundment Pools. Cascade Plunge Pools also formed a distinct grouping in terms of pool volume, as indexed by residual pool profile area (RPA). These large pools had a geometric mean volume 5.7 times the combined mean of Lateral Scour Pools, Step Pools, Vertical Scour Pools, Trench Pools and Glides. The geometric mean length of Cascade Plunge Pools was 2 times the combined mean of Glides and Lateral Scour Pools. Cascade Plunge Pools were not, however, distinct with regard to their ratio of depth to length. Geometric mean values of Dmax/Length ranged from a low of 0.027 for Glides to a maximum of 0.063 for Vertical Scour Pools. The 10 pool types formed a nearly even continuum in geometric mean Dmax/L, decreasing in the series: V, I, P, B, S, T, N, M, L, G. While a 1-way ANOVA test for significance of mean differences indicated that types near opposite ends of the continuum were significantly different ($p = 0.05$), no successive members of the series differed significantly from one another.

b. Aggregate Importance of Residual Pool Types and Formative Agents

Figure 5 illustrates a comparison of the relative proportions of pool types by total number and residual volume, based on 259 pools in 1300 meters of length over the three study streams (13 of 14 total reaches). Cascade Plunge Pools, because of their large individual volumes, contributed almost half of the aggregate pool volume even though they comprised considerably less than one tenth of the total number of pools. Inter-Cobble-Row Pools, by contrast, made up almost half of the pool numbers, but because of their small average size, contributed only 10 percent of the aggregate pool volume in the streams. Lateral Scour Pools and Step Pools were impor-tant components of total pool volume, each comprising about 13 percent of that total. The other pool types each contributed less than 10 percent of the aggregate pool volume in the combined streams.



*P = Cascade Plunge Pools, I = Impoundment Pools, V = Vertical Scour Pools, T = Trench Pools, B = Backwater Pools, S = Step Pools, N = Inter-Cobble Row Pools, M = Lateral Scour Trenches, L = Lateral Scour Pools, G = Glides

Figure 5. Relative Contributions of Pool Types to Total Number and Aggregate Residual Volume (based on 259 pools in 1300 meters of total channel length distributed among three study streams).

There were several noteworthy departures from the overall pattern of pool type volume contributions when each of the three streams was considered individually. There were virtually no Step Pools in the study reaches of Gwynn Creek. In Cape Creek and Little Cummins Creek, on the other hand, Step Pool volume contributions exceeded those of all the other pool types except Cascade Plunge Pools. The greatest portion of residual pool volume in Gwynn Creek was under the classification of Lateral Scour Trench, a "slackwater" type which was absent in Cape Creek and Little Cummins Creek. Lateral Scour Trenches (see definition in Appendix C) were narrow with relatively high water velocities. They would not normally be classified as a pool type in the assessment of fish habitat. The dominant contributors of actual slackwater in Gwynn Creek were Lateral Scour Pools and Inter-Cobble-Row Pools, which provided, respectively, 24 and 27 percent of the total residual pool volume in that stream. Cascade Plunge Pools, which contained the lowest water velocities, greatest depth, best cover, and probably the highest quality adult and juvenile salmonid habitat of all the pool types, constituted only 19 percent of the already meager residual pool volume in Gwynn Creek. Assuming residual pool vertical profile area to be proportional to residual pool volume, the mean residual pool volume of Gwynn Creek reaches was 2.13 m^2 per 100 m channel multiplied by a mean channel width of 3.0 meters, or an estimated 6.4 cubic meters per 100 meters of stream length. This contrasts with 13.0 m^3/100 m in Little Cummins Creek (4.87 m^2/100 m multiplied by mean stream width of 2.66 m) and 24.2 m^3/100 m in Cape Creek (7.13 m^2/100 m multiplied by mean stream width of 3.39 m).

Total pool volume in Little Cummins Creek was allocated largely among Cascade Plunge Pools (42%), Step Pools (17%), and Lateral Scour

Pools (14%). The pattern in Cape Creek was similar, with total pool volume contributions mainly by Cascade Plunge Pools (44%), Step Pools (15%), Vertical Scour Pools (13%), and Lateral Scour Pools (7%).

A plot showing a measure of mean individual pool volume versus reach aggregate pool volume (Figure 6) positions Gwynn Creek reaches at the lower left, Little Cummins Creek in the middle, and Cape Creek at the upper right with both the largest average pool volume and the greatest pool volume per reach. Pool volumes in this figure were indexed by Residual Pool Vertical Profile Area (RPA per pool and per reach). The aggregate pool volume in reaches of Cape Creek was 1.5 times greater than that in Little Cummins Creek, but this difference was not statistically significant ($p = 0.05$, 1-Way ANOVA with log-transformed means). Aggregate pool volume in reaches of Cape Creek was 3.2 times, and Little Cummins was 2.2 times, the mean for Gwynn Creek reaches ($p = 0.05$). Comparisons of pool maximum depth (not shown in Figure 6) revealed that pools in Cape Creek reaches were 2.2 times deeper than those of Gwynn Creek ($p = 0.05$, 1-Way ANOVA). Though the mean pool maximum depth in reaches of Little Cummins was intermediate between the other two streams, the observed differences were not statistically significant ($p = 0.05$).

The individual data points plot close to a straight line on Figure 6 because there was very little deviation from the average number of 22 ± 4 residual pools per 100 meters of stream, causing aggregate pool volume to be closely correlated with the mean volume per pool in the study reaches. The longitudinal frequency of 22 residual pools per 100 m of stream converts to a spacing equal to a distance of 1.5 channel widths. This spacing is considerably less than the typical spacing of 5 to 7 channel widths

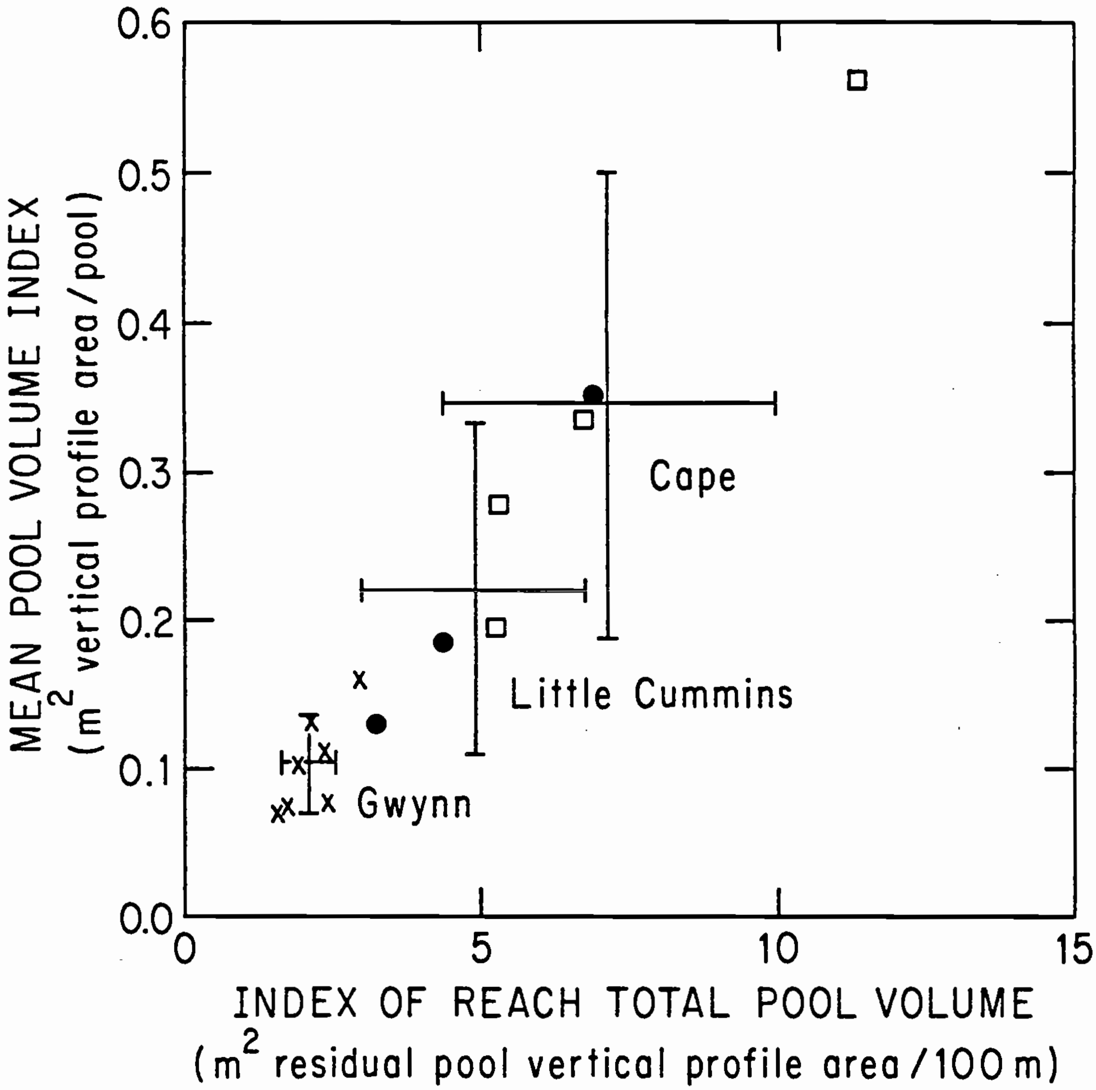


Figure 6. Mean Individual Pool Volume vs. Aggregate Pool Volume in Study Reaches (error bars show mean ± 1 standard deviation).

reported for alluvial channels by many researchers, including Leopold et al. (1964). The pool frequency I have reported above is that of individual residual pools greater than 0.015 m^2 in vertical profile area (see definitions in Appendix C). The "pools" tallied by such a procedure include many slackwater features too small or shallow to be classified as pools by most fluvial geomorphologists or fishery biologists.

To better match the somewhat subjective criteria often used to identify "pools", I identified all residual pools with 10 times the volume used in the previous case, tallying only those with vertical profile areas greater than 0.15 m^2 (residual volumes > 0.45 m^3 in these streams). This selection includes only pools which would be classified as pools by most observers or stream surveyors. In seven 100-meter reaches in Little Cummins and Cape Creeks, the frequency of these larger pools was 8.0 $\pm$ 1.3 per 100 meters, a pool spacing of about one pool per 4 channel widths of thalweg distance. In Gwynn Creek, where organic debris was more sparse and the substrate was more consistent over the length of reaches, one might expect pool spacings more typical of alluvial channels. The more typical spacing might be expected because channel form should be more influenced by unimpeded fluvial sediment transport processes than would be the case in the complex channels of the other two streams, where abundant large organic debris, boulders and bedrock might mask strictly fluvial influences. The mean longitudinal frequency of the larger residual pools in Gwynn Creek was approximately one pool in every 11 channel widths of thalweg distance. Paucity of larger pools in this stream was likely the result of debris torrent scouring effects. The average large pool spacing for thirteen 100 m reaches among the three study streams was one pool every 5.9 channel widths (a frequency of 5.7 ± 2.9 pools per 100 m of thalweg distance).

In comparing the aggregate volume of larger pools only (see above paragraph) among reaches in the three streams, I saw the same pattern, though exaggerated, as seen when all pools were considered. The geometric mean aggregate volume of such larger pools in reaches of Cape Creek was 1.6 times that of Little Cummins Creek, but this difference was not significant (t-test, $p = 0.10$). Reaches in Cape Creek had 5.3 times, and Little Cummins Creek 3.3 times, the aggregate volume of this larger pool class than did Gwynn Creek reaches (t-tests, $p = 0.01$).

The importance of organic debris, and in particular log clusters, in pool formation is illustrated in Figure 7, a plot of the mean values of maximum residual depth and residual pool profile area (volume index) for pools grouped by their dominant formative agents. The plot is based on measurements of 288 individual pools in a total stream length of 1300 meters in the three study streams. The largest and deepest pools were associated with log clusters. Progressively smaller pool volumes and depths were associated, in descending order, with rootwads, bedrock, boulders, single logs, and cobbles. On the whole, pools which were associated with some type of large organic debris had a geometric mean vertical profile area 1.9 times that of pools not associated with organic debris (one-sided t-test on log transformed data, $p < .01$ with 144 df).

Table 7 shows the arithmetic mean residual profile area (RPA) and maximum residual depth (Dmax) of pools associated with various formative agents. One-way analysis of variance on log-transformed raw data was employed to contrast the residual profile area (indexing pool volume) and maximum residual depth of pools formed by different agents. The

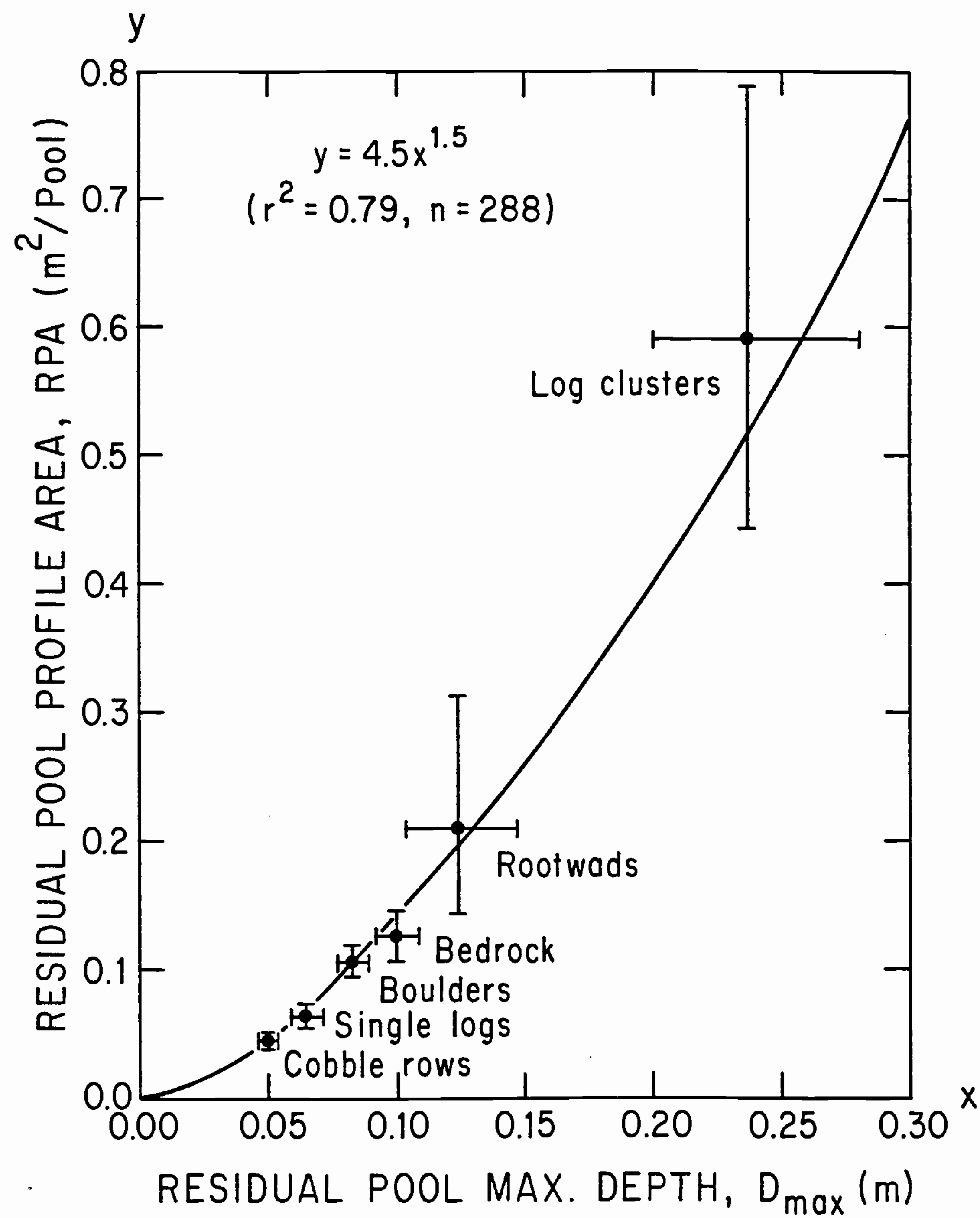


Figure 7. Residual Pool Profile Area (RPA) and Maximum Residual Depth (Dmax) of Individual Pools Formed by Various Agents (logarithmic means ± 1 standard error of mean; regression calculated from log transformed raw data).

Table 7. Arithmetic Mean (± 1 standard deviation) Residual Pool Profile Area (RPA) and Maximum Depth (Dmax) of Pools Formed by Various Agents**.

Pool Formative Agent/Code		RPA (m^2)	Dmax (m)	L (m)	n
Log cluster	(j)	1.07 ± 1.50	0.28 ± 0.15	5.0 ± 3.6	17
Rootwad	(r)	0.43 ± 0.58	0.14 ± 0.09	3.8 ± 3.3	10
Single log	(w)	0.13 ± 0.30	0.08 ± 0.06	1.8 ± 1.8	34
Bedrock	(g)	0.23 ± 0.29	0.12 ± 0.07	2.8 ± 2.4	43
Boulders	(b)	0.16 ± 0.18	0.09 ± 0.05	2.4 ± 1.6	71
Cobbles	(c)	0.06 ± 0.05	0.05 ± 0.02	1.4 ± 0.84	67
not identified		-----	-----	-----	17

					259
Contrast Statements:					
j > r		*	*		
r > w		*	*		
j > g		*	*		
g > b		n.s.	n.s.		
b > c		*	*		
j + r + w > g + b + c		*	*		

** Dominant formative agent was subjectively determined in the field.
* p < .05 (1 way ANOVA on log transformed raw data, Bonferroni method of multiple contrasts).

Bonferroni method of multiple contrasts was used to yield a value of $p < 0.05$ for the families of simultaneous contrast statements listed at the bottom of the table. The geometric mean volume of log cluster-associated pools was nearly 5 times that of bedrock-associated pools, the largest within the category of pools associated primarily with inorganic formative agents. Rootwad-associated pools were the second largest, in terms of individual pool volume.

The geometric mean maximum residual depth of pools associated with organic debris was 1.5 times that of pools without associated organic debris (Table 7). Pools associated with log clusters were the deepest and were, on the average, more than twice as deep as those primarily associated with bedrock. Rootwad-associated pools were second (before bedrock-associated pools) in terms of maximum residual depth.

While Figure 7 and Table 7 show the relative effectiveness of the various pool forming agents by their association with mean dimensions of *individual* pools, Figure 8 illustrates the importance of these agents in terms of their influence on the *total* number and volume of pools in the study streams. Those pools formed by log clusters, despite their small numbers (only 7% of the total), comprised 35 percent of the total residual pool volume in the surveys. Transverse rows of cobbles, by contrast, were identified as the primary formative agent of nearly 26 percent of the pools, but those pools made up only a little more than 6 percent of the total pool volume. In terms of pool *frequency*, almost equal proportions (each approx. 26%) of pool or slackwater features were associated with boulders and cobbles, followed in decreasing order by pools associated with bedrock, single logs, log clusters, and rootwads as pool forming agents. In terms of *total volume* contributions, by contrast, the ranking of pool forming agents was, in diminishing order: log clusters, boulders, bedrock, single logs, rootwads, and cobbles. Log clusters, as mentioned, formed a disproportionately large amount of the pool volume in these streams. Rootwads, though least frequently identified as pool forming agents, formed large pools which significantly contributed to the total pool volume in the streams.

The importance of various pool formative agents differed among the three study streams. Pool formation in 400 meters of Cape Creek was dominated on a volume basis by log clusters and boulders, which were associated with, respectively, 43 and 32 percent of the pool volume in this stream. Bedrock and log clusters dominated pool formation and contri-

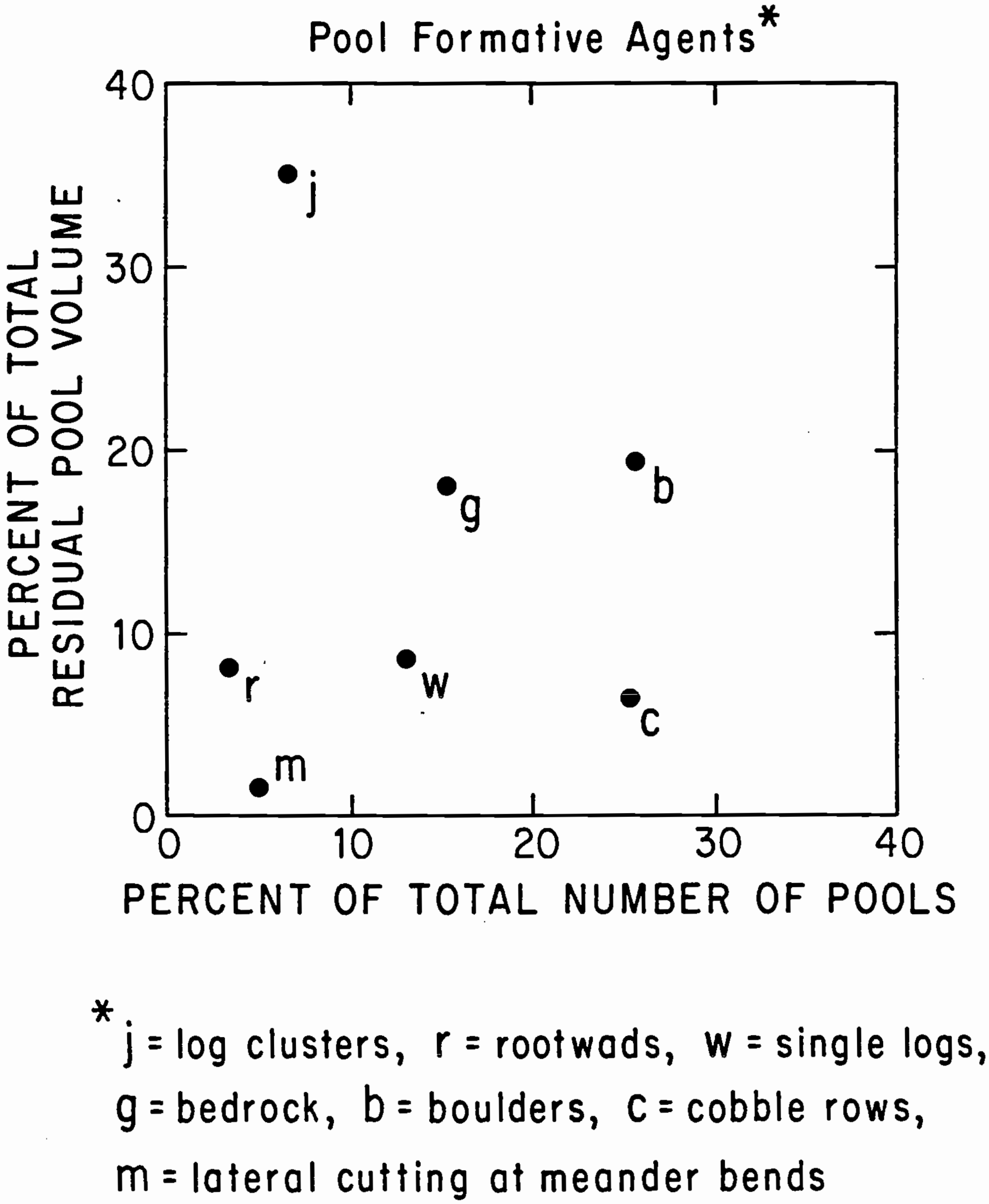


Figure 8. Relative Contribution of Pool Forming Agents to the Number and Aggregate Volume of Pools in Study Streams (based on 259 pools in 1300 meters of total channel length distributed among three study streams).

tributed about equally (29 and 26%) to the residual pool volume in 300 meters of Little Cummins Creek. In 600 meters of Gwynn Creek (data not available in one of the 7 study reaches), where there was a conspicuous absence of large pools, approximately equal portions of the aggregate pool volume were associated with bedrock, cobbles, single logs, and log clusters.

Figure 9 is a plot of aggregate residual pool profile area (a pool volume index) of the 14 reaches in the three study streams versus large woody debris volume in the active channel of these same reaches. Note the clustering of Gwynn Creek's seven reaches in the lower left with small volumes of wood and small reach aggregate pool volumes. Cape Creek reaches C1, C2, and C3, and Little Cummins Creek reach L1, four reaches with abundant large woody debris and sediment derived from torrent deposition, position themselves in the upper right hand portion of the plot, with high pool and debris volumes. Cape Creek reach C4 also has high pool volume but it is primarily due to the interaction of boulders (left as torrent lag deposits) and bedrock. Reaches L2 and L3 in Little Cummins Creek resembled the more highly debris-loaded reaches g4, g6 and g7 of Gwynn Creek in wood volume, but had about twice the reach total pool volume because of scouring near bedrock. Like reach C4, reaches L2 and L3 show evidence of progressive downcutting over a long period of time. In addition, the lower half of L2 shows evidence of local scouring as a result of the breaching of an old debris dam near the middle of this reach. Debris pieces in the breached dam are well-decomposed conifer wood, making it possible that the dam may have been in place for several decades, or perhaps more than a century. Much of the pool volume in reaches L2 and L3, like that in C4, was associated with bedrock. The

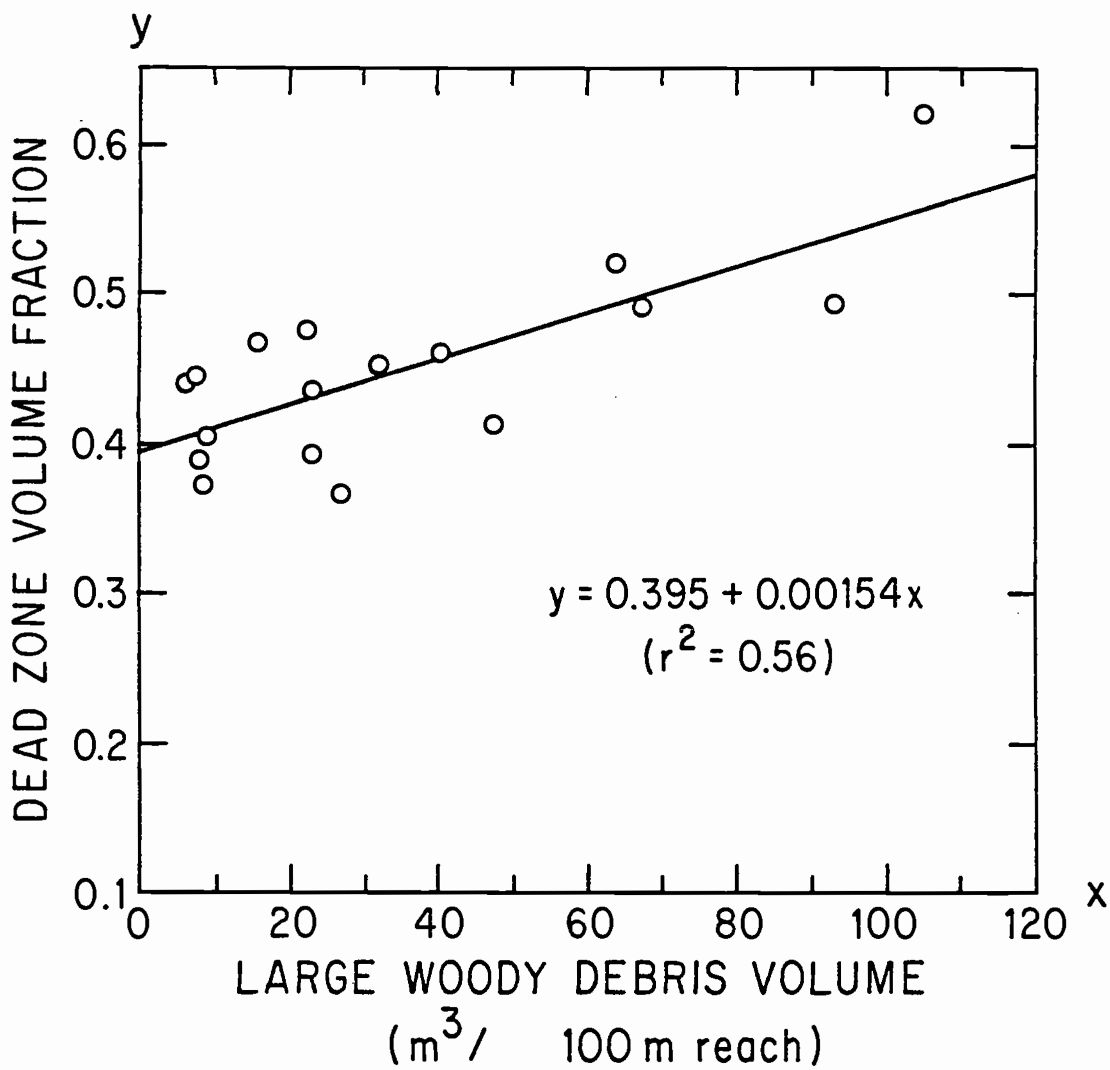


Figure 9. Residual Pool Volume Index (RPA per Reach) vs. Large Woody Debris Volume.

total pool volume in these reaches was therefore higher than would be predicted on the basis of debris loading alone. As shown by the regression in Figure 9, 74 percent of the variance in reach total pool volume can be explained by the volume of large woody debris in the active channels of the study reaches.

B. Gwynn Creek Treatment

The general association of stream channel complexity, and perhaps most importantly pools, with large woody debris has been discussed by others (e.g., Swanson et al., 1976; Swanson & Lienkaemper, 1978; Keller & Swanson, 1979; Sedell et al., 1981; Sedell & Luchessa, 1982). It would not be surprising, therefore, to find that wood additions to a relatively simple channel scoured by a debris torrent might generally enhance channel complexity by creating and enlarging pools and backwaters, thereby increasing hydraulic resistance. Just how quickly and to what degree these changes might occur under given circumstances is a question that needs to be answered if streams are to be managed to optimize certain types of channel form for fish habitat or other reasons.

The experimental debris placement for fish habitat enhancement in Gwynn Creek involved 3 control and 4 treatment reaches, each 100 meters long. The three control reaches of Gwynn Creek received no woody debris introductions. Neither were there evident any naturally-caused additions of large woody debris to these reaches during the study. Initial pretreatment woody debris piece number and total volume were, however, higher in control than in treatment reaches. The average total volume in control reaches was almost twice that of reaches destined for treatment. These control reaches, however, were still very low in debris volume, the mean of their volumes still only 24 and 40 percent, respectively, of those observed in Little Cummins and Cape Creeks. The mean number of debris pieces in the control reaches was over 3 times as high as that in the treatment reaches prior to debris additions. The bulk of the excess debris in the control reaches was made up of small pieces, as is evident in comparing the mean woody debris piece size prior to treatment, which in control reaches was just over one half that in treatment reaches (Table 8).

Table 8. Channel Characteristics of Gwynn Creek Reaches During Summer Low Flow, Before and One Year After August 1984 Treatment.

	Control Reaches (n=3)		Treatment Reaches (n=4)	
	1984	1985	1984	1985
Gradient	0.0345 ± 0.0039	---	0.0310 ± 0.0041	0.0310 ± 0.0035
Width (m)	2.96 ± 0.30	2.86 ± 0.48	3.03 ± 0.26	3.06 ± 0.44
Coef. Var. Width[a]	0.31 ± 0.10	---	0.27 ± 0.068	0.32 ± 0.066
Thalweg Depth (m)	0.143 ± 0.0052	0.129 ± 0.0067	0.144 ± 0.0098	0.169 ± 0.021
S.D. Thalweg Depth (m)	0.0426 ± 0.0072	0.0432 ± 0.0102	0.0451 ± 0.0071	0.0841 ± 0.0445
Coef. Var. Thalweg Depth[a]	0.297 ± 0.056	0.332 ± 0.062	0.313 ± 0.050	0.480 ± 0.184
Width/Depth Ratio	22.9 ± 3.0	---	23.5 ± 4.1	---
Coef. Var. W/D[a]	0.486 ± 0.135	---	0.464 ± 0.106	---
Width*Depth Product (m^2)	0.414 ± 0.044	---	0.426 ± 0.0063	---
Coef. Var. W*D[a]	0.358 ± 0.103	---	0.378 ± 0.098	---
RPA per Reach, Total (m^2/100 m)[b]	1.90 ± 0.36	---	2.30 ± 0.45	5.38 ± 2.39
RPA Per Pool (m^2/pool)	0.0847 ± 0.0220	---	0.118 ± 0.0362	0.254 ± 0.375
Woody Debris Vol. (m^3/100 m)[c]	4.5 ± 2.6	---	2.4 ± 2.4	36 ± 26
Woody Debris No. (pieces/100 m)[c]	29 ± 14	---	8.0 ± 1.4	25 ± 13
Woody Debris Size (m3/piece)[c]	0.15 ± 0.04	---	0.29 ± 0.26	1.48 ± 0.87

[a] Standard deviation + mean of 100 separate measurements at 1 meter intervals along thalweg of each 100 meter reach.

[b] Aggregate profile area of residual pools (RPA) calculated from long profile of elevations at 0.5 m intervals along thalweg of each 100 m reach.

[c] Woody debris pieces ≥ 1.0 m long and ≥ 0.10 m diameter in a swath 9 meters wide and 100 meters long (same as used by Heiman, 1987). In Gwynn Cr. treatment reaches, the entire volume of added logs directly impacting the bankfull channel was included, rather than being cut-off at 9 m channel width.

Mean stream channel morphologic and hydraulic characteristics of 3 control and 4 treatment reaches in Gwynn Creek before wood additions (mid-summer 1984), immediately after additions (late summer 1984), following treatment and winter floods (April 1985), and in late summer (September 1985) of the year following wood additions are listed in Tables 8, 9, and 10. The largest flow during the winter storm season was approximately 1.2 m^3/s (0.48 m^3 sec^{-1} km^{-2} or 44 c.s.m.), as estimated by calibration with flows measured by the U.S.G.S. in Big Creek, near Roosevelt Beach, Oregon, a stream with a drainage area of 31 km^2. Flood flows of approximately 0.6 m^3/s (measured) and 1.1 m^3/s (estimated) occurred respectively in March and late May of 1985. These storms and the several storm flows of the winter season resulted in visible scouring in both control and treatment reaches. They also caused rearrangement and increased clustering of large woody debris pieces placed in the four treatment reaches.

Table 9. Hydraulic Characteristics of Gwynn Creek Reaches During Summer Low Flow Before and One Year After August 1984 Treatment.

	Control Reaches (n=3)		Treatment Reaches (n=4)	
	1984	1985	1984	1985
Discharge (m^3/s)	0.040	0.032	0.045	0.036
Mean Convective Velocity (m/s)	0.18 ± 0.019	0.12 ± 0.010	0.19 ± 0.018	0.12 ± 0.031
f = Darcy-Weisbach Friction Factor	6.4 ± 2.2	16.6 ± 2.3	5.2 ± 1.9	27.3 ± 27.1
a_L = Dead Zone Volume Fraction	0.36 ± 0.025	0.42 ± 0.027	0.37 ± 0.018	0.46 ± 0.098
δ = Vol.-Based Storage Exch. Rate Coef (sec^{-1})	0.052 ± 0.0072	0.020 ± 0.0050	0.61 ± 0.0095	0.025 ± 0.011

Table 10. Hydraulic Characteristics of Gwynn Creek Reaches During Spring Season Flows 8 Months After Treatment.

Characteristics	Untreated Control Reaches (n=3)	Treatment Reaches (n=4)
Discharge (m^3/s)	0.055	0.062
Mean Convective Velocity (m/s)	0.24 ± 0.016	0.22 ± 0.050
f = Darcy-Weisbach Friction Factor	3.3 ± 1.1	5.4 ± 4.5
a_L = Dead Zone Volume Fraction	0.36 ± 0.030	0.38 ± 0.076
δ = Volume-Based Storage Exchange Rate Coef. (sec^{-1})	0.071 ± 0.00075	0.065 ± 0.30

In August 1984, large woody debris was pulled into the channels of the treatment reaches from the edges of the narrow valley bottom, where it had been distributed in clusters during the catastrophic flood event of 1982. The pieces were placed in the channel close to where they had been lying in the riparian zone. Most pieces were not moved more than 30 meters, so some clumping of added debris was inherited from pre-treatment distribution of riparian woody debris. After treatment, the dimensions, arrangement and location of all debris pieces impacting the bankfull channel were measured. Pre- and post-treatment debris characteristics of the four treatment reaches are shown in Table 11. Before treatment, debris in Gwynn Creek was contained primarily in small, breached debris dams associated with the majority of pools important as fish habitat in this stream.

Table 11. Large Woody Debris in Gwynn Creek: Pre- and Post-Treatment Loadings and Size Ranges.

	Pre-Treatment(1984)		Post-Treatment (1984)		Pre-Existing		Added Debris	
Reach	Pieces /100m	Volume m^3/100m	Pieces /100m	Volume m^3/100m	Diameter (m)	Length (m)	Diameter (m)	Length (m)
g1	8	1.6	21	52.0	0.15 - 0.60	0.3 - 6	0.20 - 1.5	1.0 - 15
g2	9	0.99	36	21.0	0.10 - 0.5	1 - 3	0.11 - 0.95	0.5 - 11
g3	6	1.0	8	7.7	0.15 - 0.45	1 - 3	0.11 - 0.95	0.8 - 5.2
g4	9	6.1	33	63.0	0.25 - 0.75	1 - 7	0.12 - 1.3	0.9 - 16.5
g5	13	4.3	--	--	0.06 - 0.7	0.4 - 5	---	---
g6	33	1.6	--	--	0.08 - 0.45	0.5 - 5	---	---
g7	41	5.4	--	--	0.03 - 0.7	0.5 - 5.6	---	---

Fifty cubic meters of large woody debris were added to reach g1, 20 m^3 to g2, 7 m^3 to g3, and 57 m^3 to g4. Because pre-treatment debris volumes differed among the reaches (Table 11), the proportionate increases in debris were not in the same rank order as the additions, creating a confounding factor. Post-treatment/pre-treatment woody debris volume ratios for the 4 reaches were 32:1, 21:1, 7.5:1, and 10:1. I had only indirect control over the amount, spacing and arrangement of debris added by the U.S.F.S. Their objective was to experiment with different arrangements of debris, but to also produce maximum salmonid rearing habitat enhancement over the entire treatment area. Consequently, the experimental design was unavoidably flawed from a research perspective, with regard to the location of treatment and control reaches as well as the uniformity of debris placement patterns in reaches receiving different levels of debris addition.

Debris placed in treatment reaches of Gwynn Creek was mostly arranged in clumps of 2 to 3 pieces at various angles intended primarily to create channel bottom scouring and to enhance lateral cutting in locations where such cutting had to some extent previously taken place. Single debris piece arrangements took the form of single pieces oriented at right angles and oblique angles to flow. Debris combinations ranged from herringbone and "V" arrangements directed up- or downstream to debris jams and somewhat random scatterings along the channel. In reach g1, several log sills were placed to form a series of three large plunge pools with two impoundment pools sandwiched between.

Measurements of the standard deviation of 100 thalweg depth measurements (SDD) in study reaches were used to quantify changes in pool volume observed to result from debris additions undertaken for fish habitat enhancement. Use of this nearly flow-independent variable was employed in treatment/control comparisons in lieu of repetitious and time-consuming measurements of aggregate residual pool profile area (RPA). It was found that SDD was a very good surrogate for RPA, a pool volume index independent of discharge. Figure 10 shows the relationship between RPA and SDD in parallel measurements on 14 natural reaches 100 m long plus 8 debris-treated reaches (2 measurements on each of 4 reaches after debris addition). RPA is expressed in square meters and SDD is expressed in meters. Calculation of RPA was from thalweg bottom elevation profiles taken at 0.5 meter intervals of thalweg length. SDD was calculated as the sample standard deviation of 100 measurements of thalweg depth at 1.0 meter intervals of thalweg distance. As indicated previously, RPA multiplied by the width of the stream gives an approximation of the

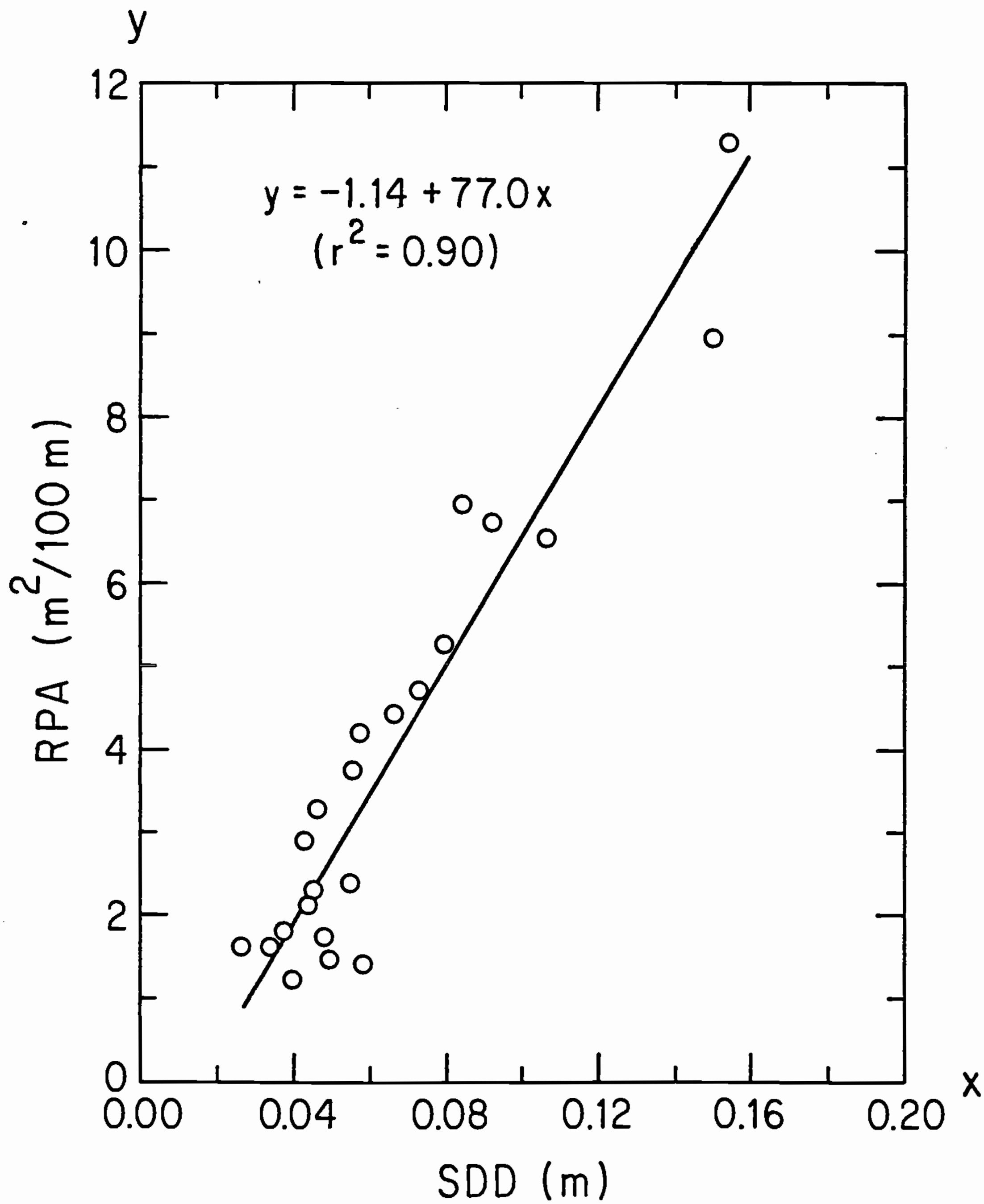


Figure 10. Aggregate Residual Pool Profile Area (RPA) vs. Standard Deviation of Thalweg Depth (SDD).

residual pool volume, or low water storage volume in the reach length over which it is calculated.

The result of large woody debris additions to the four treatment reaches of Gwynn Creek was a significant increase in pool volume, as indexed by changes in the standard deviation of thalweg depth measurements (SDD). Comparisons were by paired t-tests in which debris placement effects on individual treatment reaches were compared with control reach changes observed over the same time period. This method of analysis allowed the separation of treatment effects from those due to flow differences. Pairwise comparisons of treatment effects immediately after debris additions showed significant increases ($p = 0.05$) in SDD, the coefficient of thalweg depth variation (CfVarD), coefficient of width variation (CfVarW), dead zone volume fraction (a_L), and hydraulic flow resistance (f). There was also a relative decrease in transient storage exchange coefficient δ ($p = 0.05$). The next spring following winter floods, SDD, CfVarD, δ, and f still differed significantly ($p = 0.10$) from control conditions. Treatment reaches still exceeded controls in CfVarW and a_L, but these differences were no longer significant because of relative increases in the mean values and variances of these characteristics in the control reaches.

By the summer one year following treatment, significant differences from control conditions were discernible only in coefficient of depth variation ($p = 0.10$) and the standard deviation of thalweg depth ($p = 0.05$), the most precise and robust indicators of treatment change. While changes had taken place in the treatment reaches, the amount of change was variable because of the different levels of debris addition. This variability decreased the power of the statistical tests used to detect significant differences. There were also changes in the control reaches in the same direction as those observed in treatment reaches, perhaps indicating a process of "recovery" in control reaches towards greater channel complexity over time. Between the spring and summer sampling periods during the year following treatment, a large peak flow of approximately 1.1 m^3/s ($\approx$42 c.s.m.) took place, causing changes in both treatment and control channels. Mean morphologic and hydraulic characteristics of treatment and control reaches during the low flow periods of 1984 and 1985 are listed in Tables 8 and 9.

Considering SDD as a pool volume index, the combined pool volume in the treatment reaches increased 41, 65, and 86 percent over pre-treatment volumes immediately, 8 months, and 12 months after debris additions. Figures 11 and 12 show the mean Gwynn Creek pre- and post-treatment values of SDD, dead zone fraction, and RPA in comparison with values measured in the other study streams. As already mentioned, the responses of the four reaches were not homogeneous. Immediate increases in pool volume ranged from 6 to 141 percent of pre-treatment volumes. After 8 months, these increases ranged from 13 to 181 percent, and after a full year, pool volumes had increased by 26 to 240 percent over pre-treatment pool volumes in the four reaches.

The stream changes that occurred immediately following debris additions (but prior to winter storm flows) was the impoundment of water, often in wide, shallow backwaters. Winter floods caused filling of many impoundment pools with fine gravel and sand mobilized by bottom scour in areas upstream. Some shallow lateral backwater areas dewatered as a result of downcutting in the mainstream, as the channel re-established itself after disturbance by the bulldozer used to move logs during treatment.

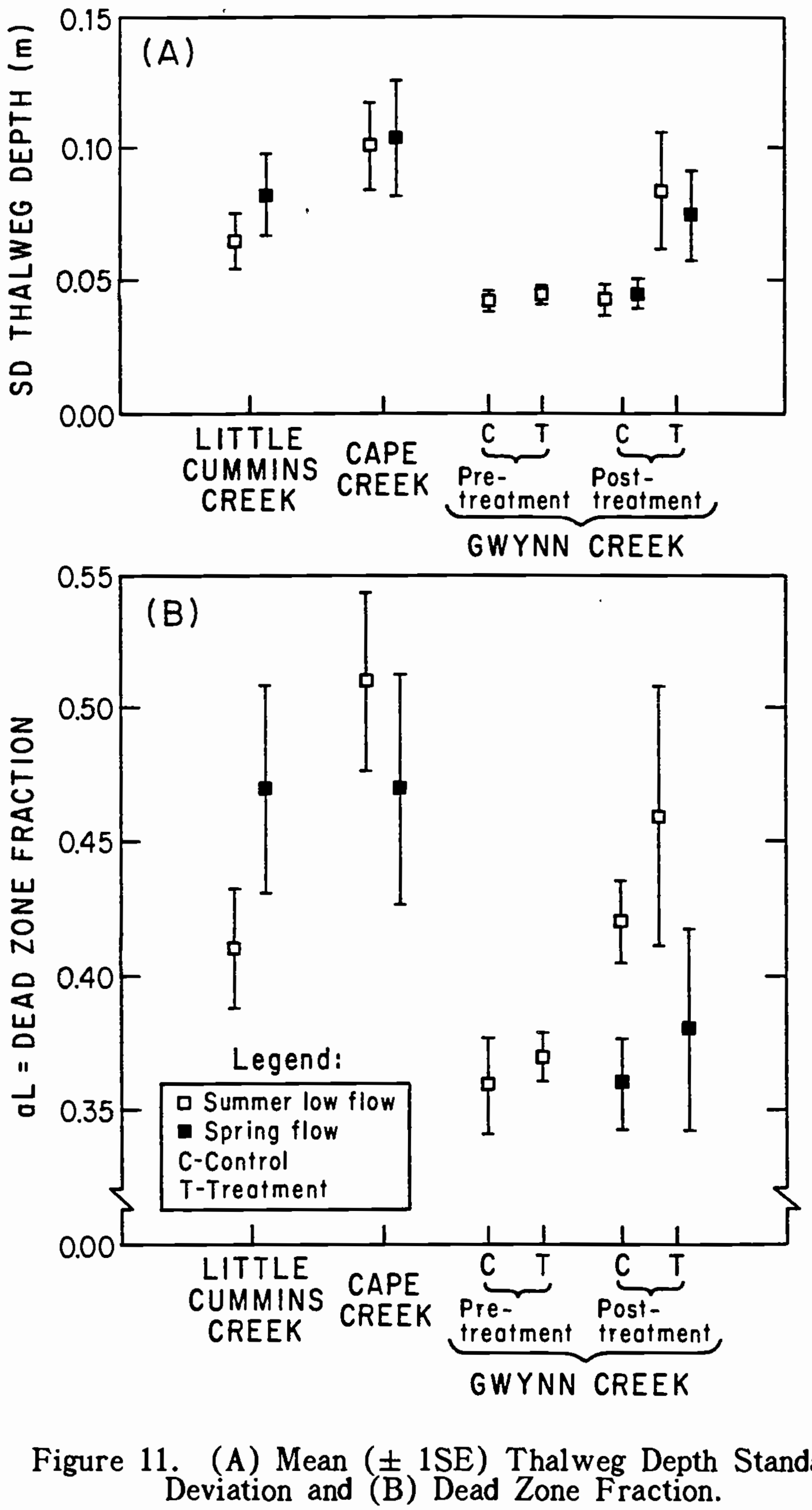


Figure 11. (A) Mean (± 1SE) Thalweg Depth Standard Deviation and (B) Dead Zone Fraction.

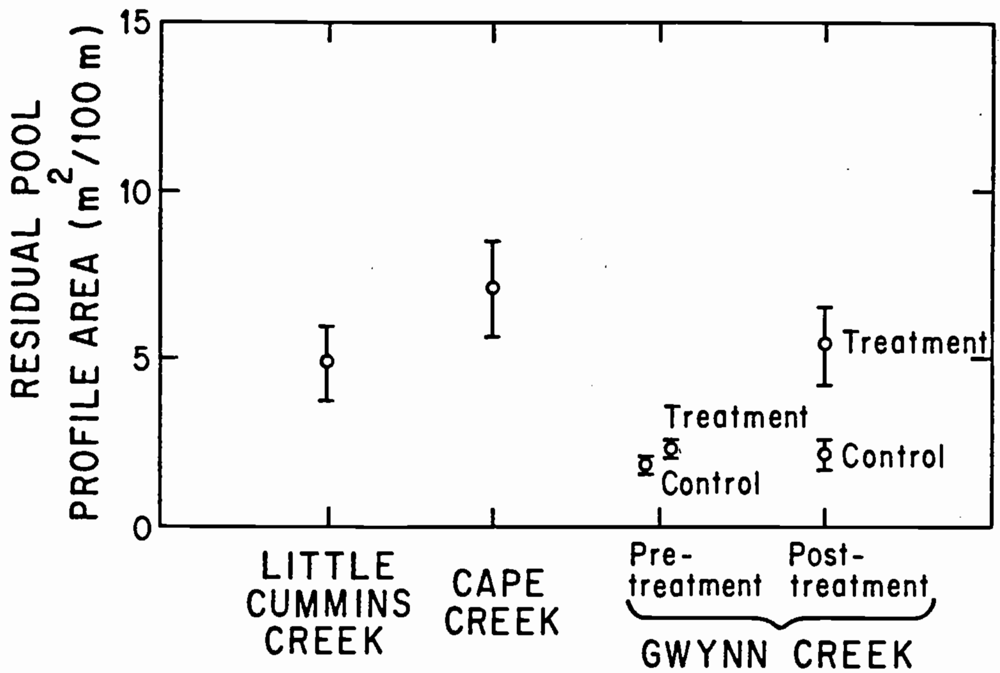


Figure 12. Mean (± 1SE) Residual Pool Profile Area (RPA) Per Reach.

Scour pockets and scour pools were created in association with added large woody debris. These features became progressively larger after each flood episode. Scouring took place in three general situations: below plunges, below vertical flow constrictions, and near lateral flow deflections or constrictions. The largest scour pools were created downstream of the three log sills in reach g1 which created vertical plunges of 0.3 to 0.4 meter. Scour pools beneath these plunges produced downstream displacement and piling of cobbles and gravel into fan-shaped bars which were often exposed during low flows.

Short, deep scour holes were created under logs which had been placed above the stream bottom gravels but below the flood water surface, creating vertical flow constriction at various flows. Logs spanning the channel at right angles to flow created rolling turbulent eddies beneath the logs, much like those described by Beschta (1983) in experiments simulating the two dimensional behavior of such systems in narrow flumes with erodible bottoms. Also in agreement with the findings of Beschta in flumes, the depth of scour beneath logs was proportional to the diameter of the logs--given the same flow history. Depth appeared to be maximized where logs were positioned low enough to obstruct flood flows but high enough to avoid being overtopped by these flows, thereby constricting flow and directing high velocity flows toward the gravel and cobbles of the stream bottom. The effect of placing one end of these low spanning logs downstream, and especially upstream, was the creation of an eddy resembling a vortex, which appeared to spiral downstream along the length of the log. These qualitative statements are based on visual observation of fluorescent dye tracer behavior in these scour pockets. The edges of newly scoured pockets beneath logs nearly always had very rough, nearly vertical downstream edges, as if the separate cobble and gravel particles had been individually plucked out by intermittent, intense pulses of high water velocity. Lateral flow deflection and convergence produced longer, smoother-edged scour areas with rapid water velocity even at low flow. Arrangements like a downstream-pointed "V" were quite effective in producing deep lateral backwaters which were quiescent during low and moderate flows.

Figure 13 shows the change in thalweg depth variation (SDD) relative to the amount of large woody debris added in the 4 treatment and 3 control reaches of Gwynn Creek. Changes in SDD index changes in aggregate pool volume in the reaches. The figure shows results of measurements immediately after treatment, 8 months later, and one year after treatment. An increase in pool volume due to the treatment is certainly evident, as is an increase in pool volume resulting from progressive scouring during flows subsequent to treatment. The rate of increase in pool volume over time and the absolute increase in pool volume appear to be only weakly related to the amount of woody debris added. Correlations between added woody debris and the resulting change in pool volume index (SDD) were all positive, but linear regressions accounted for only 34, 33, and 44 percent of the variance in SDD changes at the three sampling times. This is perhaps an unexpected result, but one with a simple likely explanation. Reach g4, which showed an aberrantly small increase in SDD, had a pretreatment woody debris volume 3 to 6 times those measured in the other three reaches. The process of channel recovery involving the scouring of pools associated with large organic debris and other hydraulic roughness elements was already well underway prior to treatment in this reach, which had an aggregate pool volume (indexed by SDD) 1.3 to 1.5

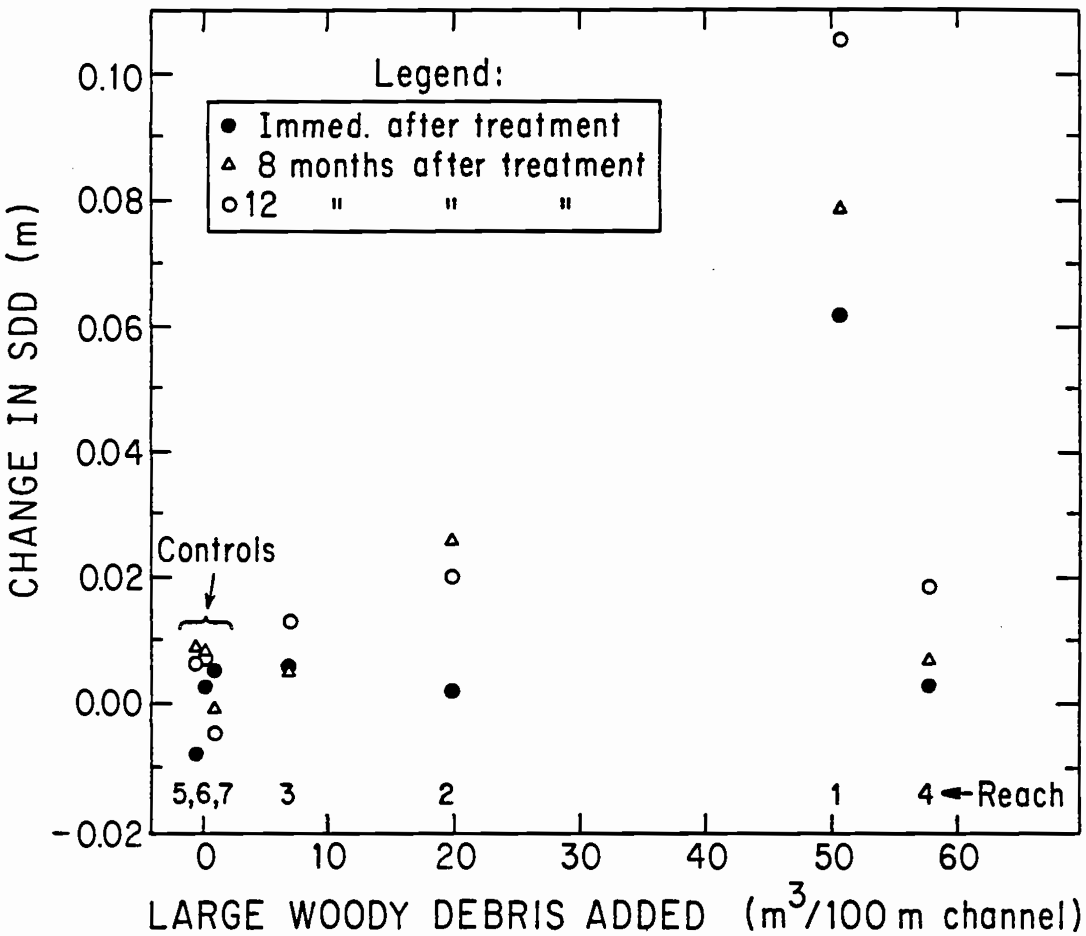


Figure 13. Cumulative Change in SDD (indexing pool volume) vs. Volume of Woody Debris Added--Gwynn Creek Treatment.

times those of the other three treatment reaches. Examination of *proportional*, rather than absolute, changes in woody debris and pool volume may better elucidate the role of woody debris when initial conditions differ.

Figure 14A shows the progression of *proportional* increases in pool volume (indexed by changes in SDD) in the 7 reaches of Gwynn Creek resulting from the *proportional* increases in large woody debris volume in each reach. Measurements made on three dates following treatment give an indication of the rate of change in pool volume over time. The proportional change and the time rate of change in pool volume were related to the ratio of post-treatment/pre-treatment woody debris volume. After one year of channel adjustments, this relationship approximates an exponential function fairly closely (R^2 = 0.83).

A similar regression analysis was conducted with residual pool cross sectional area (RPA), rather than SDD data. Post-treatment control reach RPA values were unavailable, so were calculated using the regression describing the close relationship between RPA and SDD. One year following the Gwynn Creek treatment, a linear regression (r^2 = 0.91) described the relationship between the post-/pre-treatment ratios of RPA and added woody debris (Figure 15).

The construction of large pools in reach g1 tended to exaggerate the pool volume response to the amount of debris added to this reach. However, it should be noted that informal observations two years after treatment revealed that channel adjustments had directed flow around and under the constructed log sills, greatly reducing pool volume associated with these particular treatment features. When the data points for this reach were adjusted to reflect only the work of the streamflow itself in scouring pools by the spring and summer sampling periods following treatment,

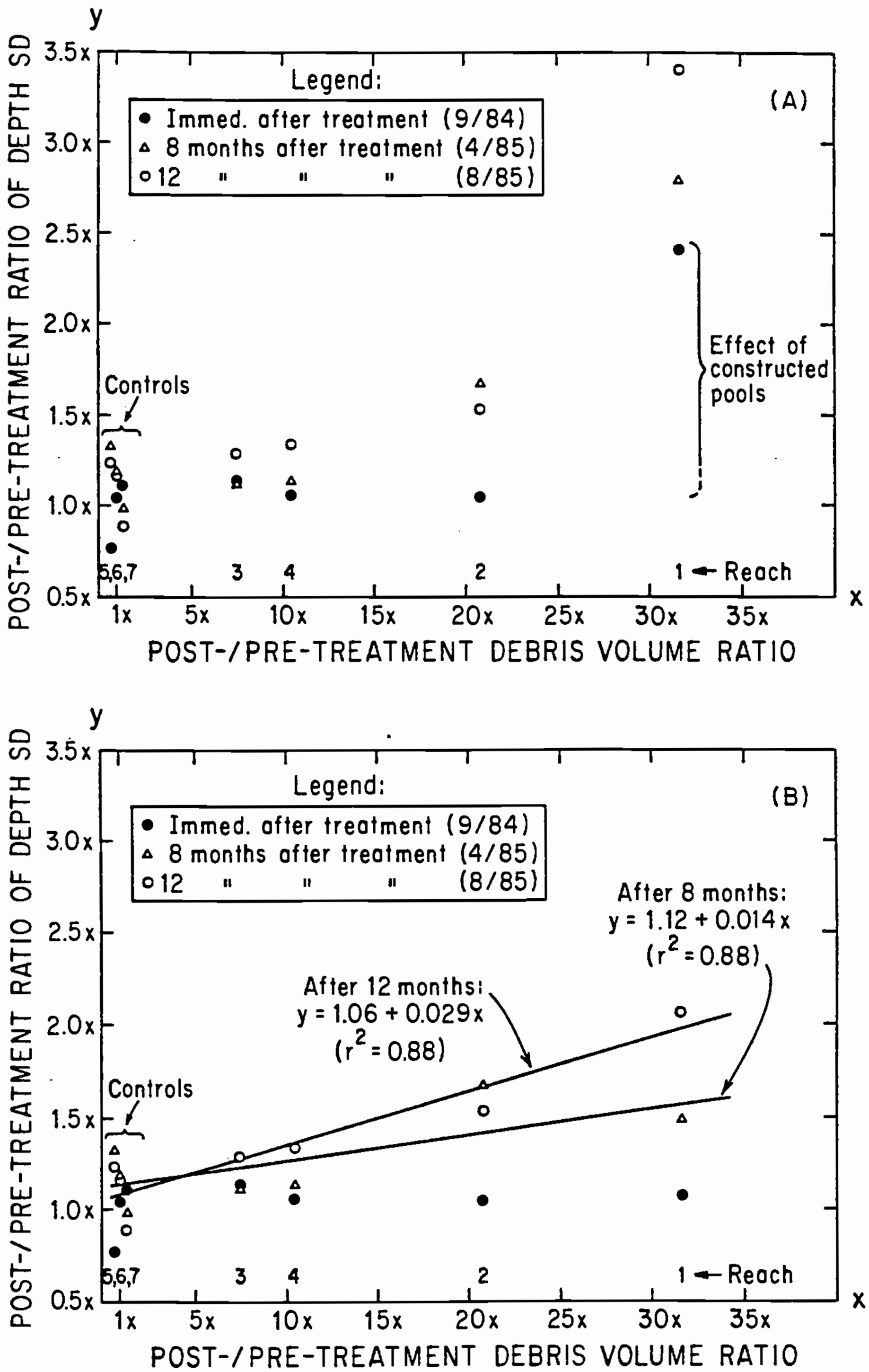


Figure 14. Relative Change in Pool Volume Index (SDD) vs. Relative Increase in Large Woody Debris Volume--Gwynn Creek Treatment: (A) Unadjusted Data; (B) Reach 1 Data Points Adjusted to Remove Volume of Initially Constructed Pools.

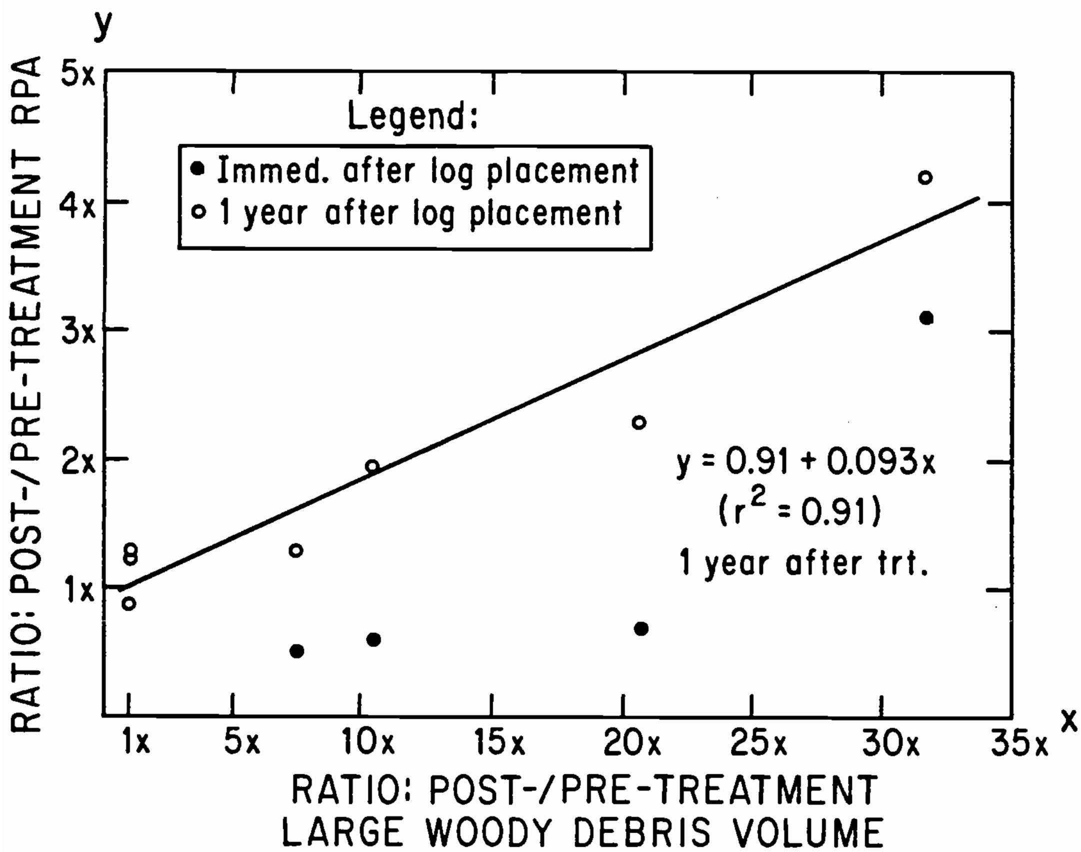


Figure 15. Relative Change in Residual Pool Profile Area (RPA) Per Reach vs. Relative Increase in Large Debris Volume--Gwynn Creek Treatment.

the relationship between relative additions of wood and relative change in pool volume appears to be more linear than logarithmic, as shown in Figure 14B. A linear relationship between these variables seems intuitively more logical than a logarithmic one. There is no reason to suppose that the effectiveness of organic debris in altering channel morphology should become proportionately greater at higher levels, as implied by the exponential expression. If anything, one might hypothesize the opposite. Further experimentation is necessary to more clearly define the relationship between woody debris volume change and pool volume change. Not only did this study lack the necessary replication to definitively describe this relationship, but it also lacked experimental debris additions to reaches with high pre-treatment loadings. Even beyond these considerations, the pool volume response to debris additions would be expected to be affected by channel slope, amount of inorganic sediment, flow history, and specific patterns of debris placement and size.

C. Relationships between Morphology and Hydraulics

1. Dispersion Modeling Parameters

The characteristics of concentration-time curves obtained for the study reaches under a variety of flow conditions are tabulated in Appendix E. The dead-zone volume fraction (a_L) and the dead-zone exchange coefficient (δ) were calculated for each reach and flow in accordance with the methods of Sabol and Nordin (1978) as described in the Chapters I and II. Dead zone fraction is interpreted as the dimensionless ratio of the mean dead zone flow cross sectional area of the channel divided by the total flow cross sectional area. The exchange coefficient is expressed as the fraction of reach water volume exchanged per second. Mean summer low flow dead zone proportion and exchange coefficient for 14 study reaches grouped by stream are shown in Table 4.

Figure 16 shows the general linear correspondence between calculated dead zone fraction and residual pool cross-sectional area (RPA) at summer low flow. Gwynn Creek's morphometrically uniform pretreatment reaches (g1, g2, g3, g4, g5, g6, g7) cluster in the lower left of Figure 16. The high extreme values for RPA (11.3 m^2/100 m) and a_L (0.59) were measured in a torrent deposit reach (C2) in Cape Creek affected by blowdown of large trees. The treated Gwynn Creek reach p1 (designated gs1 1yr after treatment), where pools and plunges were actually constructed, had RPA values of 6.5 and 8.9 m^2/100 m immediately after treatment and 1 year later, respectively. Corresponding dead zone fractions were 0.56 and 0.58. Within a year after treatment, Gwynn Creek reaches in which debris was added showed increases in dead zone fraction which roughly corresponded with measured increases in RPA.

The standard deviation of thalweg depth measurements (SDD) showed a correspondence with dead zone fraction similar to that of RPA (Figure 17). This correspondence was not surprising given the high correlation between SDD and RPA ($r = +0.98$). Again, Gwynn Creek pretreatment reaches cluster in the lower left, Cape Creek reaches showed a lot of variability but tended to have high values of both variables, and Little Cummins Creek reaches fell generally midway. Within each stream, the highest values of both variables were observed in reaches which had experienced the greatest degree of sediment and large organic debris deposition by torrents. Lowest values were observed where torrent passage resulted primarily in scour. Linear regressions best described a_L as a

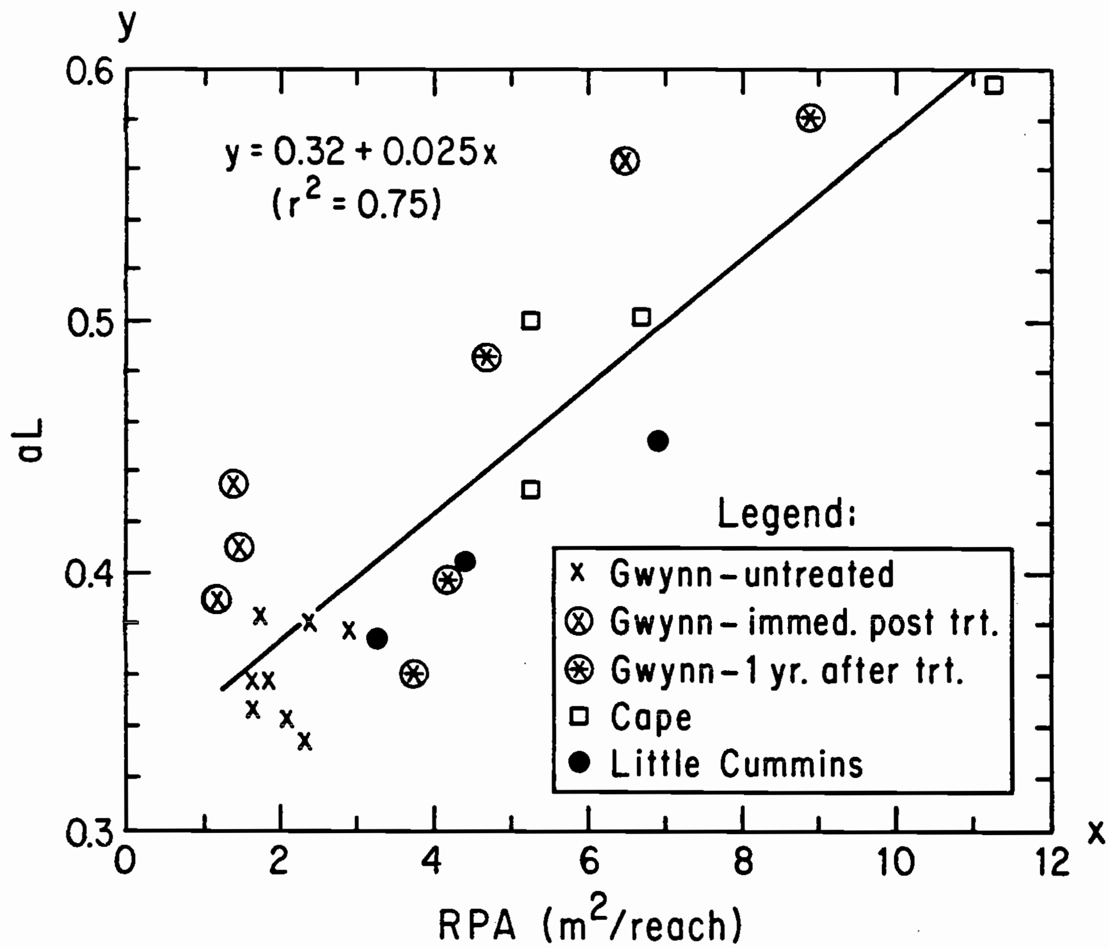


Figure 16. Dead Zone Fraction (a_L) vs. Aggregate Residual Pool Profile Area (RPA).

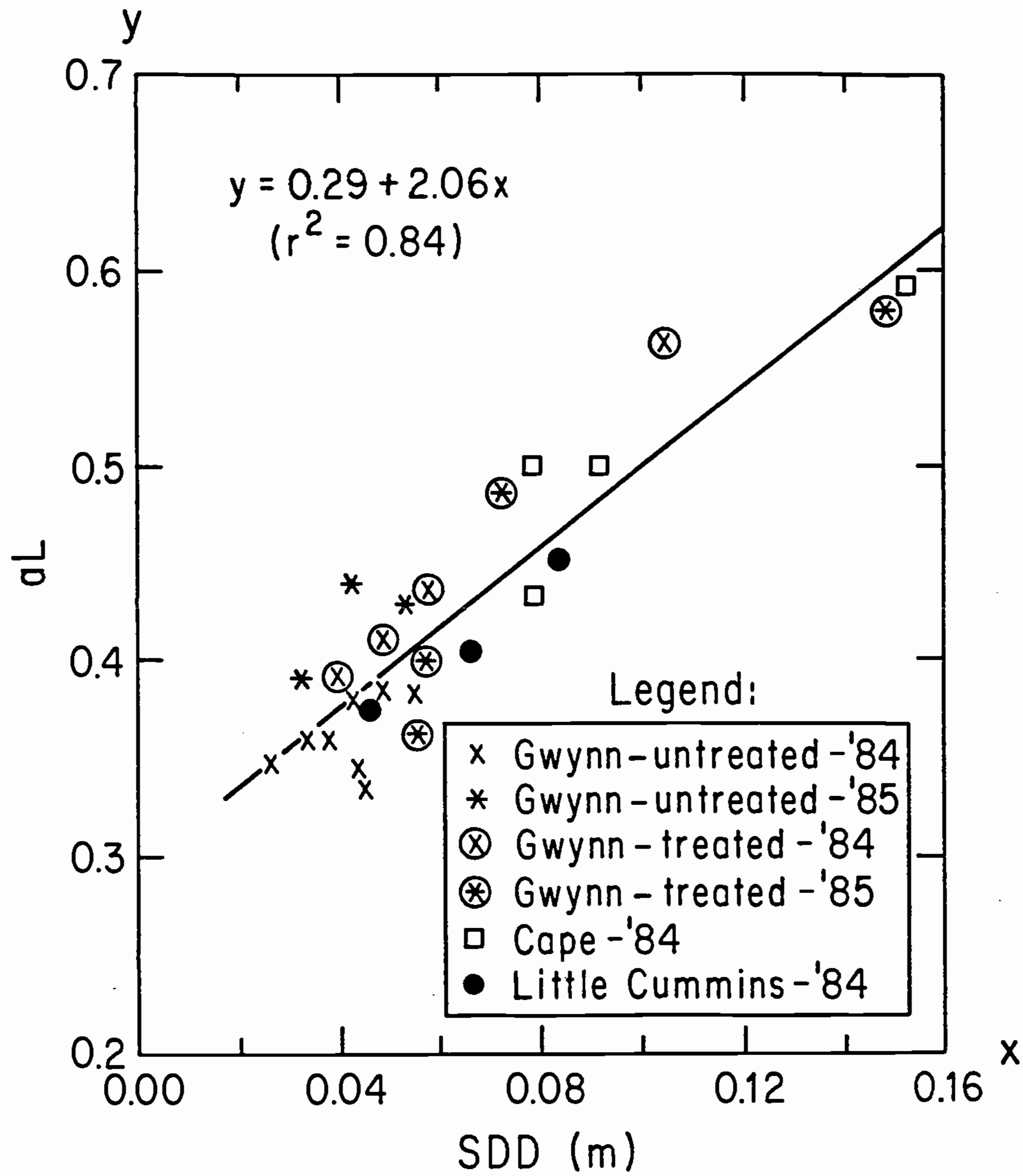


Figure 17. Dead Zone Fraction (a_L) vs. Standard Deviation of Thalweg Depth (SDD) at Summer Low Flow.

function of SDD, accounting for 84 percent of the variance in a_L when all low flow data were included and 91 percent when Gwynn Creek reaches affected by debris placement were excluded. The general effect of debris addition to Gwynn Creek reaches was an increase in pool volume, to some extent immediately, but increasing over time. The changes in pool volume were reflected in the observed increases in SDD and dead zone fraction.

Unlike dead zone fraction, which should be at least somewhat sensitive to discharge, RPA and SDD are relatively static characteristics of a stream channel. RPA is, in the absence of changes in the streambed itself, completely independent of discharge, being calculated entirely from detailed longitudinal profiles of stream bottom elevation. SDD is nearly independent of discharge, as it is primarily a measure of large scale bottom irregularity, measuring the same thing as RPA when measured over a long reach at low flow. However, SDD may in theory reflect the smoothing of the water surface profile which occurs as pool-riffle structure is "drowned out" upon increasing discharge, making this measure also somewhat dependent on discharge.

The robustness of the relationship between a_L and SDD with changing flows is dependent upon the dynamics of interchange between dead zones and the mainstream as discharge varies. This dynamic aspect of dead zone volume involves changes in both the spatial pattern and the intensity of turbulent exchange between the mainstream and dead zones. Forty data pairs, including a_L and SDD measured during summer and spring flows in natural reaches as well as in the treated reaches of Gwynn Creek, were plotted and analyzed (Figure 18). Stream discharges at the times of these measurements ranged from 0.019 to 0.11 cubic meters per second. The linear regression predicting dead zone fraction from SDD

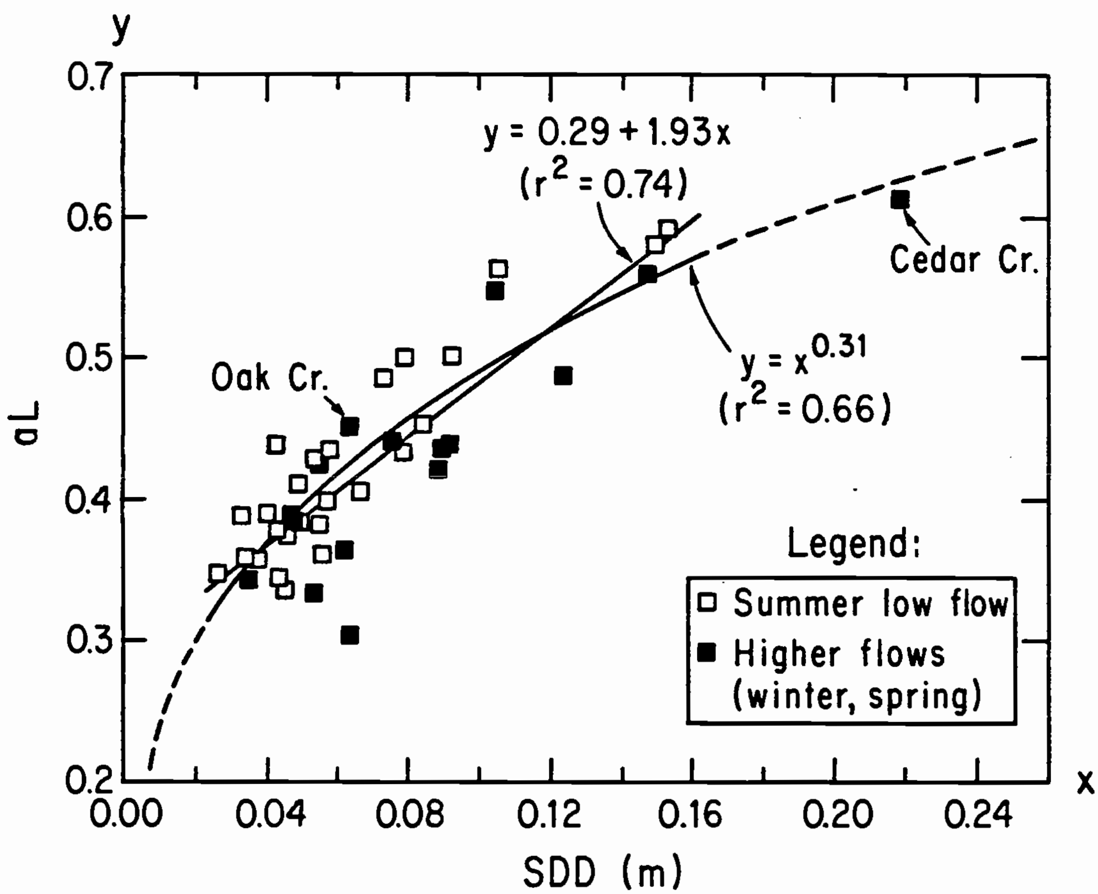


Figure 18. Dead Zone Fraction (a_L) vs. Standard Deviation of Thalweg Depth (SDD) at Low and High Flows (Cedar and Oak Creek data were not included in regression calculations).

within this mixed range of flows declined in precision ($R^2 = 0.74$), compared to that describing the relationship at low flows only ($R^2 = 0.84$).

Values of a_L measured during a small number of near-bankfull flows either increased or decreased with discharge depending upon the reach. In simple channels, a_L would be expected to decrease progressively as discharge increases, because transient storage decreases with increases in velocity and turbulence. The lack of any systematic relationship between transient storage and discharge at very high flows may perhaps be accounted for by major changes in channel shape as backwaters develop at near bankfull flows.

As a rough test of the applicability of the a_L versus SDD relationship (Figure 18) at high flows, both variables were measured in a third order reach of Cedar Creek, a stream in the northern part of the Oregon Coast Range, during an unusual period of snowmelt flooding. This reach was steeper in gradient (6%) than those in the three intensive study streams and its 4.0 km^2 drainage area was slightly larger than drainage areas of those reaches (2.1 to 3.3 km^2). The Cedar Creek reach was heavily loaded with large woody debris, with 105 m3 of debris per 100 m of channel length (Heimann, 1986). The values of a_L and SDD measured in this reach (0.61 and 0.219 m) did not deviate excessively from a linear regression of data shown in Figure 18 (predicted a_L was 0.71), considering that the discharge in this case was 33 times the lowest flow and 6 times the highest flow of the data set used to calculate that regression. Extrapolation of the power curve shown in Figure 18, however, predicted a value of 0.62 for dead zone fraction in Cedar Creek, almost exactly the measured value of 0.61. The Cedar Creek data point was not employed in calculating either of the regression relationships shown in Figure 18.

There are conceptual reasons, discussed later in this section, which favor the use of a curvilinear relationship between a_L and SDD.

Further study involving higher and lower discharges than those encountered in this study would be necessary in order to more clearly define the relationship between a_L and SDD in a given size of channel. Scaling problems would surely arise in applying the relationship to channels of widely ranging size. Use of the non-dimensional morphometric variable CfVarD may avoid scaling problems.

As a check on the applicability of the a_L versus SDD regression in streams of higher gradient than streams used in my study (which averaged 3.4%), these two variables were measured in a second order reach of 8.3 percent gradient in Oak Creek, near Corvallis, Oregon. Measured values were a_L = 0.45 and SDD = 0.063 m. The value of a_L predicted by the linear regression in Figure 18 was 0.41, and that predicted by the power curve regression was 0.42. This isolated set of measurements suggests that the described relationship between dead zone volume fraction and the standard deviation of thalweg depth measurements may hold in reaches with slopes considerably steeper than those of the study reaches used in calculating the regressions. Though certainly not conclusive, the agreement of these Oak Creek data and those from Cedar Creek should encourage the further investigation of this relationship at different slopes and discharges.

Dead zone volumes, and in fact "real" pool and backwater volumes, would be expected to change with stream discharge, as would their contribution to nutrient retentiveness and their effectiveness to fish as refuges from high water velocities in the mainstream. Progressive increases in discharge would be expected to eventually "drown out" pools, making dead zone volume decrease with increases in discharge, unless additional slack-water areas were created at high flows through the inundation of complex channel banks and flood plain areas. Since dead zone fraction (a_L) is intended to be a ratio of dead zone volume to the combined volume of mainstream plus dead zone, the effect of discharge variations on a_L is not intuitively obvious, except in situations of extremely low flow. At such low flows, irregular stream channels become a series of still water reservoirs with small spillways connecting quiescent pools. Dead zone volume fraction should approach 1.0 as the velocity of the moving main-stream portion of the stream cross section approaches zero. LeGrand-Marqu and Laudelout (1985) studied dispersion at discharges ranging from 0.0003 to 0.0125 m^3/s in a small forested stream said to be typical of those found in Belgium and France. They found that the "immobile fraction" (dead zone fraction) decreased very rapidly from a value in excess of 0.8 at a discharge of 0.00033 m^3/sec to a relatively constant value of about 0.25 for flows in excess of 0.0015 m^3/sec. There appeared to be no systematic change nor any great variation in dead zone fraction over a range of discharge from 0.0015 to at least 0.0125 m^3/sec in the same channel.

For the reasons illustrated above, one might not expect good agreement between dead zone fraction and a flow-independent index of pool volume (e.g., RPA) over a wide range of discharge in a given channel, particularly if the flow range included very low discharges. One might expect the same problems relating dead zone fraction to a two-dimensional, flow-conservative measure like SDD. In addition, it is unlikely that the dimensionless parameter a_L would retain a consistent relationship with dimensional channel morphometric parameters if the relationships were examined in channels of widely varying size. For these reasons, I examined the relationship between a_L and the dimensionless variables Do/D (the ratio of mean residual depth to mean thalweg total depth at a given flow) and CfVarD, the coefficient of variation of multiple measurements of water depth at the channel thalweg (see Chapter III). The mean residual pool depth ratio is a measure closely resembling the conceptual meaning of dead zone fraction, if the width dimension is ignored and one considers areas comprising this residual depth to retain relatively low time-averaged velocities when inundated during higher discharges. Because of the high correlation ($r > +0.95$) between Do and SDD in reaches of my study, the ratios formed by dividing these variables by the reach-averaged depth were correlated to the same degree.

I believe CfVarD to be a useful index of residual pool depth ratio or channel feature scale "roughness" in the vertical and longitudinal dimensions. Since the distribution of individual measurements of thalweg depth were positively skewed in the fairly complex channels of my study, much of the variance in depth was due to large positive deviations (pools, scour pockets, etc.). Therefore, CfVarD also appears to serve as a channel feature scale equivalent of the relative roughness coefficient (k = particle diameter/flow depth) used in standard hydraulic theory. In this case, CfVarD is a dimensionless representation of the quantitative relationship between channel bottom irregularity and flow depth. Only when CfVarD is calculated over sufficiently long reaches, however, does it reflect reach-scale bottom irregularities such as riffles and pools. Over shorter distances or in channels with no large scale bottom irregularities, CfVarD should be linearly related to the relative roughness coefficient k, measuring particle-scale roughness.

There are conceptual reasons why the transient storage or dead zone *fraction* should be linearly related to *dimensionless* residual pool volume Do/D or dimensionless channel bottom irregularity (SDD/D or CfVarD). If dead zone volume is linearly related to pool volume, considering both in the absolute sense (Figure 19 part A), then the *dimensionless* representations of these qualities should be *linearly* related (Figure 19, part C). When dimensionless a_L, which has 1.0 as its upper limit, is plotted against a *dimensional* index of pool volume (such as SDD in Figure 18), the relationship should probably be described by a *curve* in which a_L approaches 1.0 as a limit (as shown in Figure 19, part B). The ranges of dead zone fraction and pool volume variables in Figure 18, for example, are not great enough to support a curvilinear relationship on statistical grounds alone. However, the conceptual arguments above support the use of a curvilinear relationship asymptotically approaching 1.0. The power curves shown in Figures 17 and 18 are fairly close approximations of such curves within the range illustrated. In contrast, one would expect *linear* relationships between a_L and *dimensionless* variables such as CfVarD and Do/D.

Figure 20 shows dead zone fraction (a_L) as a function of CfVarD during summer low flows. Dead zone fraction (a_L) was positively correlated with CfVarD in natural, untreated reaches ($r = +0.92$) and also in a data set which included both natural reaches and those to which woody debris had been added ($r = +0.92$). The coefficient of determination for a linear regression between the two variables (all points in Figure 20) was 0.84, equalling the precision of a linear regression expressing a_L as a function of SDD (Figure 17).

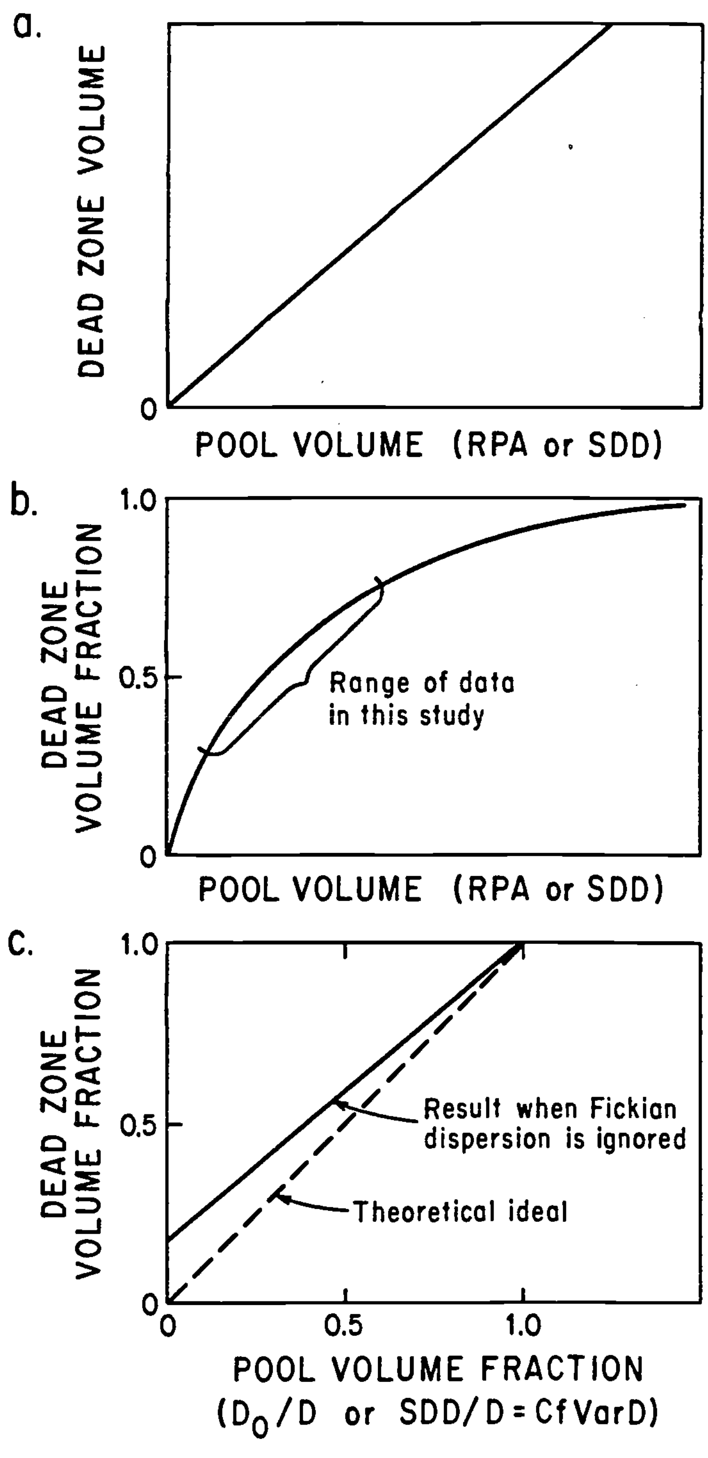


Figure 19. Hypothetical Relationships Between Dead Zone and Pool Index Variables.

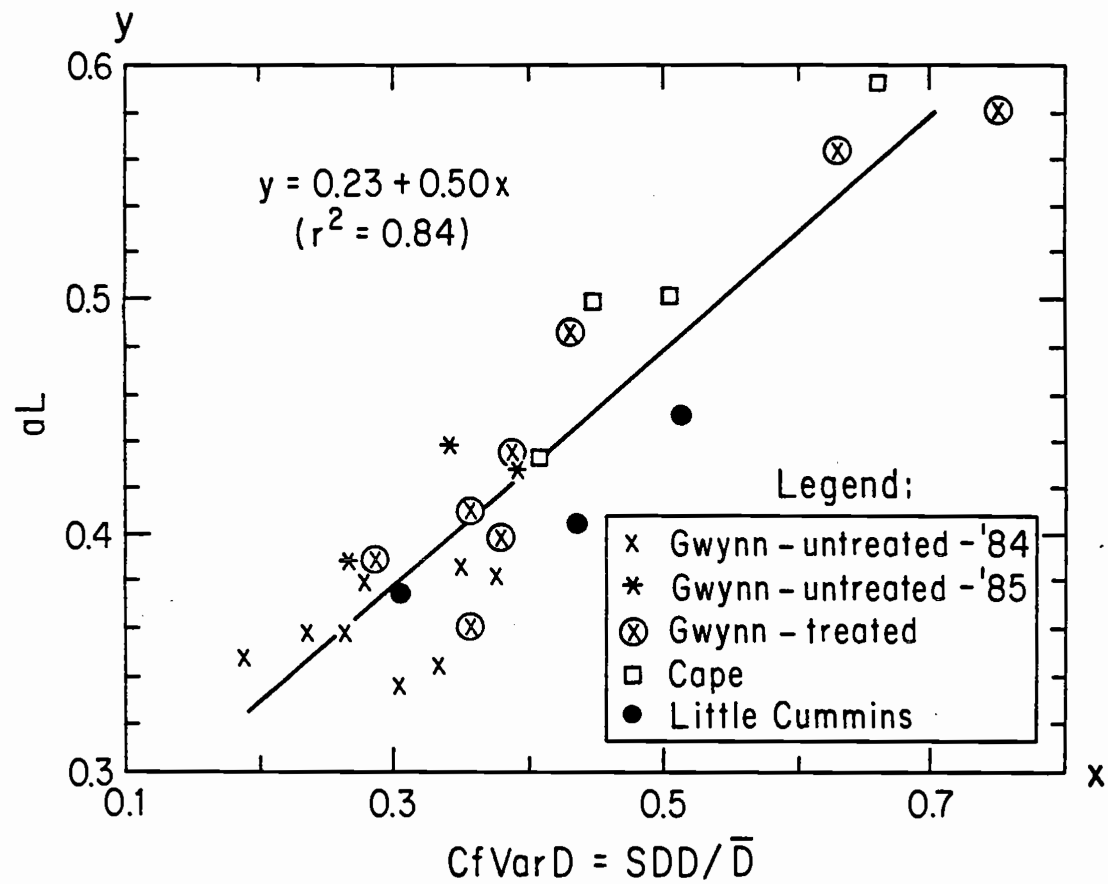


Figure 20. Dead Zone Fraction (a_L) vs. Coefficient of Variation in Thalweg Depth (CfVarD)--Summer Low Flow.

Figure 21 shows that the variables a_L and CfVarD both showed roughly parallel increases in response to woody debris additions in Gwynn Creek. Such evidence supports an inference that pool volumes indexed by CfVarD were important contributors to the transient storage characteristics measured by dye tracers.

The inclusion of high flow in addition to low flow data points produced the same regression with a_L as that obtained for low flow data alone. Increased scatter of the data, however, reduced its precision (Figure 22). In fact, the coefficient of determination ($R^2 = 0.72$) for this relationship between dimensionless variables was, surprisingly, slightly lower than that for the regression between a_L and the dimensional variable SDD. Apparently a_L was not as sensitive to flow changes (at least in the range measured) as had been expected. In reference to the work of LeGrand-Marqu and Laudelout (1985) previously discussed, it appears that the range of flows encompassed by this study did not include flows low enough for a_L to be highly dependent upon discharge. The use of the non-dimensional variable CfVarD, though not as closely related to a_L in these streams, seems conceptually more logical than the use of the dimensional variable SDD for describing large scale "roughness" under conditions where relative submergence of bottom features might vary widely at different flows. Also, it would seem to overcome scaling problems if one were examining the relationship between a_L and channel morphology in a data set which included streams much smaller and much larger than those of my study. For reasons illustrated in Figure 19, the variable CfVarD is more likely to retain a linear relationship with a_L over wide ranges in both variables.

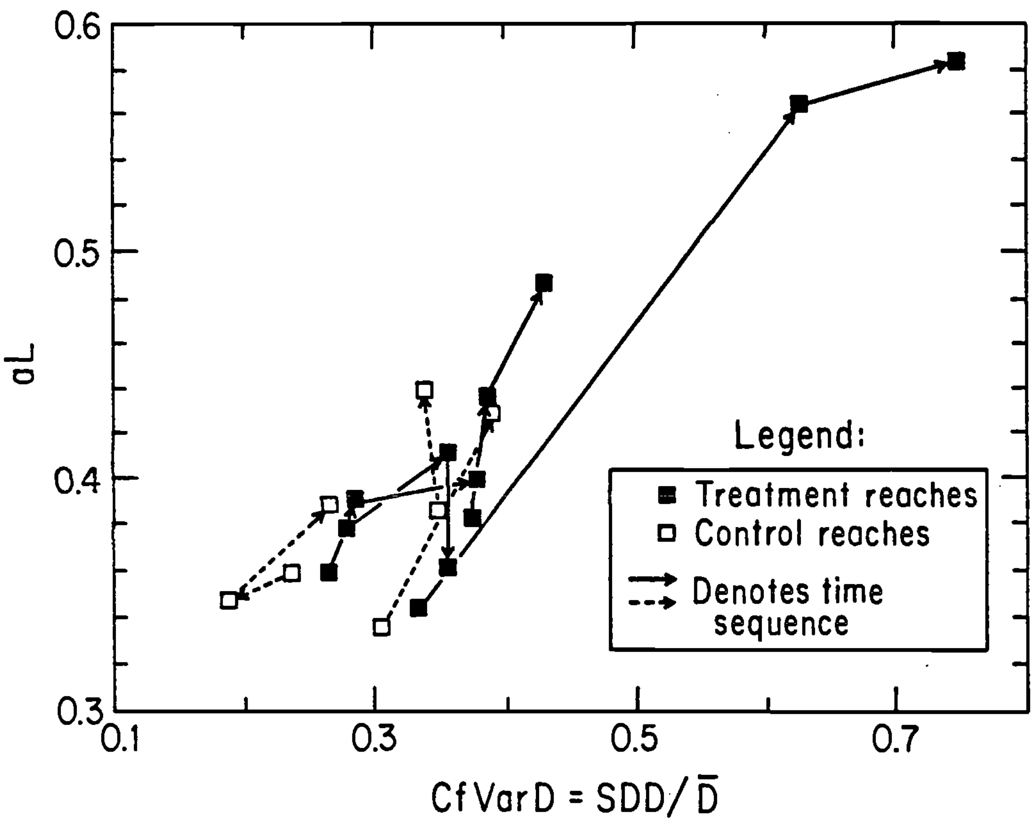


Figure 21. Effect of Gwynn Creek Treatment on Dead Zone Fraction (a_L) and Coefficient of Variation of Thalweg Depth (CfVarD) at Summer Low Flow.

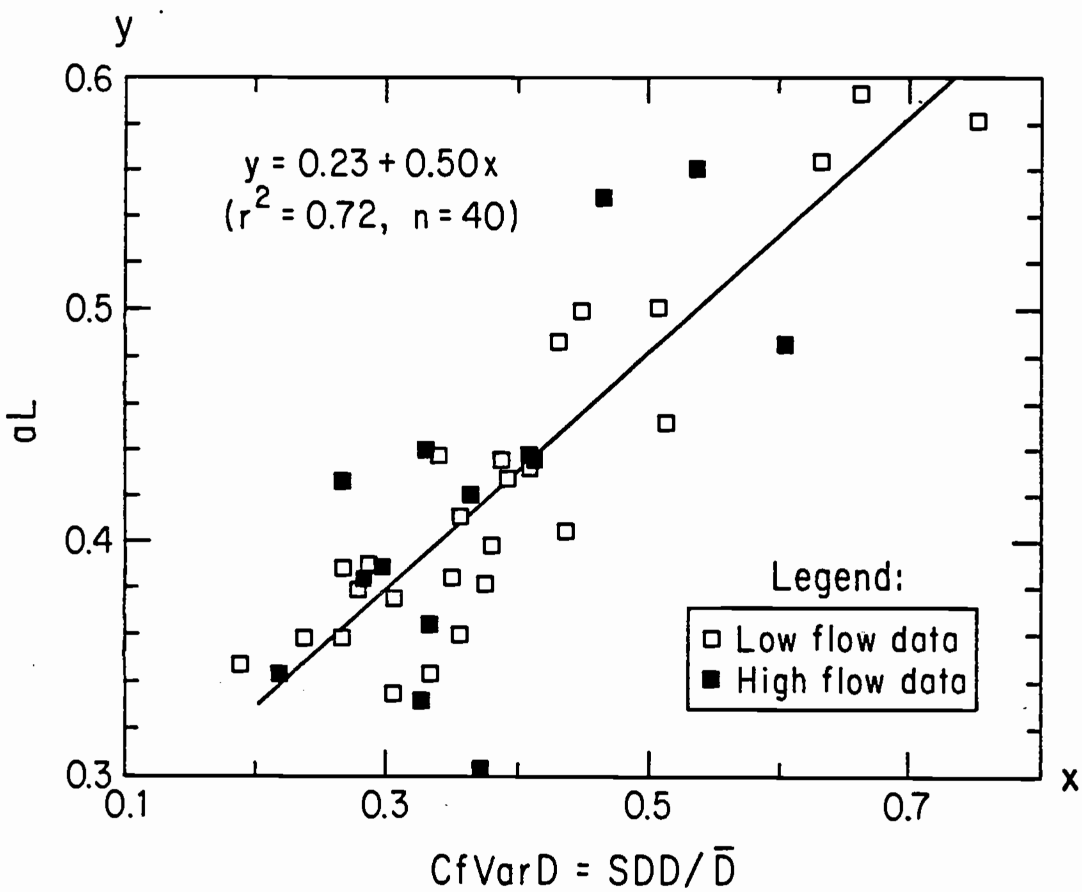


Figure 22. Dead Zone Fraction (a_L) vs. Coefficient of Variation in Thalweg Depth (CfVarD)-- High and Low Flow Data.

Employing similar logic to that discussed for CfVarD, the relationship between a_L and the dimensionless variable CfVarWD, the coefficient of variation in multiple measurements of width-depth product was also examined (Figure 23). CfVarWD is a measure of variation in the flow cross sectional area of a channel, taking into account variations in vertical as well as horizontal dimensions along the length of a reach. As such, it is intended as an easily-measured dimensionless parameter which should describe three-dimensional channel features causing energy loss due to flow convergence and divergence.

The distributions of individual Width × Depth measurements used to calculate CfVarWD in study reaches were positively skewed, with much of the variance contributed by large positive deviations from the mean value of W×D. CfVarWD should, therefore, reflect those channel features such as pools and lateral backwaters which presumably influence the amount of dead zone volume in a reach. If one considers W×D to be a surrogate measure of channel cross-sectional area, CfVarWD, which is calculated as SD{WxD}/mean{W×D}, is similar to the conceptual definition of dead zone volume fraction, which for a prismatic channel is the cross-sectional area of slackwater (indexed by deviations from mean W×D) divided by the total flow cross-sectional area (indexed by mean W×D). The coefficient of variation in width-depth product (CfVarWD) should provide a measure of variance in the vertical plane (riffles and pools) combined with variance in the horizontal plane (peripheral backwaters and side channels).

When interpreting variables calculated from simple variance, it should be remembered that the linear order of width-depth pairs, for example, is not a factor accounted for in the calculation of variance. Consequently, width and depth oscillations over the length scale of interest

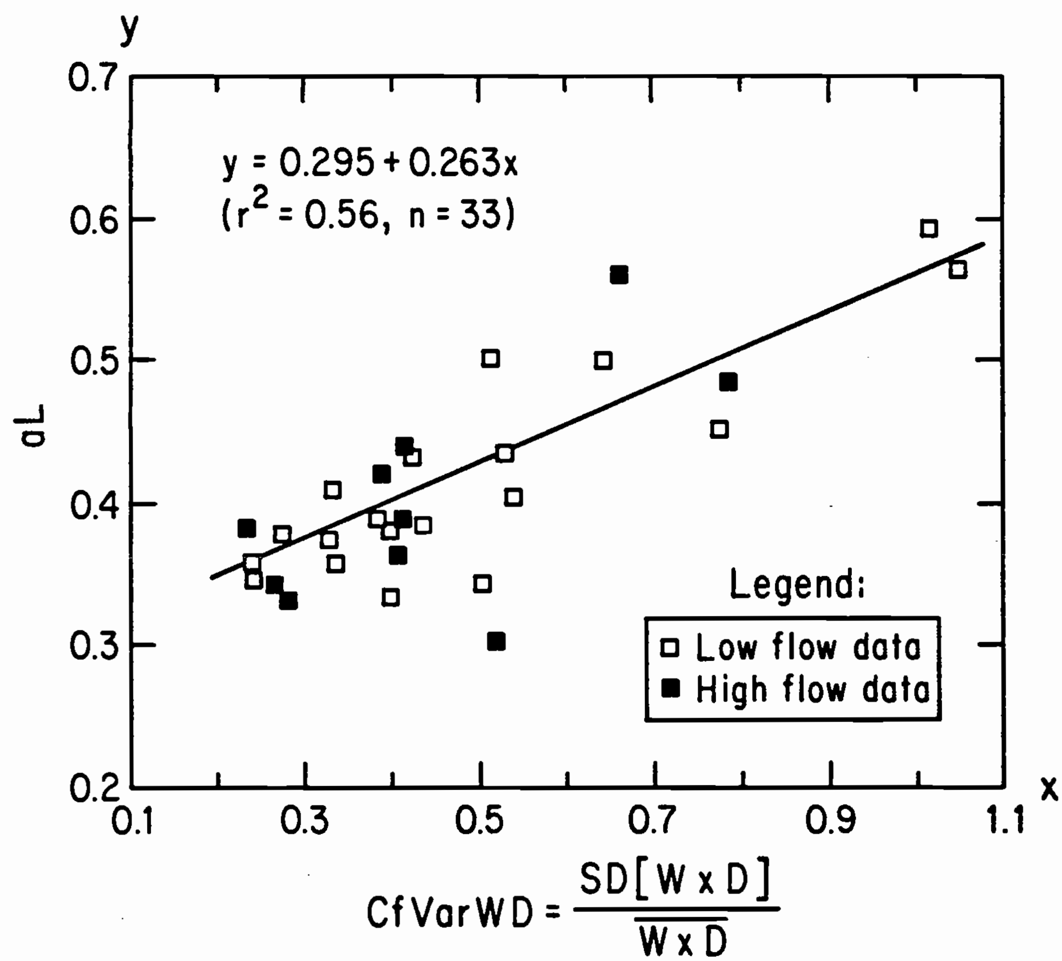


Figure 23. Dead Zone Fraction (a_L) vs. Coefficient of Variation in Width-Depth Product (CfVarWD).

as well as those trends on a larger scale which have no great effect in dissipating energy will both affect the value of measures such as CfVarD, CfVarWD, and CfVarW. It is possible for width and depth variation to consist of channel irregularities on a pool-riffle scale as well as those consisting of oscillations too gradual to cause turbulent eddies and zones of flow separation (see width-depth profiles in Appendix F). In order for a measure based on simple variance to reflect comparative differences in the amount of pools or backwaters among reaches, one must depend upon the existence of a relatively consistent pattern in the downstream spatial organization of width-depth information from reach to reach.

At summer low flow in 14 natural, untreated reaches, dead zone fraction (a_L) was correlated with CfVarWD ($r = +0.82$), but not to the degree seen with CfVarD ($r = +0.92$, as previously discussed). The linear regression $y = 0.272 + 0.291x$ with $R^2 = 0.68$ ($n = 14$) best described a_L as a function of CfVarWD for this low flow data. The inclusion of data points for Gwynn Creek immediately following debris addition yields a very similar regression ($y = 0.282 + 0.275x$), but improved its precision ($R^2 = 0.75$, $n = 21$). With all available data, including treated and untreated reaches over a range of low and high flows (Figure 23), the regression equation was again similar ($y = 0.295 + 0.263x$), but precision declined considerably ($R^2 = 0.56$, $n = 33$).

The comparison of these regressions, expressing a_L as a function of CfVarWD, with the previously discussed regressions between a_L and CfVarD, suggests that the hydraulic measure of dead zone fraction using tracers is more sensitive to slackwater features in the vertical plane (pools) than to those in the horizontal plane (channel edge backwaters) or other changes in flow cross-section which cause energy loss through horizontally directed turbulent eddies. Fishery ecologists at Oregon State University (Moore, Speaker, & Gregory, pers. comm.) have used fluorescein dye for measuring stream discharge, mainstream time of travel, and off-channel backwater flushing rates. These researchers believe, on the basis of their observations, that slug releases of dye to the mainstream do not evenly reflect backwaters over a reach. Experimental enhancement of peripheral backwaters of a small stream during a Cutthroat Trout rearing habitat experiment by Moore and Gregory (1985), however, resulted in a noticeable increase in the tailing of curves of dye concentration versus time (Moore, pers. comm.). Destruction of such backwaters in another reach during the same study resulted in a reduction in tailing of dye curves. I have visually observed dye dispersion into even the most quiescent of peripheral backwaters and side channels during tracer slug release experiments. However, I found only a very weak relationship ($r = +0.33$ at low flow, $r = -0.19$ at spring flow) between dead zone fraction (a_L) and the coefficient of variation in stream width alone, which might be expected to reflect the abundance of peripheral slackwater. It is quite possible, however, that the coefficient of variation in width may be primarily affected by large scale oscillations in width which take place over channel lengths considerably greater than those important in causing transient storage of water in peripheral stagnant water zones.

Values of the transient storage exchange rate parameter δ ranged from approximately 0.01 sec^{-1} during low flow in complex channels with large pool volume to 0.1 sec^{-1} during higher spring flows in fairly simple channels. Interpretation of the parameter definition suggests that 1% of the total stream volume in complex channels moves into or out of the dead zone volume fraction every second. The figure for simpler channels is about 5% at low flow and 10% at high flow.

The parameter δ showed weak negative correlation (r = -0.35 to -0.63) with various measures of channel complexity (CfVarD, SDD, woody debris volume and number) and with the dispersion modeling parameter a_L. Within a narrow range of discharge, δ showed strong negative correlation with dead zone fraction (a_L) and measures of flow resistance. It was positively correlated (r = +0.89) with mean convective velocity over a wide range of discharges and with dimensionless velocity ($U/U^* = U/(gRS)^{0.5} = (8/f)^{0.5}$), an inverse measure of hydraulic resistance (r = +0.92). Since mean convective velocity (Uc) and the time variance of tracer transit time (reflecting the degree of spreading of the tracer cloud) are both components used in the calculation of the exchange coefficient (δ) in the Sabol and Nordin (1978) model, the correspondence is not surprising.

The exchange coefficient would seem (quite logically) to be related to the Fickian coefficient of turbulent eddy dispersion. Dispersion coefficients are reported to be positively correlated with discharge, mean velocity, and roughness (Fischer, 1967; Calkins & Dunne, 1970). Because reaches in my study were closely matched in slope, width, and drainage area (therefore discharge), differences in hydraulic resistance in these reaches became primarily a function of reach transit velocity, which tends to affect dispersion and friction similarly in channels of the same size and slope. It is not intuitively obvious whether δ would be primarily a function of hydraulic resistance or transit velocity if the data set included a wider range of discharges, slopes and channel dimensions.

Figure 24 shows a plot of $(8/f)^{0.5}$ versus δ for various reaches over a range of discharges. Values of δ were quite sensitive to discharge

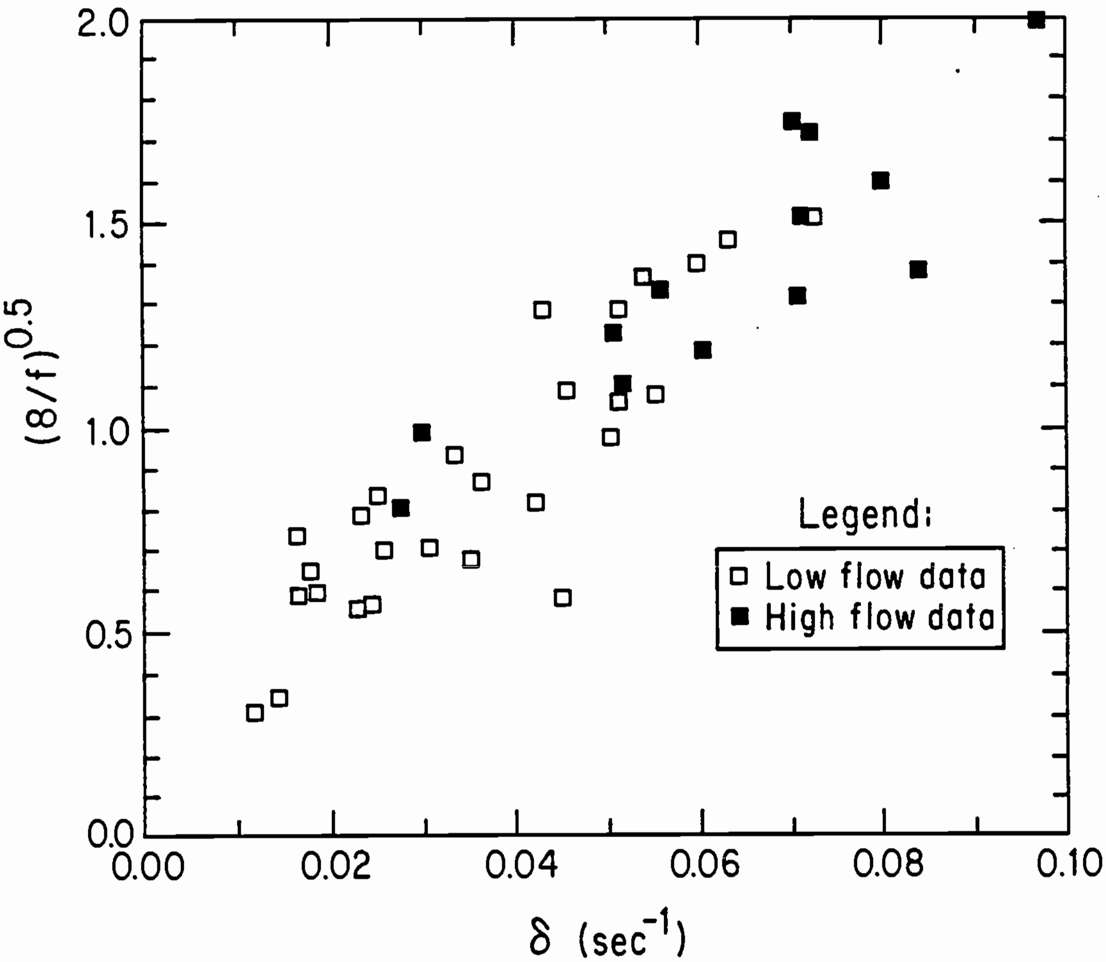


Figure 24. $(8/f)^{0.5}$ vs. Dead Zone Exchange Coefficient (δ).

within a given reach. Among reaches, however, δ appeared to be relatively independent of discharge differences but strongly controlled by hydraulic resistance. The lowest value measured was 0.012 s^{-1} at a low flow discharge of 0.029 m^3/s in reach C2 of Cape Creek. This reach was the most "complex" in the study, with abundant woody debris and the highest measured pool volume. The highest measurement of δ was 0.097 s^{-1} at a springtime flow of 0.062 m^3/s in a reach of Gwynn Creek with low pool volume. This measurement coincided with the lowest friction factor value measured (2.0).

Table 12 relates dead zone model parameters to discharge in reach L1, a relatively complex reach of Little Cummins Creek, where data had been collected over a wide range of discharge.

Table 12. Channel and Hydraulic Parameters over a Range of Discharges in Reach L1 of Little Cummins Creek.

Flow Condition	Q (m^3/s)	a_L	δ (s^{-1})	Uc (m/s)	f	SDD (m)	CfVarD
summer low	0.019	0.45	0.016	0.093	23	0.085	0.51
springtime	0.090	0.55	0.030	0.21	8.2	0.10	0.46
winter base	0.12	0.52	0.042	0.24	--	--	--
storm	0.29	0.57	0.055	0.41	--	--	--
near bankfull	0.38	0.47	0.065	0.51	--	--	--

The exchange coefficient ranges from 0.016 to 0.065 s^{-1} over a discharge range from 0.019 to 0.38 m^3/s. For comparison, the three control reaches of Gwynn Creek showed δ values of 0.07 s^{-1} at discharges of only 0.055 m^3/s and reach transit velocities of only 0.24 m/s. The Little Cummins reach, therefore, showed roughly the same exchange coefficient at a flow velocity more than twice as high. Dead zone fraction in the complex Little Cummins Creek reach increased to a maximum at a level of discharge just below bankfull stage. The increase coincided with the inundation of peripheral backwaters and the expansion of impounded areas. Figures 25 and 26 contrast the pattern of channel change with discharge in simple and relatively complex stream channels. Unfortunately, I did not collect sufficient channel data during the storms in Little Cummins Creek to calculate hydraulic resistance at very high flows. The slowly rising value of δ and the increase in dead zone fraction observed as flows approached bankfull stage in the Little Cummins reach suggest that, like dead zone fraction, friction factor may have increased in that reach as complex off-channel backwaters and vegetation were inundated. These observations also suggest that the correspondence between δ and transit velocity is perhaps coincidental in the closely matched streams of my study, but that a continued correlation between δ and $(8/f)^{0.5}$ would probably be seen in a data set including larger and smaller streams.

While the pattern of variation in the exchange coefficient appears to make physical sense within the context of this study, I do not know whether the absolute values of this measured model parameter bear any true relationship with actual volumetric rates of transport into and out of quiescent compartments (dead zones) in the study reaches. The only study of which I am aware that used exactly the same exchange coefficient formulation is that of Sabol and Nordin (1978). These researchers measured exchange coefficients ranging from approximately 0.00003 to 0.03 s^{-1} in a wide variety of streams and rivers ranging in width from 12 to 740 meters, mean depth from 0.3 to 18 meters, mean velocity from 0.13 to 1.7 m/s, and discharge from 0.99 to 7,000 m^3/s (Sabol and Nordin 1981). Values of a_L measured by Sabol and Nordin (1978) in these same stream and river reaches ranged from 0.1 to 0.4, with a mean of 0.25. The

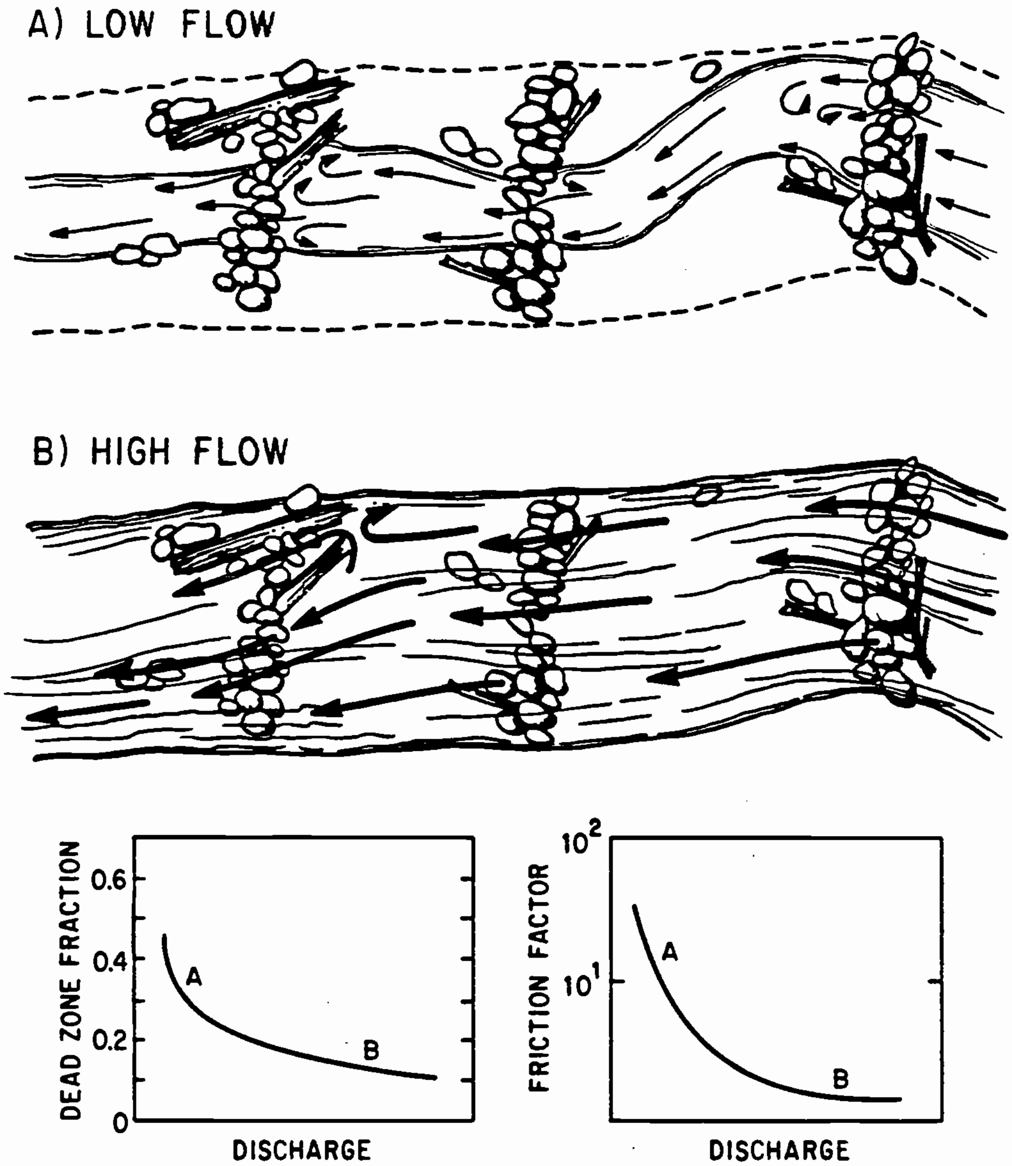


Figure 25. Hypothesized Changes in Dead Zone Fraction (a_L) and Flow Resistance (f) Over a Range of Discharge in a Simple Channel.

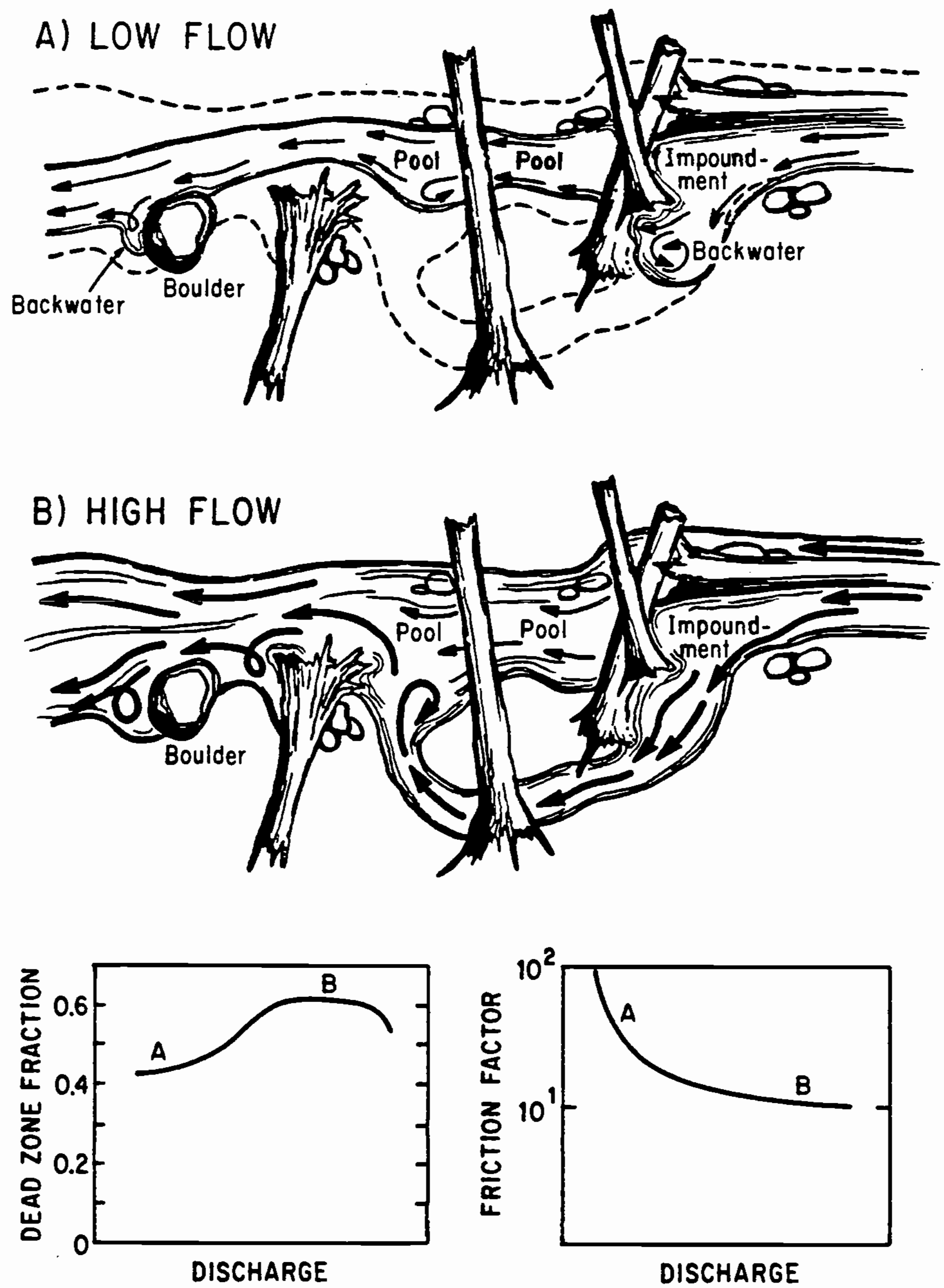


Figure 26. Hypothesized Changes in Dead Zone Fraction (a_L) and Flow Resistance (f) Over a Range of Discharge in a Complex Channel.

streams used in my study were considerably smaller than those studied by these researchers (see Tables 3 and 4). They also showed higher exchange coefficients (0.01 to 0.1 s^{-1}) and higher dead zone fractions (0.3 to 0.6). The comparative values of the dead zone parameter a_L appear to be in line with what might be expected by extrapolating the data of Sabol and Nordin (1978) in light of the general pattern of increasing flow complexity and hydraulic resistance normally observed with decreasing stream size.

The pattern of variation of δ in streams of my study and in rivers studied by Sabol and Nordin (1978) was an increase within a given reach as discharge increases. This pattern is seen as well with dead zone exchange coefficients calculated from other dispersion-storage models (e.g., Nordin & Troutman, 1980; Beltaos, 1983). The pattern of variation among different stream channels, however, is the opposite. Volume-based dead zone exchange coefficients in stream channels formed by high discharge (e.g., the Missouri River) show dead zone exchange coefficients orders of magnitude lower than those observed in smaller streams (compare data of Sabol & Nordin, 1978; Nordin & Troutman, 1980; Bencala & Walters, 1983; and this study).

Some effort has been made to relate the dispersion modeling parameters a_L and δ (or their equivalents according to different authors) to bulk hydraulic and morphometric characteristics of channels. Valentine and Wood (1976b) related tracer-derived estimates of dead zone volume fraction to estimates of dead zone volume based on detailed point gage measurements taken on short longitudinal and transverse profiles in a straight, 1-meter-wide (rectangular) water "race" (earthen and gravel canal) in New Zealand. The depth of vertical dead zones was taken to be twice the standard derivation of longitudinal profile readings from the mean, and the proportion of bed area in dead zones was taken to be the number of readings deviating by more than one standard deviation. Peripheral dead zones were estimated visually using simple dye studies. Their experiments showed that for two cases, a "rough" canal and a "cleared" canal, dead zone volume fractions estimated from tracer curves (0.38 and 0.116) were both approximately 1.4 times those estimated from channel measurements. This result strengthens the basis of my results showing a relationship between dead zone fraction (from tracer curves) and measures of channel bottom variability, although my study extended depth variability measurements over larger longitudinal distances. Bencala and Walters (1985) measured very high dead zone fractions in small, forested California streams and noted the high degree of depth variation in long profiles of thalweg depth. There has as yet been no systematic description of a relationship between measured channel morphology and tracer-derived dead zone volume fraction.

Bencala and Walters (1983) examined dead zone exchange coefficients from a wide range of flow situations in a number of dispersion studies and found a generally positive relationship between the dimensionless Nusselt number (employing the exchange coefficient in the numerator) and a dimensionless grouping of fluid, channel and dead zone storage parameters. The dead zone exchange coefficient has not, however, been successfully related to bulk channel properties. It is important to point out that the dead zone exchange coefficient (as well as the parameter a_L) in the Sabol and Nordin (1978) model, which lacks a separate Fickian dispersion term, must incorporate the transit time variance due to such a velocity field dispersion process. It would, therefore, be of greater magnitude and would bear closer relation to flow and channel properties known to affect Fickian dispersion (see Fisher, 1967) than might a dead zone exchange coefficient calculated from a model such as that of Hays (1967), which contains a separate term describing Fickian dispersion.

Several authors (Thackston & Schnelle, 1970; Pederson, 1977; Bencala & Walters, 1983; LeGrand-Marqu & Laudelout, 1985) have described a positive relationship between dead zone fraction and hydraulic resistance expressed as overall reach friction factor $\{8gRS/(Uc)^2\}$. I have plotted dead zone fraction versus Darcy-Weisbach friction factor using the data of Thackston and Schnelle (1970), Pederson (1977), Nordin and Troutman (1980), and Bencala and Walters (1983) along with my own data and a number of points calculated from data of other authors in Figure 27. This plot is an expansion of similar plots presented by Thackston and Schnelle (1970), Pederson (1977) and Bencala and Walters (1983). The data span a range of dead zone fraction from 0.003 in a canal to 0.64 in a small mountain stream with abundant pools and plunges and highly variable width and depth. The range of f spans almost 5 orders of magnitude. In the limit, it seems logical that as f tends to zero, a_L (or β, as calculated by a Hays-type model) should also tend to zero. At the high extreme, however, total reach friction factor should tend towards positive infinity as dead zone fraction approaches a maximum limit of 1.0. This hypothesis fits the observations of LeGrand-Marqu and Laudelout (1985) regarding rapidly increasing flow resistance with dead zone fractions approaching 1.0 as flows neared extinction in a small mountain stream. LeGrand-Marqu and Laudelout observed, in disagreement with earlier findings of Thackston and Schnelle (1970), a negative curvature in their plot of β versus f. Unfortunately they did not report or plot their hydraulic resistance values,

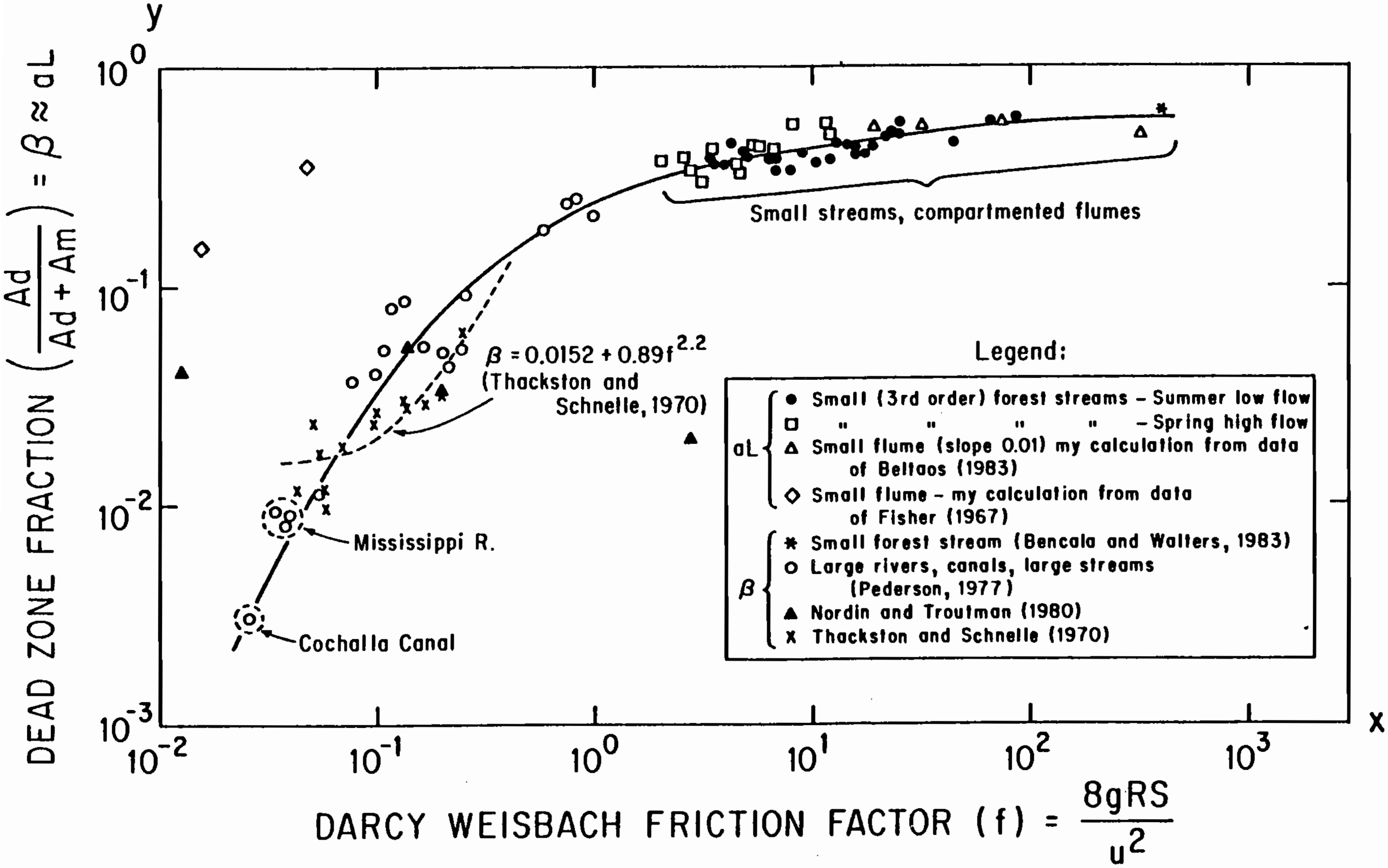


Figure 27. Dead Zone Volume Fraction vs. Flow Resistance.

so I was unable to evaluate them in the context of other data. When the data of Thackston and Schnelle (1970) are placed in the context of more recent findings over an expanded range of β (or a_L) and f (see Figure 27), they fit the general pattern of progressively diminishing slope of the plot of Log[dead zone fraction] versus Log[f] at ever-increasing values of f. The regression reported by these authors is shown on the figure. It can be seen that its progressively increasing slope is probably inappropriate as resistance increases beyond the range of their data. Thackston and Schnelle's contribution has been valuable, however, in that they were the first to recognize and demonstrate a relationship between dead zone fraction and hydraulic resistance.

Pederson (1977) borrowed ideas from the sediment transport literature to suggest a hypothetical theoretical basis for the relationship between the dead zone volume fraction model parameter and energy losses in streamflow. The result of his derivation is an expression relating dead zone fraction to expansion loss friction factor:

$$\text{Dead Zone Fraction} = cf\{1 - (f'/f)\} = cf''$$

where: c = a dimensionless constant,

f = total friction factor = f' + f",

f' = friction factor associated with shear stress along the bottom, and

f" = friction factor associated with expansion losses.

The magnitude of friction factor associated with bottom shear stress is dependent upon particle size and relative submergence. Pederson (1977) states, and offers supporting empirical evidence from other authors, that the proportion of friction factor associated with expansion losses rises as total friction factor increases. Evidence cited showed the expansion loss portion increasing from 29 to 56 percent as friction factor increased from 0.04 to 0.12.[1] Pederson (1977) found that the linear regression (dead zone fraction = 0.5f{1 - (f'/f)} describing the relationship between dead zone fraction and expansion loss friction factor fit his data and that of Thackston and Schnelle (1970) quite well. (Note that I have modified Pederson's equation--see footnote.) This data is in the total friction factor range between 0.02 and 1.0. Addition of my data points and others in the friction factor range of 1 to over 10^2 to the plot of dead zone fraction versus total friction factor suggests that the linear relationship would overestimate dead zone fraction at very high values of f (Figure 27). To visualize an approximate plot of dead zone fraction versus expansion loss friction factor, it is necessary to decrease the friction factor for data points at the far left of Figure 27 by a factor of about 30 percent, those midway by about 10 percent, and those at the far right by 2 to 10 percent. A pattern of decreasing slope of the dead zone versus friction factor plot persists even if the f values are thus adjusted to remove the portion of energy loss associated with bottom shear.

It should be noted that because my dead zone values were calculated using a model lacking a Fickian dispersion term, they would be expected to be higher than values obtained using the Hays-type models used by the other researchers whose data is plotted in Figure 27. Such discrepancies should be greatest at small values of dead zone fraction and might possibly be insignificant in the high range of dead zone fraction encountered in

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[1]Values of f reported by Pederson (1977) have a value 0.25 times those calculated according to convention in the U.S.A. I have multiplied all his f values by 4 in my plots and discussion. Pederson used a definition of $(2/f)^{0.5} = U/U^*$ in contrast to common usage of $(8/f)^{0.5} = U/U^*$ in the U.S.A.

streams of my study (Figure 19C). Problems arising because of different model definitions are discussed in the following paragraphs. It seems prudent, however, to avoid direct comparison of a_L, as calculated according to Sabol and Nordin (1978) with β, the Hays-type dead zone volume parameter (calculated from models which attempt to separate the effects of transient storage and Fickian dispersion) when a_L is below about 0.25 and β is below about 0.10.

One of the problems encountered in relating the dead zone volume and exchange parameters to physical channel morphology and streamflow hydraulic characteristics stems from the fact that various authors *define* the model parameters in different ways. I have defined dead zone fraction as used by Hays (1966) and LeGrand-Marqu and Laudelout (1985). They define dead zone fraction as the cross sectional area in dead zones divided by the combined cross-sectional area of the main stream plus dead zones {Ad/(Am + Ad)}. Other authors (e.g., Bencala & Walters, 1985; Nordin & Troutman, 1980) have defined dead zone fraction as the cross-sectional area in dead zones divided by the active flow cross sectional area (Ad/Am). In Figure 27, I have converted reported values of Ad/Am to Ad/(Am + Ad) when it was clear that the author was expressing relative dead zone volume as Ad/Am. At small values of dead zone fraction (below about 0.10) the definitions become nearly synonymous.

The second and more critical problem in comparing the values of model parameters stems from the fact that different authors *calculate* the parameters in different ways. Because the Sabol and Nordin (1978) model can be demonstrated to be equivalent to the Hays (1966) model without a velocity field (Fickian) dispersion term (Sabol and Nordin, 1978), all of the variance from mean tracer travel time must be explained by the dead zone volume (a_L) and exchange (δ) parameters. Tracer studies in channels without physically recognizable dead zones will, therefore, yield values of a_L greater than zero (Figure 19C). This is perhaps why the regressions I obtained between a_L and the coefficient of variance in thalweg depth in cobble-bedded streams had y- intercepts greater than zero (approximately 0.2).

Pederson (1977) reports values of dead zone fraction (β according to a Hays-type model) of 0.038 to 0.051 for two U.S.G.S test sites on the Chattahoochi River in Georgia. Sabol and Nordin (1978) report dead zone fractions (a_L) of 0.17 to 0.30 for the same river, but I do not know if the sites and discharges are the same or similar. If so, these measurements contrast values of dead zone fraction yielded by the two different models. It should be noted that Sabol and Nordin (1978) did not interpret a_L as dead zone *volume* fraction, but as the ratio of time spent in the dead zone to the total transit time in the stream reach. The Introduction (Ch. I) explains the simplifying assumptions I have made in order to also interpret a_L as a measure of effective dead zone volume fraction.

Thackston and Schnelle (1970) display concentration-time curves simulated by a Hays-type dead zone storage model at various values of dead zone fraction and exchange rate. I estimated the value of a_L (according to the Sabol and Nordin model) to be about 0.137 to 0.14 when the Hays model value of β was equal to zero. I calculated a value of $a_L = 0.15$ from data of Fischer (1967) for a smooth flume with a friction factor of 0.016. In consideration of the above examples of a_L measurements in very "smooth" channels relatively unaffected by transient storage, it seems likely that the Sabol and Nordin model would probably calculate a_L values from 0.13 to 0.20 in flow situations of very low transient storage where β values calculated by a Hays-type model would approach zero. The actual value of a_L under such circumstances would depend upon particle roughness, channel width, and mean velocity--factors controlling velocity field dispersion. The difference between values of dead zone fraction (a_L and β) yielded by the two types of models would likely decrease as transient storage mechanisms succeed in overshadowing velocity field dispersion in complex channels with abundant pools and backwaters, as characterized those of my study and that of Bencala and Walters (1983).

2. Flow Resistance Measurements

Channel hydraulic resistance, while perhaps a sensitive measure of differences in channel morphology, is not independent of discharge. The sensitivity of flow resistance, as measured by the dimensionless Darcy-Weisbach friction factor, is particularly acute at low flows, when hydraulic radius (flow cross-sectional area divided by wetted perimeter) and relative submergence of substrate particles and bedforms change most rapidly. For this reason, direct comparisons of flow resistance among channels of unequal discharge must be made with caution. However, a reasonable comparison of the differences among channels may be made by regressing hydraulic resistance against discharge and then comparing predicted resistances at a given flow, giving due consideration to the confidence intervals about the regressions. If the differences in f among channels are much larger than the range of f observed in individual channels, then discharges need only be approximately matched in order to make meaningful comparisons on the basis of hydraulic resistance.

Darcy-Weisbach friction factors (f) measured during summer low flows in streams of my study ranged from 4.1 to 87. During higher winter and springtime flows, f values ranged from 2.0 to 12. Mean values of hydraulic and morphometric variables in reaches grouped by the three study streams are summarized in Tables 3, 4, 5, 8, and 9. The measurements within each 100-meter study reach at a number of flows are tabulated in Appendix E. The values of f were not computed for a channel flow cross section or a short, uniform reach, as is normally the practice. They were, rather, values of "total" friction factor calculated using the mean convective velocity and mean hydraulic radius over 100 meters of stream channel (about 30 to 35 channel widths of stream length). As such, these hydraulic resistance values take into account momentum transfer and energy losses due to flow expansion, flow deformation and transient storage, in addition to skin friction losses (associated with bottom shear) over a long reach of stream.

Conventional hydraulic practice is to calculate flow resistance over short, relatively uniform lengths of stream, where most flow resistance is the result of fluid shear stresses against the channel boundaries. An understanding of the factors controlling hydraulic resistance at a localized channel cross section is certainly important for calculating discharge from known gradient and flow depth information. Such at-a-section hydraulic resistance calculations are also important in the study of boundary shear stresses controlling sediment transport. However, in applications such as the study of pollutant transport, stream temperature dynamics, reoxygenation, and nutrient retention, estimations of the overall transit time and mean rate of energy expenditure over long sections of stream channel are needed. One then needs a way of estimating, from channel information, hydraulic friction factors which include expansion losses. In relatively simple channels, channel hydraulic resistance factors calculated as a function of hydraulic radius and substrate size may yield reasonably good estimates of mean velocity over long reaches. In complex channels, however, one would be forced to carry out a tedious flow routing procedure through each change in channel flow cross section, such as one might use for estimating time of travel through a series of reservoirs. If flow resistance over a long section of channel could be related to easily-measured physical properties and their variability over a reach, then transit times might be predicted from such information. The effective friction factor measures in this study were related to measured channel properties in an effort to gain a quantitative understanding of the factors controlling energy expenditure over long sections of stream channel.

Channel flow resistance was calculated according to procedures outlined in Chapter III. The total apparent Darcy-Weisbach friction factor (f) measurements, back-calculated from measured mean reach convective velocities and channel dimensions, are tabulated in Appendix E. Mean summer low flow values of f for the study reaches grouped by stream were 17, 38 and 5.7 for Little Cummins Creek, Cape Creek and Gwynn Creek. During springtime discharges averaging about 5 times as high as those during the summer, mean values of friction factor were 5.8, 7.9 and 3.3 for Little Cummins, Cape and Gwynn Creeks. The flow dependence of friction factor is obvious in this comparison. The data illustrate, however, that within a restricted range of discharge, the complex, torrent-deposit affected reaches of Cape Creek show hydraulic resistances consistently higher than the torrent-scoured reaches of Gwynn Creek. The relatively undisturbed reaches of Little Cummins Creek show intermediate friction factor values.

It should be recognized at this point that the values of hydraulic resistance reported here are extremely high in comparison with values generally measured in larger streams or in streams with relatively low variation in channel cross-section. For comparison, Pederson (1977) reported total friction factors near 0.06 for the Mississippi River and near 0.8 to 1.0 for smaller rivers and streams. Fischer (1967) reported total friction factors ranging from 0.015 to 0.33 for flows 0.02 to 0.23 meters deep in straight, 1 meter wide, rectangular and trapezoidal flumes with smooth bottoms and sides ranging from smooth material to gravel 2 to 3 cm in diameter. Thackston and Schnelle (1970) reported total friction factors from 0.04 to 0.26 in "relatively short, smooth, and uniform reaches." Manning's "n" values of 0.07 and 0.15 are reported by Chow (1959) to be appropriate for calculations involving, respectively, stream reaches with cobbles and large boulders and stream reaches with deep pools. Manning's "n" values would correspond with Darcy-Weisbach friction factors of 0.5 and 2.0 for mean flow depths of about half a meter. Dingman (1984) reported measured Manning's "n" values as high as 0.42 at very low flows in small vegetated stream channels. A corresponding f value would be 20 to 40 for a mean flow depth of 5 to 10 centimeters.

Consideration of the comparative data listed above suggests the overriding influence of energy losses due to large substrate particle form drag (at high values of relative roughness) and especially variation in channel cross-section (causing expansion losses) in the stream reaches used in my study. These streams had substrates dominated by small cobbles (0.10 m diam.) to small boulders (0.35 m diam.) and flowed at low flow mean thalweg depths of 0.16 to 0.19 meters. Straight stream reaches of rectangular cross-section flowing under these conditions of relative roughness might be expected to have friction factors from 0.7 to 4, as calculated by the semi-logarithmic flow resistance equation of Hey (1979). The Hey equation provides an estimate of the flow resistance imparted by grain resistance ("skin resistance") and the form drag of individual large substrate particles. The complex equation of Bathurst et al. (1979), which expresses hydraulic resistance as a function of relative roughness concentration, yielded f values for streams of my study ranging from 0.9 to 4 at low flow and from 0.7 to 1.9 at springtime flows approximately 5 times higher. It is apparent that overall reach friction factor in these streams, which varied from 4 to 87, incorporated a major component of resistance due to expansion losses and momentum transfer by transient storage.

Using the flow resistance estimates yielded by the Bathurst et al. (1979) equation (see Chapter I) as estimates of resistance due to skin friction and form drag of substrate particles, I was able to estimate, by difference, the portion of total resistance due to expansion losses and other modes of energy loss arising from channel cross-sectional variation in the longitudinal direction. Such losses accounted for 68 to 82 percent of the total in Gwynn Creek, which on the average was the least complex of the study streams. In the more complex channels of Cape Creek, expansion losses accounted for 75 to 98 percent of the total, and in Little Cummins, 63 to 88 percent. During the higher springtime flows, expansion losses comprised 60 to 71 percent of energy losses in untreated reaches of Gwynn Creek, while such losses in Cape and Little Cummins Creek were 66 to 91 percent and 59 to 89 percent of the total, respectively. Increases in pool volume resulting from woody debris addition to Gwynn Creek increased the portion of energy losses by expansion to 86 to 98 percent of total losses during low flows and 66 to 93 percent at higher spring flows. The decrease in the expansion loss portions at high flows is an indication that certain bedforms and other channel features which act as downstream controls (flow impoundments) during low flow are "drowned out" as discharges increase.

The following discussions refer to the total friction factor, taking into account energy losses due to skin friction, substrate particle form drag, and expansion losses arising from changes in channel cross section.

Total effective Darcy-Weisbach friction factor measurements for 14 natural stream reaches in this study were highly correlated with the standard deviation of channel thalweg depth measurements (SDD) at low flow ($r = +0.95$) and at higher springtime flows ($r = +0.98$). When both high and low flow data were combined, the correlation between f and SDD was low ($r = +0.66$) as a result of the flow dependence of f. CfVarD, the dimensionless counterpart of SDD, was not as highly correlated as was its dimensional counterpart with friction factor at either low flows ($r = +0.87$) or high ($r = + 0.95$), but its relationship was closer ($r = +0.75$) when data included high and low flows.

An unorthodox modification of the semi-logarithmic flow resistance equation might be made by substituting some measure of channel feature scale relative submergence for relative substrate particle submergence (d/D85). Semi-logarithmic flow resistance equations are based upon the theory that the mean velocity and the shape of the velocity distribution profile, as expressed by dimensionless velocity $\{U/U^* = U/(gRS)^{0.5} = (8/f)^{0.5}\}$ is proportional to the logarithm of relative submergence. Strictly speaking, the theory underlying such equations is approximately correct only for steady, uniform flow with small scale roughness, i.e., for relative submergences in excess of about 4. As previously discussed, the semi-logarithmic equation of Hey (1979) was developed for small to intermediate scale roughness (relative submergences up to 1). Velocity profiles under conditions of relative submergence less than 4 are known to deviate greatly from the logarithmic ideal (Bathurst et al., 1979; Bathurst, 1985). Nevertheless, the Hey equation is able to predict mean velocity at relative submergence values from 4 to less than 1 in cobble and boulder-bedded streams as accurately as several other detailed, more process-oriented flow resistance equations recently developed (Thorne & Zevenbergen, 1985; Bathurst, 1985).

Despite the implication that the use of the semi-logarithmic flow resistance equation form presupposes a logarithmic vertical flow velocity profile (and steady, uniform flow), the success of the Hey equation under flow conditions which violate that assumption prompted me to explore such a semi-empirical relationship between flow resistance and channel morphometric measures which might be related to the degree of energy loss by flow expansion and transient storage. In addition, Bathurst (1981) stated that there is a good possibility that "bar resistance" (total resistance minus grain resistance) could be calculated directly from residual depth. He suggested that this would be more satisfactory than deriving bar resistance from shear stress criteria which are less directly related to the processes involved. I derived the following empirical relationship between $(8/f)^{0.5}$ and the natural logarithm of D/Do (the ratio of mean thalweg depth to mean thalweg residual depth) in 14 stream reaches over a discharge range from 0.019 to 0.10 m^3/s:

$$(8/f)^{0.5} = 0.62\mathrm{LN}[D/Do], \quad (R^2 = 0.57, n = 40)$$

The D/Do ratios were calculated from residual and mean depth data, in contrast to the estimation of this ratio from velocity data, a concept that was suggested by Bathurst (1981). The determination of mean residual pool depth (Do) for a reach can be difficult and time-consuming. It requires either the measurement of an elevation profile or a back-extrapolation of mean depth at zero discharge on a linear plot of reach-averaged depth taken over a range of known discharges (as suggested by Bathurst, 1981). It may be possible, however, to use the ratio of mean thalweg depth to standard deviation of thalweg depth (D/SDD = 1/CfVarD) as an approximate index of the mean depth/residual depth ratio D/Do, as a very high correlation ($r > +0.95$) between the two variables SDD and Do was observed in reaches of this study.

Figure 28 is a plot of $(8/f)^{0.5}$ versus the natural logarithm of the ratio D/SDD. I derived the following semi-logarithmic formula from 40 data pairs during summer low flow and springtime flows up to 10 times as high:

$$(8/f)^{0.5} = LN[D/SDD]^{0.92}, \quad (R^2 = 0.60, n = 40)$$

The precision of the relationship was slightly greater than that involving residual depths. Like that relationship, its precision was considerably higher when high and low flow data were separated. Similar separate regressions with R^2 values in excess of 0.83 were calculated for high and low flow. The two variables were measured at more closely matched discharges during high flow than during low flow, causing these points to plot with less scatter at high flow in Figure 28. The figure shows that the high flow data points plot as a line roughly parallel to the line of low flow points but with a higher y-intercept. As found by Bathurst (1985) in his analysis of the relationship between $(8/f)^{0.5}$ and relative submergence,

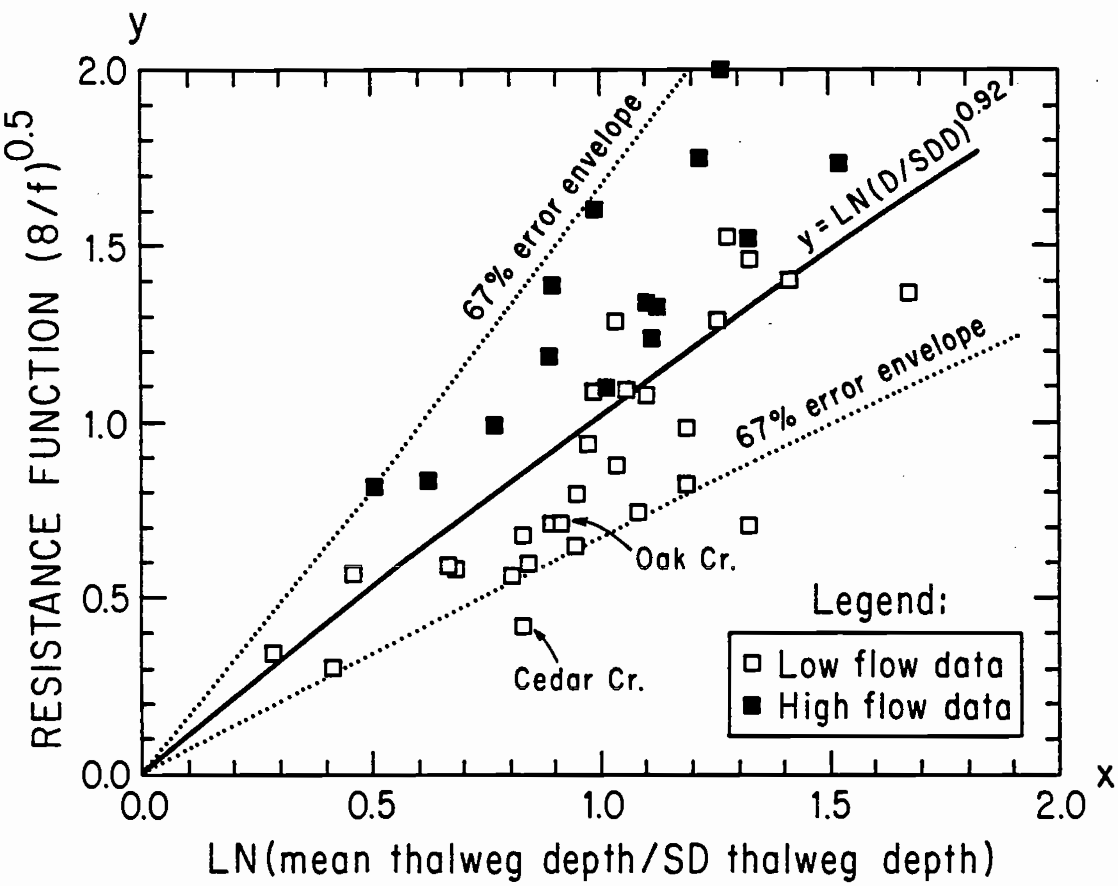


Figure 28. Flow Resistance vs. 1/CfVarD.

I observed that the pattern of variation in flow resistance with change in D/SDD among different reaches of my study did not necessarily reflect that seen at different flows in the same reach. Flow resistance measurements over a wide assortment of discharges and in channels of various shapes (and values of D/SDD) would be necessary to accurately determine the nature of the functional relationship between friction factor and D/SDD in a given channel as discharge varies.

Two additional points are plotted in Figure 28 from stream reaches differing greatly in slope and discharge from the primary streams of my study. One data point is from Cedar Creek in the Oregon Coast Range during a rather unusual period of snowmelt flooding, when its 0.62 m^3/s discharge was about 6 times greater than the highest flow of data points used to calculate the regression shown in the Figure. This reach is steeper (6% gradient) than the primary study reaches and its 4.0 km^2 drainage area is slightly larger than those of the primary study reaches (2.1 to 3.3 km^2). The Cedar Creek data point plots within the envelope of the other data but has higher resistance than would be expected for its value of D/SDD (i.e., 1/CfVarD). A possible explanation might be that a large component of flow resistance was due to large woody debris within the flow profile. The Cedar Creek reach spanned a large log jam and had a total debris loading of 105 m^3/100 m, almost four times that of the most heavily loaded natural reach of the primary study reaches (1.7 times the highest volume among the treated Gwynn Creek reaches). Flow through the log jam was deep, affecting flow velocity much as might a filter, rather than a boulder bed or a series of pools. The Oak Creek reach was a smaller channel (W = 2.3 m) of lower order (2nd) and higher gradient (8.3%) than those of the primary study reaches. Its data point, collected during a springtime base flow discharge of 0.048 m^3/s, plots where expected on Figure 28. Though certainly not conclusive, the Cedar and Oak Creek data points suggest that the relationship between hydraulic resistance and the coefficient of variation in thalweg depth may extend to stream reaches of lower Strahler order (second), higher gradient (up to 8.3%), and higher discharge (0.62 m^3/s) than those 14 primary study reaches used to derive that relationship.

V. DISCUSSION

A. Towards a Morpho-Hydraulic Approach to Stream Study

1. Approach

This dissertation describes and applies an approach to the functional evaluation of stream "physical habitat." The approach uses relatively simple tools commonly used by biologists, hydraulicians and engineers. These tools include elevation profile surveys, width and depth measurements, and hydraulic tracer techniques. The morphologic and hydraulic characteristics chosen for study are those affecting habitat space, water velocity, nutrient retention, and the dispersion and transit velocity of chemical substances in small streams. The effective volume and exchange rate of transient hydraulic storage zones ("dead zones") in stream channels were estimated from tracer data using dispersion modeling theory developed by other researchers (see Ch. I, Introduction). These dispersion modeling parameters were quantitatively related to morphometric channel variables in a way I believe not previously accomplished for natural streams. Similarly, established theory regarding flow resistance in channels was applied to obtain a simple flow resistance equation (albeit preliminary) enabling the prediction of transit velocity from thalweg depth information in complex reaches containing such non-uniform flow features as pools, riffles and plunges.

The approach outlined was applied in the context of assessing the impact of debris torrents on small streams in the Oregon Coast Range and the pattern of recovery of channel structure in those streams over time.

An anadromous fish habitat enhancement project employing large woody debris placement was evaluated with regard to its effect on increasing channel structure and slackwater habitat.

2. Structure of the Study

- Individual components of total pool volume in stream reaches and the agents forming those features were described.
- The total pool volume and the contribution of the various pool types and pool-forming mechanisms in stream reaches of different torrent impact recovery class (recent, intermediate, or long - term) and type of impact (scour or deposition) were contrasted.
- Several surrogate measures of pool volume: Residual Pool Profile Area (RPA), the standard deviation of sequential thalweg depth measurements (SDD), and the respective flow-compensating, nondimensional derivations of these two measures (Do/D and SDD/D) were developed and tested.
- Changes in channel morphology occurring after a fish habitat improvement project in which large woody debris was added to Gwynn Creek, a torrent-scoured stream, were measured and interpreted.
- Parallel measurements were made of channel morphology and tracer-derived estimates of transient storage volume, storage exchange rate, and flow resistance. These hydraulic variables were related to easily measured channel variables which quantitatively describe the slackwater features and channel cross-sectional irregularities hypothesized to be controlling the processes of transient storage and momentum transfer.

- Areas of stream research and management in which the morpho-hydraulic stream evaluation scheme described may have potential utility are discussed in part C of this Chapter.
- The morpho-hydraulic relationships, stream enhancement results, and torrent recovery contrasts described in this study were used to construct a conceptual model of torrent recovery in small Oregon Coast Range streams. This model is outlined in part E of this Chapter.

B. Channel Morphology

The results of these investigations described a series of stream reaches ranging in dominant surficial substrate size from small cobbles (0.10 m diameter) to medium boulders (0.35 m diameter). The smallest substrates were observed in the recently scoured reaches of Gwynn Creek where a poorly sorted mixture of small cobbles, very coarse gravel (0.05 m diameter), and large cobbles (0.20 m diameter) formed a thin, discontinuous veneer of bedload sediment (0 to 2 m thick) overlying bedrock, and in reaches of the other streams where torrents had left massive deposits of sediment and large woody debris. In the latter case, which was represented only in the two streams of intermediate and long term torrent recovery, sediments were well sorted, with large cobbles and medium boulders in short cascades and very coarse gravel and small cobbles in lower gradient areas. The coarsest substrates observed were dominated by large cobbles and medium boulders and were observed in reaches where boulders had been deposited during the torrent event or were subsequently left as lag deposits as the stream reincised through torrent deposits.

Qualitative field observations and examination of longitudinal profiles of width and depth showed that perhaps the most notable characteristic of many of these small stream channels is their variability. Appendix F shows example width-depth profiles. Auto-correlation analysis of these "spatial series" data revealed only weak periodicity (at a length frequency of 10 to 20 channel widths for width data and 5 to 10 channel widths for depth data). Cycle lengths were longest in scoured reaches and shortest in complex torrent deposit reaches. There was, however, a distinct "memory effect" in both width and depth series data. Series data for thalweg depth in scoured channels were positively correlated until they were 2 channel widths downstream from each other; width data was positively correlated until 3 to 5 channel widths distant. This "memory effect" persisted in complex torrent deposit reaches for a little over 1 channel width downstream distance in depth data and for about 2.5 channel widths distance in width data. These data suggest the typical lengths of width oscillations and of depth variations like transverse bars and glides in these streams.

The lack of strong periodicity or trends in the data discussed above indicate that short length scale deviations in width and particularly in depth along the length of these streams dominated over longer oscillations or trends which may have existed. Because of this characteristic, measures employing the statistical variance of such measurements from mean reach values were useful quantitative indicators of channel morphologic features causing flow deformation and therefore energy losses through flow expansion, form drag, and transient slackwater storage. In fact, the correlations between measurements of standard deviation of thalweg depth (SDD) and direct measures of Residual Pool Profile Area (RPA) or mean residual depth (Do) were in excess of +95 percent for data from a variety of reaches. These included both natural reaches and those experiencing large woody debris additions for fish habitat enhancement. Both SDD and RPA provided objective, flow-independent indices of aggregate pool volume in reaches. Division of mean residual depth or SDD by mean total thalweg depth yielded flow-compensating, nondimensional measures of residual pool volume to which hydraulic measures were later related.

Residual Pool depth, length, or vertical profile area measurements on individual pools provided a useful flow-independent quantitative description of the dimensions of these features. Division of individual pool mean or maximum residual depth by mean reach thalweg depth would yield nondimensional pool morphometric variables which give a relative indication of the degree to which pools of different sizes are "drowned out" by increasing discharge--a measure of habitat quality.

Examination of qualitative field notes and residual profile analysis of individual pools revealed 10 pool types. The most numerous were small Inter-Cobble-Row Pools and Step Pools formed above and below transverse cobble or boulder bars. These pools, however, tended to be smaller than would normally be considered "pools" in stream habitat assessments. Their depths and velocities were more like those typical of glides. In 100 meter reaches containing a large aggregate residual pool volume, one or more large Cascade Plunge Pools were invariably present. These pools were usually associated with large woody debris and were most common in torrent deposit areas. Lateral Scour Pools dominated the meager aggregate pool volume of recently torrent-scoured Gwynn Creek reaches, though Inter-Cobble-Row Pools were most numerous. Step pools were most common where boulders occurred, which was often in incised torrent deposits where bedrock and lag deposits of boulders were present.

The rank order of pool volumes and maximum depths associated with various formative agents was, in descending order: those associated with log clusters, rootwads, bedrock, boulders, single logs, and, finally, cobbles.

The aggregate residual pool volume was lowest in reaches of Gwynn Creek recently scoured by a torrent. It was highest in Cape Creek, where massive torrent deposition of sediments and large woody debris was common, and where medium boulders and bedrock were present in scoured reaches lacking abundant sediment and wood. Aggregate residual pool volume was intermediate in Little Cummins Creek, where there was evidence that several former debris dams had deteriorated and breached, allowing pool-forming sediments to "leak" through the system. Suggestion of an ensuing lack of sediment was evident in the prevalence of bedrock exposure in these reaches undisturbed by torrent scour or deposition for over a century. Exposed bedrock in Little Cummins Creek, however, unlike Gwynn Creek, was often associated with large pools due to the downstream scouring and deposition of mobile sediments. These bedrock-associated pools in Little Cummins Creek provided high quality anadromous fish habitat.

In Gwynn Creek, bedrock, cobbles, log clusters and single logs all contributed about equally to the small aggregate pool volume found in these scoured reaches. In Cape Creek, log clusters and boulders dominated pool formation in two reaches where logs and sediment were deposited by a torrent and in two others where boulders were left associated with bedrock after scouring which occurred during the torrent or subsequent normal flood flows. Bedrock and log clusters contributed about equally to total residual pool volume in relatively undisturbed Little Cummins Creek.

A recurring theme in the results of this study has been the importance, if not the dominance, of large woody debris in controlling channel characteristics. Woody debris was particularly important in forming channel features containing low water velocity. Such features are important in providing high quality stream habitat and nutrient retention in relatively high gradient Pacific Northwest streams such as those in my study. Aggregate reach residual pool volume was correlated with woody debris volume ($r = +0.86$) and with the number of debris pieces ($r = +0.80$) in the 14 reaches of my study. Bilby (unpublished) found a similar correlation, but between debris volume and pool surface area in streams. The correlation improved as stream channel width increased from less than 7 meters to greater than 10 meters. In Gwynn Creek, my results demonstrated that the addition of large woody debris to wood-impoverished, torrent-scoured reaches (which, however, contained bedload sediment) produced increases in pool volume proportional to the relative increase in wood volume. Some pool volume increases were immediate, but most were realized subsequently, as flood flows progressively sculpted the channel for at least a year after debris placement.

Dave Heimann (1987) recently completed a study of large woody debris loadings in a series of third order Oregon Coast Range streams ranging in "age" from 20 to 135 years since removal of riparian vegetation by fire or timber harvest. To test the generality of the association between woody debris and pool volume, Heimann and I undertook tracer studies in many of his study reaches. I had found the tracer-derived variable a_L, dead zone volume fraction, to be a good surrogate for pool volume if measured at low flow. (Note: a_L appears to be a reasonably good surrogate for flow-adjusted pool volume, Do/D, when measured at any discharge, but the influence of peripheral backwaters on a_L appears to increase at high flows.) Tracer studies were carried out on 17 reaches distributed among 9 streams with locations shown in Figure 2. Dead zone fraction, indexing pool volume, was positively correlated (r = +0.76) with large woody debris volume in this regional sample of reaches with woody debris loadings ranging from 6 to 105 m^3 per 100m reach (Figure 29).

These results, in combination with the Gwynn Creek debris placement results and those of Bilby (unpublished), support the growing body of knowledge regarding the importance of woody debris in providing slackwater habitat in small Pacific Northwest streams. Large woody debris creates areas of water and bedload impoundment which must be followed downstream by steeper areas where energy expenditure is intensified through local scour. The presence of wood tends, therefore, to produce an irregular channel bottom elevation profile. Woody debris also causes flow deflection which intensifies energy dissipation through local scour. It allows disruption of an established armor layer, allowing movement and rearrangement of bed material, but eventually the rearrangements tend to produce bedforms more stable (more retentive of bedload) than those existing in the absence of woody debris.

C. Utility of Dispersion Model Parameters in Stream Research

This study constituted a field test of the dispersion modeling parameters a_L and δ, as calculated according to Sabol and Nordin (1978). The parameter a_L was defined by these authors as the ratio of time spent by water molecules in transient storage zones to the total transit time through the stream reach. I have extended the interpretation of this parameter to an estimation of effective dead zone volume fraction, given the

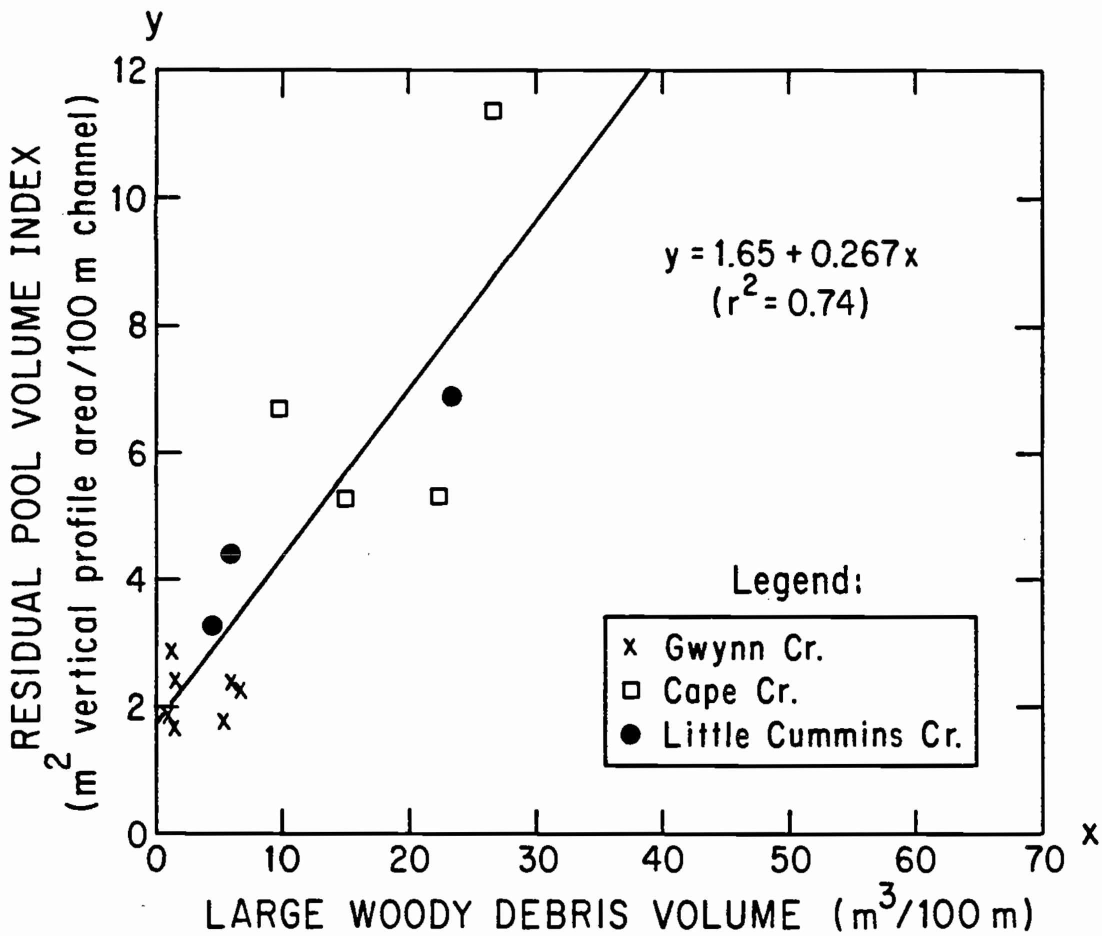


Figure 29. Dead Zone Volume Fraction (Pool Volume Index) vs. Woody Debris Volume in a Regional Sample (n=17) of Stream Reaches (debris volumes from Heiman, 1987).

assumptions of the Sabol and Nordin model. The parameter a_L was found to be positively correlated with hydraulic resistance (Figure 27), as has been found by several other researchers. In addition, however, this study demonstrated that dead zone volume fraction (a_L) was linearly related to dimensionless measures of longitudinal channel bottom irregularity (SDD/D) and pool volume (Do/D). The dead zone exchange coefficient δ was found to generally increase as a_L decreased. The parameter δ was, unlike a_L, very sensitive to changes in discharge within a reach and among different reaches. It was found to bear close relationship to the inverse flow resistance measure $(8/f)^{0.5}$. It was not clear whether this relationship would be likely to extend over wider ranges of discharge, slope, and channel size than those investigated in this study.

The above findings are of theoretical interest, demonstrating that the dispersion modeling parameters (particularly a_L) have logical physical meanings. The quantified relationships between flow resistance and dead zone volume and exchange rates aid the understanding of processes involved in energy expenditure in nonuniform stream reaches. If further research demonstrates that the relationships between a_L and such morphometric measures as Do/D and SDD/D (and the nonuniform flow resistance equation employing LN(D/SDD)) can be generalized to streams and rivers of widely varying discharge, slope and morphology, then such relationships will aid in the quantitative prediction of pollutant dispersion in complex streams. Conversely, the measurement of dead zone volume fraction in channels may be useful in the classification of stream reaches according to their transient storage characteristics, a possibility that was suggested by Vallentine and Wood (1979b) and Chatwin (1980). Such a functional basis for stream reach classification would be useful as a lower order classification of reach types within a more encompassing hierarchical scheme based on geoclimatic, topographic and hydrologic considerations. It would ordinate stream reaches according to the relative magnitude of their terrestrial interaction because transient storage increases with complexity of channel form, bank, and backwater areas. If measured at overbank flows, it indexes the degree of interaction of the stream with its riparian zone. A classification according to dead zone volume fraction and exchange rate would ordinate stream reaches of similar water chemistry and hydrology according to their vulnerability to pulsed inputs of introduced pollutants such as pesticides or acid snowmelt. Dissolved pollutant peak concentrations would be attenuated by the process of transient hydraulic storage. In addition, the increased contact time and surface area of contact of such pollutants with aquatic organisms and substrate materials would influence the impact of such pollutants on a given stream reach and on the pattern of pollutant export to other downstream reaches.

If the dead zone volume fraction parameter a_L bears a consistent relationship to channel morphology and slackwater characteristics in channels over a wide range of discharge, slope and channel size, then it might also be a useful tool to aid the classification and evaluation of fish habitat within a given region. Measurements of a_L on small streams can be made quickly and inexpensively. Measurement of this parameter over a wide range of discharge may allow the indexing of available slackwater habitat for juvenile salmonids in stream reaches during different seasons. Similarly, a determination of the relationship between discharge and the dispersion parameters a_L and in a reach would provide an index of an important hydraulic component of dissolved and fine particulate material retention. Other components of stream retention for dissolved and particulate materials are chemical and biological uptake and transformation.

Sabol and Nordin's (1978) dead zone exchange coefficient (δ) is defined as the relative portion of the total stream reach volume exchanged between the mainstream and transient storage (dead zone) per unit time. As such, its reciprocal ($1/\delta$) is the mean cycle time for a water molecule moving into and out of dead zone storage (including its transit time in the main stream). Similarly, the dead zone volume fraction (a_L) divided by the exchange coefficient (δ) is the mean water residence time in dead zone storage alone. The product (Uc/δ) of the mean reach transit velocity and the mean dead zone cycling time can then be considered the hydraulic "spiral length," borrowing the terminology of Webster (1975), referring to a similar concept of transient storage of nutrients in stream ecosystems. Spiral length was quantitatively defined with respect to nutrient dynamics by Elwood et al. (1983) as the mean downstream displacement of a substance between successive storage episodes. The dead zone storage exchange coefficient (δ) and the hydraulic "spiral length" I calculated based on Sabol and Nordin's tracer dispersion model parameters are directly analogous to the concepts of nutrient storage exchange coefficient ("k") and spiral length ("S") derived by Elwood et al. (1983).

As previously indicated, part of the transient storage of any dissolved nutrient (or pollutant) is due to transient storage in channel dead zones. For a nonconservative substance like phosphorus, for example, the remainder is due to other physical, chemical, and biological processes which entrain that nutrient in relatively stationary parts of the stream ecosystem (e.g., sediment, periphyton). An evaluation of the relative contribution of strictly hydraulic processes to nutrient cycling provided by measurements of dead zone storage exchange coefficient and hydraulic spiral length would provide a useful "scaler" through which the contributions of biological processes alone could be evaluated in ecological studies of the dynamics of dissolved and fine particulate nutrients. Naiman and Sedell (1979a) stated that because physical processes often dominate the retention and transport of such nutrients, a scaler indicating the magnitude of such physical processes is necessary to evaluate the role and effectiveness of biotic retention. Sedell et al. (1978, pp. 1374-1375) stated:

> Development of adequate indices for retention devices in streams is a necessity since the present state of knowledge for natural channels remains chiefly an art. Indices for such characteristics as interstitial and crevice spaces, bed roughness, retention by woody debris and boulders in streams, as well as such biological retention features as macrophytes, filamentous algae, and filter feeding invertebrates have been developed through experience rather than through quantitative relationships.... Development of quantitative procedures for determining retention characteristics, coupled with the unit stream power, will provide a valuable tool for examining organic storage and transport characteristics of running waters.

Researchers have attempted to relate the transport and storage of dissolved and particulate organic material to physical and hydraulic stream variables such as stream power, discharge and stream size (e.g., Sedell et al., 1978; Naiman & Sedell, 1979a,b; Dahm, 1984). Dahm recognized three factors potentially affecting the uptake of dissolved organic material in mountain streams in the Oregon Cascades. These included the source of the organic material, the order of the stream (controlling discharge and stream power), and the vegetational structure of the riparian zone. He recognized that while stream order may influence dissolved organic carbon uptake, sediment size and type as well as the structural complexity of the stream channel may ultimately be more important than size. Speaker et al. (1985, p. 1839), working primarily in small streams of the Oregon

Cascades, found retention of leaves to be related to be closely related to the channel hydraulic and morphometric variables described below:

> As hydrologic retention (time required for passage of peak dye concentration through a 50 m reach) increased, instantaneous rates of leaf retention were also greater. We also observed that leaf retention rates were greater in reaches with higher ratios of wetted perimeter to channel cross-sectional area.

The hydraulic measure employed by Speaker and his colleagues is related to flow resistance, transient storage, and discharge. The channel morphometric measure is the reciprocal of hydraulic radius but employed very detailed measurements of wetted perimeter, reflecting bottom irregularities due to sediment particles (Speaker, pers. comm.). The presence of debris dams, pools, peripheral backwaters and coarse sediments tended to enhance leaf retention as well as values of the hydraulic and morphometric variables described. Such characteristics were associated with high transient hydraulic storage volume and low storage exchange rates in streams of my study.

A study of particulate organic matter retention similar to that of Speaker et al. (1985) was carried out by Cedarholm and Peterson (1985). These researchers observed a positive correlation between retention of adult Coho Salmon carcasses and the volume of large woody debris in stream reaches of northwestern Washington. In light of the positive correlations I have reported between large woody debris and dead zone fraction or pool volume, it is likely that retention of salmon carcasses would also be related to these variables, had they been measured.

The dead zone modeling parameters I have described may provide useful physical "scalers" for evaluation of the role of hydraulic retention in nutrient dynamics, as previously discussed. They may also provide theoretically sound measures of transient storage volume (nondimensional) and exchange rate (relative volume basis) to which experimental nutrient retention measurements, such as those of Speaker et al. (1984) and Cedarholm and Peterson (1985) could be related.

The values of dead zone volume fraction (a_L) and dead zone exchange coefficient (δ) obtained for various discharges in the stream reaches of my study suggest the following hypotheses regarding nutrient retention and fish habitat in these Oregon Coast Range streams:

1. In comparison with undisturbed stream reaches, those reaches recently scoured by debris torrents should be less retentive of dissolved and fine particulate nutrient and pollutant materials, due to their low transient storage volumes and high storage exchange rates.
2. The process of recovery from torrent scour should produce an increase in stream nutrient retentivity over time.
3. Large woody debris plays a dominant role in providing the channel structure required to promote high nutrient retentivity in small Oregon Coast Range streams.
4. Streams of complex morphology, which invariably contain abundant large woody debris, retain structural complexity over a wide range of discharge (Figures 25 and 26). They should retain high retentivity for nutrients over this wide range of flows. Similarly, such complex channels should provide low velocity fish habitat even at flood flows. Stream channels simplified in channel structure by debris torrent scouring, on the other hand, may be retentive and may provide low velocity fish habitat at low discharges, but they rapidly lose structural and hydraulic complexity as flows increase.

D. Factors Affecting Stream "Physical Habitat"

Figure 30 is a conceptual description of factors controlling "physical habitat" in small streams of the Oregon Coast Range where debris torrents and floods play an important role. Physical habitat could be described as a combination of channel morphologic and hydraulic characteristics which vary with discharge. In the short term, the hydraulic characteristics of a given channel are, for most flows, controlled by channel morphology. In the long term, however, streamflow largely controls the morphology of the channel through the processes of scour and deposition.

The elements of discharge, slope, sediment and large woody debris, which largely define the physical character of stream channels, are not without external influences and constraints. Both upland and riparian management may influence the inputs of runoff, sediment and large woody debris that interact in the formation of "physical habitat." The major impact of such upland management activities as logging and road building on channel morphology is through their effect upon the frequency and intensity of debris torrents and debris floods. Such events occur naturally at low frequency, usually triggered by high intensity storm precipitation on soils of high antecedent moisture. Torrents play a dominant role in the supply and removal of both sediment and large woody debris in second to fourth order streams in the Oregon Coast Range. They usually remove these materials from first and second order channels. Deposition is more likely as stream gradient decreases downstream. Large streams (fourth order and greater) are not often impacted by torrents running the length of their channels, but may receive wood and sediment inputs from steep side

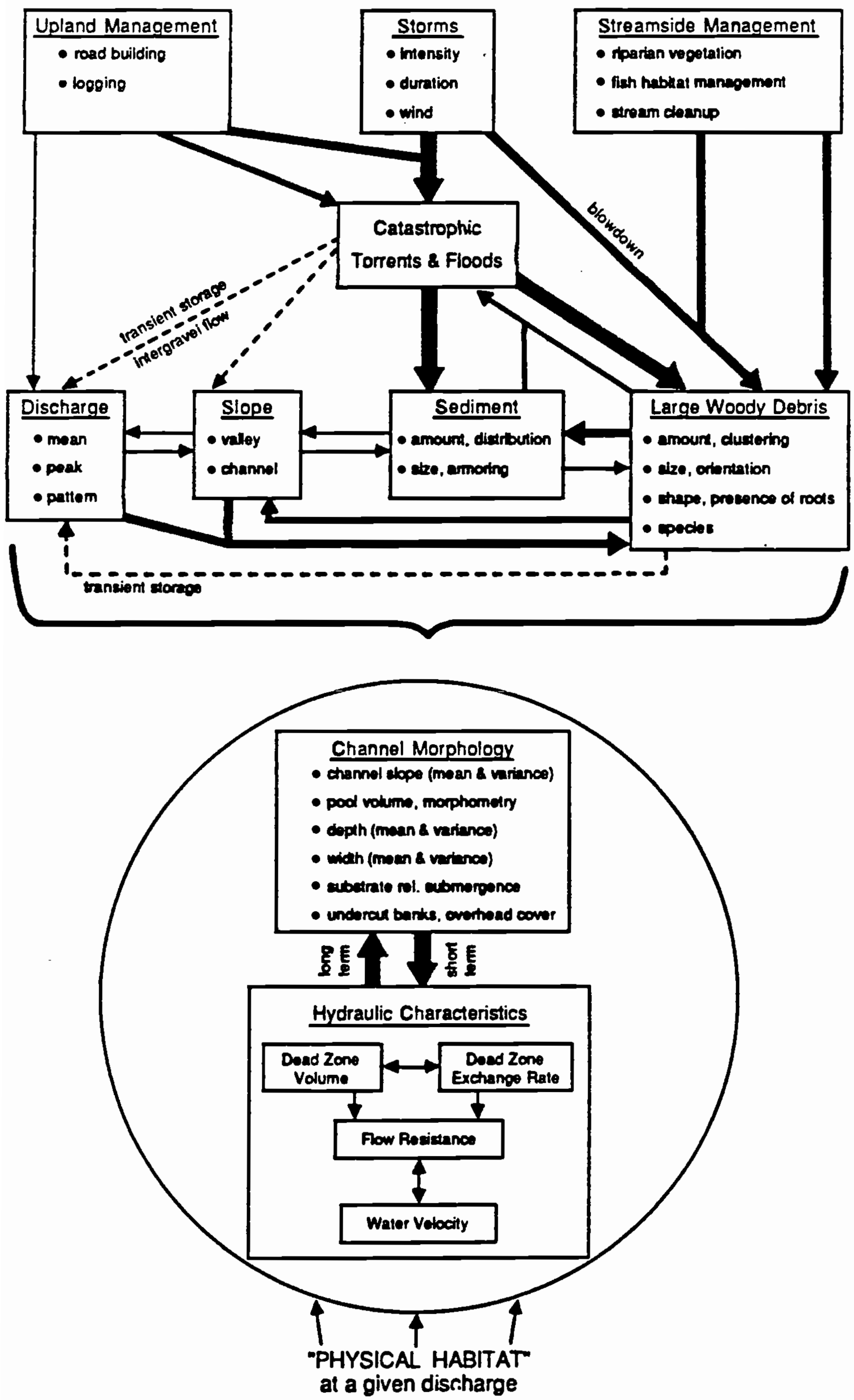


Figure 30. Factors Influencing "Physical Habitat."

tributaries. Management of upland vegetation in locations of high slide potential will not only affect the probability of slope failure, but will largely determine the quantity and size of large woody debris ultimately deposited in stream channels when a slope fails. The presence of at least moderate amounts of large woody debris will enhance the stability of torrent deposits and will promote the rapid recovery of complex channel structure important for anadromous and resident fish. Management of riparian zones will also influence the amount and size of large woody debris in channels before and after torrent passage. The input of large woody debris after torrent scouring will hasten the recovery of structural features of fish habitat.

E. Stream Recovery from Debris Torrent Impacts

The findings of this study prompted me to propose a hypothetical model describing the impacts of debris torrents on stream channel structure and the subsequent recovery of that structure over time. Patterns of recovery for torrent-scoured reaches are reminiscent of those described and hypothesized by Likens and Bilby (1982) for recovery of debris dam frequency and erosion control following logging near various sizes of streams in the White Mountains of New Hampshire. Patterns of riparian revegetation similar to those they describe would control the nature and timing of woody debris input to Oregon Coast Range streams and are a major influence on the recovery process. The following model is strictly applicable only to reaches of 2 to 5 percent gradient in third order forested streams of basaltic geology in the Oregon Coast Range. However, because it is conceptually based on *processes* common to streams in general, many aspects of the model may be applicable to other geoclimatic regions and to different combinations of stream discharge and gradient.

The region and climate determine the size and species of forest vegetation and therefore the nature of large woody debris inputs and the pattern of wood decay. The geoclimatic setting controls bedrock competence and resistance to weathering. These factors, in turn, control the rate and pattern of sediment input, which, in combination with streamflow, determine the amount, size, and shape of bedload particles. The precipitation pattern, discharge, channel structure and stream gradient all influence the initial pattern of torrent scour and deposition as well as the rate and pattern of transport of torrent deposits. In the stream gradient range of 2 to 5 percent, there may likely be one or more cycles of scour and deposition over the length of a given torrent track. The model describes two basic patterns, depending upon whether the initial effect of the torrent was primarily scour or deposition. It also describes differing patterns of recovery depending upon the large organic debris and boulder content of the torrent deposits. Figure 31 is a conceptual illustration of the projected patterns of recovery following the passage of torrents through these types of stream reaches.

1. <u>Recovery in Torrent-Scoured Reaches</u>

   a. The initial effect of torrent scouring is a reduction in channel morphometric complexity, as reflected by decreases in pool volume, smoothing of longitudinal profiles, and reductions in width variance, dead zone fraction and flow resistance. After severe scouring, the channel is straightened, banks are smoothed, boulders may be removed, and large organic debris

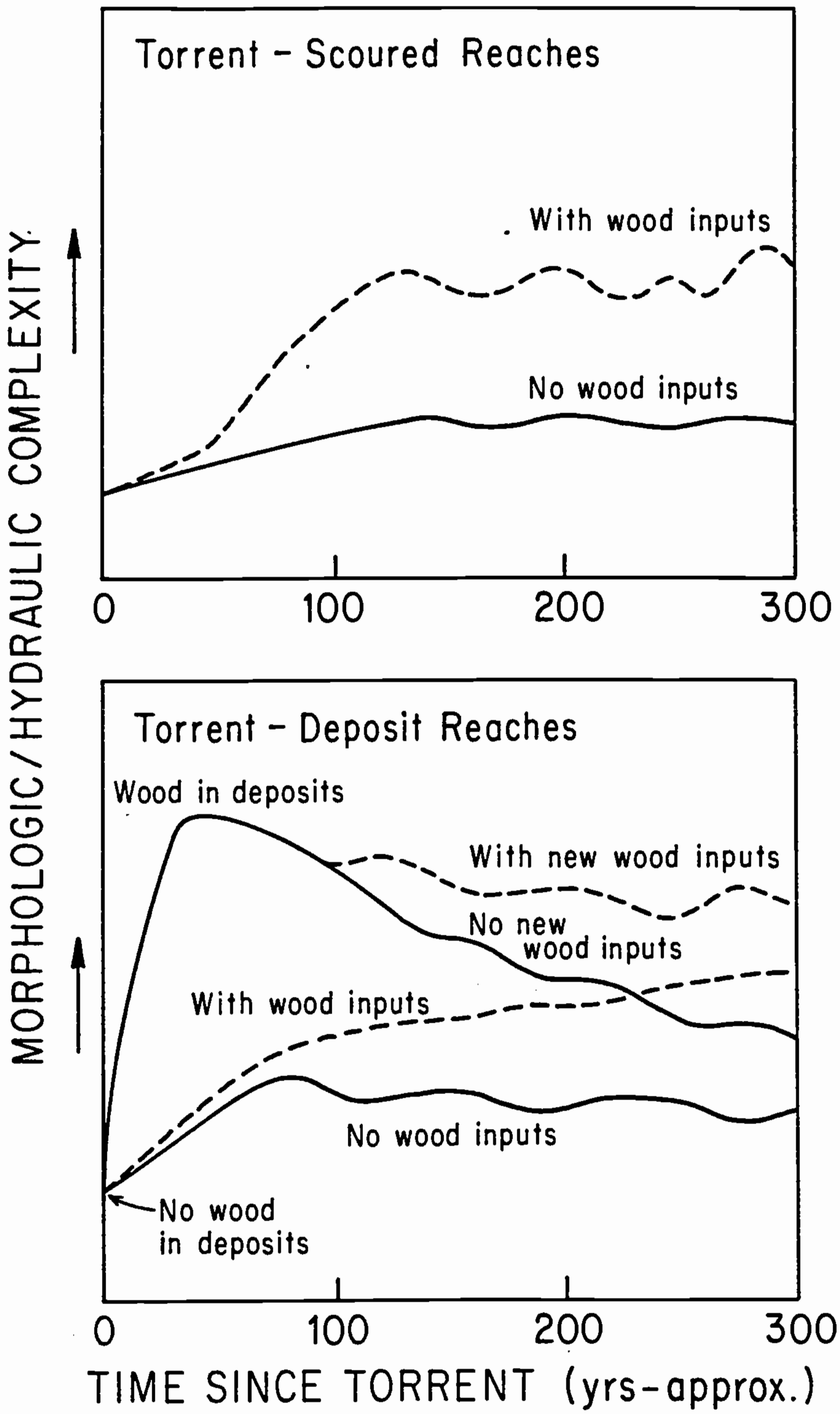


Figure 31. Hypothetical Model of Morphologic/Hydraulic Complexity Following Occurrence of a Debris Torrent.

is either moved downstream or deposited high above the reach of normal flood flows.

b. There is an increase in complexity over time due to sediment inputs and sorting of new and existing sediments by fluvial action.

c. The rate of increase in channel complexity in torrent-scoured channels and the degree of complexity at "equilibrium" are greater if there are large organic debris inputs over time and if these inputs consist of pieces that are large in relation to the size of the channel. The increases in complexity result not only because of the hydraulic effects of the wood itself (flow deflection, constriction and impoundment) but also because of the effect of wood in enhancing the retention and local scouring of sediments.

d. The rate of "recovery" in torrent-scoured channels is also increased by coarse sediment (bedload) input from upstream and from adjacent banks and hillslopes. These coarse materials (gravel, cobbles, boulders) create flow resistance by themselves but, in addition, they also provide the "raw material" from which channel flows and large organic debris deflectors or dams sculpt channel bedforms.

e. The "endpoint" or equilibrium complexity at a given level of woody debris loading is a function of the balance between bedload sediment input and transport rates. In the absence of coarse sediment inputs, channel recovery is largely thwarted. High rates of sediment input, on the other hand, particularly if it consists of fine materials, may eventually decrease channel structural complexity.

f. A longterm continuous or pulsed supply of large woody debris is necessary to maintain channel complexity at levels typical of "undisturbed" or pristine streams in the Oregon Coast Range.

g. Enhancement of complexity by large woody debris placement in torrent-scoured streams is possible if the reaches contain at least some minimum amount of coarse sediment. Substantial increases in pool volume can be realized after one flood season where sufficient gravel substrate is present. Informal observations 2 years after debris placement suggest that efforts taken to actively "construct" pools may not be as successful as those aimed at allowing peak flows to produce pools through scouring of bed materials.

2. Recovery in Torrent-Deposit Reaches

a. The initial effect of torrent deposition on channel structural complexity (as indexed by high values of measures of pool volume, unevenness in elevation profile, variance in width, dead zone fraction, and flow resistance) can be unpredictable, depending upon the pattern of torrent deposition. The initial effect is often the creation of an extensive impoundment. Such impoundments can be greatly reduced through natural breaching. In recent decades, human intervention shortly after the torrent evens has been oriented toward removing the woody debris associated with these impoundments.

b. The presence of large woody debris and boulders on and embedded in the torrent deposits greatly increases channel complexity initially and probably for at least a century hence. Woody debris causes localized scouring of pools and plunges and the presence of dams creates impoundment pools. Boulders cause local scouring during high flows and may create peripheral backwaters.

c. Channel structural complexity may increase for several decades after the torrent, even without embedded woody debris in the deposits. The increases result from the creation of transverse bars, glides, riffles, pools and side channels through sorting and scouring of inorganic deposits. In the absence of large, stable woody debris, however, the aggraded stream channel is likely to widen and braid. Such channels will generally lack large stable pools. The addition of large woody debris through enhancement efforts or through natural recruitment from the riparian zone, however, speeds and enhances the recovery of channel complexity by stabilizing the sediment deposits and creating high quality pools through scour and impoundment. Sustained inputs of stable debris also allow the attainment of a higher "endpoint" complexity.

d. Where large organic debris is present in the initial torrent deposits (or is added through stream enhancement efforts), but a continued supply of wood from the riparian zone is absent, the deterioration of the large wood "superstructure" within the stream reach and the attendant loss of stored sediment gradually causes a decrease in channel complexity. Likens and

Bilby (1982) described a similar progressive loss of stream structure upon deterioration of debris dams in New Hampshire streams following the removal of woody debris sources by logging in the riparian zone.

3. Management Implications of Torrent-Recovery Model

Consideration of the torrent-recovery model presented and the introductory discussion of fish habitat and management impacts leads to the following preliminary conclusions:

a. Torrent scour and deposition usually result in an immediate and massive destruction of fish and fish habitat. However, periodic catastrophic inputs of sediment and large woody debris from torrent deposition are probably necessary to create and maintain the high degree of channel complexity and pool volume desirable for high quality anadromous fish habitat.

b. Stream reaches extensively scoured by debris torrents may take a long time (est. > 100 years) to redevelop the channel structural complexity typical of undisturbed streams. Their recovery is dependent upon coarse sediment inputs and recruitment of large stable woody debris. The likelihood of repeated scouring rather than deposition in the event of another torrent is increased during the recovery time due to the lack of flow-impeding channel structure. The only likely source of sizable woody debris is the adjacent riparian zone, so it should be protected or managed to provide sustained or pulsed long term debris inputs. Addition of structural wood to severely scoured channels in enhancement projects should increase in effectiveness in proportion to the amount and size of large woody debris added and the amount of residual sediment left after torrent scouring.

c. The presence of large woody debris in torrent deposits is necessary for establishing a high degree of channel complexity in the decades immediately following torrent deposition. Thereafter, as woody debris deteriorates, inputs from the riparian zone are necessary to maintain that complexity over time. Recent studies of debris loading by Heimann (1987) indicate that Douglas Fir and Western Red Cedar wood may remain structurally important in streams for over a century. Heimann's work, however, suggested that less resistant woods such as that of Red Alder may deteriorate within years to decades. Sitka Spruce logs remain sound for perhaps one century. Coastal streams in the Sitka Spruce Zone which lack riparian inputs of Western Red Cedar or Douglas Fir wood at least once every 1.5 to 3 centuries may be dependent upon alder and spruce wood for structure. The measurements and observations of Heimann and myself in various Oregon Coast Range streams suggest that relatively undisturbed streams without Western Red Cedar or Douglas Fir tend to lack the woody debris loadings, debris dam stability, and complex channel structure characteristic of relatively "pristine" streams in the Douglas Fir Zone or those in coastal streams with riparian Western Red Cedar. These findings and observations emphasize the importance of streamside riparian zones in supplying a continued or pulsed supply of large (and persistent) woody debris to maintain complexity in their associated stream channels. They also suggest the importance of debris torrents in delivering a pulsed long term supply of decay-resistant wood downstream from Douglas Fir growth in upland areas of the drainages of streams in the Sitka Spruce Zone. Similarly, such torrent-delivered supplies of coniferous woody debris may be important in providing a source of structure for downstream reaches lacking riparian conifers or tree growth in general. From a woody debris supply perspective, streamside riparian wood inputs may be more important in portions of the stream network not likely to receive inputs from torrent deposition. Riparian protection of unstable headwater areas may insure a supply of large woody debris for downstream areas where torrent deposition may eventually occur.

VI. SUMMARY

This study described the morphometry of individual slackwater or pool types and their contribution to aggregate pool volume in stream reaches. Study streams were chosen to represent a time series of recovery time since major torrent scour or deposition in third order forest streams of basaltic geology in the Oregon Coast Range. Randomly chosen reaches, 100 meters in length (30 to 35 channel widths), were selected within each stream recovery class. These reaches were chosen to encompass the variability in channel form, large organic debris loading and degree of scour or deposition found in portions of the streams exhibiting roughly equal gradient and drainage area.

Detailed longitudinal profiles were made of channel width, thalweg depth, thalweg elevation, water velocity, and large woody debris. Qualitative channel features, particularly various types of slackwater features, were classified and measured, and the probable formative agents of these features were identified (e.g., rootwads, log clusters, bedrock). Hydraulic tracers were used to measure reach mean transit time and to obtain plots of tracer concentration versus time. The hydraulic resistance of each reach was calculated from transit time and channel morphology. Dead zone dispersion modeling parameters were back-calculated from the tracer concentration-time plots. Total reach hydraulic resistance and dead zone volume fraction were related to measures and indices of aggregate pool volume and channel morphometric variability over the reaches. The major findings of the study were as follows:

1. Dead zone volume fraction, as calculated from dye dispersion data, showed close positive correlated with morphometric measures and indices of pool volume in reaches. It was also positively correlated with measures of flow resistance, but less sensitive to discharge than such measures. High pool volume and dead zone volume in study reaches was almost always due to the presence of large Cascade Plunge Pools formed by scouring downstream of large woody debris accumulations (log clusters).
2. Measures and indices of pool volume (including dead zone volume fraction) were positively correlated with the total volume of large woody debris in and near the active channel. There were, however, instances where high pool volume and dead zone volume occurred in the absence of correspondingly high debris volumes. In these cases, large Step Pools formed by the interaction of boulders and bedrock were present.
3. A preliminary equation was developed for estimating flow resistance in complex stream reaches containing such non-uniform flow features as pools, flow constrictions, and plunges. The form of the equation is semi-logarithmic:

$$(8/f)^{0.5} = LN(D/SDD)^{0.92} \quad ,$$

where: f = the dimensionless Darcy-Weisbach friction factor,

D = the mean thalweg depth in a stream reach, and

SDD = the standard deviation of thalweg depth.

This equation was developed from 40 sets of channel and flow measurements and explained 60 percent of the variance in $(8/f)^{0.5}$. Ranges of mean reach channel and hydraulic data were as indicated in Table 13.

Table 13. Range of Morphologic and Hydraulic Characteristics in Channels Used to Drive Flow-Resistance Equation.

Channel/Hydraulic Characteristic	Range			
Discharge	0.019	to	0.11	m^3/s
Transit velocity	0.065	to	0.29	m/s
Gradient (mean)	0.026	to	0.039	
Thalweg depth (mean)	0.12	to	0.27	m
Width (mean wetted)	2.3	to	4.6	m
Width/Thalweg depth (mean)	17	to	29	
Large woody debris	1.0	to	63	m^3/100m reach
Dominant substrate diam.	0.10	to	0.35	m
D/SDD	1.5	to	5.3	
f (grain resistance)	0.7	to	4.0	
f (total)	2.0	to	87	

Limited tests on other streams, including one with substantially higher gradient (0.083) and one with substantially greater discharge (0.62 m^3/s), indicated that the equation was a relatively good predictor of flow resistance.

4. Among the three study streams, the greatest reach pool volume, dead zone volume, and channel morphometric variability occurred in torrent deposit reaches of Cape Creek, the stream representing an "intermediate" torrent recovery stage (12 years). Torrent scour reaches of Gwynn Creek, in early stages of recovery (2 years), had the lowest pool volume, dead

zone volume, and channel morphometric variability. The relatively undisturbed reaches of Little Cummins Creek (120 years since torrent) showed pool volume, dead zone volume, and morphometric variability intermediate between Cape and Gwynn Creeks. Pool volume and channel complexity in Little Cummins were affected by local events of scour and deposition which influenced the amount of sediment and large woody debris within short lengths along the channel.

5. The effect of torrent scouring was to reduce pool volume, dead zone fraction and channel morphometric variability. The effect of torrent deposition and subsequent local reworking of these sediments by the stream was to increase pool volume, dead zone fraction, and morphometric variability. This effect was particularly enhanced when torrent deposits contained large woody debris and boulders.
6. The rank order of mean pool volumes and maximum depths of the three largest pool types was: Cascade Plunge Pool, Vertical Scour Pool, and Lateral Scour Pool. Cascade Plunge Pools, however, had a mean volume over 4 times that of Vertical Scour Pools, and a mean maximum depth over twice as great.
7. The rank order of effectiveness of formative agents in producing large pools was, in decreasing order: log clusters, rootwads, bedrock, boulders, single logs, and cobbles.
8. In terms of their contribution to the total stream reach residual pool volume, the relative importance of pool formative agents varied with time since torrent disturbance and degree of aggradation. Bedrock, cobbles, log clusters, and single logs

contributed about equally to the small total residual pool volume in reaches recently scoured by a torrent (Gwynn Creek). Log clusters and boulders dominated in two reaches of Cape Creek where logs and sediment were deposited by a torrent and in two reaches where boulders occurred as lag deposits. Bedrock and log clusters contributed about equally to total residual pool volume in Little Cummins Creek, a stream unaffected by major debris torrents for about 120 years.

REFERENCES CITED

Abd El-Hadi, N. D., and K. S. Davar. 1976. Longitudinal dispersion for flow over rough beds. ASCE J. Hydraulics Div. 102(HY4):483-498.

Allen, K. R. 1969. Limitations on production in salmonid populations in streams, p. 3-18 . IN: Northcote, T. G. (Editor), Proc. Symp. on Salmon and Trout in Streams. H. R. MacMillan Lectures in Fisheries, 1968, Feb. 22-24. Univ. of British Columbia, Vancouver, B.C. 388 p.

Armantrout, N. B. 1981. Aquatic Habitat Inventories...the current situation, pp. 7-9. IN. Armantrout, N. D. (Editor), Acquisition and Utilization of Aquatic Habitat Inventory Information. Proc. Symp. Am. Fish. Soc., Portland, Oregon.

Barnett, D. 1982. File entry on Gwynn Creek debris flood. USDA Forest Service, Siuslaw Natl. Forest, Waldport District, 1 p.

Bathurst, J. C. 1978. Flow resistance of large-scale roughness. ASCE J. Hydraulics. Div., 104(HY12): pp. 1587-1603.

Bathurst, J. C. 1981. Discussion of bar resistance of gravel-bed streams. ASCE J. Hydraulics. Div., 107:1276-1278.

Bathurst, J. C. 1985. Flow resistance estimation in mountain rivers. ASCE J. Hydraulics. Div., 111(4):625-643.

Bathurst, J. C., Ruh-Ming Li, and D. B. Simons. 1979. Hydraulics of mountain rivers. Colorado State University Experiment Station Report CER78-79JCB-RML-DB555, Fort Collins, Colorado. 229 pp.

Bathurst, J. C., Ruh-Ming Li, and D. B. Simons. 1981. Resistance equation for large-scale roughness. ASCE J. Hydraulics. Div., 107:1276-1278.

Beltaos, S. 1980a. Longitudinal dispersion in rivers. ASCE J. Hydraulics Div. 106(HY1):151-172.

Beltaos, S. 1980b. Transverse mixing tests in natural streams. ASCE J. Hydraulics Div. 106(HY10):1607-1625.

Beltaos, S. 1982. Dispersion in tumbling flow. ASCE J. Hydraulics. Div., 108(Hy4):591-612.

Bencala, K. E., and R. A. Walters. 1983. Simulation of solute transport in a mountain pool-and-riffle stream: a transient storage model. Wtr. Resour. Res. 19(3):718-724.

Benda, L. E. 1985. Influence of debris flows on channel morphology in a mountain basin. Proc. 33rd Annual Meeting N. American Benthological Society, Corvallis, Oregon.

Beschta, R. L. 1978. Inventorying small streams and channels on wildland watersheds. pp. 104-113 IN: Proc. National Workshop on Integrated Inventories of Renewable Natural Resources, Tucson, AZ. USDA Forest Service, Gen. Tech. Rep. RM-55.

Beschta, R. L. 1979. Debris removal and its effect on sedimentation in an Oregon Coast Range stream. Northwest Science 53:71-77.

Beschta, R. L. 1983. The effects of large organic debris upon channel morphology: a flume study, pp 8-63 to 8-78. Proc. D. B. Simons Symposium on Erosion and Sedimentation. Fort Collins, Colorado.

Bilby, R. E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62(5):1234-1243.

Bilby, R. E., unpublished data.

Bilby, R. E., and G. E. Likens. 1979. Effect of hydrologic fluctuations on the transport of fine particulate organic carbon in a small stream. Limnol. Oceanogr. 24(1):69-75.

Bilby, R. E., and G. E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61(5):1107-1113.

Bisson, P. A., J. L. Nielsen, R. A. Palmason, and L. E. Grove. 1981. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow, p. 62-73. IN: N. B. Armantrout (Editor), Acquisition and Utilization of Aquatic Habitat Inventory Information, Proc. Symp. Am. Fish. Soc., Portland, OR.

Brown, B. 1982. *Mountain in the clouds*. Simon and Schuster, Inc., New York. 249 p.

Brown, G. W. 1980. Forestry and water quality. Oregon State University, Bookstores, Inc., Corvallis, Oregon.

Brown, G. W., A. R. Gahler, and R. B. Marston. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. Water Resour. Res. 9(5):1450-1453.

Bryant, M. D. 1980. Evolution of large, organic debris after timber harvest; Maybeso Creek, 1949 to 1978. Gen Tech. Rep. PNW-101, USDA Forest Service, PNW Range & Experiment Station. 300 pp.

Bustard, D. R. 1983. Queen Charlotte Islands stream rehabilitation studies--a review of potential techniques. Fish/Forestry Interaction Program, Working Paper 8/83. British Columbia Ministry of Forests, British Columbia Ministry of Environment, Canada, Dept. of Fisheries and Oceans. 31 p.

Bustard, D. R., and D. W. Narver. 1975a. Aspects of the winter ecology of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). J. Fish. Res. Board Can. 32:667-680.

Bustard, D. R., and D. W. Narver. 1975b. Preferences of juvenile coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Salmo clarkii*) relative to simulated alteration of winter habitat. J. Fish. Res. Board Can. 32:681-687.

Calkins, D. and T. Dunne. 1970. A salt tracing method for measuring channel velocities in small mountain streams. J. Hydraulics. 11: 379-392

Cedarholm, C. J. and N. P. Peterson. 1985. The retention of Coho salmon (*Oncorhynchus kisutch*) carcasses by organic debris in small streams. Can. Journ. Fish. Aquat. Sci. 42:1222-1225.

Chamberlin, T. W. 1982. Influence of forest and rangeland management on anadromous fish habitat in western North America, 3. Timber harvest. Gen.Tech. Rep. PNW-136. USDA Forest Service, PNW For. Range Exp. Stn. 30 p.

Chapman, D. W. 1966. Food and space as regulators of salmonid populations in streams. The American Naturalist 100:345-357.

Chapman, D. W., and T. C. Bjornn. 1969. Distribution of salmonids in streams, with special reference to food and feeding, pp. 153-176. IN: T. G. Northcote (Editor), Proc. Symp. on Salmon and Trout in Streams. H. R. MacMillan Lectures in Fisheries. Univ. of British Columbia, Vancouver. 388 p.

Chatwin, P. C. 1971. On the interpretation of some longitudinal dispersion experiments. J. Fluid Mech. 48(4):689-702.

Chatwin, P. C. 1980. Presentation of longitudinal dispersion data. ASCE J. Hydraulics Div. 106(HY1):71-83.

Chow, V. T. 1959. *Open-channel Hydraulics*, McGraw-Hill Book Co., New York, 680 pp.

Cummins, K. W. 1974. Structure and function of stream ecosystems. BioScience 24:631-641.

Cummins, K. W., J. R. Sedell, F. J. Swanson, G. W. Minshall, S. G. Fisher, G. E. Cushing, R. C. Petersen, and R. L. Vannote. 1983. Organic matter budgets for stream ecosystems: problems in their evaluation. IN: Stream ecology: application and testing of general ecological theory. Plenum Press, New York. pp. 299-353.

Dahm, C. N. 1984. Uptake of dissolved organic carbon in mountain streams. Berh. Internat. Verein. Limnol. 22:1842-1846.

Davies, T. R. and A. J. Sutherland. 1980. Resistance to flow past deformable boundaries. Earth Surface Processes, 5:175-179.

Davies, T. R. and A. J. Sutherland. 1982. Hypotheses for prediction of river channel characteristics. Proc. Symp. for Practical Catchment Mgt., New Zealand Hydrological Soc.

Day, T. J. 1975. Longitudinal dispersion in natural channels. Wtr. Resour. Res. 11(6):909-918.

Day, T. J., and I. R. Wood. 1976. Similarity of the mean motion fluid particles dispersing in a natural channel. Wtr. Resour. Res. 12(4):655-666.

Dietrich, W. E. and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. Z. Geomorph. N. F. Suppl. Bd. 29, p 191-206.

Dingman, S. L. 1984. *Fluvial Hydrology*, W. H. Freeman and Company, USA. 383 pp.

Elwood, J. W., J. D. Newbold, R. V. O'Neill, and W. Van Winkle. 1983. Resource Spiralling: an operational paradigm for analyzing lotic ecosystems. p 3-27, IN T. D. Fontaine, III and S. M. Bartell (Editors), *Dynamics of Lotic Ecosystems*, Ann Arbor Science Pub., Kent, England. 494 p.

Everest, F. H., and P. B. Summers. (in press). The sport fishing resource of the national forests--its extent, recreational use, and value. USDA Forest Service, Washington, D.C.

Everest, F. H., and R. D. Harr. 1982. Influence of forest and rangeland management on anadromous fish habitat in western North America, 6. Silvicultural treatments. Gen. Tech. Rep. PNW-134. USDA Forest Service, PNW For. Range Exp. Stn. Portland, OR. 19 p.

Fischer, H. B. 1966., Longitudinal dispersion in laboratory and natural channels. Ph.D. Thesis, Cal. Inst. Technology, Pasadena, CA. (Report No. KH-R-12).

Fischer, H. B. 1967. The mechanics of dispersion in natural streams. ASCE J. Hydraulics Div. 93(HY6):187-216.

Forward, C. D. 1984. Organic debris complexity and its effect on small scale distribution and abundance of Coho (*Oncorhynchus kisutch*) fry populations in Cornation Creek, British Columbia. Unpublished B.S.F. Thesis, University of British Columbia Forestry Dept., Vancouver, B.C. 60 pp.

Franklin, J. F. and C. T. Dyrness, 1973. Natural vegetation of Oregon and Washington. USDA Forest Service Gen Tech. Rep. PNW-8, PNW Range & Experiment Station, Portland, OR.

Gorman, O. T., and J. R. Karr. 1978. Habitat structure and stream fish communities. Ecology 59(3):507-515.

Hall, J. D., and R. L. Lantz. 1969. Effects of logging on the habitat of Coho salmon and cutthroat trout in coastal streams, p. 355-375. IN: T. G. Northcote (Editor), Proc. Symp. on Salmon and Trout in Streams. H. R. MacMillan Lectures in Fisheries, Univ. British Columbia, Vancouver. 388 p.

Hartman, G. F. 1965. The role of behavior in the ecology and interaction of underyearling coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). J. Fish. Res. Board Can. 22:1035-1081.

Hays, J. R. 1966. Mass transport mechanisms in open channel flow. Ph.D. Thesis, Vanderbilt University, Nashville, Tennessee. 138 p.

Heede, B. H. 1972. Influence of a forest on the hydraulic geometry of two mountain streams. Water Resources Bulletin, AWRA 8(3):523-530.

Heede, B. H. 1976. Mountain watersheds and dynamic equilibrium, pp. 407-420. IN: Proc. of Watershed Management Symp., Amer. Soc. Civil Engr., Irrig. and Drainage Div., Logan, UT.

Heimann, D. 1987. Recruitment Trends and Physical Characteristics of Large Organic Debris in Oregon Coast Range Streams. Master's Thesis, Oregon State University Dept. of Forest Engineering/Hydrology, Corvallis, Oregon. (DRAFT).

Hey, R. D. 1979. Flow resistance in gravel-bed rivers. ASCE J. Hydraul. Div. 105 (HY4):365-379.

Hoar, W. S. 1953. Control and timing of fish migration. Biol. Rev. 28:437-452.

Holmes, E. 1984. Project Proposal for Fish Habitat Improvement at Gwynn Creek. USDA Forest Service file report. Waldport District, Suislaw NF. 2p.

Hubbard, E. F., F. A. Kilpatrick, L. A. Martens, and J. F. Wilson, Jr. 1982. Measurement of time of travel and dispersion in streams by dye tracing. Ch. A9 in Techniques of Water-Resources Investigations of the USGS.

Hynes, H. B. N. 1975. Edgardo Baldi memorial lecture: The stream and its valley. Verh. Internat. Verein. Limnol. 19:1-15.

Johnson, L. 1981. The thermodynamic origin of ecosystems. Can. J. Fish. Aquat. Sci. 38:571-590.

Kaijser, T. 1971. A stochastic model describing the water motion in a river. Nordic Hydrology II, 243-265.

Kalleberg, H. 1958. Observations in a stream tank of territoriality and competition in juvenile salmon and trout (*Salmo salar L.* and *S. trutta L.*). Rep. Inst. Freshwater Res. Drottningholm 39:55-98.

Keller, E. A., and R. J. Swanson. 1979. Effects of large organic material in channel form and fluvial processes. Earth Surface Processes 4:361-380.

Kelsey, H. A. 1982. Hillslope evolution and sediment movement in a forested headwater basin, Van Duzen River, North Coastal California, pp. 86-96. IN: F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston (Editors). Sediment Budgets and Routing in Forested Drainage Basins.Gen. Tech. Rep. PNW-141. USDA Forest Service, PNW For. Range Exp. Stn. Portland, OR. 165 p.

Kirkby, M. J. 1977. Maximum sediment efficiency as a criterion for alluvial channels. IN: K. J. Gregory (Editor), *River Channel Changes*, Wiley and Sons. 450 p.

Langbein, W. B. and L. B. Leopold. 1964. Quasi-equilibrium states in channel morphology. Am. Journ. of Science. 262:782-794.

Larkin, P. A. 1972. Introduction, pp. 11-15. IN: R. C. Simon and P. A. Larkin (Editors), The Stock Concept in Pacific Salmon, H. R. Macmillan Lectures in Fisheries, Univ. British Columbia, Vancouver, B.C.

LeGrand-Marqu, C. and H. Laudelout. 1985. Longitudinal dispersion in a forest stream. J. Hydrol. 78:317-324.

Leopold, L. B., G. M. Wolman, and J. P. Miller. 1964. *Fluvial processes in geomorphology*. W. H. Freeman and Co., San Francisco, CA. 522 pp.

Li, H. W., and C. B. Schreck. 1982. Formulation and validating models of habitat quality for cutthroat trout (*Salmo clarki clarki*) and coho salmon (*Oncorhynchus kisutch*) for Oregon's coastal streams. Oregon Coop. Fish. Res. Univ. Report prepared for U.S. Fish and Wildlife Serv., Habitat Evaluation Program, Oregon State Univ., Corvallis, OR. 69 p.

Likens, G. E., and R. E. Bilby. 1982. Development, Maintenance, and role of organic-debris dams in New England streams, pp. 122-128. IN: Swanson, F. J., Janda, R. J., Dunne, T., Swanston, D. N. (Tech.

Editors), Workshop on sediment budgets and routing in forested drainage basins: Proc. Gen. Tech. Rep. PNW-141, Portland, OR. USDA Forest Service, PNW Range & Experiment Station. 165 p.

Lisle, T. E. (in press) Effects of woody debris on anadromous salmonid habitat. N. Am. Journ. Fish. Mgt.

Lisle, T. E. 1982. Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, Northwestern California. Wtr. Resour. Res. Vol 18, No. 6. 1643-1651.

Lyons, J. K., and R. L. Beschta. 1983. Land use, floods, and channel changes: upper middle fork Willamette River, Oregon (1936-1980). Wtr. Resour. Res. 19:463-471.

Madej, M. A. 1982. Sediment transport and channel changes in an aggrading stream in the Puget Lowland, Washington, pp. 97-108. IN: F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston (Editors). Sediment Budgets and Routing in Forested Drainage Basins. Gen. Tech. Rep. PNW-141, USDA Forest Service, PNW For. Range Exp. Stn., Portland, OR. 165 p.

McFadden, J. T. 1969. Dynamics and regulation of salmonid populations in streams, pp. 313-319. IN: T. G. Northcote (Editor). Proc. Symp. on Salmon and Trout in Streams, H. R. MacMillan Lectures in Fisheries. Univ. British Columbia, Vancouver. 388 p.

McQuivey, R. W., and T. N. Keefer. 1976. Convective model of longitudinal dispersion. ASCE J. Hydraulics Div. 102(HY10):1409-1424.

Meehan, W. R., F. J. Swanson, and J. R. Sedell. 1977. Influences of riparian vegetation on aquatic ecosystems with particular reference to salmonid fishes and their food supply, pp. 137-145. IN: Importance, Preservation, and Management of Riparian Habitat: A Symposium. Tucson, AZ. USDA Forest Service, Washington, D.C.

Moeller, J. R., G. W. Minshall, K. W. Cummins, R. C. Peterson, C. E. Cushing, J. R. Sedell, R. A. Larson, and R. L. Vannote. 1979. Transport of dissolved organic carbon in streams of differing physiographic characteristics. Organic Geochemistry 1:134-150.

Moore, K. M. and S. V. Gregory. 1985. The role of edge habitats in headwater streams. Proc. 33rd annual meeting, N. American Benthological Society, Corvallis, OR.

Moring, J. R., and R. L. Lantz. 1974. Immediate effect of logging on the freshwater environment of salmonids. Project Report AFS-58. Oregon Wildlife Commission, Portland. 101 p.

Morisawa, M. 1968. *Streams, their dynamics and morphology*. McGraw-Hill Book Company, New York. 175 p.

Mundie, J. H. 1969. Ecological implications of the diet of juvenile coho in streams, pp. 135-152. IN: T. G. Northcote (Editor) Proc. Symp. on Salmon and Trout in Streams. H. R. MacMillan Lectures in Fisheries, Univ. British Columbia, Vancouver. 388 p.

Naiman, R. J., and J. R. Sedell. 1979a. Benthic organic matter as a function of stream order. Oregon. Arch. Hydrobiol. 87(4):404-472.

Naiman, R. J., and J. R. Sedell. 1979b. Characterization of particulate organic matter transported by some Cascade Mountain streams. J. Fish. Res. Board Can. 36(1):17-31.

Nordin, C. F. and B. M. Troutman. 1980. Longitudinal dispersion in rivers: the persistence of skewness in observed data. Wtr. Resour. Res. 16(1):123-128.

Oregon Dept. of Fish and Wildlife, Fisheries Division. 1981. Comprehensive plan for production and management of Oregon's anadromous salmon and trout. Part II: Coho Salmon Plan. Oregon Dept. Fish and Wildlife, Portland. 188 p.

Parker, G. and A. W. Peterson. 1980. Bar resistance of gravel-bed streams. ASCE J. Hydraul. Div. 106 (HY10):1559-1575.

Pedersen, F. B. 1977. Prediction of longitudinal dispersion in natural streams. Series Paper 14, Institute of Hydrodynamics and Hydraulic Engineering, Technical Univ. of Denmark, 69 pp.

Platts, W. S., W. F. Megahan, and G. W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. Gen. Tech. Rep. INT-138. USDA Forest Service, Intermountain For. Range Exp. Stn., Ogden, UT. 70 p.

Prigogine, I. 1978. Time, Structure, and Fluctuations. Science 201:777-785.

Reid, L. M. 1982. Evaluating and mapping sources and temporary storage areas of sediment, pp. 138-142. IN:. F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston (Editors), Sediment Budgets and Routing in Forest Drainage Basins. Gen. Tech. Rep. PNW-141. USDA Forest Service, PNW For. Range Exp. Stn., Portland, OR. 165 p.

Reiser, D. W., and T. C. Bjornn. 1979. Influence of forest and rangeland management on anadromous fish habitat in western North America, 1. Habitat requirements of anadromous salmonids. Gen. Tech. Rep. PNW-96. USDA Forest Service, PNW For. Range Exp. Stn., Portland, OR. 54 p.

Ruth, R. H. 1954. Cascade Head climatological data 1936 to 1952. USDA Forest Service, PNW Range & Experiment Station, Portland, Oregon. 29 p.

Sabol, G. V., and C. F. Nordin, Jr. 1978. Dispersion in rivers as related to storage zones. ASCE J. Hydraulics Div. 104(HY5):695-708.

Sabol, G. V., and C. F. Nordin, Jr. 1981. Dispersion in Rivers as Related to Storage Zones--Closure. ASCE J. Hydraulics Div. 107(HY6):779-783.

Sayre, W. W. 1967. Dispersion of mass in open-channel flow. Ph.D. Thesis, Colorado State Univ., Fort Collins, CO. 192 p.

Schlicker, H. G., R. J. Deacon, G. W. Olcott and J. D. Beaulieu. 1973. Environmental geology of Lincoln County, Oregon. Department of Geology and Mineral Industries, Bulletin 81. 171 pp.

Schlicker, H. G., R. J. Deacon. 1974. Environmental geology of coastal Lane County, Oregon. Department of Geology and Mineral Industries, Bulletin 85, 116 pp.

Sedell, J. R. and J. L. Froggatt. 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verh. Internat. Verein, Limnol. 22:1828-1834.

Sedell, J. R. and W. S. Duval. 1985. Influence of forest and rangeland management on anadromous fish habitat in western North America: water transportation and storage of logs. USDA Forest Service. Gen Tech. Rep. PNW-186, Portland, OR. 68 pp.

Sedell, J. R., and K. J. Luchessa. 1982. Using the historical record as an aid to salmonid habitat enhancement, pp. 210-223. IN: N. B. Armantrout (Editor), Acquisition and Utilization of Aquatic Habitat Inventory Information. Proc. Symp., Amer. Fish. Soc. Portland, OR.

Sedell, J. R., F. H. Everest, and F. J. Swanson. 1981. Fish habitat and streamside management: past and present. Proc. 1981 Conference, Society of American Foresters.

Sedell, J. R., R. J. Naiman, K. W. Cummins, G. W. Minshall, and R. L. Vannote. 1978. Transport of particulate organic material in streams as a function of physical processes. Verh. Internat. Verein. Limnol. 20:1366-1375.

Shields, F. D., Jr. and N. R. Nunnally. 1983. Environmental aspects of clearing and snagging. ASCE J. of Envir. Engr. 109(5):152-165.

Simons, D. B. and E. V. Richardson. 1966. Resistance to flow in alluvial channels. USGS Prof. Paper 422J. 61 pp.

Simons, D. B. and F. Senturk. 1977. Sediment transport technology, Water Resources Publications, Fort Collins, Colorado. 807 pp.

Speaker, R., K. Moore, and S. Gregory. 1984. Analysis of the process of retention of organic matter in stream ecosystems. Verh. Internat. Verein. Limnol. 22:1835-1841.

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. American Geophysical Union, Transactions 38(6): 913-920.

Summers, R. P. 1983. Trends in riparian vegetation regrowth following timber harvesting in western Oregon watersheds. M.S. Thesis, Oregon State University, Corvallis, OR. 151 p.

Swanson, F. J. 1979. Geomorphology and ecosystems. IN R. W. Waring (Editor), Forest: Fresh perspectives from ecosystem analysis. Proc. 40th Annual Biology Coloquium, Oregon State University, Corvallis, OR.

Swanson, F. J. and C. T. Dyrness. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3:393-396.

Swanson, F. J. and G.W. Lienkaemper. 1978. Physical Consequences of Large Organic Debris in Northwest Streams. Oregon State University, Corvallis, OR. 14 pp.

Swanson, F. J. and Swanston, D. N. 1977. Complex mass-movement terrains in the western Cascade Range, Oregon, pp. 199-221. IN: D. R. Coates (Editor), *Geomorphology and engineering*. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, PA.

Swanson, F. J., G. W. Lienkaemper, and J. R. Sedell. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. USDA Forest Service, Gen. Tech. Report PNW-56. PNW For. Range Exp. Stn., Portland, OR. 24 p.

Swanston, D. N., and Swanson, F. J. 1976. Timber harvesting, mass erosion, and stepland forest geomorphology in the Pacific Northwest. IN D. R. Coates (Editor), *Geomorphology and engineering*, Dowden, Hutchinson, and Ross, Inc., Stroudsburg, PA. p. 199-221.

Thackson, E. L., and Schnelle, K. B., Jr. 1970. Predicting effects of dead zones on stream mixing. ASCE J. San. Engr. Div. 96(SA2):319-331.

Thompson, S. M. and P. L. Campbell. 1979. Hydraulics of a large channel paved with boulders. Journal of Hydraulic Research, 17(4):341-354.

Thorne, C. R. and L. W. Zevenbergen. 1985. Estimating mean velocity in mountain rivers. J. Hydraulic Engr. 111(4):612-624.

Triska, F. J. 1984. Role of wood debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: A historical case study. Verh. Internat. Verein. Limnol. 22:1876-1892.

Triska, F., and J. Sedell. 1975. Accumulation and processing of fine organic debris. IN: Debris in streams: Workshop I. Oregon State Univ., Corvallis, OR. 12 pp.

Tschaplinski, P. J., and G. F. Hartman. 1983. Winter distribution of juvenile coho salmon (*Oncorhynchus kisutch*) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Can. J. Fish Aquat. Sci. 40:452-461.

U. S. Weather Bureau. 1960. Climates of the States, Oregon. Climatography of the United States. 60-35. 20 p.

Valentine, E. M., and I. R. Wood. 1977. Longitudinal dispersion with dead zones. ASCE J. Hydraulics Div. 103(HY9):975-990.

Valentine, E. M., and I. R. Wood. 1979a. Experiments in longitudinal dispersion with dead zones. ASCE J. Hydraulics Div. 105(HY8):999-1016.

Valentine, E. M., and I. R. Wood. 1979b. Dispersion in rough rectangular channels. ASCE J. Hydraulics Div. 105(HY12):1537-1553.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Can. J. Fish Aq. Sci. 37(1):130-137.

Waters, T. W. 1969. Invertebrate drift ecology and significance to stream fishes, pp. 121-134. IN: T. G. Northcote (Editor), Proc. Symp. on Salmon and Trout in Streams. H. R. MacMillan Lectures in Fisheries, Univ. British Columbia, Vancouver. 388 pp.

Webster, J. R. 1975. Analysis of potassium and calcium dynamics in stream ecosystems on three southern Appalachian watersheds in contrasting vegetation. Ph.D. thesis, Univ. of Georgia, Athens.

Webster, J. R., J. B. Waide, and B. C. Patten. 1975. Nutrient cycling and the stability of eco-systems, pp. 1-27. IN: F. G. Howell, J. B. Gentry, and M. H. Smith (Editors), Mineral Cycling in Southeastern Ecosystems. ERDA (CONF-740513).

Wilzbach, M. A. 1985. Relative roles of food abundance and cover in determining the habitat distribution of stream-dwelling Cutthroat Trout (*Salmo clarki*). Can. J. Fish-Aquat. Sci., 42:1668-1672.

Yang, C. T. 1971a. Potential energy and stream morphology. Wtr. Resour. Res. 7(2):311-322.

Yang, C. T. 1971b. On river meanders. J. Hydrol. 13:231-253.

Yang, C. T. 1971c. Formation of riffles and pools. Wtr. Resour. Res. 7(6):1567-1574.

Yang, C. T. 1972. Unit stream power and sediment transport. ASCE J. Hydraul. Div. 98(HY10):1804-1826.

Yang, C. T., C. C. S. Song, and M. J. Woldenberg. 1981. Hydraulic geometry and minimum rate of energy dissipation. Wtr. Resour. Res. 17(4):1014-1018.

APPENDICES

APPENDIX A

Summaries of:

- General Longitudinal Dispersion Model
- Dead-Zone Dispersion Model (Hays, 1966)
- Dead-Zone Dispersion Model (Sobol & Nordin, 1978)

APPENDIX A -- Summaries of Tracer Dispersion Models

1. General One-Dimensional Longitudinal Dispersion Model ("Fickian Dispersion")

The following is modified from Chatwin (1980):

$$\frac{\partial}{\partial t}(AC) = -\frac{\partial}{\partial x}(AUC) + \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) \qquad \text{(EQ 1)}$$

where:

t = time since release of tracer

x = downstream distance from point of tracer release

A = channel cross-sectional area

C = cross-sectional tracer concentration

U = cross-sectional mean downstream velocity ("advective" velocity downstream)

D = longitudinal dispersion coefficient

The general expression can be simplified to allow analytical solution by employing certain restrictions.

Restrictions on the model:

a) A sufficiently long time has elapsed since release of the dispersant so that the dispersant mass has had adequate opportunity to "sample" the full range of streamflow velocities in a reach.

b) The flow cross section is independent of x and t.

c) The turbulence is stationary in time and homogeneous along the length of the reach.

d) The dispersant is passive, i.e., it has no effect on the flow of water.

When the above conditions can be assumed, the following simplification is possible:

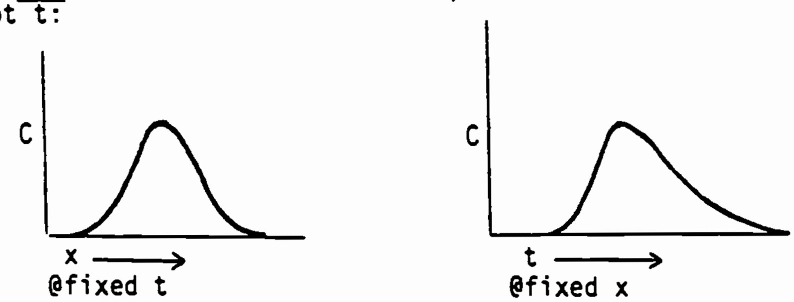
$$\frac{\partial C}{\partial t} = -\frac{\partial}{\partial x}(UC) + \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) \qquad \text{(EQ 2)}$$

The conditions listed on the previous page are also exactly those which insure that C is Gaussian with respect to x. Therefore, an analytical solution of EQ 2 can be stated, with suitable choices for the origins of x and t:

$$C_{(x,t)} = \frac{M}{2A(\pi Dt)^{1/2}} \exp\left[-\frac{(x-Ut)^2}{4Dt}\right] \qquad \text{(EQ 3)}$$

where M = total mass of dispersant.

Note that the estimated profile of concentration is Gaussian with respect to x but <u>not</u> t. Skewness arises when profiles are measured at fixed values of x, not t:



2. <u>Dead Zone Dispersion Model of Hays (1966)</u>

The following summary is modified from Hays (1966) and Thackston and Schnelle (1970):

$$\frac{\partial C_a}{\partial t} = D_a\left(\frac{\partial^2 C_a}{\partial x^2}\right) - \bar{U}\left(\frac{\partial C_a}{\partial x}\right) + Ka(C_a - C_d) \qquad \text{(EQ 4a)}$$

$$\frac{\partial C_d}{\partial t} = Kd(C_a - C_d) \qquad \text{(EQ 4b)}$$

where: C_a = avg. cross-sectional conc. in main stream

C_d = avg. cross-sectional conc. in dead zone

D_a = dispersion coefficient in main stream

Ka = volume-based mass transfer coeff. in main stream

Kd = volume-based mass transfer coeff. in dead zone

$\bar{U}$ = average velocity in main stream

t = time elapsed since release of tracer

x = downstream distance from point of tracer release

Assume a mass M of tracer is released into the main stream at x = 0 and concentration $C_{(x=0,\ t=0)} = L$:

<u>Initial Conditions</u>: $C_{a(x,o)} = \frac{M}{A_a}\ \delta(x)$

$C_{d(x,o)} = 0$

<u>Boundary Conditions</u>: $x = \infty$

$C_{a(x,t)} = \text{finite}$

where: A_a = cross-sectional area of main stream

A_d = cross-sectional area of the dead zone (used later)

$\delta_{(x)}$ = Dirac or delta function

Hays (1966) gives the following solution for this set of equations employing a LaPlace transformation (allows calculation of a profile of.mainstream concentration over time at a fixed downstream position L):

$$C_a(L,s) = \frac{\frac{M}{A_a}\left\{\exp(\bar{U}-[\bar{U}^2+4D_a(1+(\frac{A_d}{A_a})\Psi)^{\frac{1}{2}}s](\frac{L}{2D_a})\right\}}{\left\{\bar{U}^2+4D_a[1+(\frac{Ad}{Aa})\psi]s\right\}^{\frac{1}{2}}} \qquad \text{(EQ 5)}$$

$$\text{where: } \Psi = \frac{1}{\frac{s}{Kd}+1} \qquad \text{(EQ 6)}$$

s = the LaPlace variable

The LaPlace transformation solution above (EQ 5) can be simplified by defining physically meaningful parameters that are combinations of the variables in the equation. The following combinations were used by Hays (1966):

The average residence time of a particle entering the dead zone is defined as T_d:

$$T_d = \frac{1}{K_d} \qquad \text{(EQ 7)}$$

The average (over reach length L) mainstream volume fraction is defined as α:

$$\alpha = \frac{A_a}{A_a+A_d} \qquad \text{(EQ 8)}$$

The average (over reach length L) dead zone volume fraction is defined as β:

$$\beta = \frac{A_d}{A_a + A_d} \qquad \text{(EQ 9)}$$

The average residence time of a particle in the mainstream in the absence of a dead zone or velocity field longitudinal dispersion is defined as T_v:

$$T_v = \frac{L}{\bar{U}} \qquad \text{(EQ 10)}$$

The average residence time of a particle in the mainstream if transported by velocity field dispersion only is T_{dp}:

$$T_{dp} = \frac{5}{12}\frac{L^2}{D_a} = \frac{L^2}{2D_a} \qquad \text{(EQ 11)}$$

The average residence time in the entire stream is T:

$$T = \frac{L(A_a + A_d)}{\bar{U}A_a} = \frac{L}{\bar{U}\alpha} \qquad \text{(EQ 12)}$$

The ratio of the average residence time by advective transport to the average residence time by velocity field dispersion is τ:

$$\tau = \frac{L/\bar{U}}{L^2/2D_a} = \frac{2Da}{L\bar{U}} = \frac{2}{Pe} \qquad \text{(EQ 13)}$$

where: $Pe = L\bar{U}/D_a$ = the Peclet number (EQ 14)

The ratio of the average residence time in the dead zone to the average residence time in the entire reach is τ_d:

$$\tau_d = \frac{T_d}{T} = \frac{1/K_d}{L(A_a + A_d)/\bar{U}A_a} \qquad \text{(EQ 15)}$$

Substitution of Equations7, 8, 9, 12, 13, and 15 into Equations 5 and 6 yields the following expression of the analytical solution:

$$C_{a(L,S)} = \frac{M}{A_a\bar{U}}\left\{\frac{\exp\left[\dfrac{1-\left[1+\left(\frac{4}{Pe}\right)(\alpha+\beta\psi)S\right]^{1/2}}{2/Pe}\right]}{\left[1+\frac{4}{Pe}(\alpha+\beta\psi)S\right]^{1/2}}\right\} \qquad \text{(EQ 16)}$$

where: the LaPlace variable s is replaced by $S = Ts$

and $\psi = \dfrac{1}{\frac{s}{K_d}+1} = \dfrac{1}{T_d s+1} = \dfrac{1}{T_d Ts+1} = \dfrac{1}{T_d S+1}$ (EQ 17)

3. <u>Dead Zone Storage Model of Sabol and Nordin (1978)</u>

Consider the stream to be divided into an "upper" compartment in which water is moving uniformly at a velocity equal to the convective velocity of the dye tracer cloud, and a "lower" compartment in which the water is at virtually zero velocity.

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

$$C(t,x_i) = f(t,x_i)\left(\frac{W}{\gamma Q}\right)$$

where: e = the base of natural logs

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

$$\pi_2 = a_u \delta$$

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

U = convective velocity = the centroid of the C vs. t curve

a_U = the probability that at a given instant, a particle is in the upper (moving) layer

$a_u = \dfrac{t_L}{t_c} = \dfrac{\text{time from zero to leading edge of tracer cloud @ } X_i}{\text{centroid of the concentration-time distribution}}$

a_L = the probability that a particle is in the lower (zero velocity) layer at a given instant = $1-a_u$

$\sigma_t^2 = \dfrac{2\pi_1}{\pi_2^2} = Var\left[T(x)\right]$, by assumption ("frozen cloud")

$\delta = \dfrac{2a_L x_i}{U a_u \sigma_t^2}$ = the average number of times a particle goes into storage per unit time

W = weight of tracer released

γ = specific weight of dispersant

Q = discharge rate

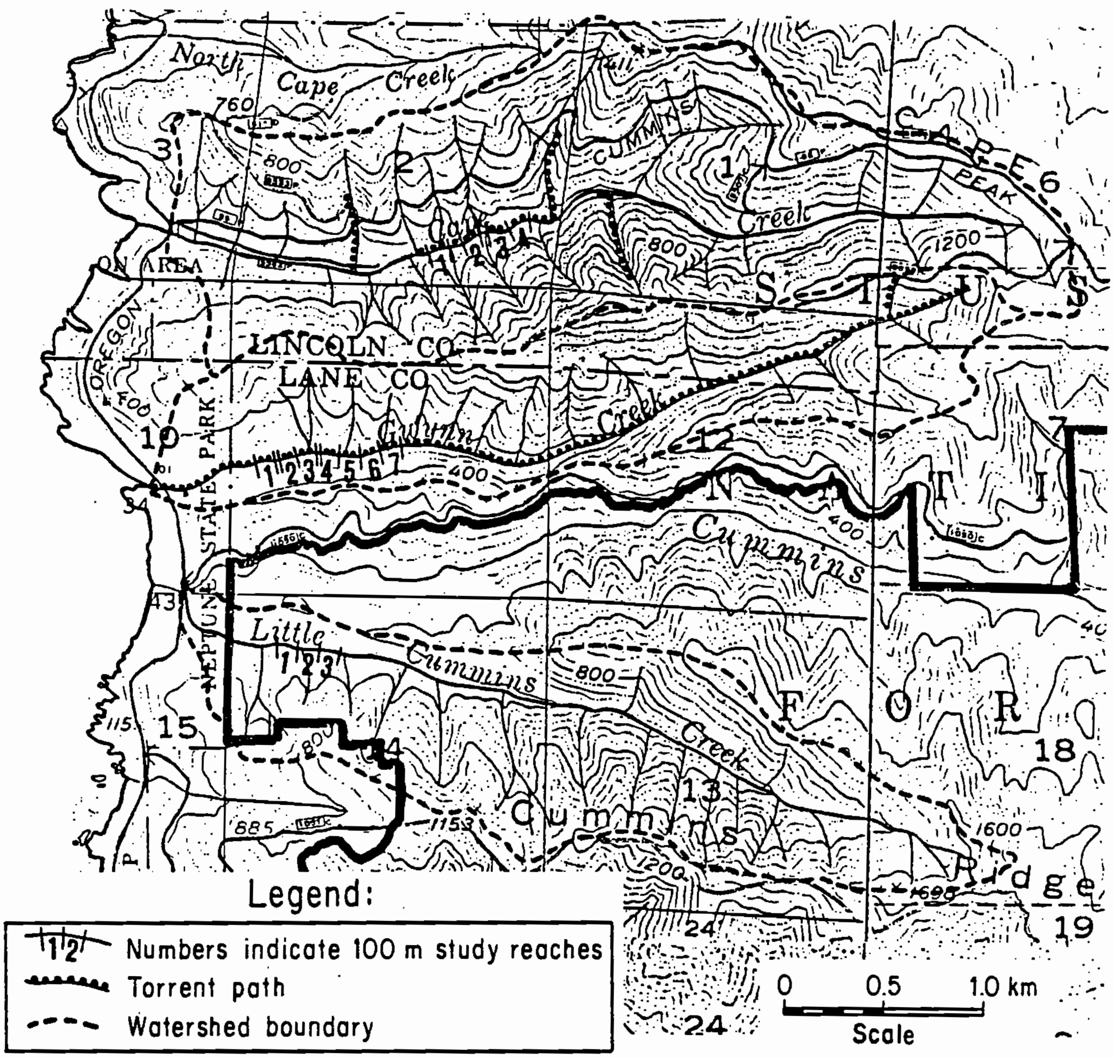
n = numbered occurrence of a tracer particle in the "upper" layer

σ_t^2 = the variance of concentration-time data

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

APPENDIX B

Detailed Site Map



APPENDIX C

Residual Pool Classification[1]

IMPOUNDMENT POOL (I):

Any pool formed primarily by impoundment, with scour absent or playing a minor part.

CASCADE PLUNGE POOL (P):

Usually a large, deep pool formed by scouring downstream of a cascade over organic debris, boulders, or cobbles. Plunge pools often have a downstream portion ("tail out") where relatively fine grained bed material (typically ASCE "Very Coarse Gravel") impounds flow, enhancing pool depth and volume. These tail-out areas are often sites of salmonid spawning.

VERTICAL SCOUR POOL (V):

An area of mid-channel deepening as a result of scouring. Vertical (or downward) scouring usually results when large organic debris spans the channel or when a large boulder causes high flow turbulence. Unlike Cascade Plunge Pools, no plunge or cascade is found immediately upstream of Vertical Scour Pools.

TRENCH POOL (T):

A narrow, elongated, deep section of channel with its deepest portion near the center of the channel. Trench pools in streams of my study were nearly all associated with bedrock constrictions. They were sites of high water velocity during moderate and high discharge.

BACKWATER POOL (B):

This is a catch-all classification for slackwater areas separated from the mainstream by shallow or emergent barriers formed by sediment, bedrock or organic debris. Backwater pools may become main channel pools during stormflows.

---

[1]Modified from Bisson et al., 1981.

STEP POOL (S):

Step Pools, usually found in series, were apparently formed as a result of bed material sorting, unless formed in bedrock. Regularly spaced step pools were found between transverse rows of boulders or large cobbles. There was scouring downstream and impoundment upstream of successive boulder rows. The depth and volume of Step Pools may be greatly enhanced when bedrock constrictions trap boulders or where boulders or bedrock trap large organic debris. Small stepping pools carved in bedrock have been included in this classification.

INTER-COBBLE-ROW POOL (N):

This pool classification is simply a smaller, shallower, shorter version of the Step Pool. Inter Cobble Row Pools are usually formed by sorting of cobbles, rather than boulders. Unlike most Step Pools they would not usually be termed "pools" in fish habitat assessments because their small volume, shallow depths, and relatively greater water velocities provide habitat conditions more similar to glides than pools.

LATERAL SCOUR TRENCH (M):

A narrow deep area along the channel margin, usually in a bend. Lateral Scour Trenches were distinguished from Lateral Scour Pools in this study on the basis of low flow water velocities. Lateral Scour Trenches were relatively swift even at low flows and would not normally be termed "pools."

LATERAL SCOUR POOL (L):

A narrow deep area along the channel margin, usually in a bend. Lateral scour pools, unlike Lateral Scour Trenches, provide "pool" conditions of quiescent, low velocity water during summer low flow. They were often associated with undercut banks, overhanging roots and vegetation cover along the stream margin.

GLIDE (G):

A transition type between riffle and pool conditions, Glides are lower in gradient than are riffles and their water surface is unbroken and relatively smooth. Glides, however, are distinguished from pools in that they do not contain "still" water.

APPENDIX D

Tracer Curve Analysis--Program Listing

```
type b:digiflex.bas
10 CLS
20 PRINT "***********************************************************************
*********"
30 PRINT
40 PRINT "                                   DYE PLOT DIGITIZER"
50 PRINT
60 PRINT "***********************************************************************
*********"
70 CLEAR
75 DIM A (500,6),X(5000),Y(5000)
80 ' A( ,1) = TIME
90 ' A( ,2) = CONCENTRATION = Ct
100 ' H      = MIN/CM ON THE HORIZONTAL SCALE
110 ' V      = Ct/CM  ON THE VERTICAL SCALE
120 ' T      = STARTING TIME IN MINUTES FOR A GIVEN GRAPH
130 ' X()&Y()= X,Y COORDINATES FOR THE DIGITIZED POINTS
140 '
150 '===(INPUTS)===
160 LOCATE 8,1
170 INPUT "ENTER CURVE ID";ID$
180 PRINT
190 INPUT "HOW MANY DIGITIZED POINTS TO DEFINE CURVE? (100, 200, OR 500)";NO
200 'IF NO=100 THEN DIM A(100,6),X(3000),Y(3000)
210 'IF NO=200 THEN DIM A(200,6),X(3000),Y(3000)
220 'IF NO=500 THEN DIM A(500,6),X(3000),Y(3000)
230 PRINT
240 INPUT "DO YOU WISH TO CALCULATE DISCHARGE?";DOG$
250 IF DOG$="N" OR DOG$="n" THEN 320
260 INPUT "ENTER VOL (ml's) OF TRACER SOLN";VOL
270 PRINT
280 INPUT "ENTER CONC (mg/l) OF TRACER SOLN";C
290 PRINT
300 INPUT "ENTER STREAM REACH LENGTH (meters)";L
310 PRINT
320 INPUT "ENTER THE MINUTES PER CM ON THE HORIZONTAL SCALE";H
330 PRINT
340 INPUT "ENTER THE CONC (micrograms/l) PER CM ON THE VERTICAL SCALE";V
350 PRINT
360 INPUT "ENTER THE STARTING TIME (MINUTES) FOR THE GRAPH";T
370 CLS
380 FOR I=8 TO 14: LOCATE I,1: PRINT "
                                       ";NEXT:LOCATE 8,1
390 PRINT "TO DIGITIZE A GRAPH, PLACE THE GRAPH ON THE DIGITIZER BEING CAREFUL T
O ALIGN"
400 PRINT "THE GRAPH AS STRAIGHT AS POSSIBLE.  START BY DEPRESSING THE STYLUS PE
N ON THE"
410 PRINT "POINT MARKING THE START OF THE GRAPH.  LEAVE STYLUS DEPRESSED AND "
420 PRINT "TRACE THE GRAPH FROM RIGHT TO LEFT................................ "
430 PRINT "WHEN YOU REACH THE END OF THE GRAPH, LIFT UP THE PEN. THE PROGRAM "
440 PRINT "WILL THEN ASK IF YOU ARE DONE WITH THAT GRAPH OR WOULD LIKE TO DIGITI
ZE THE "
450 PRINT "NEXT SECTION."
460 PRINT
470 PRINT "PRESS ANY KEY TO CONTINUE"
480 A$=INKEY$:IF A$="" THEN 480
490 SOUND 100,3
500 SOUND 200,3
510 SOUND 300,3
520 CLS
```

```
530 '
540 '===(DIGITIZE GRAPH)===
550 OPEN "COM1:9600,E,7,1,RS" AS #1  'OPENS DIGITIZER LINES
560 '
570 '===(DATA INPUT LOOP)===
580 I=1:XI=T:YI=0          'I IS THE COUNTER, TI STORES THE LAST X-COORD
590 X(0)=0+T : Y(0)=0  'FROM THE PREVIOUS SECTION OF THE SAME GRAPH
600 PRINT #1,CHR$(77)   'THIS STARTS THE STREAM MODE ON THE DIGITIZER
610 INPUT #1,X,Y,Z       'Z=1 WHEN STYLUS IS DEPRESSED
620     IF Z=1 THEN XO=X:YO=Y: ELSE 610
630 INPUT #1,X,Y,Z
640     IF Z=1 THEN X(I)=.0127*(XO-X)*H+XI:Y(I)=.0127*(Y-YO)*V+YI:I=I+1:GOTO 630
650 PRINT #1,CHR$(83)                  'THIS STOPS THE DIGITIZER OUTPUT
660 SOUND 400,1
670 I=I-1 'THIS IS NECESSARY SINCE THE LAST POINT (I) HAS A Z=0
680 PTS=I
690 INPUT "PLOT ANOTHER SECTION OF THE SAME GRAPH Y/N ";ANS$
700 IF ANS$="Y" OR ANS$="y" THEN XI=X(I) : YI=Y(I) : CLS : SOUND 100,3:SOUND 200
,3:SOUND 300,3:GOTO 600
710 CLOSE #1
720 '
730 '===(FIND PEAK CONC AND TIME OF PEAK)===
740 CP=0                                    'CP IS PEAK CONCENTRATION (ug/l)
750 FOR R=1 TO I
760     IF Y(R)>CP THEN TP=X(R) : CP=Y(R)       'TP IS TIME OF PEAK
770 NEXT
780 '
790 '===(CONVERT t AND Ct DATA)===
800 'THE X(I) NUMBERS MUST BE REDUCED TO 100, 200 OR 500 UNITS ON THE TIME AXIS
810 DT=(X(I)-X(0))/NO
820 'TTIME=0+T
830 W=1 : A(0,1)=X(0) : A(0,2) = Y(0)
840 FOR B=1 TO I
850     IF X(B)>=T+W*DT THEN A(W,1)=X(B) : A(W,2)=Y(B) : W=W+1
860 NEXT
870 PRINT "I=";I,"B=";B,"W=";W          'B SHLD =I+1  W SHLD =101 201 501
880 '===(ALIGN THE X-AXIS)===
890 IF NO=100 THEN ADJ=A(100,2)/100     'ADJUSTS Y VALUES SO THEY COME BACK TO ZE
RO
900 IF NO=200 THEN ADJ=A(200,2)/200     'ADJUSTS Y VALUES SO THEY COME BACK TO ZE
RO
910 IF NO=500 THEN ADJ=A(500,2)/500     'ADJUSTS Y VALUES SO THEY COME BACK TO ZE
RO
920 FOR K=0 TO NO
930     A(K,2)=A(K,2)-K*ADJ
940 ' PRINT K,A(K,1),A(K,2)
950 NEXT
960 '
970 '
980 '===(PRODUCE COLUMNS 3,4,5 AND THEIR SUMS)===
990 SUM3=0:SUM4=0:SUM5=0
1000 FOR J=0 TO NO-1
1010     A(J,3) = (A(J,1) + A(J+1,1))/2
1020     SUM3 = SUM3 + A(J,3)
1030     A(J,4) = (A(J,2) + A(J+1,2))/2
1040     SUM4 = SUM4 + A(J,4)
1050     A(J,5) = A(J,3)*A(J,4)
1060     SUM5 = SUM5 + A(J,5)
1070 NEXT
1080 IF NO=100 THEN A(100,3)=A(100,1) : A(100,4)=A(100,2) : A(100,5)=A(100,3)*A(
100,4)
1090 IF NO=200 THEN A(200,3)=A(200,1) : A(200,4)=A(200,2) : A(200,5)=A(200,3)*A(
200,4)
```

```
1100 IF NO=500 THEN A(500,3)=A(500,1) : A(500,4)=A(500,2) : A(500,5)=A(500,3)*A(
500,4)
1110 '===(CALC DEVIATION COLUMN 6 AND SUM SQ'S, CUBE'S, QUART'S)===
1120 MO=SUM4*OT                  'MO IS THE AREA UNDER THE CONC/TIME CURVE (min*ug/l)
1130 M1=(SUM5*OT)/MO             'M1 IS THE MEAN TRANSIT TIME (CENTROID OF CURVE)
1140 SUM46=0 : SUM47=0 : SUM48=0
1150 FOR J=0 TO NO-1
1160      A(J,6)=A(J,3)-M1
1170      SUM46=SUM46+A(J,4)*(A(J,6))^2
1180      SUM47=SUM47+A(J,4)*(A(J,6))^3
1190 SUM48=SUM48+A(J,4)*(A(J,6))^4
1200 NEXT
1210 M2=(SUM46*OT)/MO            'M2 IS VARIANCE OF TRANSIT TIME
1220 M3=(SUM47*DT)/MO            'M3 IS 3RO MOMENT ABOUT THE MEAN TRANSIT TIME
1230 M4=(SUM48*DT)/MO            'M4 IS 4TH MOMENT ABOUT THE MEAN TRANSIT TIME
1240 G1=M3/(M2)^1.5               'COEF OF SKEWNESS
1250 G2=M4/(M2)^2                 'COEF OF KURTOSIS
1260 IF DOG$='N' OR DOG$='n' THEN 1350
1270 '===(CALCULATION OF OISCHARGE AND VELOCITY)===
1280 UL=L/(T*60)                  'CALC VELO OF LEAOING EDGE  (M/S)
1290 UP=L/(TP*60)                 'CALC VELO OF PEAK   (M/S)
1300 UC=L/(M1*60)                 'CALC VELO OF CENTROID    (M/S)
1310 M=VOL*C                      'M IS TRACER MASS IN MICROGRAMS (ug)
1320 MG=M/1000                    'MG IS TRACER MASS IN MILLIGRAMS (mg)
1330 Q=M/(MO*60*1000)         'Q IS OISCHARGE IN M^3/S w/convert sec/min, 1/m^3
1340 CFS=Q/.0283168              'CFS IS OISCHARGE IN CFS
1341 '=================(CALCULATE VARIOUS RATIOS)=====================
1342 AU=T/M1                'SABOL & NOROIN (78) P[being in upper layer]
1343 AL=1-AU                 ''          '      P[being in lower--DZ--layer]
1344 SIG=(2*AL*L)/(UC*AU*M2)      '  '  ' SIGMA: MEAS. OF ANG NO OF TIMES PARTIC
GOES INTO STORAGE PER UNIT TIME
1345 PR=M1/TP               'RAW POOLISH RATIO
1346 APR=PR/UC              'POOLISH RATIO ADJ FOR CENTROID VELOCITY
1350 '===( OUTPUT TO SCREEN )===
1360 CLS
1370 PRINT "CURVE IDENTIFICATION      = ";ID$;"----";L;" METERS
1380 PRINT "=================================================================="
1390 PRINT "LEAOING EOGE               = ";T;" min"
1400 PRINT "TIME OF PEAK               = ";TP;" min"
1410 PRINT "PEAK CONCENTRATION         = ";CP;"  micrograms/l"
1420 IF OOG$='N' OR DOG$='n' THEN 1500
1430 PRINT "TRACER MASS: ";VOL;" ml @ ";C;" mg/l = ";MG;" mg"
1440 PRINT "CALCULATEO DISCHARGE      = ";Q;" m^3/s    (";CFS;" CFS)"
1450 PRINT "******************************************************************"
1460 PRINT "                         "
1470 PRINT "VELOCITY OF LEAOING EDGE  = ";UL;" m/s"
1480 PRINT "VELOCITY OF PEAK          = ";UP;" m/s"
1490 PRINT "VELOCITY OF CENTROID      = ";UC;" m/s"
1500 PRINT "                 "
1510 PRINT "AREA UNDER CURVE          = ";MO;" (ug-min)"
1520 PRINT "MEAN TRANSIT TIME         = ";M1;" min      (this is the centroid)"
1530 PRINT "VARIANCE OF TRANSIT TIME = ";M2;" (sqmin)"
1540 PRINT "THIRO MOMENT ABOUT MEAN  = ";M3
1550 PRINT "FOURTH MOMENT ABOUT MEAN = ";M4
1560 PRINT "COEF OF SKEWNESS          = ";G1
1570 PRINT "COEF OF KURTOSIS          = ";G2
1580 PRINT "OT FOR CALC'S = ";DT;" min"
1590 PRINT "NO. OF DIGIT PTS = ";PTS;", ";NO;" USED FOR FILE AND CALCS.
1600 PRINT "PRESS ANY KEY TO CONTINUE"
1610 A$=INKEY$:IF A$="" THEN 1610
1620 PRINT "=================================================================="
1621 PRINT "SABOL & NOROIN P(being in upper layer):    AU=TL/M1        = ";AU
1622 PRINT "   "     "    P(being in lower layer):    AL=1-AU         = ";AL
```

```
1623 PRINT "    "    "  MEAS. NO TIMES INTO STG/TIME (2AL*L)/(UC*AU*M2) = ";SIG
1624 PRINT "                          "
1625 PRINT "RAW POOLISH RATIO           PR=M1/TP       = ";PR
1626 PRINT "VELO-ADJ. POOLISH RATIO     APR=PR/UC      = ";APR
1627 PRINT "=================================================================="
1628 INPUT "ENTER (S) TO SKIP DETAIL OUTPUT ON SCREEN";A$
1629 IF A$="S" OR A$="s" THEN 1720
1630 PRINT "                 "
1631 PRINT "=================================================================="
1640 PRINT "     RAW-T      RAW-C      AVG-T     AVG-CONC      (C*T)      (T-M1)"
1650 PRINT "=================================================================="
1660 FOR I=0 TO NO
1670    FOR J=1 TO 6
1680      PRINT USING "#####.#####";A(I,J);
1690   NEXT J
1700   PRINT
1710 NEXT I
1720 '===(STORE THE DATA)===
1730 'CLS
1740 INPUT "DO YOU WISH TO STORE THIS DATA Y/N ";ANS$
1750 IF ANS$="N" OR ANS$="n" THEN 1840
1760 CLS : INPUT "ENTER NAME FOR FILE";NAM$
1770 OPEN NAM$ FOR OUTPUT AS #2
1780 FOR J=0 TO NO
1790      WRITE #2,A(J,1),A(J,2)
1800 NEXT
1810 J=0
1820 CLOSE #2
1830 '
1840 '===( FINAL OUTPUT TO PRINTER )===
1850 '
1860 INPUT "DO YOU WANT A PRINTOUT?";ANS$
1870 IF ANS$="Y" OR ANS$="y" THEN 1880 ELSE END
1880 LPRINT "CURVE IDENTIFICATION      = ";ID$;"----";L;" METERS
1890 LPRINT "================================================================="
1900 LPRINT "LEADING EDGE                  = ";T;" min"
1910 LPRINT "TIME OF PEAK                  = ";TP;" min"
1920 LPRINT "PEAK CONCENTRATION            = ";CP;"  micrograms/l"
1930 IF DOG$="N" OR DOG$="n" THEN 2010
1940 LPRINT "TRACER MASS: ";VOL;" ml @ ";C;" mg/l = ";MG;" mg"
1950 LPRINT "CALCULATED DISCHARGE          = ";Q;" m^3/s    (";CFS;" CFS)"
1960 LPRINT "******************************************************************
"
1970 LPRINT "                          "
1980 LPRINT "VELOCITY OF LEADING EDGE  = ";UL;" m/s"
1990 LPRINT "VELOCITY OF PEAK          = ";UP;" m/s"
2000 LPRINT "VELOCITY OF CENTROID      = ";UC;" m/s"
2010 LPRINT "                 "
2020 LPRINT "AREA UNDER CURVE          = ";M0;" (ug-min)"
2030 LPRINT "MEAN TRANSIT TIME         = ";M1;" min     (this is the centroid)"
2040 LPRINT "VARIANCE OF TRANSIT TIME = ";M2;" (sqmin)"
2050 LPRINT "THIRD MOMENT ABOUT MEAN  = ";M3
2060 LPRINT "FOURTH MOMENT ABOUT MEAN = ";M4
2061 LPRINT "                                        "
2070 LPRINT "COEF OF SKEWNESS          = ";G1
2080 LPRINT "COEF OF KURTOSIS          = ";G2
2081 LPRINT "                                      "
2082 LPRINT "                                      "
2083 LPRINT "              DIGITIZING RECORD       "
2084 LPRINT "              ================        "
2085 LPRINT "HORIZONTAL SCALE (min/cm)          =  ";H
2086 LPRINT "VERTICAL SCALE (ug/l-cm)           =  ";V
2090 LPRINT "DT FOR CALC'S = ";DT;" min"
```

```
2100 LPRINT "NO. OF DIGIT PTS = ";PTS;", ";NO;" USED FOR FILE AND CALCS.
2106 LPRINT "=====================================================================
"
2107 LPRINT "                                        "
2108 LPRINT "                                        "
2109 LPRINT "             -----RATIOS-----
2110 LPRINT "=====================================================================
"
2111 LPRINT "SABOL & NOROIN P(being in upper layer):       AU=TL/M1      = ";AU
2112 LPRINT "   "        "   P(being in lower layer):       AL=1-AU       = ";AL
2113 LPRINT "          MEAS. NO TIMES INTO STG/TIME (2AL*L)/(UC*AU*M2)    = ";SIG
2114 LPRINT "                              "
2115 LPRINT "RAW POOLISH RATIO             PR=M1/TP      = ";PR
2116 LPRINT "VELO-ADJ. POOLISH RATIO    APR=PR/UC     = ";APR
2117 LPRINT "=====================================================================
"
2120 LPRINT CHR$(12)                        'FORM FEED
2121 INPUT "ENTER (S) TO SKIP PRINTING DETAIL";A$
2122 IF A$="S" OR A$="s" THEN END
2130 LPRINT "CURVE IDENTIFICATION      = ";ID$;"----";L;" METERS
2140 LPRINT "====================================================================
2150 LPRINT "                "
2160 LPRINT "    RAW-T      RAW-C       AVG-T      AVG-CONC      (C*T)      (T-M1)"
2170 LPRINT "=====================================================================
"
2180 FOR I=0 TO NO
2190    FOR J=1 TO 6
2200     LPRINT USING "#####.#####";A(I,J);
2210   NEXT J
2220   LPRINT
2230 NEXT I
```

APPENDIX E

Reach/Sampling Period Data Summary

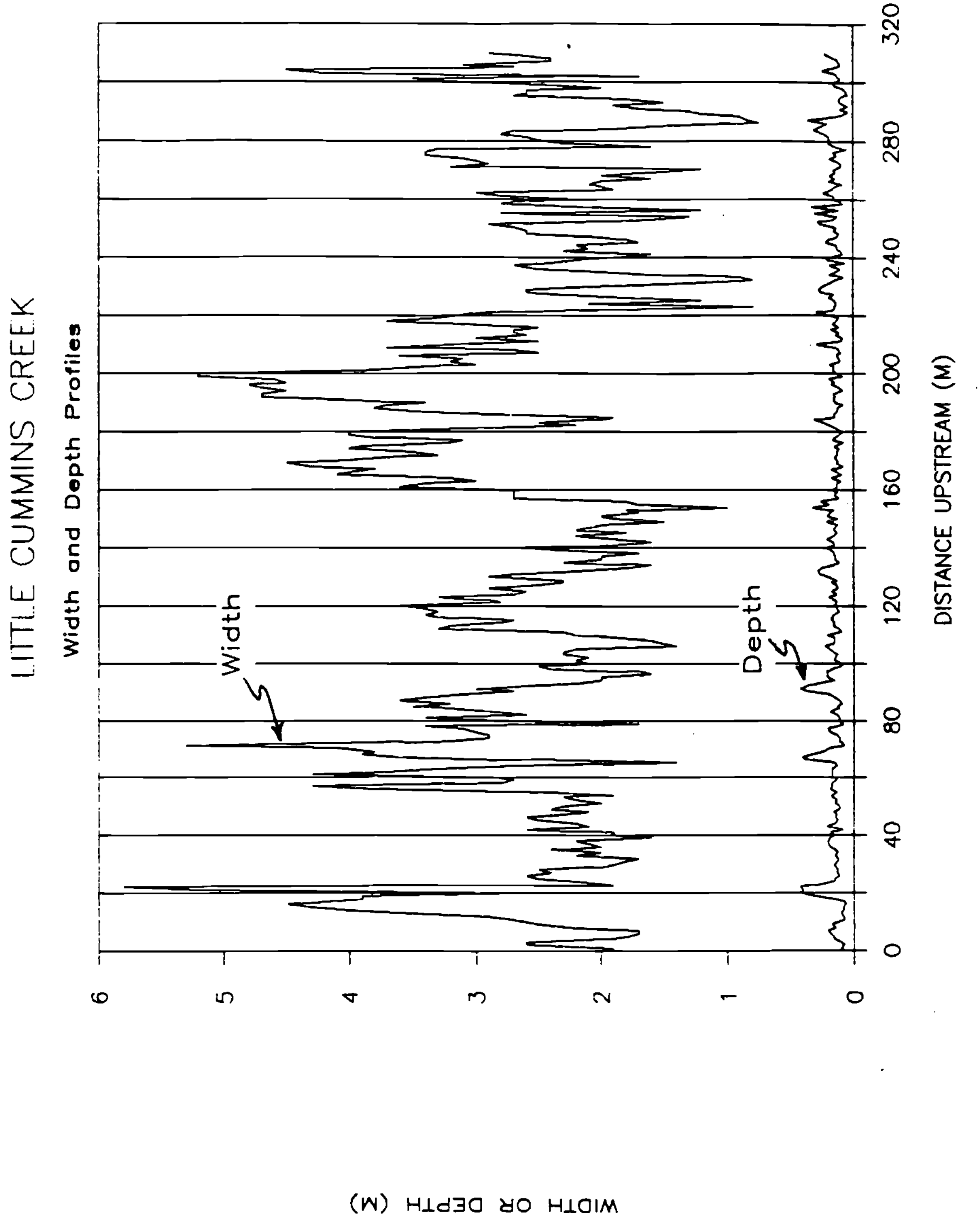
(variables are defined in text)

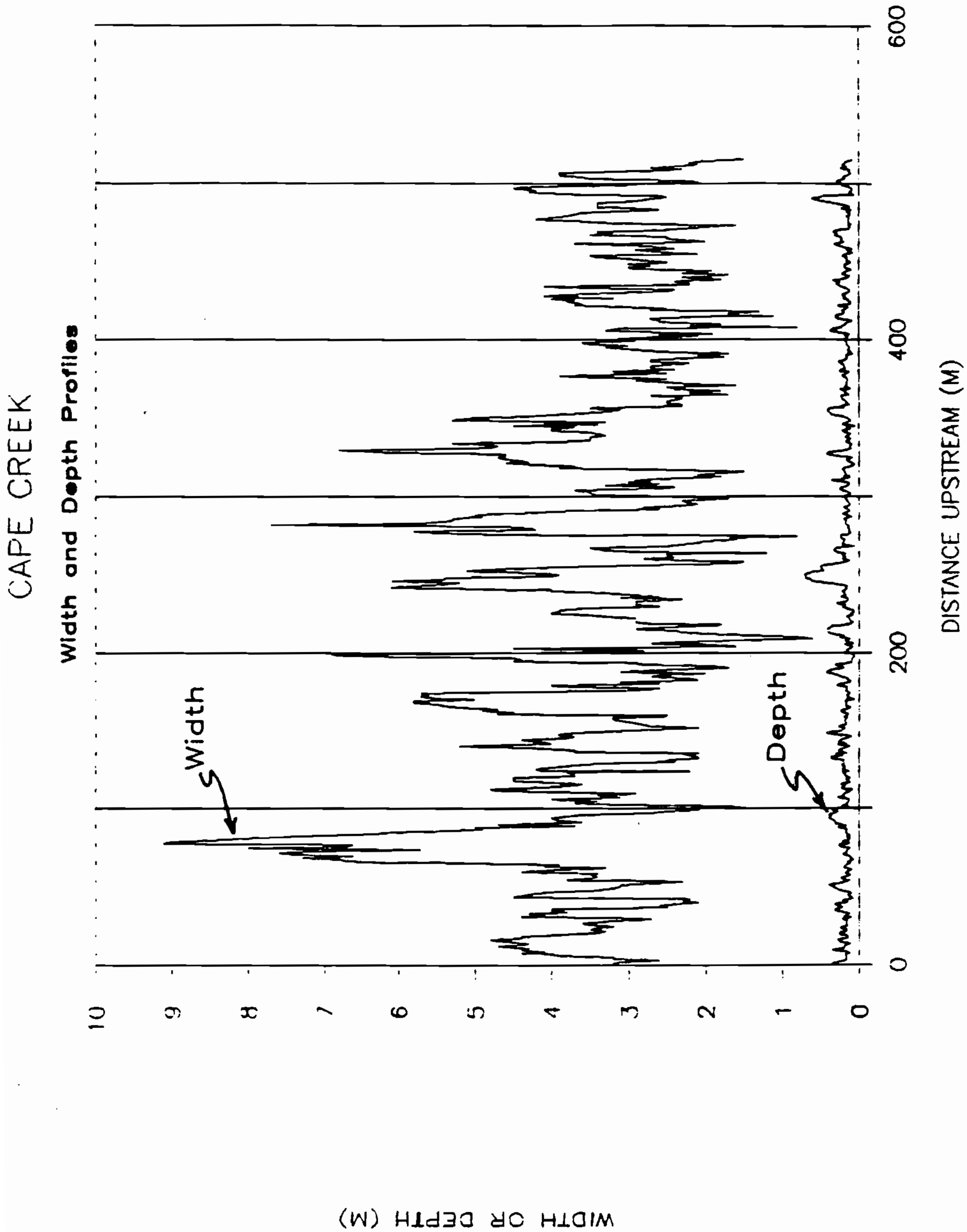
RCH-ID	D (m)	CfVarD	W (m)	CfVarW	W/D	CfVarW/D	W*D (m^2)	CfVarW*D	Q (m^3/s)	Uc (m/s)	aL	δ Exchg-cf (s^-1)
CDsm	0.50010	0.43704	5.15018	0.32437	12.16840	0.59678	2.71159	0.65154	0.61696	0.23092	0.61205	0.04550
OKu	0.15535	0.40708	2.28257	0.33851	17.64980	0.60058	0.35350	0.54601	0.04812	0.20443	0.45049	0.08270
plst	n	n	n	n	n	n	n	n	0.37551	0.36612	0.45082	0.05691
L1sta	n	n	n	n	n	n	n	n	0.28541	0.40719	0.56756	0.05475
L1stb	n	n	n	n	n	n	n	n	0.37575	0.50769	0.46693	0.06485
L1s	0.22594	0.46387	3.39286	0.25093	19.18290	0.51800	0.70295	0.47904	0.09049	0.20580	0.54684	0.03033
L2s	0.20515	0.26625	3.54524	0.29689	20.95871	0.53374	0.64290	0.19762	0.10180	0.28785	0.42660	0.07153
L3s	0.21941	0.41157	3.20952	0.26835	17.73334	0.61693	0.70386	0.55576	0.10540	0.25624	0.43575	0.06015
L1w	n	n	n	n	n	n	n	n	0.11691	0.23764	0.51522	0.04237
L2w	n	n	n	n	n	n	n	n	0.11359	0.31198	0.39164	0.07392
L3w	0.22515	0.40873	3.32143	0.33120	22.22327	1.42806	0.73452	0.53578	0.10586	0.28140	0.43776	0.08412
C1s	0.22980	0.32948	4.56190	0.37216	24.27017	0.54641	0.94157	0.40542	0.08230	0.21442	0.44036	0.05130
C2s	0.27446	0.53722	3.89050	0.22616	17.13153	0.50565	1.11690	0.72055	0.08230	0.16886	0.55928	0.02580
C3s	0.24465	0.36352	4.08570	0.26136	17.97805	0.37544	0.99210	0.37922	0.07330	0.19785	0.42068	0.05210
p1s	0.20475	0.60341	4.07140	0.31272	25.81709	0.52793	0.84119	0.76598	0.06527	0.15262	0.48535	0.02810
p2s	0.17079	0.37229	3.54286	0.25538	20.87715	0.35021	0.66781	0.50755	0.06408	0.23927	0.30371	0.08010
p3s	0.17426	0.28245	3.11905	0.20292	19.45585	0.40663	0.53871	0.22861	0.06154	0.26945	0.38404	0.09690
p4s	0.18554	0.33340	3.18571	0.19454	18.24100	0.39356	0.61567	0.39701	0.05723	0.22034	0.36411	0.05580
g5s	0.16277	0.21821	2.85710	0.14514	20.18221	0.38993	0.44224	0.25965	0.05260	0.25328	0.34350	0.07190
g6s	0.16515	0.32520	3.41430	0.37040	22.97274	0.53103	0.53081	0.27465	0.05939	0.22469	0.33268	0.07100
g7s	0.15911	0.29639	3.54290	0.32680	24.82208	0.65540	0.57119	0.37450	0.05285	0.25024	0.38892	0.07040
L1	0.16475	0.51328	2.75594	0.31881	20.51660	0.62769	0.46870	0.77397	0.01927	0.09321	0.45192	0.01640
L2	0.15200	0.30516	2.89700	0.33833	21.65579	0.54715	0.41929	0.32874	0.01888	0.11663	0.37480	0.04220
L3	0.15280	0.43631	2.31900	0.31747	18.57899	0.61123	0.35369	0.53909	0.01860	0.11026	0.40461	0.03490
C1	0.19500	0.40710	4.31700	0.39402	27.31900	0.67192	0.79360	0.42349	0.03163	0.10958	0.43262	0.03050
C2	0.23130	0.66240	3.15250	0.41171	20.43760	0.95497	0.77040	1.01529	0.02864	0.06523	0.59217	0.01150
C3	0.17740	0.44800	3.17400	0.34329	22.01730	0.67346	0.56130	0.64147	0.02611	0.09813	0.49954	0.02390
C4	0.18280	0.50606	2.91400	0.25782	19.71920	0.54961	0.52120	0.51331	0.02315	0.10124	0.50069	0.04490
g1	0.13190	0.33348	3.36350	0.31585	29.08400	0.60775	0.43510	0.50532	0.04976	0.17873	0.34371	0.05120
g2	0.14320	0.26520	3.07270	0.34196	23.47230	0.47151	0.42440	0.33548	0.04233	0.20559	0.35855	0.06320
g3	0.15560	0.27846	2.75700	0.19132	19.27320	0.36552	0.42120	0.27475	0.04563	0.21212	0.37889	0.07270
g4	0.14690	0.37369	2.94000	0.25009	22.30800	0.40944	0.42250	0.39604	0.04169	0.17789	0.38201	0.05520
g5	0.14160	0.23630	2.62300	0.18733	19.42891	0.33007	0.36970	0.24085	0.03777	0.20336	0.35877	0.05970
g6	0.14830	0.30490	3.18400	0.36987	24.22621	0.57050	0.45740	0.39973	0.04280	0.16882	0.33552	0.05030
g7	0.13800	0.34836	3.07550	0.36129	25.01350	0.55715	0.41430	0.43478	0.03841	0.17262	0.38480	0.04560
p1	0.16790	0.63170	3.60760	0.35426	26.13800	0.47561	0.67897	1.04875	0.04139	0.10501	0.56276	0.02280
p2	0.14010	0.28560	2.93000	0.36655	23.46320	0.53439	0.39880	0.41308	0.03369	0.17525	0.38967	0.05100
p3	0.13880	0.35566	2.59600	0.22158	21.25070	0.41508	0.35018	0.33189	0.02932	0.17269	0.41038	0.04280
p4	0.15010	0.38749	2.66600	0.24716	19.86550	0.39510	0.40392	0.52981	0.02851	0.12908	0.43575	0.02330
p5	0.14160	0.18771	2.62300	0.18733	19.42891	0.33007	0.36970	0.24085	0.02566	0.17546	0.34730	0.05390
gs1	0.19910	0.75210	3.64650	0.42210	-	-	-	-	0.04023	0.07684	0.58043	0.01453
gs2	0.15220	0.37910	2.97400	0.29650	-	-	-	-	0.03472	0.14322	0.39848	0.03346
gs3	0.15650	0.35560	2.59340	0.28430	-	-	-	-	0.03500	0.14014	0.36095	0.03660
gs4	0.16930	0.43210	3.02200	0.28970	-	-	-	-	0.03538	0.10986	0.48586	0.01737
gs5	0.12410	0.26630	2.30940	0.20760	-	-	-	-	0.03763	0.13379	0.38830	0.02554
gs6	0.13690	0.39020	3.18400	-	-	-	-	-	0.03002	0.11368	0.42840	0.01765
gs7	0.12730	0.33950	3.07600	-	-	-	-	-	0.02749	0.11925	0.43840	0.01641

RCH-ID	Ss gradient	f	n	R (m)	RPA RPsm (m^2/100m)	RPLRAT	SDD (m)	MdVOL (m^2/100m)	Md#	MdSZ (m^3/pc)	RPlg ≥ .15 m² (m^2/100m)
CDsm	0.0600	45.80998	0.68484	0.08987	n	n	0.21856	n	n	n	n
OKu	0.0830	16.07289	0.30988	0.15101	n	n	0.06324	n	n	n	n
p1st	n	n	n	n	n	n	n	51.80	21	2.470	n
L1sta	n	n	n	n	n	n	n	23.40	36	0.650	n
L1stb	n	n	n	n	n	n	n	23.40	36	0.650	n
L1s	0.0340	8.16521	0.22944	-0.05375	n	n	0.10481	23.40	36	0.650	n
L2s	0.0368	3.47683	0.14333	-0.17605	n	n	0.05462	4.41	26	0.170	n
L3s	0.0374	5.72890	0.19183	-0.13697	n	n	0.09030	5.97	22	0.271	n
L1w	0.0340	n	n	n	n	n	n	23.40	36	0.650	n
L2w	0.0368	n	n	n	n	n	n	4.41	26	0.170	n
L3w	0.0374	4.19814	0.16087	-0.17220	n	n	0.09202	5.97	22	0.271	n
C1s	0.0368	5.28521	0.17177	-0.04497	n	n	0.07571	15.06	29	0.386	n
C2s	0.0337	11.61972	0.27216	0.04023	n	n	0.14744	26.55	97	0.274	n
C3s	0.0366	6.65380	0.19515	-0.01401	n	n	0.08894	22.17	43	0.516	n
p1s	0.0340	12.03104	0.26892	0.08390	n	n	0.12355	51.80	21	2.470	n
p2s	0.0302	3.12931	0.12983	-0.12384	n	n	0.06358	20.60	36	0.572	n
p3s	0.0255	2.01842	0.10372	-0.20012	n	n	0.04922	7.70	8	0.962	n
p4s	0.0342	4.50798	0.15781	-0.06988	n	n	0.06186	63.40	33	1.920	n
g5s	0.0303	2.69426	0.11969	-0.14305	n	n	0.03552	1.62	13	0.125	n
g6s	0.0380	4.57337	0.15758	-0.05551	n	n	0.05371	6.50	33	0.197	n
g7s	0.0352	2.62970	0.11440	-0.10213	n	n	0.04716	5.39	41	0.131	n
L1	0.0340	23.03980	0.35185	0.26339	6.9325	0.6750	0.08456	23.40	36	0.650	6.2800
L2	0.0368	11.86591	0.24040	0.17253	3.2600	0.5700	0.04638	4.41	26	0.170	2.0775
L3	0.0374	17.56509	0.30564	0.21440	4.4205	0.6000	0.06667	5.97	22	0.271	3.5900
C1	0.0368	16.08564	0.28841	0.20703	5.2625	0.5950	0.07939	15.06	29	0.386	3.9700
C2	0.0337	86.57470	0.75615	0.52490	11.2750	0.6200	0.15321	26.55	97	0.274	10.3325
C3	0.0366	25.00507	0.37339	0.26931	5.2700	0.6250	0.07948	22.17	43	0.516	4.4850
C4	0.0389	23.36884	0.35700	0.26202	6.7175	0.6600	0.09251	9.78	24	0.408	6.0000
g1	0.0340	6.91468	0.19594	0.01252	2.1050	0.4850	0.04399	1.64	8	0.205	1.5125
g2	0.0302	3.75699	0.13943	-0.06219	1.8350	0.5000	0.03798	0.99	9	0.110	0.8575
g3	0.0255	3.47057	0.13745	-0.11131	2.8860	n	0.04333	1.03	6	0.172	2.4670
g4	0.0342	6.76051	0.19253	0.01535	2.3775	0.4800	0.05490	6.08	9	0.676	1.2825
g5	0.0303	4.07159	0.14649	-0.05875	1.6300	0.5300	0.03450	1.62	13	0.125	0.4025
g6	0.0380	8.33234	0.21370	0.05684	2.3125	0.4700	0.04522	6.50	33	0.197	1.4200
g7	0.0352	6.70792	0.18871	0.03173	1.7550	0.4900	0.04807	5.39	41	0.131	0.7425
p1	0.0320	24.84503	0.38900	0.24025	6.5250	n	0.10606	51.80	21	2.470	6.4150
p2	0.0290	4.85403	0.15793	-0.01084	1.2260	n	0.04001	20.60	36	0.572	0.6300
p3	0.0284	4.87866	0.15824	-0.00928	1.4700	n	0.04937	7.70	8	0.962	1.0750
p4	0.0328	12.79715	0.26659	0.13595	1.4200	n	0.05816	63.40	33	1.920	0.7000
p5	0.0303	4.30648	0.14477	-0.00275	1.6300	n	0.02658	1.62	13	0.125	0.4025
gs1	0.0351	66.98338	0.66848	0.45919	8.9160	n	0.14974	51.80	21	2.470	8.2060
gs2	0.0292	9.11000	0.22433	0.07050	4.1820	n	0.05770	20.60	36	0.572	3.6135
gs3	0.0272	10.47898	0.24737	0.06982	3.7250	n	0.05565	7.70	8	0.962	2.9365
gs4	0.0326	22.55561	0.36911	0.22156	4.6925	n	0.07315	63.40	33	1.920	3.8835
gs5	0.0303	16.18061	0.31966	0.12501	n	n	0.03305	1.62	13	0.125	n
gs6	0.0380	19.14141	0.32611	0.21663	n	n	0.05342	6.50	33	0.197	n
gs7	0.0352	14.55917	0.27965	0.17491	n	n	0.04322	5.39	41	0.131	n

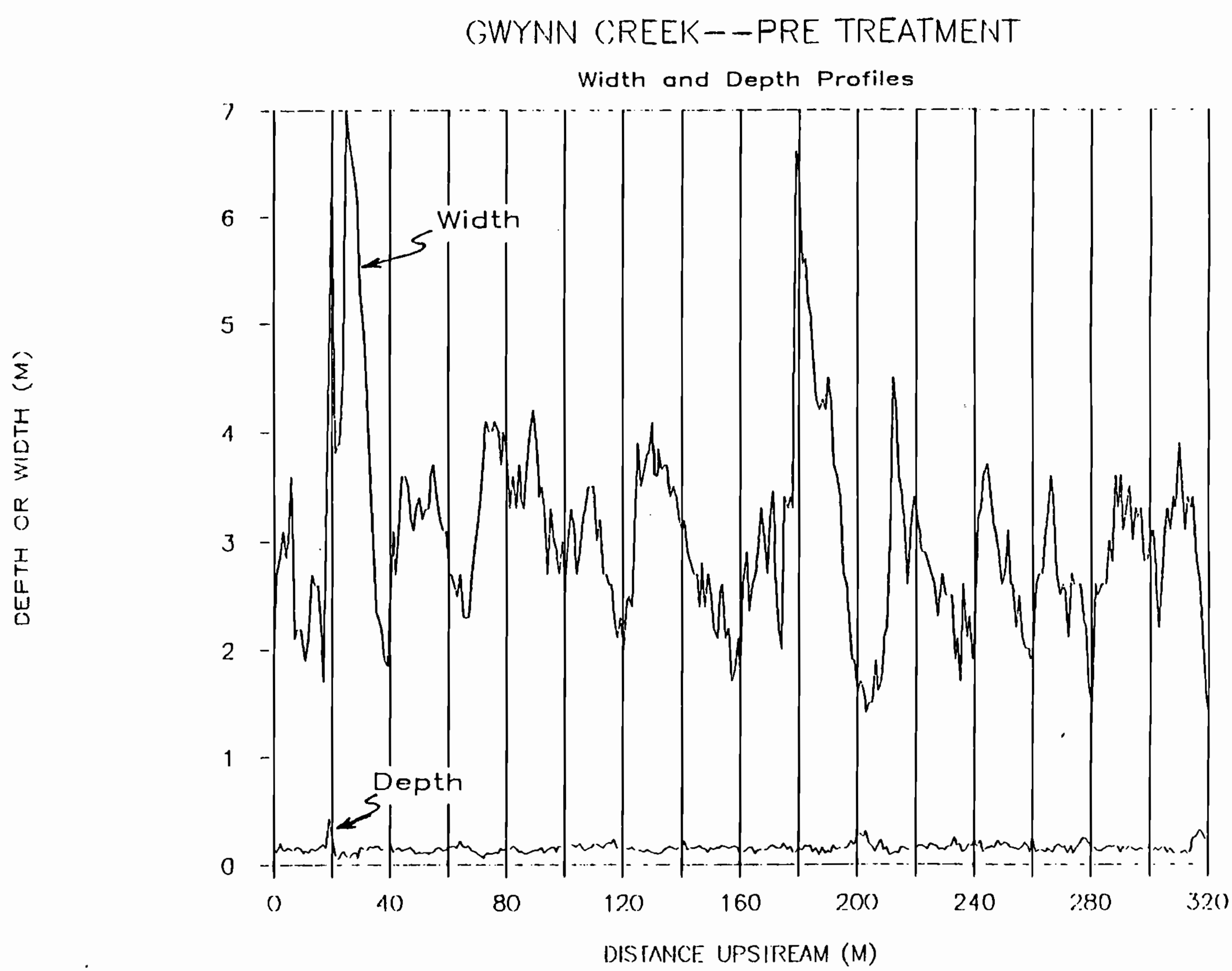
APPENDIX F

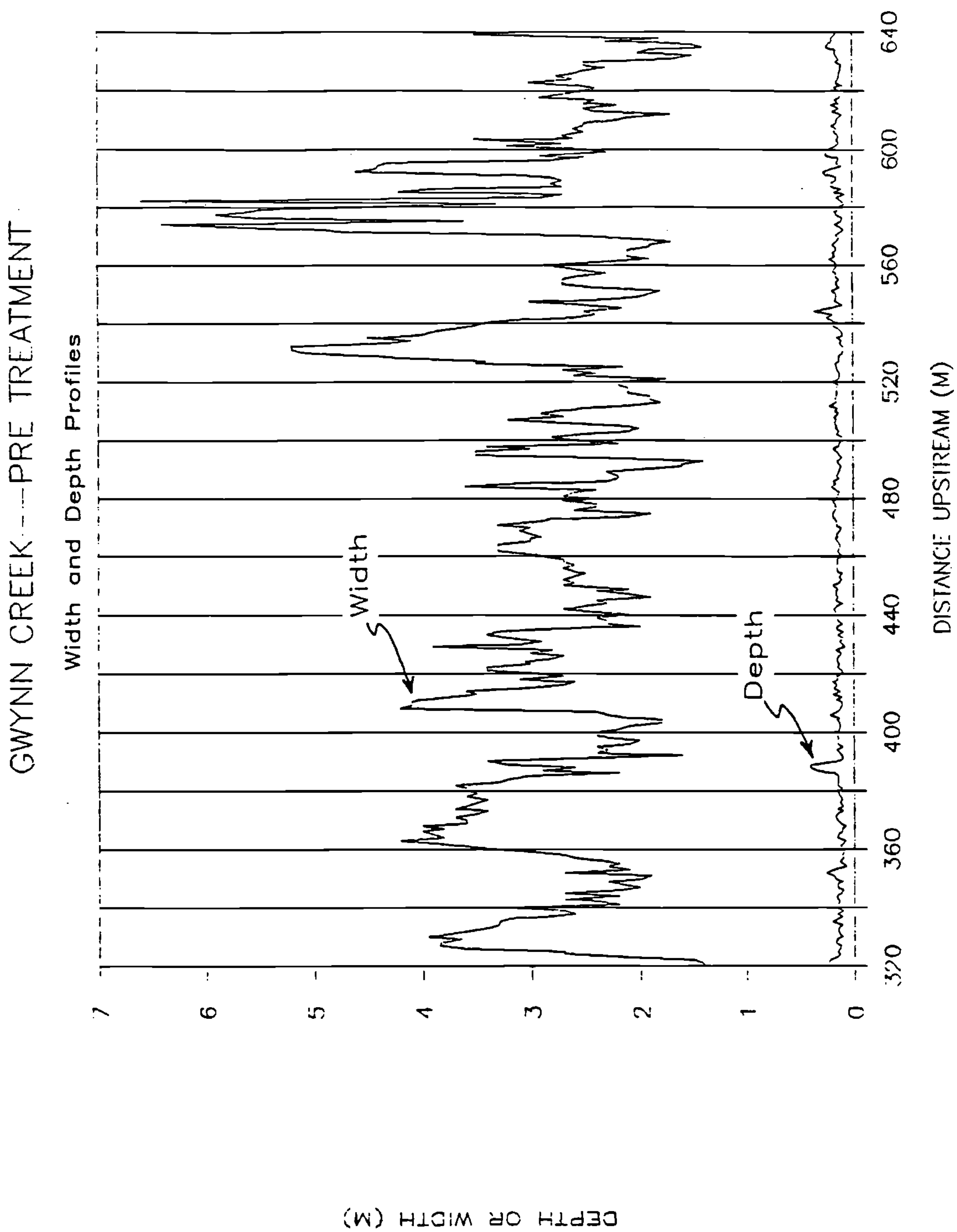
Example Width-Depth Profiles


LITTLE CUMMINS CREEK
Width and Depth Profiles
Width
Depth
WIDTH OR DEPTH (M)
DISTANCE UPSTREAM (M)
0
1
2
3
4
5
6
0
40
80
120
160
200
240
280
320



CAPE CREEK
Width and Depth Profiles
Width
Depth
WIDTH OR DEPTH (M)
DISTANCE UPSTREAM (M)
0
1
2
3
4
5
6
7
8
9
10
0
200
400
600


GWYNN CREEK--PRE TREATMENT
Width and Depth Profiles
Width
Depth
DEPTH OR WIDTH (M)
DISTANCE UPSTREAM (M)
0
1
2
3
4
5
6
7
0
40
80
120
160
200
240
280
320


GWYNN CREEK -- PRE TREATMENT
Width and Depth Profiles
Width
Depth
DISTANCE UPSTREAM (M)
DEPTH OR WIDTH (M)
320
360
400
440
480
520
560
600
640
0
1
2
3
4
5
6
7