AN ABSTRACT OF THE THESIS OF

William R. Stack for the degree of Master of Science in Forest engineering presented on September 28,1988.

Title: Factors Influencing Pool Morphology in Oregon Coastal Streams

Abstract approved: Robert L. Beschta

Pool morphology was surveyed in 19 stream sections within the central Oregon Coast Range. Pool locations, sizes, spacings, numbers, and factors affecting pool formation were determined for each stream section. All sections were underlain by sedimentary rocks, had drainage areas ranging from 1.3 to 17.3 km^2, and had average water surface slopes from 0.5 to 5.6%. Stream sections were divided into two categories: (1) low timber harvest (<20% of watershed area harvested) and (2) high timber harvest (>45% of watershed area harvested).

A "Rapid Bed Profile" (RBP) technique was developed to measure residual pool characteristics in each stream section. The RBP technique is a survey method that requires only thalweg depths and the average reach gradient. The technique was effective for classifying pools since it is objective, independent of flow, accurate, and time-efficient.

Residual pool size characteristics (e.g., volume) for the low timber harvest stream sections were positively

correlated to a power function of drainage area. Stream sections with beaver dams, especially those with at least 10% of their reach length in beaver-caused pools, typically had larger residual pools. Pool size characteristics for high timber harvest stream sections were not different from low timber harvest stream sections.

The average spacing between residual pools was positively correlated to a power function of drainage area for the low timber harvest stream sections (a negative correlation was found between the number of pools and drainage area). High timber harvest stream sections may be associated with an increased spacing and a decreased number of pools for larger watersheds (i.e., greater than 8 km^2). However, the potential effects of previous large storms, changes in timber management practices, and/or the small number of streams surveyed precluded a definitive conclusion.

The frequency of occurrence of pool forming processes (e.g., plunge, deflection) was correlated with average water surface slope for the low timber harvest stream sections. The percentage of plunge and impoundment processes increased as water surface slope increased while the percentage of deflection and underflow processes decreased. Two high timber harvest streams had a higher percentage of plunge pools than expected based on the relationships established for the low timber harvest streams.

The frequency of occurrence of wood and boulder pool forming elements was correlated with an index of stream power (drainage area times average water slope) for the low timber harvest stream sections. As the stream power index increased, the relative frequency of wood-formed pools decreased while boulder-formed pools increased. Wood and boulder combined, generally, made up 80% of the pool forming elements. The frequency of occurrence of pool forming elements was not different between low and high timber harvest stream sections.

FACTORS INFLUENCING POOL MORPHOLOGY
IN OREGON COASTAL STREAMS

by

William Robert Stack

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed September 28, 1988

Commencement June 1989

APPROVED:

Robert L. Beschta

Professor of Forest Hydrology in charge of major

Head of Department of Forest Engineering

John C. Ringle

Dean of Graduate School

Date thesis is presented September 28, 1988

ACKNOWLEDGEMENTS

Completing this thesis was an indirect lesson in human ecology. Ralph Waldo Emerson sums up the fundamental principle in his verse "Each and All":

> All are needed by each one;
> Nothing is fair or good alone.

Here's a salute to the "all":

First, to Bob Beschta, my major professor, for his curiosity, critical reviews, flexibility, and outstanding sense of humor that guided me, like channel banks, to develop an understanding on many issues. Gordon Grant supplied unlimited exogenous thoughts and ideas that helped me slow my anxious conclusions and focus in on specific hypotheses. While Jim Sedell urged me to clean my mental stream of extraneous, detailed conclusions and "Keep It Simple". Together this committee stimulated mental peak flows, debris avalanches, and recoveries to this project. Draft reviews and encouragement by Gary Lamberti, Paul Adams, and Phil Kaufmann were additionally appreciated.

In the woods, I had the support from two energenic field assistants: Galen Krokum and Steve Cooper. They persisted, many times eagerly, through the salmonberry, over the logs, and up and down valleys; certainly, they were a highly valued resource to me during the data collection process.

Private land owners, specifically, Elisa White and Pat and John Dickinson at Franklin Creek, and Bill Unger at Trout Creek who permitted us to cross or camp on their property and generally made our stay more memorable and pleasant.

I am grateful to Janet Cherry. Her remarkable efficiency at programing helped speed up data analysis and therefore my graduation date from 1992 to 1989. Also, to people in the Forest Service at the districts in Waldport, Alsea, and Mapleton who provided maps, historical information, and their time.

Some more thanks. I am lucky to have had a basic staple in graduate education: family and friends. Thanks go to you Paul Commandeur, Karyn Silver, Jeff Irish, the gang in Peavy 068, and my parents; they gave encouraging support, much laughter, and discussions of worldly topics.

Lastly, the Department of Forest Engineering at Oregon State University kindled my academic pursuits by supporting me financially.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FACTORS INFLUENCING POOL MORPHOLOGY IN OREGON COASTAL STREAMS

INTRODUCTION

Forests of the Pacific Northwest (PNW) have many values: (1) providing lumber, energy, pulp, food, and chemicals; (2) purifying air, water, and human spirit; (3) regulating flooding; (4) creating habitat for wildlife and fisheries; and (5) preserving a gene pool. From a human perspective, there is a similar assemblage of users associated with the forest's broad spectrum of resources. These may include loggers, hikers, hunters, conservationists, energy companies, scientists, entrepreneurs, as well as many other interest groups and individuals. About 42% of the PNW's land is forested and approximately half of this is managed by federal and state agencies (Kimerling et al., 1985). Thus, the interaction between many public forest users occurs on a small percentage of land; conflicts have developed over the use of this land. Further, long range views project continual population growth (Miller, 1982), and an 8% timberland reduction (private and public) between 1980-2030 in the United States (Alig et al., 1983). Hence, the number and severity of potential conflicts can be expected to increase. Adjusting our political structure to integrate a wide range of interest groups in land management decisions may help to resolve current and anticipated conflicts, and identify future management plans. Such a change has, within the last 15 years, been evolving between interest groups with concerns about timber and fish resources.

According to Waldo (1986), fish and timber interest groups, in the past, have been generally oblivious to each other's needs, had conflicting goals, and blamed one another for environmental degradation. Integration and compromise of resource goals between these two groups has been "forced" to develop because of a recent trend: decline of anadromous salmonid populations.

Historical records have indicated substantial reductions in fish runs in the PNW. For example, Sedell and Luchessa (1981) estimated from cannery records that annual coho and chinook salmon runs, between 1889-1896 in the Siuslaw River, Or., were approximately 27,500 and 218,750, respectively. During 1960, a run of approximately 17,000 coho was estimated from the number of fish caught by anglers along the river, and no chinook were caught at the mouth of this river. The trend of decreasing salmon populations has also been noted in Northern California. Population reductions of all species of anadromous salmonids by one-half or greater have occurred over the last 30 years (Lisle, 1982).

Why have populations of these species declined? Over-harvest? Changes in off-shore conditions? Construction of dams? Predator increase? Habitat degradation? This study will focus on adding insight on one of these questions, more specifically, the concerns associated with habitat change.

In the area of timber management, researchers have been examining how management activities (e.g., timber harvesting, stream cleaning, and road building) may change in-stream processes [e.g., woody debris movement (Swanson et al., 1984), sediment transport (Beschta, 1979; Bilby, 1984), and peak flows (Harr et al., 1975)]. These studies have inferred that changes in in-stream processes may influence fish populations since fish depend on the forest environment for an indirect food supply (e.g., allochthonous and autochthonous inputs), habitat (e.g., pools created by woody debris), temperature (e.g., shading due to riparian vegetation), and water quality regulation (e.g., aeration by log steps) (Cummins, 1974). Conversely, fisheries management projects (e.g., creating pool habitat) may influence timber resources. For example, establishing unlogged buffer strips, altering riparian zones to create side channels, or installing habitat modification structures (e.g., gabions, revetments) may result in subsequent timber value losses (e.g., blow downs, bank undermining). Thus, the management of one resource can directly or indirectly influence other resources.

The current level of riparian zone management in the PNW indicates a need for additional information. For example, how many trees and how much debris should be left along side the stream? How many pools are needed to support a given population of coho salmon? Should beaver dams be broken up? How many trees will fall into the stream each year? What type of pools (e.g., plunge pools) are needed? Unfortunately, these questions cannot be easily answered due to limitations in our current knowledge base.

This uncertainty also carries over into management projects. Habitat modification structures, for example, have been typically designed based on trial-and-error methods (Klingeman, 1984). With increasing interaction between timber and fish resource managers, there are many interdisciplinary research questions related to fish habitat that need to be addressed.

Further, interdisciplinary research may help put research into practice by developing research projects aimed at site-specific policies. The site-specific concept incorporates local geobioclimatic characteristics (i.e., slope, geology, precipitation) into management plans (McHarg, 1969). Examples of such research studies include: ranking channel stability of streams (Pfankuch, 1975); selecting an inventory system to classify mountain streams (Beschta, 1978); or categorizing terrain based on the susceptibility to mass failures (Swanson, et al., 1987). These studies provide a "natural" templet - a landscape blueprint - to design with. Additionally, site-specific policies may help improve our resource use efficiency and, therefore, reduce the predicted increase in user conflicts in the future.

The purpose of this study is to investigate a means of determining how much pool habitat is available in a stream system and what influences its formation. Hopefully, this information would allow land managers to identify current habitat status, potential affects of land use practices, and the changes in habitat associated with rehabilation projects.

HYPOTHESIS

As water moves from upland streams to lowland rivers topography, discharge, and organic and inorganic input processes change. The mechanisms of channel adjustment (i.e., longitudinal profile, sinuosity, bed roughness, and hydraulic radius) similarly change and stream energy is utilized differently. Pools are one aspect of channel morphology that may reflect these changes. Therefore, pool formation, size, and distribution (e.g., spacing, number) should be significantly associated with total stream power. Additionally, if changes associated with timber harvesting (e.g., higher Fall peak flows) have occurred then the hypothesized pool morphology relationships should be altered.

OBJECTIVES

(1) To determine if pool morphology is a function of total stream power in a "natural" (i.e., undisturbed by management activities) stream system.

(2) To determine whether, and to what extent, pool morphology is altered in a stream system that has undergone timber harvesting.

BACKGROUND

Water at the head of the channel begins with a specific amount of potential energy. As this water flows through the basin network potential energy decreases as it converts to momentum (kinetic), sound, and heat. During the transformation from potential to kinetic energy, energy becomes available to do work; erosion or transportation of organic and inorganic material can occur. The net effect of these various processes is expressed via the channel's morphology [e.g., channel unit characteristics, roughness, hydraulic geometry]. According to Leopold and Langbein (1962), energy dissipating processes (e.g., erosion) are regulated by the concept of entropy: (1) energy is dissipated uniformly over the entire stream length and (2) the rate of energy expenditure per unit area of stream bed is minimized. The concept of entropy indicates a stream has an energy budget to "manage" (i.e., not spending all its initial potential energy in one location and spending it as efficiently as possible). These two components, however, represent opposing tendencies; the management of the energy budget is generally a compromise between them (Chorely and Kennedy, 1971).

Stream power can be employed to quantify the time rate of energy expenditure (power) within a channel reach. The following equation can be used to determine total stream power (Ω) [i.e., the time rate loss of potential energy per unit length of stream - also known as available stream power (Bagnold, 1966)]:

$$\Omega = \rho * g * Q * s$$

where, ρ is the density of water, g is the acceleration due to gravity, Q is the discharge, and s is the energy slope (generally assumed to be equal to the channel gradient in uniform channels). The discharge (Q) and the channel gradient (s) essentially determine the rate of energy expenditure for a given stream (e.g., large steep streams will have a greater rate of energy dissipation than small low gradient streams). Moreover, as total stream power changes channel morphology would similarly be expected to change.

Pools and riffles are common stream morphological signatures that influence hydraulic variables of the channel (e.g., shear stress). In alluvial channels, they operate together as they adjust (i.e., scour and fill) to varying discharges. Keller (1971) found that when discharge exceeds the 1.2-year return period, pools typically scour and riffles fill while the reverse occurs below this discharge. A similar reversal was observed by Lisle (1979); velocity reversal occurred at 50-90% bankfull flow. The pool-riffle sequence seems to provide a "fine tuning" mechanism to minimize the rate of energy expenditure (entropy requirement #2).

At low flows, pool-riffle features maintain their position in the longitudinal profile; but how much stream power change can these features withstand before losing their morphological identity? Following a 5-year return interval event in a Southeast Alaska, gravel-bed, alluvial stream, Campbell and others (1985) found these features to be maintained (i.e., could be relocated). Additionally, they found that both the pool and riffle underwent local scour and fill several times during the event. More importantly, a net change (i.e., deposition or erosion) did develop in both the pool and riffle as a result of a moderate change in discharge.

Based on the general temporal scale of geomorphic processes, the approximate frequency of major fluvial adjustments is largely unknown. Schumm and Lichty (1972) hypothesize channel morphology change (e.g., width, slope, pattern) occurs at intervals of 10-100 years. Indeed the extent and frequency of major channel readjustments will depend on the local geology, climate, vegetation, and topography of the area.

Moving from mountain streams (low stream order) to lowland rivers (high stream order) may change the rate of energy expenditure because mountain streams have different environmental characteristics than lowland rivers: more woody debris, coarser sediments, constricted channels, steeper gradients, smaller discharges, and less cross-sectional area. Because of these different characteristics, factors influencing energy expenditure (i.e., channel morphology adjustments) may similarly change. For example, the mean spacing between pools (deepest point to deepest point of consecutive pools) in lowland rivers is a function of channel width and is usually 5-7 channel widths (Leopold et al., 1964). However, based on flume test results (Whittaker et al., 1982) which simulated mountain stream conditions, Grant (1986) calculated mean pool spacing to be 2.3 channel widths. Further, Grant (1986) verified the occurrence of smaller pool spacing in streams of the western Cascades, Oregon to have mean pool spacings of 4 channel widths (majority of pool spacings were between 2-6 channel widths). Thus, pool spacing may not be uniform through out a drainage system.

Beschta and Platts (1987) suggest four morphology adjustments that alluvial channels use to regulate energy expenditure. When stream power changes, a stream can change its (1) longitudinal profile, (2) channel sinuosity, (3) roughness of bed or bank, and (4) hydraulic radius. In mountain streams, however, organic and inorganic input processes may also influence these adjustments. Large roughness elements (e.g., logs, boulders) can change stream power at specific locations in the channel. For example, slope increases as water flows over large woody debris. This local increase in stream power can cause intense turbulence and energy dissipation downstream which may ultimately create a pool (Swanson and Lienkaemper, 1978). Thus, a local change in stream power may alter channel morphology.

Additionally, because mountain streams are (1) limited in their adjustments to satisfy energy expenditure requirements (entropy concept) by sinuosity and hydraulic radius since valleys are generally constricted, and (2) may not have the energy needed to move large roughness elements (e.g., float logs or entrain boulders), their longitudinal profile and bed roughness may change. Morphologically, this may be expressed as an increase in the frequency of pools which could explain the decrease in pool spacing discussed earlier. As stream power changes (mountain streams to lowland rivers), the change in environmental characteristics (i.e., valley topography, sediment and large woody debris inputs) may cause a change in pool spacing. Such changes, however, have seldom been studied.

Besides the frequency of pools, pool formation may also change. Pool formation consists of two aspects: (1) the cause (e.g., roughness element) and (2) the scouring process (e.g., plunge, deflection).

Pools in lowland, alluvial systems are generally located at bends associated with point bars. Lowland rivers appear to form pools from a combination of dispersive stresses, converging/diverging flow, and kinematic wave processes (Keller and Melhorn, 1973).

However, our understanding on the specific mechanism is limited (Keller and Melhorn, 1978; Grant, 1986).

Grant (1986) lumps pool forming mechanisms into two categories: (1) endogenous [due to "internal" causes (e.g., scour as a result of fluvial stresses during high flows)] and (2) exogenous [due to "external" causes (e.g., input of a root wad causes scour)]. Because of the absence of large roughness elements, pools in lowland rivers are generally caused by endogenous mechanisms. These pools are often called fluvial or endogenous pools. Many studies have investigated their formation (e.g., Yang, 1971a). More recently, however, research efforts have been directed at understanding pools formed by exogenous factors. Specifically, pools associated with large woody debris (Beschta, 1983a; Bilby, 1984; Lisle, 1986; Sullivan et al., 1987; Robison, 1988). These studies have stemmed primarily from concerns between timber and fisheries resources in riparian area management.

Keller and Swanson (1979) found a decreasing trend in the amount of large woody debris in the channel as stream order increased. In steep terrain, approximately 75% of 47 debris flows stopped in channels less than or equal to 6.3% slope (Swanson et al., 1987). Benda (1987) observed many debris flow deposits at tributary junctions. Thus, the range and type of organic and inorganic input processes (e.g., debris flow, windthrow, etc.) change as stream size changes. Similarly, the cause of pool formation is also expected to change as stream size (stream power) changes. The associated process of pool formation would also be expected to change with stream size. For example, upland streams may have more pools associated with the process of plunging than lowland streams because of steeper gradients.

An important morphological parameter of pools is their size (e.g., volume, depth, length). An intuitively obvious hypothesis is as streams get larger, the pools get bigger. Leopold and others (1964) developed this idea for three flow related variables (i.e., average channel width, depth, and velocity). The concept is known as hydraulic geometry and the mathematical relationships for each is expressed as a function of discharge.

Channel slope may also influence pool size throughout a stream system. Steeper slopes cause more turbulence (more energy released), thus, more scour and larger pools should be expected. Stream power encompasses both discharge and slope; therefore pool size, should accordingly change as stream power changes. But again, this has not been well studied.

Exactly what constitutes a "pool" has not been well defined. Table 1 lists some possible definitions. Each definition may yield different results; one method may determine a specific unit is a "pool" while another method does not (O'Neill and Abrahams, 1981). Many definitions

Table 1. Listing of selected pool defintions.

AUTHOR	CONCEPT
Leopold et al. (1964)	Low gradient with a smooth surface.
Dolling (1968)	Velocity/depth criteria.
Yang (1971b)	Energy gradient.
Keller & Melhorn (1973)	Deep and low percentage of coarse sediments.
Richards (1976)	Fits line to bed topography (neg. residual = pool).
Bisson et al. (1981)	Flow patterns & roughness element orientation.
Bathurst (1981) [Lisle, 1987]	Residual pool based on bed elevation.
O'Neill & Abrahams (1984)	Criteria based on the summation of bed elevation changes.
Carlson (unpublished)	Scour hole, width and length criteria.

are also dependent on flow (e.g., Dolling, 1968). Therefore, the field method chosen to define a "pool" and the associated flow conditions (i.e., discharge) during data collection can influence the quantification of pool morphology.

Pool habitat can have important effects on fish type and populations and is a useful characteristic to the fisheries biologist. For example, Everest and others (1985) found a linear relationship between coho salmon populations and pool volume. Also, pool depth influences the winter survival of this species. Apparently coho are able to survive seasonal freshets by remaining in deep pools (Tschaplinski and Hartman, 1983). The type of pool formation adds a range of possible cover, depth, and velocity requirements for different age classes and species of fish (Bisson et al., 1981).

Forest practices could change stream power by changing, for example, peak discharge (Harr, 1976). Thus, pool morphology and associated fish populations may change. Unfortunately, a majority of forest-fish studies have measured fish population changes following logging independent of habitat structure. Some researchers believe "the ultimate measure of the effects of logging on the fishery lies in the response of the fish populations to changes in their habitat" (Hall and Lantz, 1969). Thus, a need exists for more studies to monitor habitat structure (e.g., pool volume, formation) which then can be correlated to fish population changes and land use practices. However, before these inferences can be made, the factors influencing pool size, formation, and distribution must first be addressed.

Examining pool morphology and how it may change with stream power may ultimately provide insights to management issues. For example, the effect of fisheries rehabilation structures in streams could be quantified by determining the pool sizes (e.g., average pool volume) before and after emplacement of these structures (e.g., Lisle, 1987). Surveying pool morphology (e.g., number of pools, sizes, spacing, formation) as a function of total stream power, may identify patterns which fisheries managers could apply to aid decisions related to the number, formation type, and location of rehabilation structures. In addition, since the stream channel is often influenced by processes that occur on the hillslopes, monitoring the morphology of pools may provide useful information about impacts from timber harvesting methods or road building.

STUDY AREA

The general geographic location for this study is the central Oregon Coast Range which is approximately bordered on the north by the Yaquina river (near Newport) and on the south by the Umpqua river (near Reedsport). The Pacific Ocean and the crest of the Coast Range are the west and east boundaries. Figure 1 illustrates the relative location of the study area as well as the streams investigated. (More specific characterizations of the study streams are included in the Methods section.)

Public land comprises the majority of the land ownership within this region. Much of the central coast is within the boundaries of the Siuslaw National Forest. Small patches of land managed by the Bureau of Land Management are also present. Additionally, lowland valley bottoms of high order streams (>4th order) are generally privately owned.

Geology

The central Oregon Coast Range consists primarily of moderately folded marine tuffaceous sandstones and shales that have been partially blanketed and intruded by basaltic rocks (Baldwin, 1976; Kimerling et al., 1985). Most of the major formations were deposited during Eocene and Oligocene Epochs. Along the coast margin of the study region and extending approximately 8 - 16 km inland, the

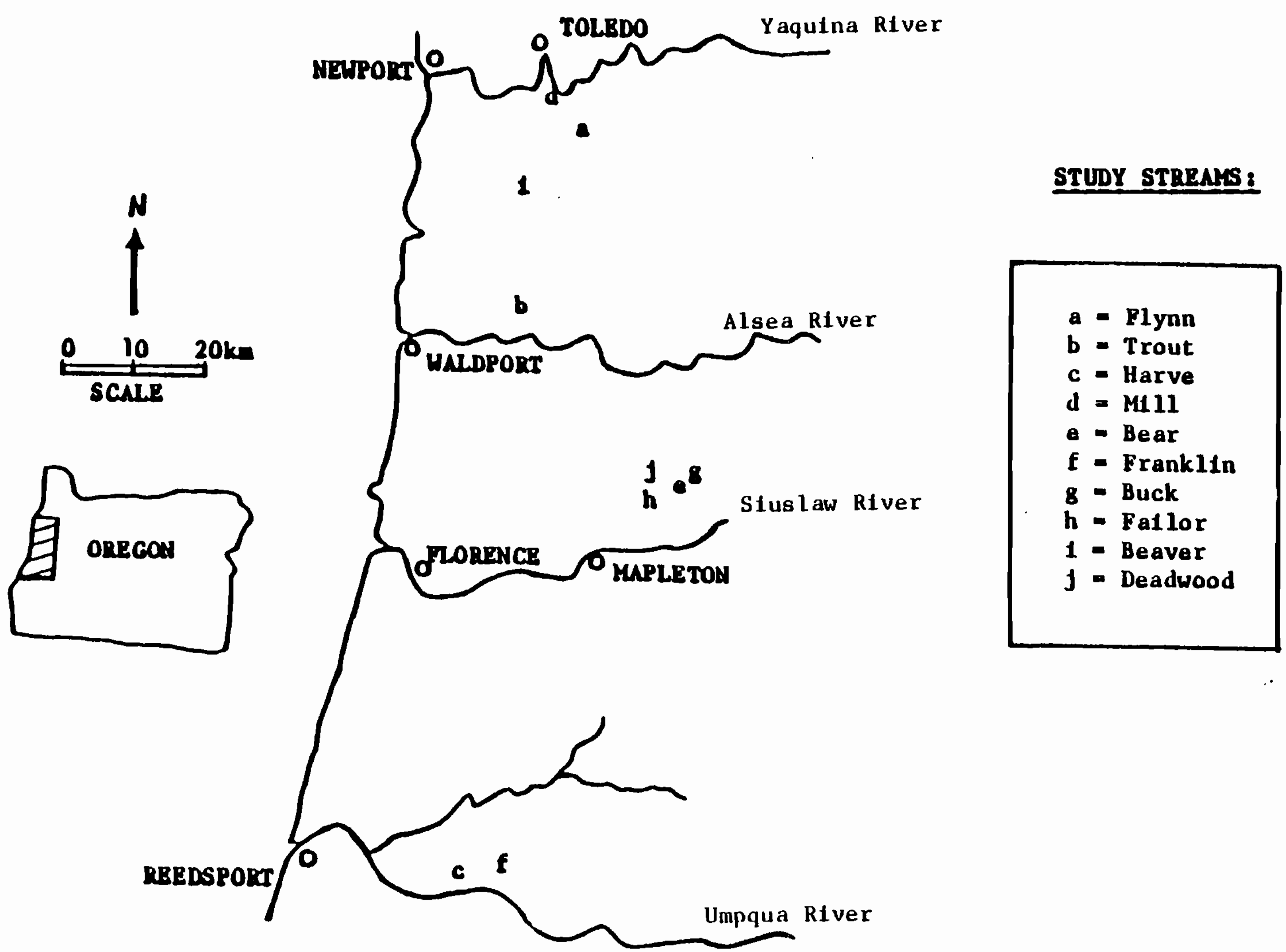

FIGURE 1. Location of study area and study streams.

surface geology is predominantly (~60%) igneous (Yachats basalt) with scattered areas of sandstone and siltstone (Yaquina and Alsea Formations). Past this basalt fringe, about 95% of the surface consists of massive sandstone beds with thin interbeds of siltstone (Flournoy Formation) (Baldwin, 1976). According to Baldwin (1976) this sandstone is "firmly compacted and characterized by an abundance of mica flakes."

Topography

The general topography of the study region is reflected by its geology and climate. Due to a slow uplift (300 - 600 m) during the Plio-Pleistocene Epochs, historical climate patterns (i.e., "wet"), and texture of the rocks, the landscape is highly dissected with rounded mountains of moderate relief (Marston, 1980; Kimerling et al., 1985). Hillside slopes are steep (40-110%). Marston (1980) studied 13 watersheds in the central Oregon Coast Range; basin relief varied between 350-630 m for sedimentary basins and 440-730 m for igneous basins. Mean channel slopes for these watersheds for stream orders 1 through 4 in the two rock types had the following respective slopes: 27, 14, 7, and 3% (sedimentary); 37, 22, 10 and 3% (igneous).

Precipitation

Precipitation typically occurs from marine, moist frontal systems that move inland from the Pacific Ocean.

These systems consist of stable (summer) and unstable (winter) air masses. Winter storms are usually sustained for long durations (i.e., several days) with low to moderate intensities (i.e., 5.0 - 25 mm/day). Storm precipitation is often enhanced by the orographic influence of the Coast Range. Hence, winters are wet with approximately 80% of annual precipitation (1520 - 2500 mm) falling during October to March. Winter precipitation consists predominantly of rain, while summers are relatively dry.

Vegetation

Conifers dominate the landscape except where there has been a history of physical disturbance. The primary overstory species inhabiting the study region include: Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and sitka spruce (*Picea sitchensis*). Douglas-fir and western hemlock are the predominant inland species with the former making up the majority. Red alder (*Alnus rubra*) is also a locally common deciduous species, especially in old clearcuts where conifer regeneration was poor or in riparian areas. Understory species consist mainly of Salmonberry (*Rubus spectabilis*), vine maple (*Acer circinatum*), and red elderberry (*Sambucus racemosa*).

Hydrology

Precipitation onto forested watersheds is usually routed to stream channels as subsurface flow. The majority of all watersheds within the study region have shallow soils (<2m) and are drained by a dendritic network of streams with V-shaped valleys. Thus, a stream's response to storm precipitation is rapid. Streams along the coast often have parallel drainages. The drainage densities (total stream length/drainage area) for both rock types of the region are approximately 3.7 km/km^2. Mean lengths of first- through fourth-order streams average 0.3, 0.4, 1.1, and 2.6 km (sedimentary), and 0.3, 0.5, 1.8, and 4.3 km (igneous), respectively (Marston, 1980).

Recent hydrologic events include (approximately): Q_{4-10} (1961 water year (WY)), $Q_{>25}$ (1965 WY), Q_{5-11} (1972 WY), Q_{3-17} (1974 WY), and Q_5 (1981 WY) [Based on approximately 20 years of record for the North Fork Alsea River, Siuslaw River, Siletz River, and Flynn Creek.] Unrecorded small local events which had high return intervals may have also occurred (Froehlich, 1986).

Soil Movement

Because of the steep topography and highly weathered sandstone bedrock, debris avalanches have a high frequency of occurrence. In the Mapleton area, approximately 70% of the debris avalanches are delivered into the stream channel (Swanson et al., 1987). Subsequently, these debris avalanches can trigger debris torrents in the stream. On gentler slopes, colluvium is often susceptible to slumping.

Once sediment is transported into the channel it moves through the watershed by solution, suspension, and/or bedload; the rates of each are variable depending on the magnitude of flow, hydrograph characteristics, sequence of storm events, channel dimensions, and orientations, size distributions, and shapes of sediment (Baker and Ritter, 1975; Vanoni, 1977; Beschta, 1983b; Nolan et al., 1987).

Fisheries

The upper portions of the stream network support natural populations primarily of coho salmon (Oncorhynchus kisutch), and steelhead (Salmo gairdneri) and cutthroat (Salmo clarki) trout. These fishes use a wide range of channel units during their life cycle but are generally found only where channel gradients are less than 5% (Everest and Harr, 1982; Sedell, 1987). However, steeper stream reaches are functionally important to fish survival (e.g., water quality, food).

Land Use History

In the latter half of the 1800's the Nestucca and Yaquina Fire denuded most of the vegetation in this region. Additionally, there have been other smaller fires in this region (Mackay, 1978; Finucane, 1980).

During the late 1800's and early 1900's stream cleaning and the construction of splash dams aided log transport in rivers (Sedell and Duval, 1985). Homesteads in the large lowland valleys were cleared for grazing and converted to pasture. In the 1920's, following World War I, clearcut logging began. Clearcut logging became more widespread in the 1950's and has continued as the predominant method of harvesting timber to date. Cleaning streams of debris jams, in an attempt to improve fish migration and to salvage high-value timber, was undertaken throughout the 1960's and 1970's (McKean, 1971). The implementation of Forest Practice Rules in 1972 began to change specific timber management policies for both public and private lands (e.g., buffer strip requirements). Within the last 5-10 years, the USDA Forest Service and BLM have initiated fishery management activities in several streams in an attempt to structurally alter fish habitat.

METHODS

Stream selection

Factors that can influence stream power and pool morphology include geology, topography, vegetation, climate, hydrology, and land use. Therefore, in order to determine how stream power influences pool morphology these variables need to be held constant, quantified, or eliminated. Table 2 indicates which approach was taken with each of these variables.

Streams in sedimentary rocks were chosen because this is the predominant surface geology within the study area. The total length of sedimentary based streams is much higher than those underlain by igneous rocks. Hence, pool morphology information in sedimentary geology is of more value to the fishery biologist because of the higher percentage of fish that utilize these streams (Kessel,1986).

To examine the influence timber harvesting may have on pool morphology, streams were selected from lands managed primarily by the USDA Forest Service. This minimizes the potential of having different management practices (e.g., road building, harvesting operations) for different study streams. Also, streams which had experienced stream rehabilitation work were not chosen.

Because of the extent of logging in the Coast Range,

Table 2. General criteria used to select study streams.

VARIABLE(S)	APPROACH
Vegetation, Climate, Topography	Study streams only in the central Coast Range. In a general sense this constraint holds many watershed characteristics relatively constant (e.g., drainage density, relief).
Surface Geology	Study only streams in Sedimentary rocks.
Channel gradient, and Hydraulics	Quantify by using stream power equation. Study only perennial streams.
Land-Use	Study only watersheds managed by USDA Forest Service. No streams with structural improvements (i.e., stream habitat rehabilation structures) or a history of splash dams.

and potential human-caused wild fires (Lucia, 1975), large "natural" watersheds (drainage area greater than 5 km^2) are not available to study. For these reasons "natural" streams were replaced with streams having relatively low timber harvest. Streams selected to represent "natural" conditions had less than 20% of the vegetation harvested (cumulative), and no debris torrents related to management activities (e.g., clear-cut or road originated debris torrent) immediately upstream of the stream section being investigated. Additionally, low timber harvested watersheds were only chosen if roads were placed along ridge tops. As drainage area increased, it became increasingly difficult to meet the less than 20% harvest criterion.

"Timber harvested" streams were selected based on the total percentage of land harvested. These were called high timber harvest streams. Watersheds with relatively high amounts of timber harvesting were sought. [These would be the most probable sites for pool morphology to change if harvesting practices were having an impact.] In general, the total percentage of land harvested decreased as watershed size increased. High timber harvest streams chosen had at least 45% of the watershed area harvested. Harvest records were obtained from USDA Forest Service district offices (i.e., Mapleton, Alsea, and Waldport). Earliest records typically started in the late 1950's. Additionally, information regarding buffer strips was not recorded because of the ambiguity in determining on-site characteristics (e.g., width of buffer in old harvest units).

Drainage area was also an important variable for stream selection. To cover a broad spectrum of stream powers (to satisfy the objectives of this study) a similarly wide range of drainage areas was chosen. Stream reaches within these drainages had to have uniform channel gradients and no confluence with major tributaries in order to keep total stream power of the reach relatively uniform. Occasionally, the same stream was studied in a few locations to help achieve a wide range of total stream powers; these sections were labelled A, B, C, etc..

Fourteen "low harvest" stream sections and five "high harvest" stream sections were chosen. Table 3 shows the range of drainage areas chosen along with land use history and site locations for each stream. [The range of total stream powers and water surface slopes will be shown later in Table 5.]

Pool Morphology Measurements

Ideally, a method to define pools should be time and money efficient, objective, reproducible, and independent of flow. A survey technique for defining pools, that has been used by Lisle (1986) and Kaufmann (1987), appears to meet several of these criteria. However, in the Coast Range, especially during summer months, first- through third- order tributaries are often densely vegetated

Table 3. Management history and geographical location of study streams.

Group	STREAM SECTION	DRAINAGE AREA (km^2)	HARVEST DATE (since 1987) 0-10 YR (%) [a]	11-25YR (%) [a]	26-50YR (%) [a]	TOTAL HARVEST (%) [a]	TOTAL ROADS (km) [b]	OWNER/ LOCATION [c]
LOW TIMBER HARVEST	FLYNN C	1.3	0.0	0.0	0.0	0.0	0.9	FS R10W,T12S
	TROUT A	1.5	0.0	0.0	0.0	0.0	0.6	FS R10W,T13S
	FLYNN D	1.6	0.0	0.0	0.0	0.0	0.9	FS R10W,T12S
	FLYNN A	1.6	0.0	0.0	0.0	0.0	0.9	FS R10W,T12S
	TROUT B	2.2	0.0	0.0	0.0	0.0	0.8	FS R10W,T13S
	HARVEY B	2.8	0.0	0.0	0.0	0.0	1.5	FS R10W,T21S
	MILL	3.1	0.0	0.6	0.0	0.6	3.0	FS R10W,T11S
	BEAR	4.6	9.3	0.0	0.0	9.3	1.4	BLM R8W,T16S
	FRANKLIN B	6.4	0.0	13.2	0.0	13.2	2.3	FS R10W,T22S
	HARVEY A	8.2	0.0	8.5	0.0	8.5	3.9	FS R10W,T21S
	FRANKLIN C	11.5	0.0	12.5	0.0	12.5	4.9	FS R10W,T22S
	FRANKLIN A	14.3	0.0	13.8	0.0	13.8	6.0	FS R10W,T22S
	TROUT C	16.0	3.1	13.3	1.2	17.6	12.5	FS R10W,T13S
	FRANKLIN D	17.3	0.0	11.4	0.0	11.4	6.0	FS R10W,T22S
HIGH	BUCK	3.0	34.4	31.2	0.5	66.1	3.0	FS R8W,T16S
	FAILOR A	5.0	17.8	31.4	34.0	83.2	3.4	FS R9W,T16S
	FAILOR B	8.1	13.1	28.5	31.3	72.9	4.5	FS R9W,T16S
	N. FORK BEAVER	9.5	13.7	28.3	14.1	56.1	15.9	85%FS,15%P R10W,T12S
	W. FORK DEADWOOD	14.8	5.4	31.5	8.8	45.7	16.9	FS R9W,T16S

[a] Percent harvest = (Area harvested/Drainage area) times 100.
[b] Total length of roads in drainage area. (Those roads on ridge tops were counted as being half in drainage.)
[c] FS=Forest Service, BLM=Bureau of Land Management, and P=Private.

making elevation measurements at each data collection location along the channel ("station") time-consuming (e.g., lots of turning points, cutting vegetation down to see stadia rod). Furthermore, recording elevation measurements, with only two people collecting data, creates logistic problems [e.g., communicating other data collected (e.g., depth, width) when the data recorder is 30m downstream]. Thus, a modification of this survey method was devised. This method because of the rapidity with which data can be collected is called the Rapid Bed Profile (RBP) technique.

The RBP technique defines pools based on hypothetical no-flow condition; pools are defined where water would collect when the flow approaches zero. These are called residual pools. The RBP technique yields information similar to the survey technique used by Lisle (1986) and Kaufmann (1987). [A comparison between these two techniques is performed in Appendix A.]

The RBP technique requires thalweg depth measurements at each station along the channel and the average water surface slope (elevation measurements are obtained only at prominent changes in channel slope (e.g., riffles), not at <u>every</u> station) to define pool locations. Thalweg depth measurements are then plotted against their respective upstream distance (i.e., station location). On the crests of this plot (i.e., downstream control points) a reference line (RBP slope) is "tilted" downward to define pools.

Figure 2 illustrates this technique and the associated pool characteristics. The relative amount of tilt for the RBP slope depends on the average water surface slope of the channel. A relationship between RBP slope and average water surface slope was developed for Coast Range streams (Appendix A) and is shown in Figure 3. More detailed information regarding the RBP technique is presented in Appendix A.

Pool location, number, spacing, and dimensions (e.g., residual pool length, maximum depth, area) were calculated for each reach. The channel cross section in low gradient (<5%), sedimentary coastal stream can be accurately determined by assuming a triangular cross section (Robison, 1988a). Pool volume was calculated by summing up the volume at each station (i.e., 1/3 * thalweg depth * low flow width * data collection interval) for the entire length of the pool. A computer program was utilized to accomplish the mechanics of the RBP technique and associated arithmetic operations. Appendix B lists the program, which was written in BASIC language.

After pool locations were identified, pool form characteristics were determined in the field. These included (1) process (e.g., deflection, plunge, etc.) and (2) element (e.g., wood, boulders), and provided a basis for classifying the characteristics associated with pool formation (Table 4). Wood pieces needed to be larger than 10 cm in diameter and at least 60 cm in length while

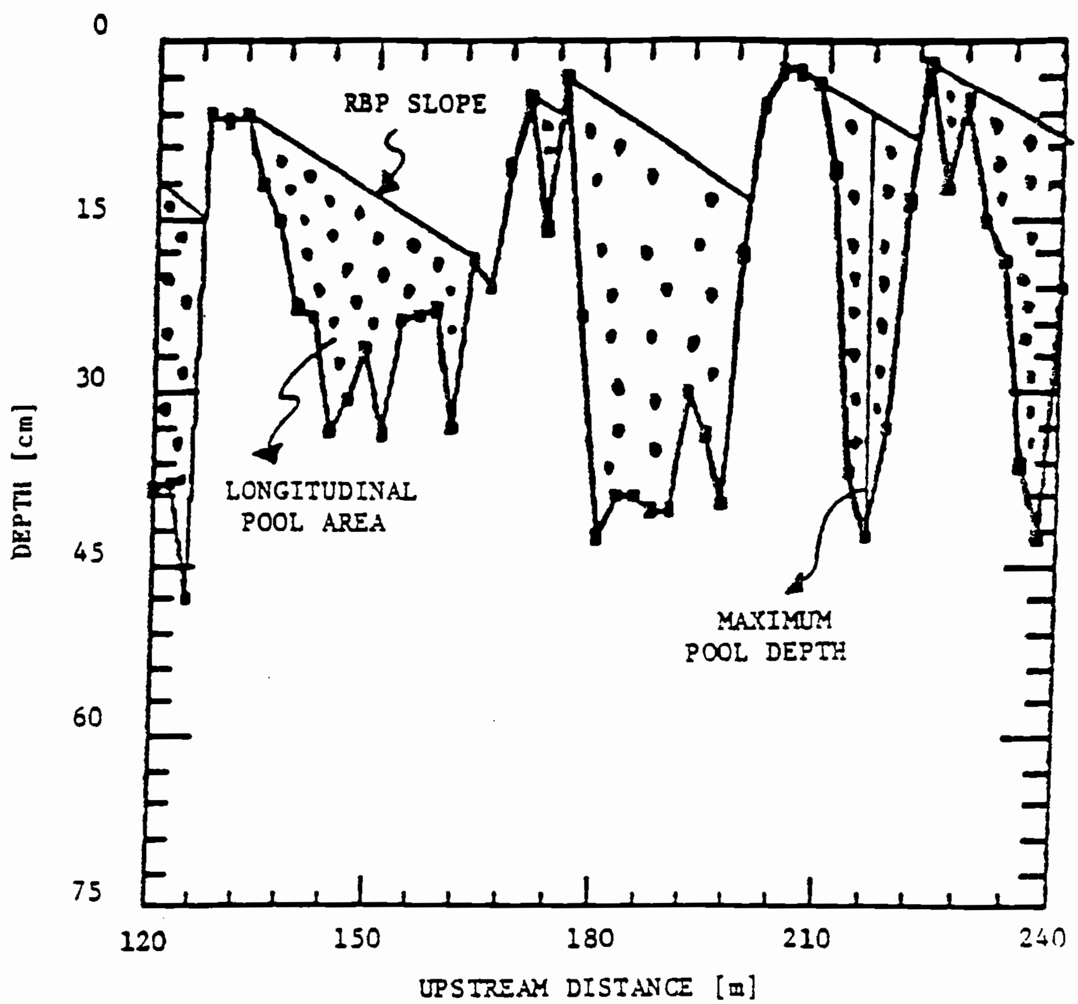

Figure 2. Rapid Bed Profile (RBP) technique used to define residual pools from a thalweg depth profile.

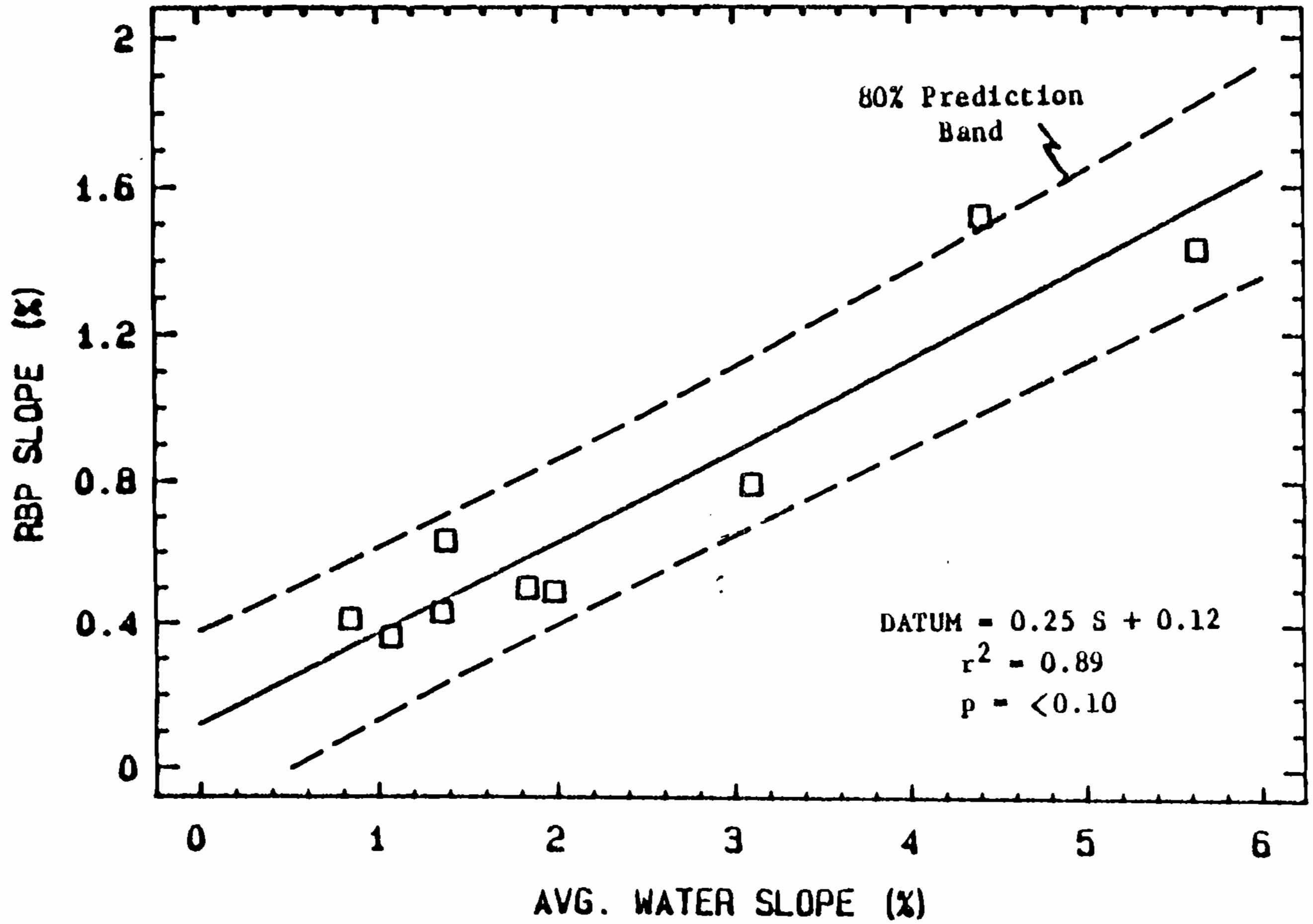

Figure 3. Rapid Bed Profile (RBP) slope versus average water surface slope.

Table 4. Categories of pool elements and processes.

ELEMENT	PROCESS
Wood	Plunge
Boulder	Deflection
Rootwad	Impoundment
Bedrock	Underflow
Beaver Dam	Endogenous
Other	
No element (i.e. endogenous)	

boulders had to be at least 25 cm in diameter in order to be classified as a specific element. The "other" category in the element section of Table 4 lumped infrequently occurring elements (e.g., small wood pieces, sediment bars) into a single category. Figure 4 shows typical elements and processes associated with exogenous mechanisms, and how pool formation was classified. Figure 5 illustrates endogenous mechanisms and their morphological characteristics.

Pools were not typically formed by a single element. For example, a beaver dam might be built upon a large log that lies across the channel. In this instance there are two elements which help create the pool: a beaver dam and a log. Multiple elements were generally observed, however, no more than two elements were recorded for each pool. Prominent elements were chosen based on the extent of scour and/or impoundment associated with each element. Once elements were chosen, the associated pool forming process (e.g., plunging) was determined. Since processes that influence the shape of a pool usually occur during high flow, the pool forming processes were estimated assuming bankfull flow.

Channel Measurements

The length of each stream section was approximately 70 bankfull channel widths. This length was chosen because of the need to sample representative lengths in

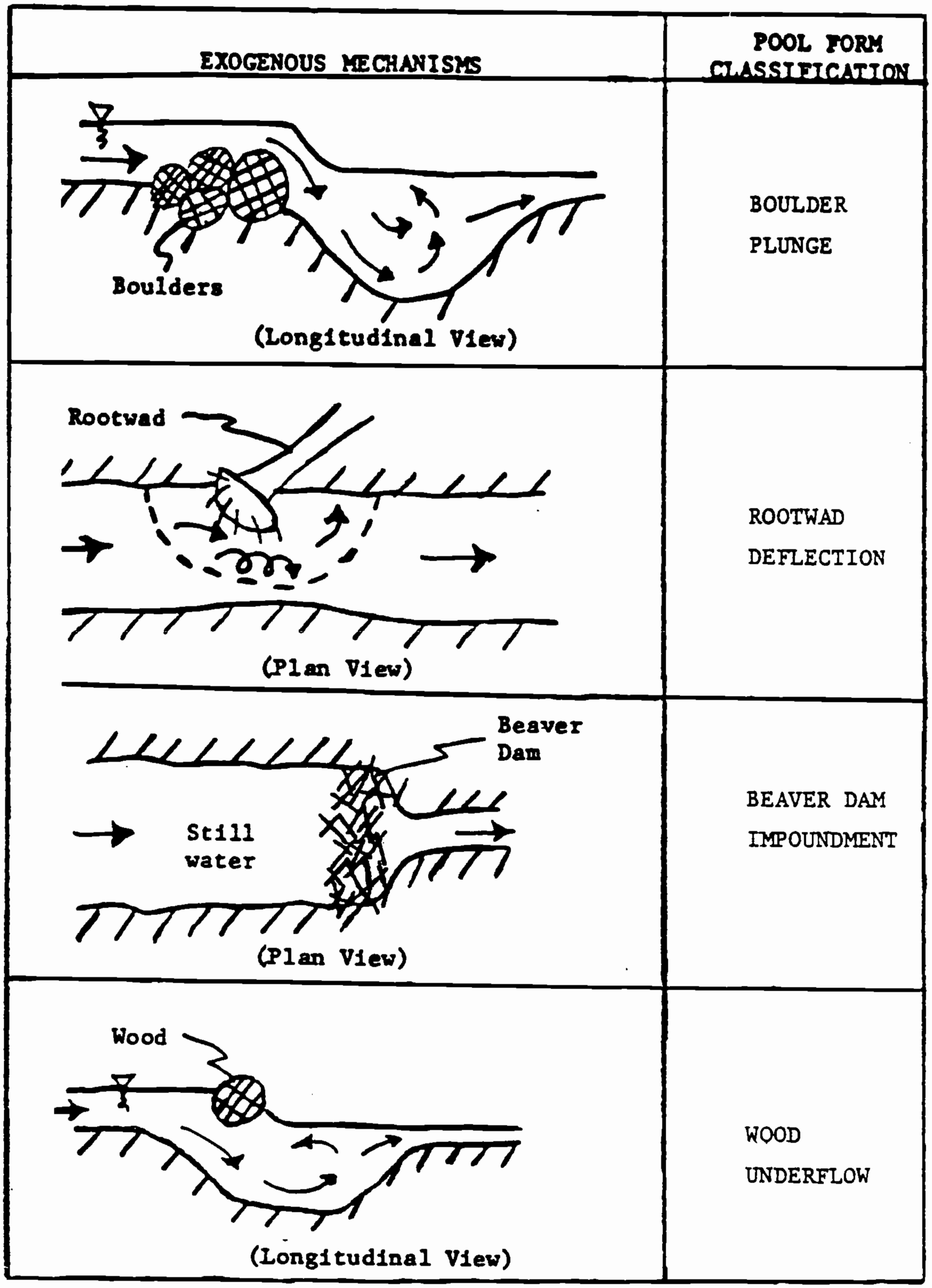

Figure 4. Exogenous pool mechanisms with examples of classification system used. [adapted from Bisson et al., 1981; Beschta and Platts, 1986; Robison, 1988b]

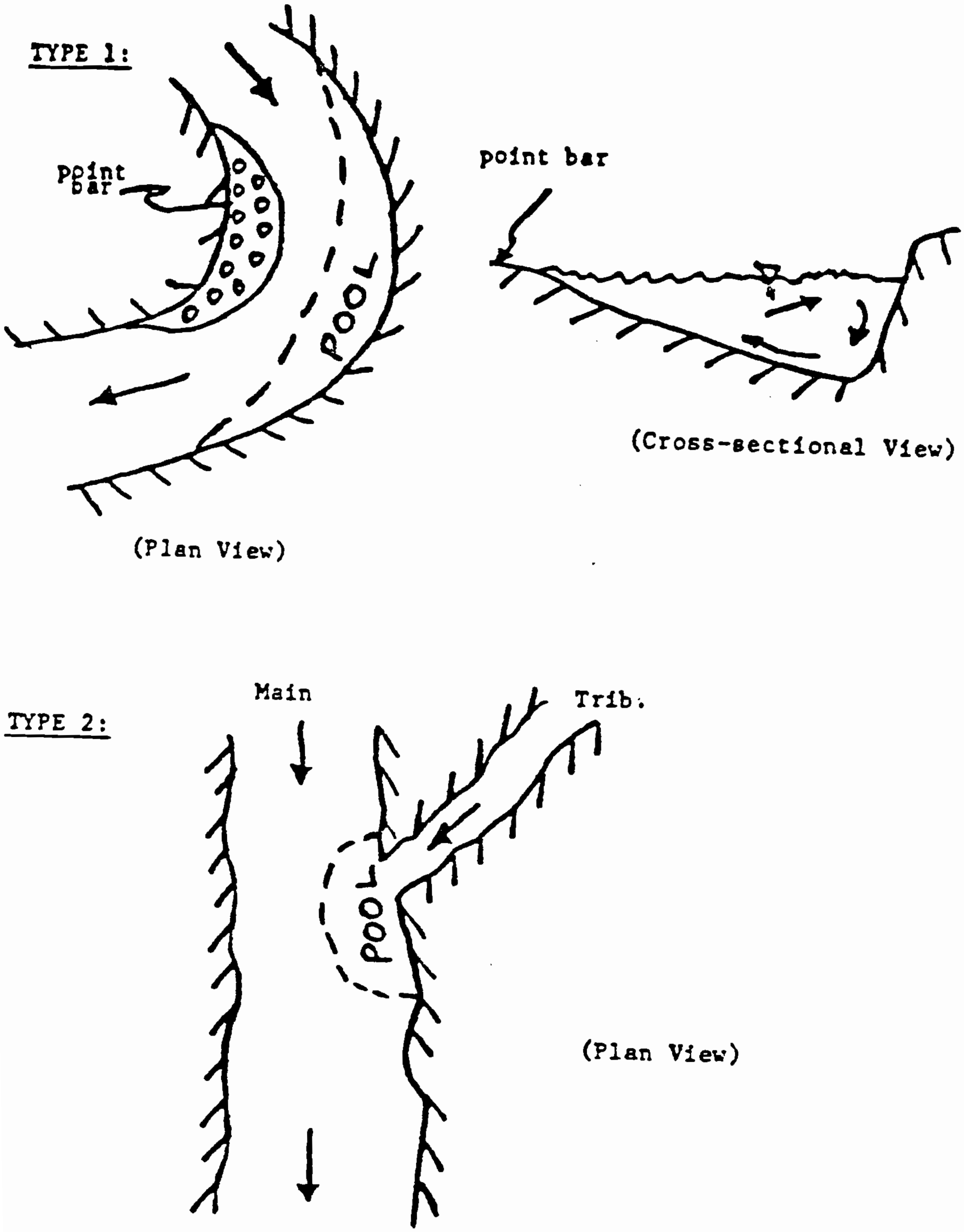

Figure 5. Endogenous pool forms.
[adapted from Robison, 1988b]

each stream section (i.e., stream size gets larger as drainage area increases). It was assumed that 70 bankfull channel widths provided an adequate length to characterize a given reach and enough time to survey the number of stream selected.

Thalweg depth, low-flow width ("wetted" width), and bankfull width were measured along the channel at every 1/3 bankfull width. One-third bankfull width was chosen as the data collection interval primarily because this distance was associated with the approximate length of pools; a measurement every one-third bankfull width was required to record at least one measurement in units that "looked" like pools.

An initial estimate of bankfull width was obtained by walking the stream section of interest and periodically recording bankfull width. An average width was then calculated and used to determine the reach length needed (70 bankfull widths) and the frequency of data collection (1/3 bankfull width).

At each station, the thalweg depth was determined along an imaginary line perpendicular to the current direction at bankfull flow (Figure 6). This line was also used for determining bankfull widths. Upstream distances (i.e., distance to next station) followed the direction of flow (i.e., parallel to current) at bankfull flow. Low-flow widths also used an imaginary line, but it was established perpendicular to the current at low flow.

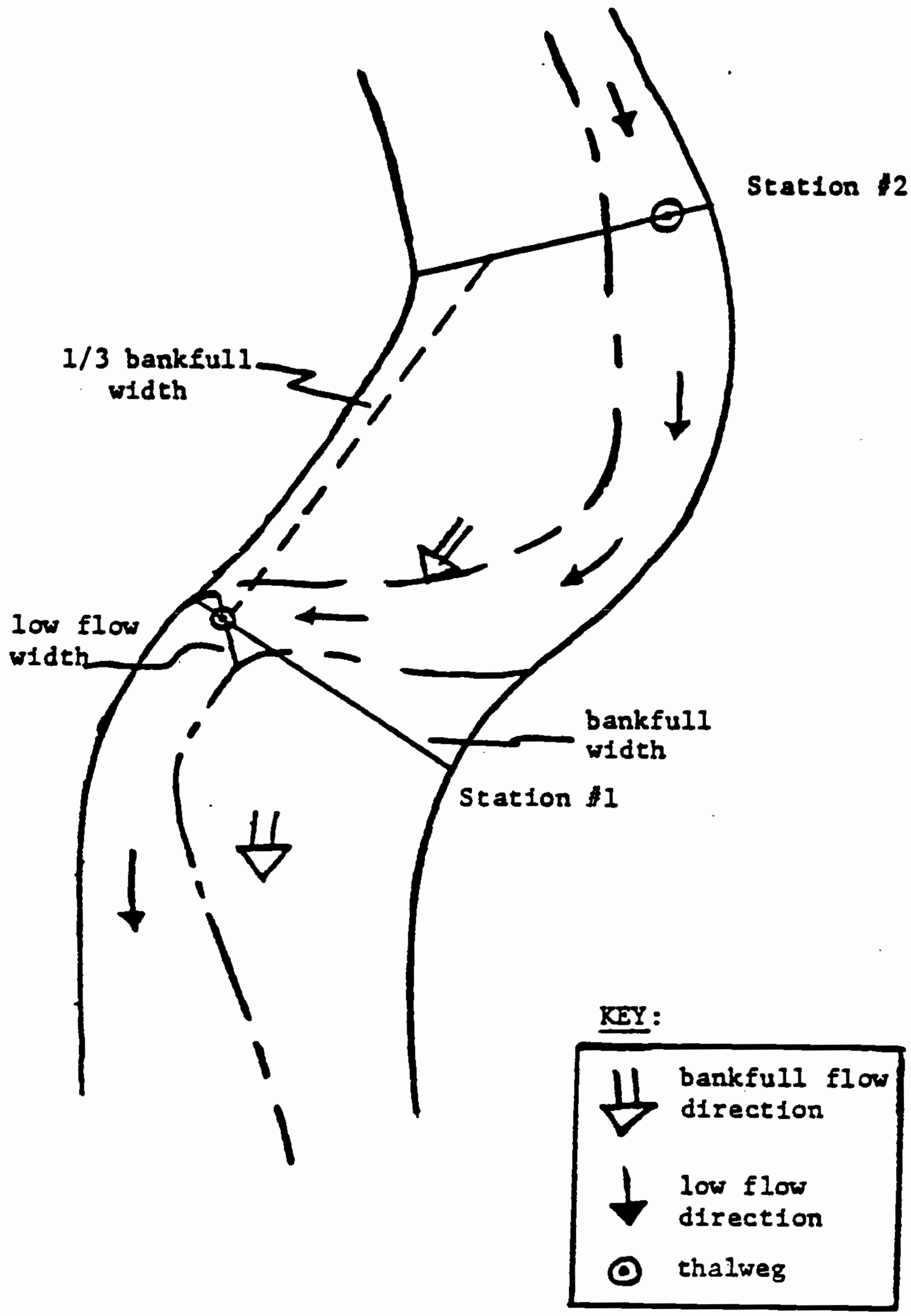

Figure 6. Stream plan view with method used to collect channel width and depth measurements. (NOTE: Not drawn to scale)

Average water surface slope was determined with the use of a p-level (with a 5x magnifier) and a stadia rod. Elevations were determined at prominent breaks in channel slope (e.g., riffles) over the entire stream reach.

Cross-sectional profiles were measured at riffles in each stream section. Pebble counts, using the method devised by Wolman (1954), were also obtained at these riffles.

In summary, the general methodology used to collect data was (1) channel morphology (i.e., thalweg depth, widths), (2) average water surface slope, (3) channel cross sections and pebble counts, (4) pool location, size, and spacing (via computer program), and (5) pool formation. The total data collection time required to measure a reach varied depending on the size of stream (smaller streams usually took longer), but on average one and one-half to two days were needed.

Calculation of total stream power

As previously noted, total stream power is a function of discharge and channel slope. Discharge measurements involve considerable time to obtain "representative velocities". Further, discharge during periods of summer low flow does not correspond to the current channel morphology (i.e., bedforms are primarily the result of high flows (Wolman and Miller, 1960; Keller and Melhorn, 1973; Baker, 1977)). Therefore, bankfull discharge was employed to calculate total stream power for each study reach. The bankfull discharge (assumed to be approximately a 2-year event [Q_2] (Leopold et al., 1964)) was calculated by the application of a statistically derived equation for the Oregon Coast Range [Harris et al., (1979)]:

$$Q_2 = 4.59 * A^{0.96} * (ST+1)^{-0.45} * I^{1.91}$$

where A equals drainage area (mi^2); ST equals the area of lakes and ponds (in percent); and I equals the maximum precipitation intensity of the 2-year 24-hr storm (in.). The average error associated with estimates of the 2-year discharge equation is 33% (Harris et al., 1979).

Channel slope was measured in the field. Drainage areas were estimated from topographic maps (USGS 7.5′) at the midpoint of each stream section. An isopluvial map of 2-year 24-hr precipitation was used to determine precipitation intensity (Harris et al., 1979).

The method for calculating total stream power is essentially independent of management practices, thus the method provides a useful independent variable to compare stream channel morphologies under different management intensities.

Data analysis

Commonly available and IBM compatible computer software packages (i.e., Statagraphics, Symphony) were used in data analysis. These programs were particularly useful for statistical analyses and plotting of data. Pool size, spacing, and location were evaluated by using the computer program shown in Appendix B.

RESULTS AND DISCUSSION

The results are divided into three sections: (1) pool size, (2) number, spacing and percentage of pools, and (3) pool formation. Channel morphology characteristics were determined for the nineteen stream sections [Flynn B was used to determine the accuracy of instrumentation (i.e., levels) and was not analyzed for morphological characteristics]. Table 5 shows these characteristics as well as the total stream power for each of these sections. Total stream power values were calculated assuming a water temperature of 13^{o}C (55^{o}F).

Mean drainage area, water surface slope, and total stream power for the study streams are as follows: 6.8 km^2, 2.5%, and 1164 Watts/m (low timber harvest); 8.1 km^2, 1.7%, and 1127 Watts/m (high timber harvest), respectively.

Pool Size

Residual pool size characteristics were determined for each stream section using the Rapid Bed Profile technique. Preliminary analyses of the 14 low timber harvest streams indicated that pools formed by beaver dams increased many pool size characteristics. For example, Franklin C had one beaver caused pool that represented 24% of the total pool volume for the stream section. Some streams had an extensive network of beaver dams that

Table 5. Channel morphology characteristics of each stream section and associated total stream power values.

STREAM SECTION	DRAINAGE AREA (km^2)	WATER SLOPE (%)	2 YEAR DISCHARGE (m^3/s)	STREAM POWER (Watts)	REACH LENGTH (m)	LENGTH IN BEDROCK (%)	LENGTH IN BEAVER POOLS (%)	AVERAGE DEPTH (cm)	LOWFLOW WIDTH (m)	BANKFULL WIDTH (m)	SEDIMENT SIZE D-50 (mm)	SEDIMENT SIZE D-84 (mm)
FLYNN C	1.3	1.36	1.42	189	244	0.0	0.0	12.6	1.68	3.44	28.0	63.5
TROUT A	1.5	3.75	1.64	603	255	0.0	0.0	13.4	2.37	3.57	43.2	134.5
FLYNN D	1.6	4.40	1.72	742	256	12.4	0.0	11.2	1.84	3.63	48.5	356.0
FLYNN A	1.6	0.91	1.80	161	237	1.5	0.0	14.0	1.76	3.32	24.0	45.1
TROUT B	2.2	5.30	2.43	1262	338	4.0	32.0	26.5	4.09	5.43	70.8	416.9
HARVEY B	2.8	5.63	2.82	1556	346	54.5	0.0	13.4	2.16	5.06	79.4	371.5
HILL	3.1	2.67	3.12	816	393	1.9	27.0	29.3	4.28	5.52	53.7	208.9
BEAR A	4.6	1.38	5.43	734	379	4.8	0.0	16.3	2.43	5.36	50.1	87.1
FRANKLIN B	6.4	3.10	6.17	1874	476	9.4	0.0	17.5	2.06	6.74	56.3	497.1
HARVEY A	8.2	1.99	7.87	1535	471	28.0	0.0	18.9	3.07	6.58	77.6	549.5
FRANKLIN C	11.4	1.07	10.82	1135	639	0.4	7.6	25.9	4.43	9.06	58.9	223.9
FRANKLIN A	14.3	1.11	13.37	1454	716	0.0	0.9	23.7	4	10.21	43.8	230.8
TROUT C	16.0	0.84	16.12	1327	674	4.5	8.9	38.8	7.28	9.57	56.6	190.7
FRANKLIN D	17.3	1.84	16.10	2903	788	0.0	0.0	24.7	5.24	11.16	51.3	467.8
BUCK	3.0	2.85	3.56	994	338	9.8	0.0	15.1	2.82	4.21	*	*
FAILOR A	5.0	2.42	5.86	1390	437	0.0	0.0	20.0	3.23	6.61	*	*
FAILOR B	8.1	1.56	9.51	1454	524	46.1	0.0	19.4	4.78	7.47	*	*
BEAVER	9.4	1.18	9.03	1044	579	44.1	0.0	26.0	4.7	6.83	*	*
DEADWOOD	14.8	0.45	17.13	755	691	0.0	49.0	62.2	8.23	10.06	*	*

* See text.

encompassed a large portion of the total pool volume (e.g., Trout B had 92% of total pool volume in beaver dams). Hence, beaver-influenced streams were initially separated from the data set in an attempt to address the effects of stream power on pool morphology.

Beaver-caused pools, which influenced less than 10% of the total reach length, were deleted temporarily from three stream sections: Franklin A, Franklin C, and Trout C. Subsequent pool size characteristics were re-calculated by "rejoining" the data set where beaver pools were deleted (e.g., connecting riffles above and below the deleted beaver pool) so that "representative" pool size characteristics could still be obtained. Depending on the stream, one to three beaver-caused pools were removed. Stream sections typically had 16-25 pools.

Two other beaver-influenced stream sections, Mill and Trout B, were dropped entirely from initial analyses since "rejoining" portions of the channel was not feasible due to the extent of beaver-caused pools (i.e., 80-90% of total pool volume was associated with beaver dams). Thus, twelve low timber harvest streams, without the influence of beavers, were initially investigated to see if pool size was a function of total stream power.

Stepwise regressions were undertaken using the variables in Table 5 and the average residual pool area (longitudinal) for each stream section. Drainage area was more closely associated with average residual pool area

(r^2 = 0.80) than total stream power (r^2 = 0.20). A comparison of the average residual pool area against these independent variables is shown in Figure 7. Also, since drainage area explained a high portion of variability for average residual pool area, analyses using sediment size characteristics were not fully developed; these size characteristics were not determined for high timber harvest streams.

Correlations between average water surface slope, drainage area, and total stream power for the 12 low timber harvest streams with no beaver influence are shown in Table 6. Figure 8 shows the distribution of average water surface slope as a function of drainage area for each stream section; variability in water surface slope decreases as drainage area increases. Even though average water surface slope for small drainages (<3km^2) varied from 1-6%, their respective average residual pool areas stayed approximately the same (i.e., ~0.5 m^2) when compared to larger drainage streams. This indicates that average water surface slope is not correlated with residual pool area for these smaller drainages.

Other residual pool size characteristics (i.e., length, width, volume) were also associated with drainage area. Taking the natural logarithms of both dependent (pool characteristic) and independent (drainage area) variables, generally reduced the unexplained variability. These relationships are analogous to the discharge

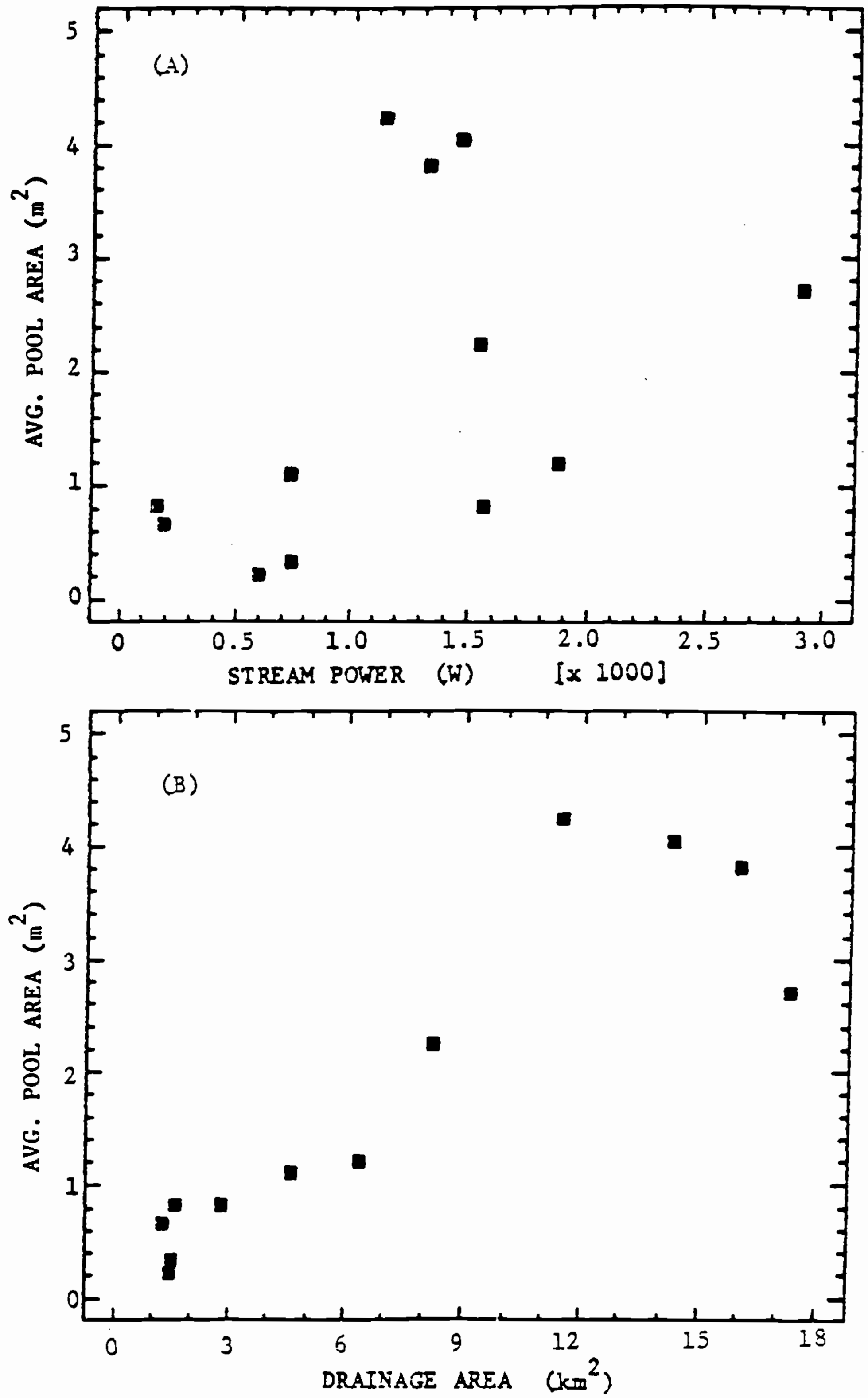

Figure 7. Average residual pool area versus (A) total stream power and (B) drainage area. [12 low timber harvest streams, no beaver]

Table 6. Correlation matrix for drainage area (DA), average water surface slope (WS), and total stream power (TP). [12 low timber harvest streams, no beaver caused pools]

	DA	WS	TP
Drainage Area	--	-0.49 (0.11)	0.72 (<0.10)
Water Slope	--	--	0.11 (0.74)

Significance level in parentheses.

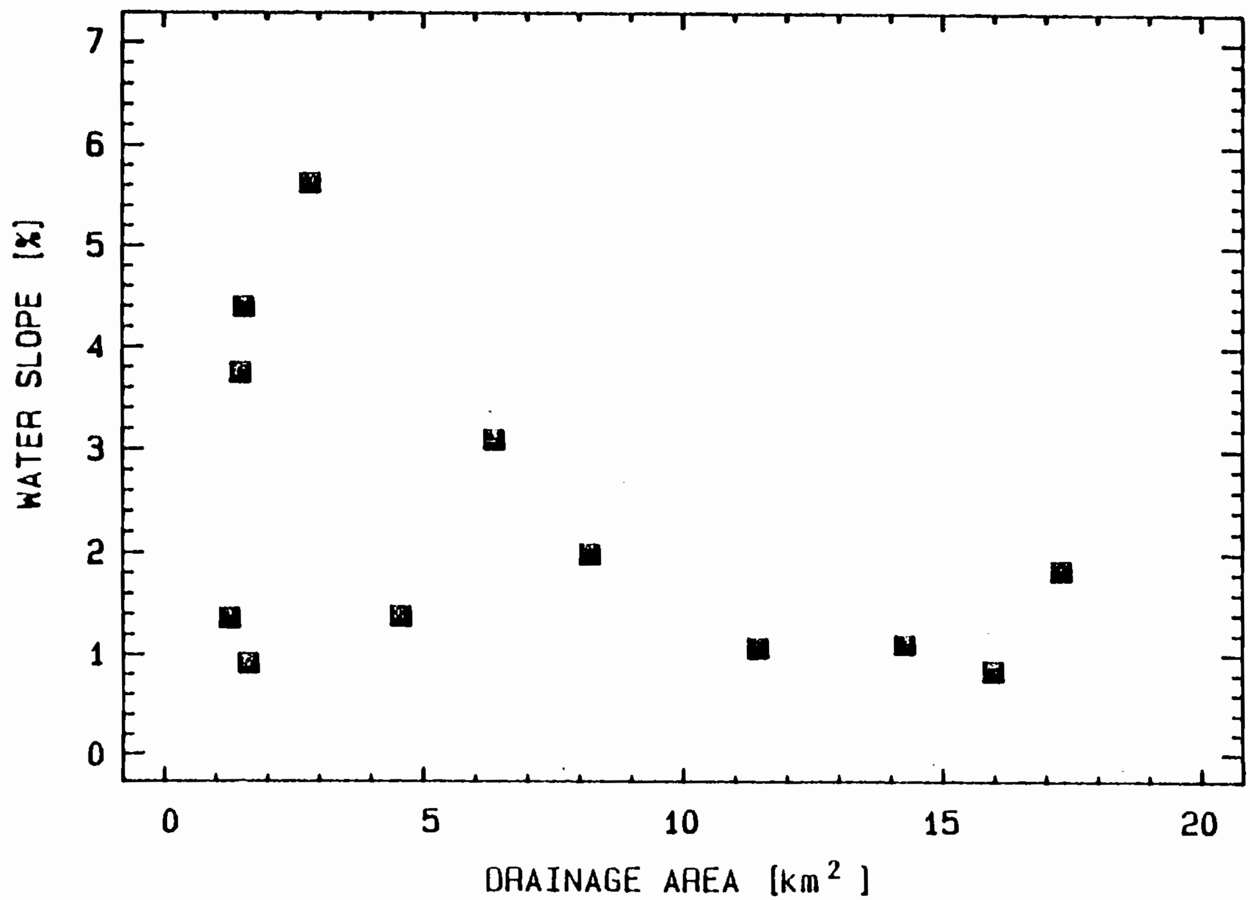

Figure 8. Average water surface slope versus drainage area. [n=12 streams, low timber harvest, no beavers]

dependent variables for the average flow related characteristics (e.g., channel width) developed by Leopold and others (1964). Because drainage area is highly correlated to discharge (r^2=0.99), this suggests a similar "hydraulic geometry" could exist for pool dimensions.

The standard deviation of thalweg depth (required to define a "pool" by the RBP technique [see Appendix A]), for the 12 low timber harvest and no beaver influence streams was also a function of drainage area (Figure 9A). Additionally, average bankfull width was a function of drainage area (Figure 9B). These two figures were used to define a pool (i.e., standard deviation of thalweg depth) and the stream reach length (i.e., 70 bankfull channel widths) for beaver-influenced streams and high timber harvest streams.

Because drainage area and two-year peak discharge (Q_2) were highly correlated a surrogate for total stream power might be represented by the product of drainage area and average water surface slope. This is further supported by comparing the slope of average bankfull width verses drainage area in Figure 9B (0.45) to other studies which have used discharge in place of drainage area. Orsborn and Stypula (1987) estimated bankfull width changed as a function of discharge raised to the 0.50 power for ten Coastal Oregon streams. Leopold and others (1964) determined a similar value for midwestern U.S. rivers.

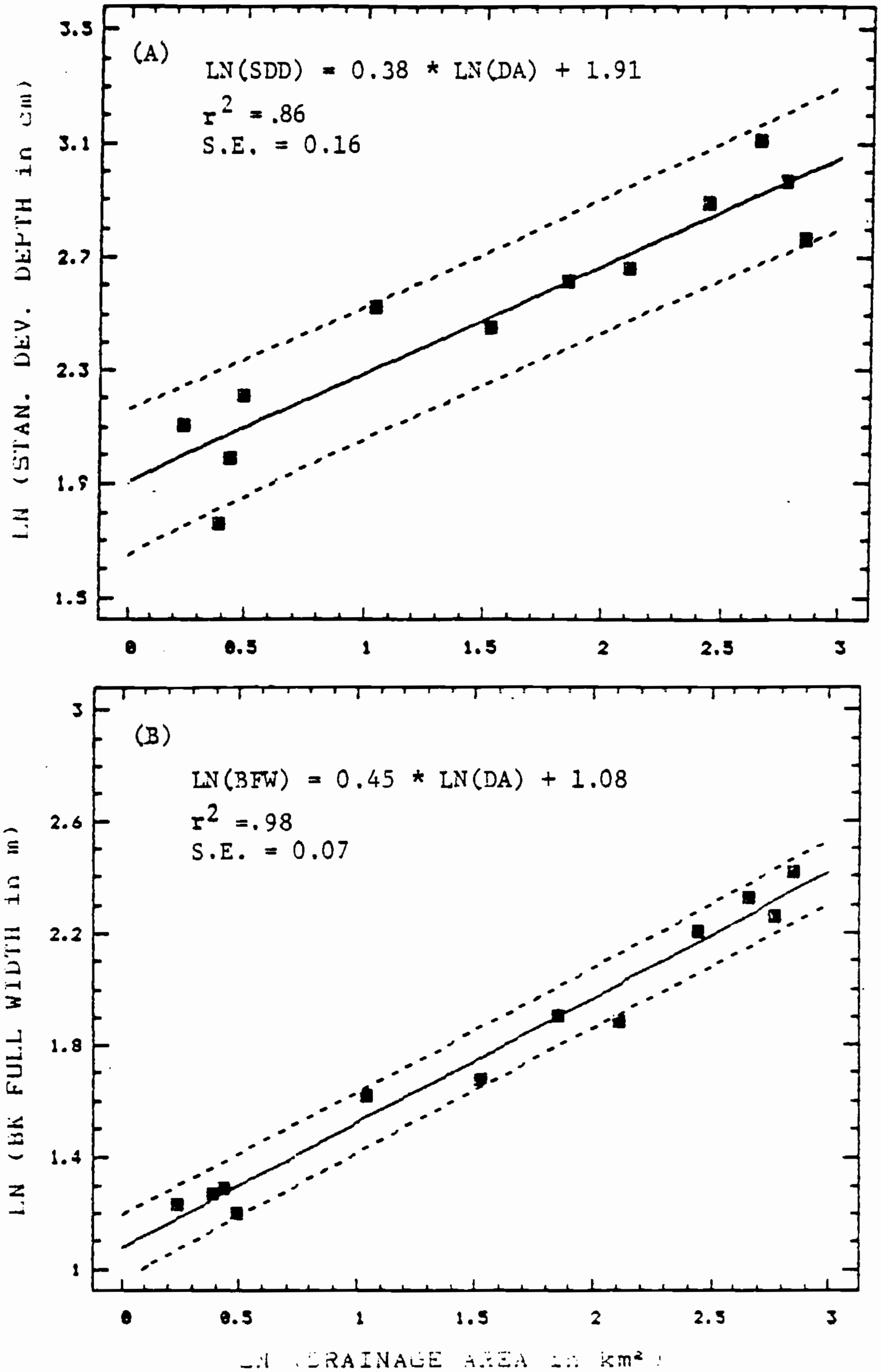

Figure 9. (A) Standard deviation (SDD) of thalweg depth and (B) bankfull channel width (BFW) versus drainage area (DA). [12 low timber harvest streams, no beavers; prediction band at alpha equal 20%]

Table 7 lists the average pool size characteristics associated with each stream section. Values attained without using the relationships in Figure 9, for beaver-influenced and high timber harvest streams, are also shown in Table 7.

An 80% prediction band was employed to determine if the temporarily deleted data points, namely beaver influenced streams or high timber harvest streams, were significantly (alpha=0.20) different from relationships established with the 12 "control" sections. Average residual pool depth (maximum), area, standard deviation of area, and volume as a function of drainage area are shown in Figures 10, 11, 12, and 13, respectively. All relationships have positive correlations with drainage area. The level of significance (alpha=0.20) was chosen because of the high variability within the "control" sections. It implies that one data point out of five outside the prediction band is a "normal" occurrence. More than one data point, for a population of five, outside the prediction band may infer one of those data points is "different", however, definitive conclusions are limited due to the number of streams investigated in this study. Additionally, those points outside the 80% prediction band are referred to as outside-the-band (OTB) points.

Figures 10, 11, 12, and 13 suggest two conclusions. First, in most cases, streams influenced by beaver pools

Table 7. Average pool size characteristics for all stream sections.

STREAM SECTION	REACH TOTAL LENGTH (m)	STAN DEV DEPTH (cm)	RBP SLOPE (%)	# OF POOLS	AVERAGE POOL CHARACTERISTICS LENGTH (m)	DEPTH MAX (cm)	WIDTH (m)	LONG. AREA (m^2)	STAN DEV AREA (m^2)	VOLUME (m^3)	VOLUME IN BEAV POOLS (%)
FLYNN C	244	8.2	0.43	20	9	17.7	1.72	0.67	0.49	0.7	0.0
TROUT A	255	5.8	1.07	23	5	12.2	2.47	0.23	0.13	0.3	0.0
FLYNN D	256	7.3	1.52	16	5	15.2	1.84	0.34	0.25	0.3	0.0
FLYNN A	237	9.1	0.35	16	9	23.3	1.80	0.83	0.61	0.8	0.0
TROUT B	338	22.9 (9.1)	1.46	23 [11]	7	30.1	3.98	1.44	2.69	5.2	92.0
HARVEY B	346	12.5	1.43	19	7	29.4	2.02	0.82	0.56	1.3	0.0
HILL A	393	22.9 (10.4)	0.79	17 [12]	12	32.3	4.07	2.80	4.86	7.8	86.0
BEAR A	379	11.6	0.63	25	10	26.1	2.38	1.10	0.64	1.5	0.0
FRANKLIN B	476	13.7	0.79	25	10	29.2	2.25	1.29	0.83	1.7	0.0
HARVEY A	471	14.3	0.49	20	16	30.8	3.11	2.24	1.58	4.0	0.0
FRANKLIN C	639	19.0 [18.2]	0.34	17 [16]	24 [22]	43.9 [42.2]	4.74	5.07 [4.24]	4.62	14.1 [11.4]	24.0
FRANKLIN A	716	22.3 [22.4]	0.40	21 [20]	19 [20]	45.7 [46.8]	3.53	3.88 [4.04]	3.34	10.0 [10.4]	1.0
TROUT C	674	20.1 [19.4]	0.41	21 [18]	22 [20]	44.8 [42.9]	7.55	4.41 [3.82]	2.54	18.0 [16.0]	24.0
FRANKLIN D	788	15.9	0.50	25	19	32.7	5.25	2.70	2.52	8.0	0.0
BUCK	338	9.8 (10.2)	0.84	21	9	22.6	3.12	0.86	0.53	1.4	0.0
FAILOR A	437	12.0 (12.4)	0.73	21	10	25.7	3.35	1.21	0.82	2.3	0.0
FAILOR B	524	12.5 (15.0)	0.51	16	15	27.1	4.58	1.82	1.68	4.6	0.0
BEAVER	579	11.6 (15.9)	0.42	16	21	28.4	4.76	2.62	1.53	6.6	0.0
DEADWOOD	691	41.2 (18.8)	0.24	14	40	50	6.95	16.10	39.2	84.0	84.0

() = values from relationships in Figure 9.
[] = calculated values after removing beaver affected data.

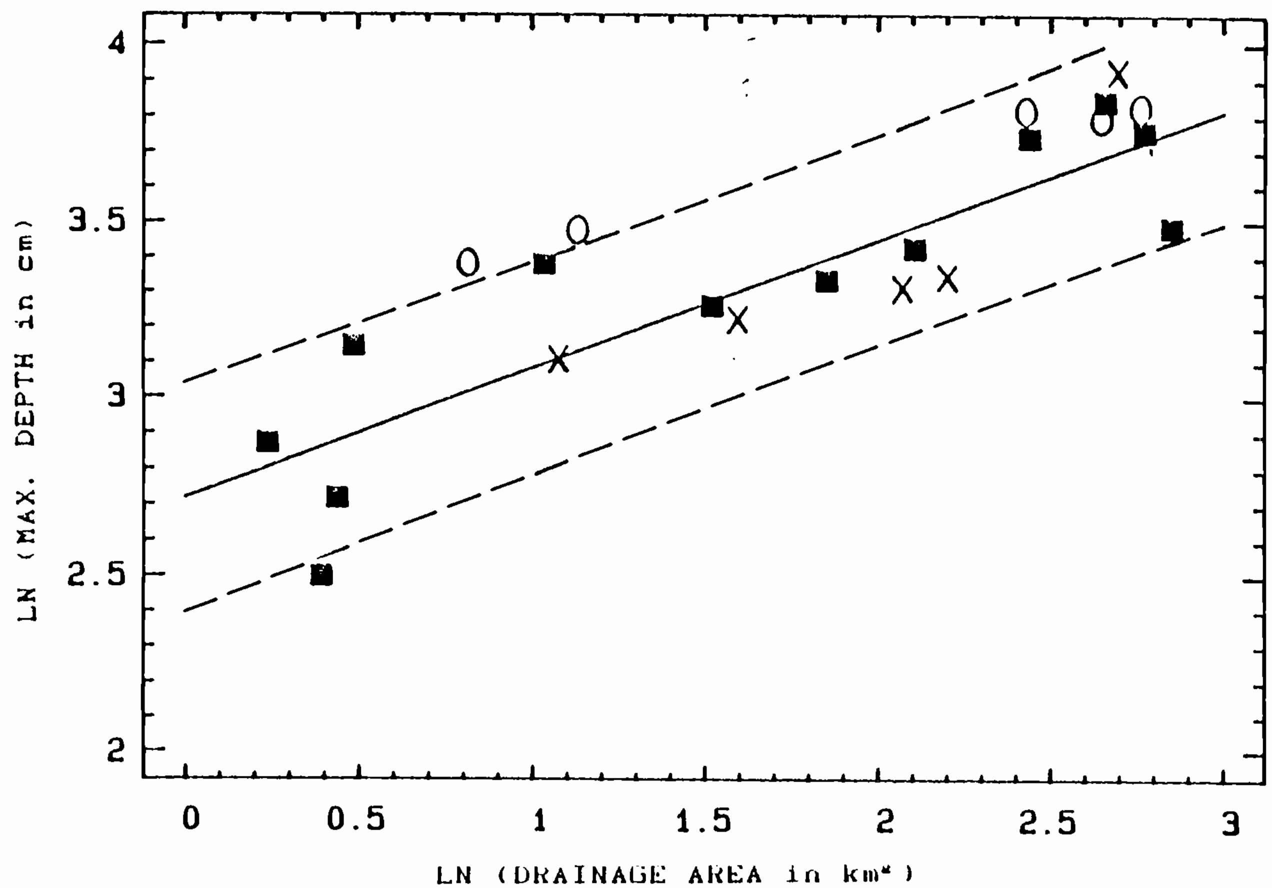

Figure 10. Average residual pool depth (maximum) versus drainage area. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

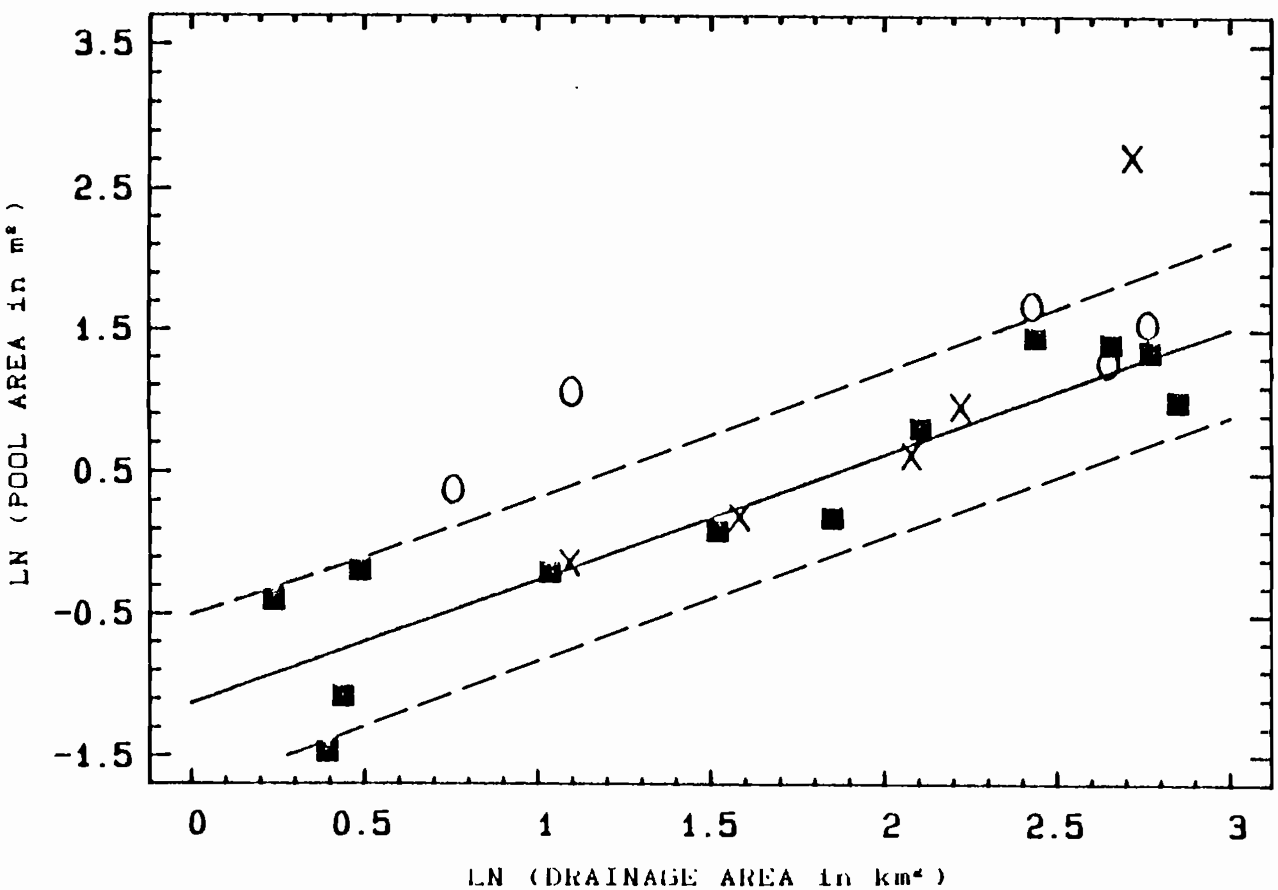

Figure 11. Average residual pool area versus drainage area. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

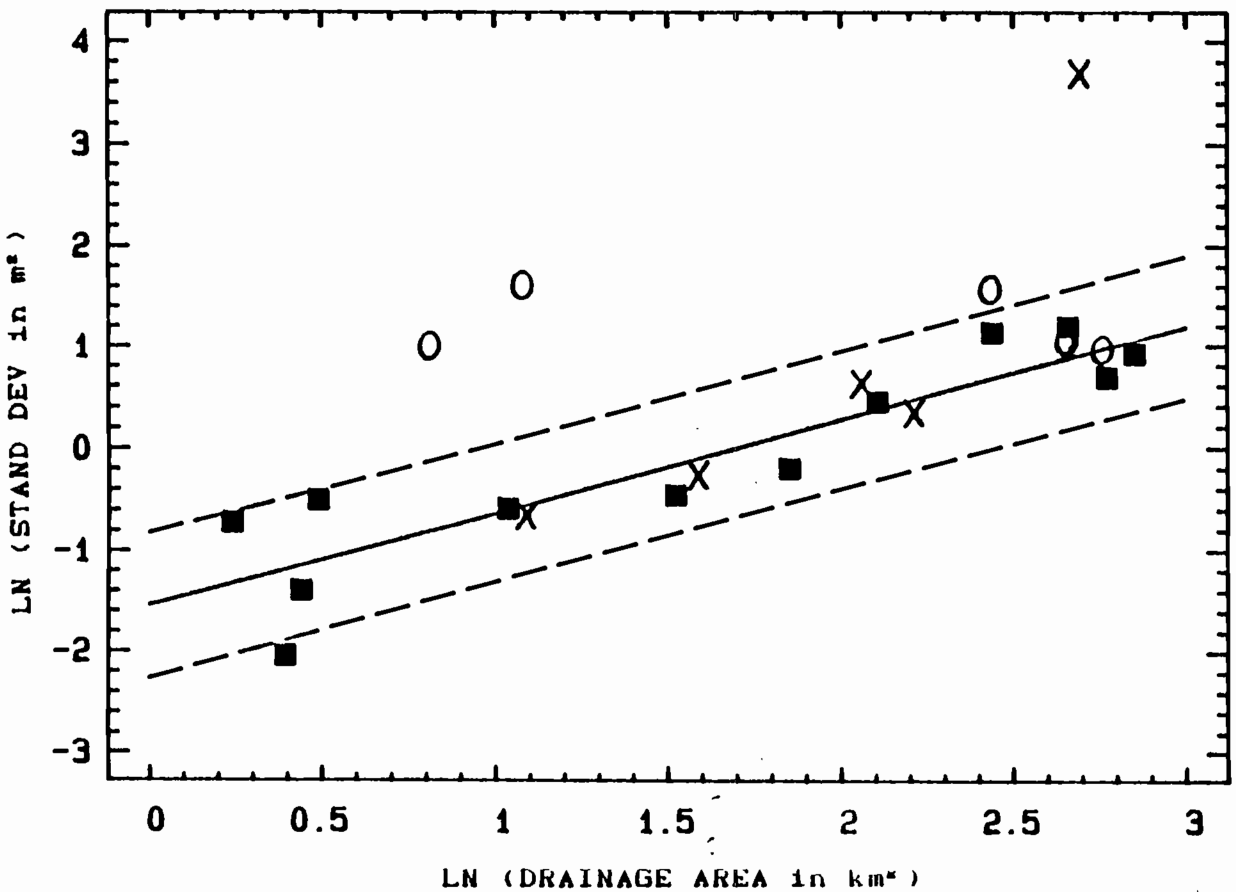

Figure 12. Standard deviation of residual pool area versus drainage area. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

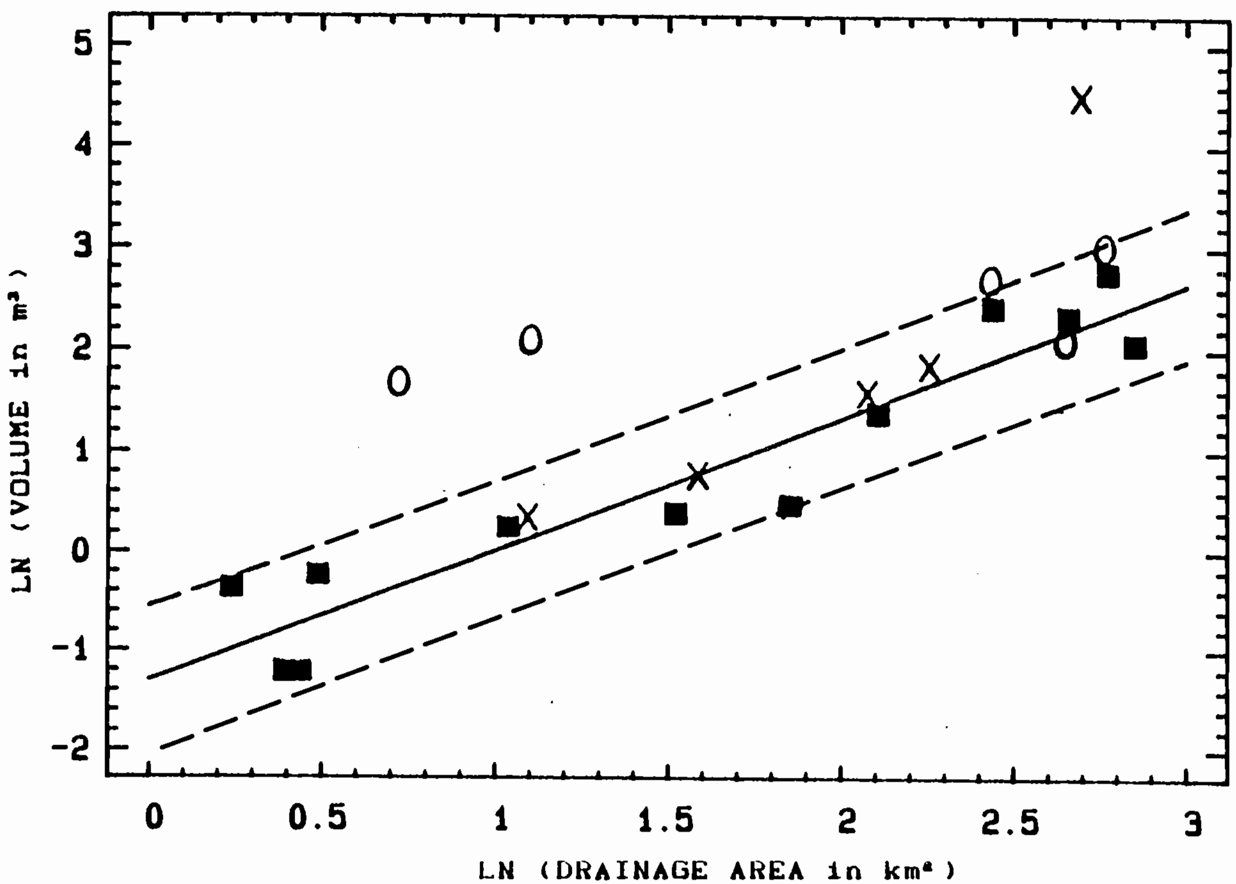

Figure 13. Average residual pool volume versus drainage area. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

are OTB. Stream sections Trout B and Mill, are especially prominent OTB points. Beaver dams, generally, cause average residual pool size characteristics to be larger. Second, average residual pool size characteristics for streams with high timber harvest are not different from values attained for low timber harvest streams. However, W. Fork Deadwood Creek, a high timber harvest stream, was outside the prediction limits in all average pool characteristics. The reason for this may be due to the high percentage of pools influenced by beavers (89% of total pool volume in beaver caused pools).

Streams with beaver-caused pools seem to have a greater impact on average residual pool size characteristics than the effects associated with timber harvesting, at least for summer flow conditions. Beaver dams impound large quantities of water relative to the total pool volume of the reach. Such channel features are apparently beneficial to the rearing needs of coho salmon and cutthroat trout (Cedarholm, 1988). This suggests that encouraging increased beaver populations may provide a mechanism to improve fish habitat.

Average residual pool size characteristics for high timber harvest streams were not OTB (except Deadwood Creek) in the drainage area relationships. This may be explained by the high variability in these relationships for low timber harvest streams (i.e., a wide 80% prediction band). A stream has to be <u>radically</u> different (e.g., beaver-influenced stream) in order to be OTB. Or, the hypothesized effects of timber management (e.g., removal of large woody debris) may not have been sufficiently large to influence average residual pool size characteristics. For example, streams which had large wood removed may be compensated by other mechanisms to initiate pool formation (e.g., flow deflection by root wads of stream side alders instead of a large log which had caused plunging). Additionally, the influence of large storms (e.g., 1965 WY event) on channel morphology may not have caused the same channel or hillslope response on each watershed (Bevin, 1981; Nolan and Marron, 1985). Channel changes due to such large storms may persist for relatively long periods (Lyons and Beschta, 1983; Grant, 1986; Madej, 1987). Thus, the influence of the 1965 storm may have had a much greater effect on channel morphology than subsequent changes caused by timber harvest [(e.g., fall peak flow increase (Harr 1979)]. There are many other possible sources of explanation (e.g., not enough high timber harvest streams investigated, changes in timber management practices, large local storms, or valley topography differences).

Number, spacing, and percentage of pools

Table 8 lists the number, average spacing, and the percentage of pools within all nineteen stream sections. The influence of beaver-caused pools on number, spacing,

Table 8. Spacing, number, and percentage of pools for each study section.

STREAM SECTION	# POOLS /100m	POOL SPACING (CHANNEL WIDTHS)	POOL SPACING (m)	POOL:RIF RATIO (X:1)	PERCENT POOLS (%)
FLYNN C	8.2	3.4	11.6	2.8	74.0
TROUT A	9.0	3.1	11.2	0.8	46.0
FLYNN D	6.3	4.1	14.8	0.5	31.0
FLYNN A	6.8	4.0	13.3	1.7	63.0
TROUT B	6.8	2.4	12.9	0.9	48.0
HARVEY B	5.5	3.7	19.0	0.6	38.0
MILL	4.3	3.8	21.2	1.2	54.0
BEAR A	6.6	2.6	13.8	2.1	68.0
FRANKLIN B	5.3	2.5	17.0	1.1	53.0
HARVEY A	4.3	3.4	22.6	2.2	69.0
FRANKLIN C	2.6	4.1	36.8	1.7	63.0
FRANKLIN A	2.9	3.3	33.4	1.2	55.0
TROUT C	3.1	3.4	32.8	2.0	67.0
FRANKLIN D	3.2	2.8	31.0	1.5	60.0
BUCK	6.2	4.0	17.0	1.3	56.0
FAILOR A	4.9	3.0	20.0	1.0	49.0
FAILOR B	3.0	4.0	30.0	0.9	46.0
BEAVER	2.8	5.4	37.0	1.4	58.0
DEADWOOD	2.0	5.1	51.0	4.3	81.0

and percentage of pools was not studied because "rejoining" stream sections would not yield representative values (e.g., eliminating a pool increases the pool spacing at that location). Only data from the prominent beaver-influenced streams (Mill and Trout B) were excluded from regression analyses. The methods of analyses used on number, spacing, and percentage of pools were the same as those used on pool size characteristics in the previous section (e.g., linear stepwise regressions, 80% prediction band). Again, in all cases except for percentage of pools, the most efficient predictor for the number of pools and spacing of pools was drainage area.

The total number of pools per 100m of reach length decreased with increasing drainage area (Figure 14) while the average distance between deepest points of consecutive pools increased with increasing drainage area (Figure 15). Pools get larger, farther apart, and decrease in number as drainage area increases. These results may support the concept of entropy (requirement #1) mentioned earlier (i.e., energy is dissipated uniformly through the stream system). Since larger pools dissipate more energy than smaller ones (Hayward, 1980) and pools get larger in the downstream direction, the number of pools needs to decrease in order to dissipate energy uniformly.

The relative pool spacing (average pool spacing per average bankfull channel width) showed no significant correlation (i.e., $p>0.10$) to drainage area. Keller and

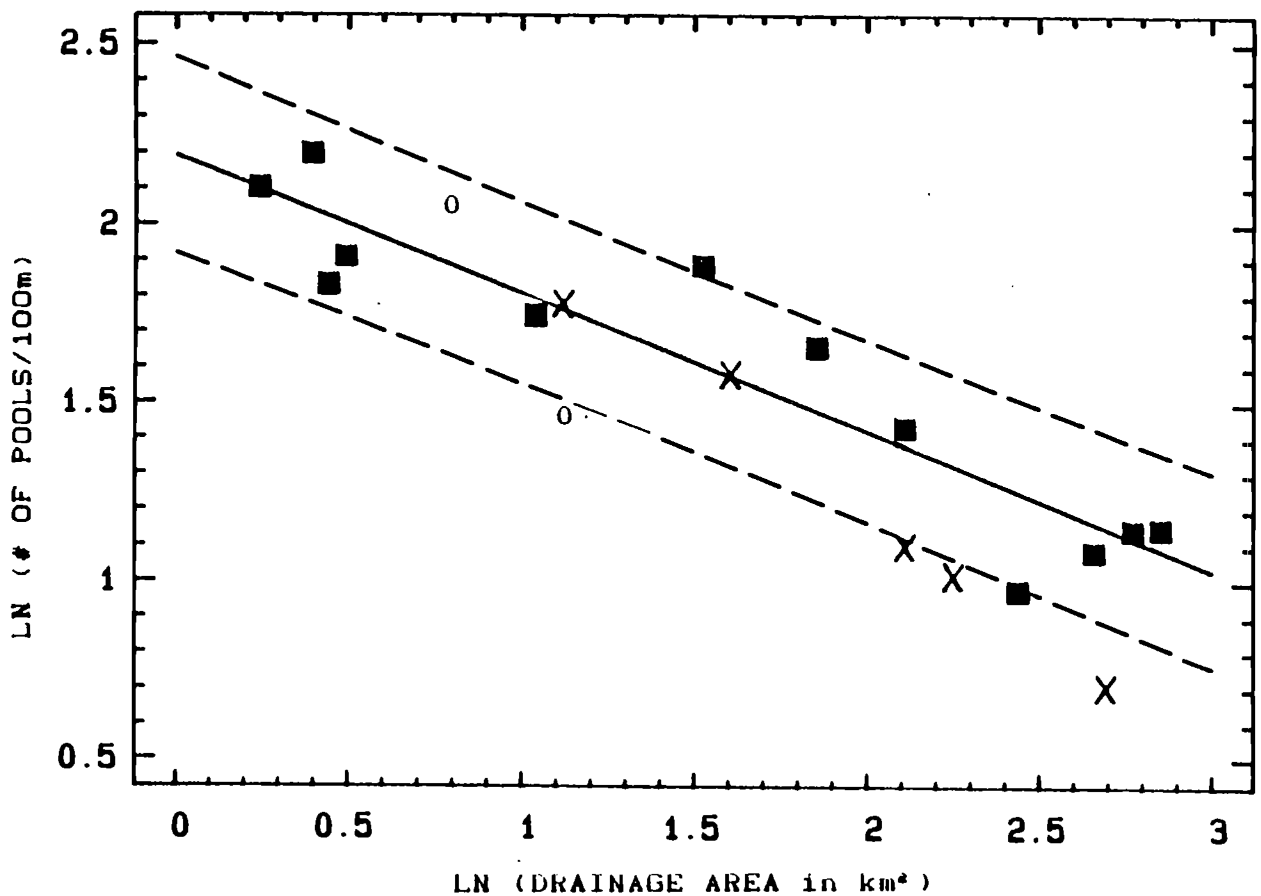

Figure 14. Number of residual pools per 100 meters versus drainage area. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

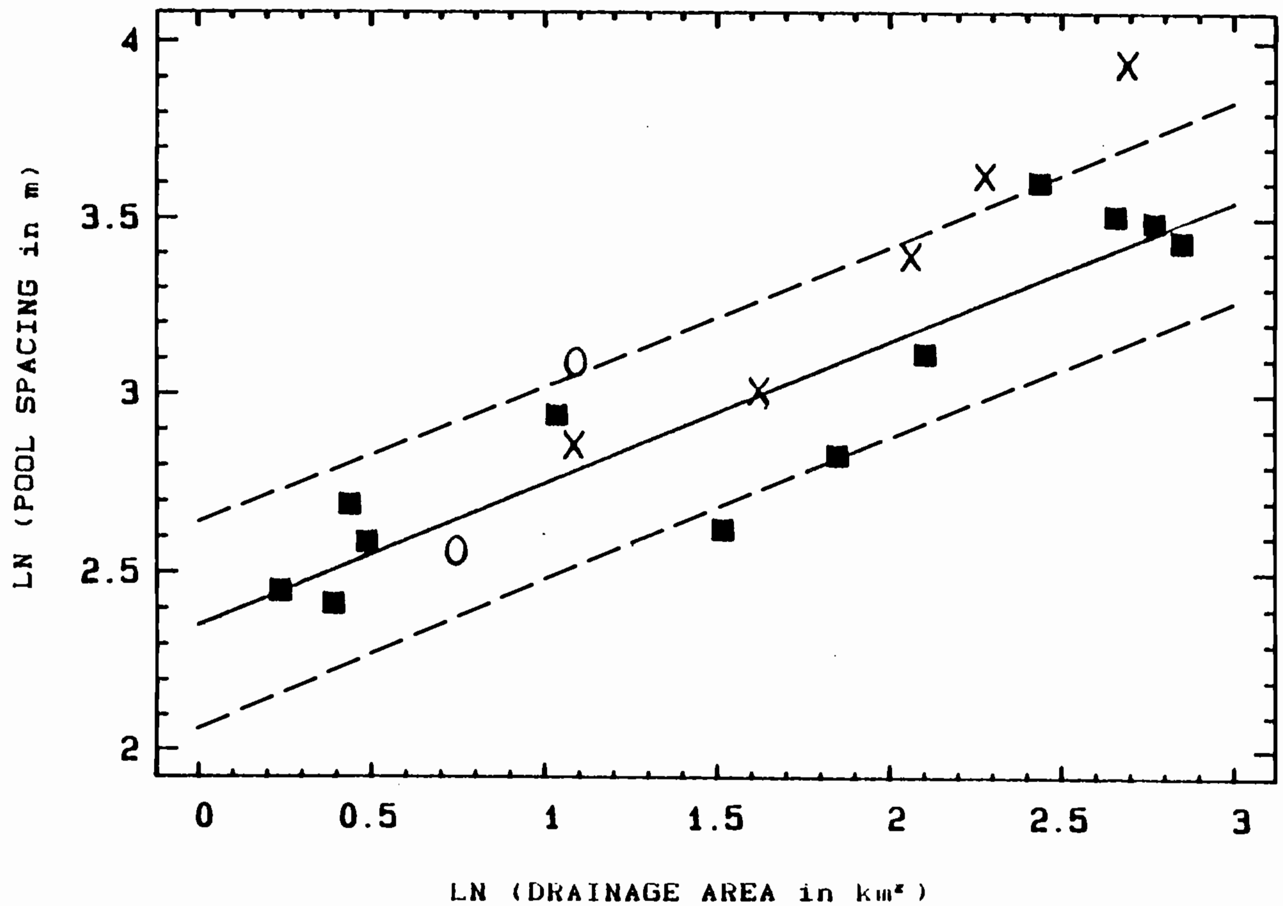

Figure 15. Average spacing between residual pools versus drainage area. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

Melhorn (1978) reported a similar finding using channel width instead of drainage area. Additionally, no significant correlation was found between relative pool spacing and percent of reach in bedrock. Mean relative pool spacings for low timber harvest streams ranged from 2.4 to 4.1, this is significantly lower than larger lowland streams (5-7 bankfull channel widths [Leopold et al., 1964]). These findings suggest that (1) pool spacing is not uniform through a drainage system and (2) exogenous inputs (e.g., debris avalanches) may cause the relative spacing between pools in upland streams to decrease.

The percentage of pools [(summation of pool length divided by total reach length) * 100] in each stream section decreased as the average water surface slope increased. Since average water surface slope for the reach includes the length of pools (which essentially have a slope of zero) then as the slope approaches zero for the reach the percentage of pools would seem likely to increase. This relationship is shown in Figure 16. Drainage area was not significantly (p-value >0.10) correlated to the percentage of pools for low timber harvest streams.

Table 9 lists the statistics, model equations, and OTB points for the relationships in this section along with those on pool size from the previous section.

Mill Creek, a beaver-influenced stream, caused an increase in the spacing of pools and a concurrent decrease

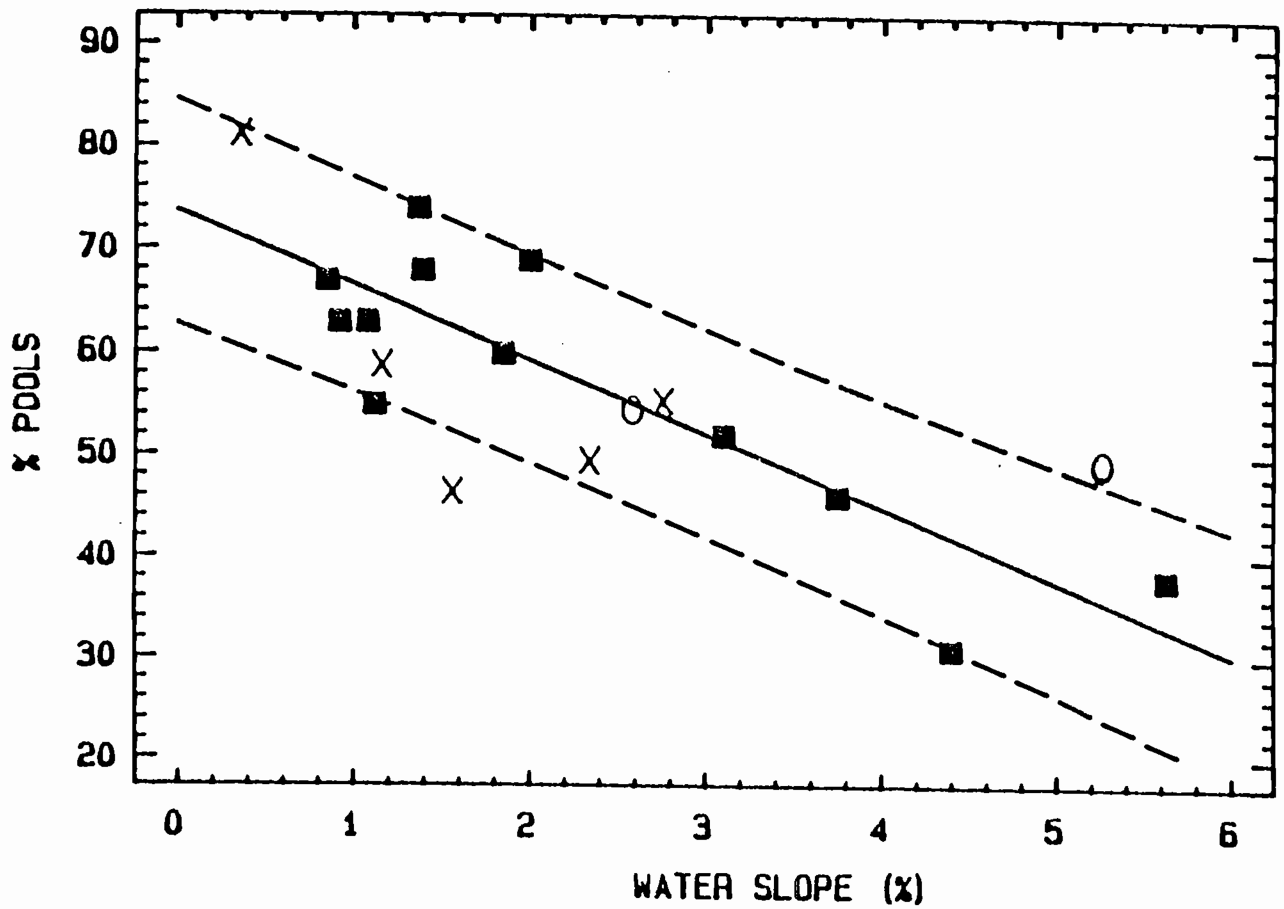

Figure 16. Percentage of residual pools (in reach) versus average water surface slope. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

Table 9. Model equations and statistics for average residual pool characteristics (based on 12 low timber harvest streams with no beavers). Also shown are the streams outside the prediction band for all 19 stream sections.

DEPEND VARIABLE	INDEPEND VARIABLE *	MODEL m	MODEL b	P-VALUE	STANDARD ERROR	r^2	OUTSIDE PREDICTION BAND BEAVERS **	OUTSIDE PREDICTION BAND OTHERS
LN(LENGTH) [m]	LN(DA)	0.48	1.70	<0.01	0.2	0.81	FRK C (+) DWOOD (+)	FLY C(+)
LN(WIDTH) [m]	LN(DA)	0.41	0.41	<0.01	0.2	0.76	MILL (+) TRT B (+) TRT C (+) DWOOD (+)	
LN(DEPTH) [cm]	LN(DA)	0.37	2.72	<0.01	0.2	0.78	MILL (+) TRT B (+)	TRT A(-)
LN(AREA) [m^2]	LN(DA)	0.88	-1.13	<0.01	0.4	0.85	TRT B (+) MILL (+) FRK C (+) DWOOD (+)	TRT A(-)
LN(ST.DEV OF AREA) [m^2]	LN(DA)	0.91	-1.55	<0.01	0.5	0.81	TRT B (+) MILL (+) FRK C (+) DWOOD (+)	TRT A(-)
LN(VOL) [m^3]	LN(DA)	1.32	-1.30	<0.01	0.5	0.90	TRT B (+) MILL (+) FRK C (+) DWOOD (+)	
LN(POOL SPACING) [m]	LN(DA)	0.40	2.35	<0.01	0.2	0.84	MILL (+) FRK C (+) DWOOD (+)	BEAR (-) BEAV (+)
LN(#/100m)	LN(DA)	-0.40	2.20	<0.01	0.2	0.86	MILL (-) FRK (-) DWOOD (-)	BEAR (-) FAIL B(-) BEAV (-)
%POOLS	H2O SLOPE [%]	-7.22	73.60	<0.01	7.1	0.74	FRK A (-) TRT B (+)	FAIL B(-)

[Note: All models are linear. (+), (-) = above and below prediction band, respectively.]
* DA= Drainage Area H2O SLOPE= Water Surface Slope

in the number of pools/100m. Causing fewer and larger pools is expected since large beaver dams encompass a relatively large portion of the stream length. However, Trout B, also a beaver-influenced stream, did not follow this trend. Trout B was not OTB in these relationships but was OTB in the percentage of pools versus average water surface slope. With a relatively steep gradient (5.3%) Trout B had many small beaver dams (12) while the section in Mill Creek had a gentler slope (2.1%) and fewer but larger beaver dams (5). Thus, the influence of beavers on the number and spacing of pools may depend on the average water surface slope prior to dam construction. In Colorado, Retzer and others (1956) found the extent of beaver dams did depend on the valley bottom gradient but also on valley width and geologic rock type.

The number of pools/100m versus drainage area (Figure 14) showed three high timber harvest streams are OTB: Failor B, Beaver, and Deadwood. The section in West Fork Deadwood Creek could be eliminated from the high timber harvest group because of the extent of beavers. Failor B and Beaver, however, did not have any beaver-caused pools. There may be an association of high timber harvest streams, particularly those with larger drainages (i.e., >8 km^2), with fewer number of pools/100m, but this is not conclusive because of the limited number of high timber harvest streams studied and historical information (e.g., detailed management records, effects of large storms), and the level of significance chosen for this analysis.

Mean values for low timber harvest streams and high timber harvest streams (Mill, Trout B, and Deadwood deleted) were 3.4 and 4.1 bankfull widths, respectively. Difference of the means was statistically different from zero at alpha equal to 0.10.

Pool formation

The processes and elements associated with pools were tabulated by frequency of occurrence. Preliminary analyses showed that beaver-influenced streams did not alter the frequency of occurrence of pool formation processes or elements; all 14 low timber harvest streams with beaver-caused pools are included in the regression models in this section.

Pool forming processes were classified into five categories: plunge, deflection, underflow, impoundment, and fluvial. Table 10 lists the frequency of occurrence in percent for each stream section along with associated values of drainage area, average water surface slope, and "stream power index". The "stream power index" is the product of average water slope and drainage area (i.e., % * km^2). Although the stream power index is not numerically equivalent to total stream power it is highly correlated with total stream power.

The prominent processes, generally, were deflection,

Table 10. Frequency of occurrence for pool forming processes. [19 stream sections]

STREAM SECTION	DRAINAGE AREA (km^2)	WATER SLOPE (%)	POWER INDEX (%*km^2)	FREQUENCY OF OCCURRENCE DEFLECT (%)	IMPOUND (%)	PLUNGE (%)	UNDER (%)
FLYNN C	1.3	1.36	1.8	52.5	5.0	25.0	7.5
TROUT A	1.5	3.75	5.6	57.0	4.4	32.1	6.5
FLYNN D	1.6	4.40	7.0	34.4	28.1	34.4	3.1
FLYNN A	1.6	0.91	1.5	43.8	0.0	15.6	12.5
TROUT B	2.2	5.30	11.7	28.3	34.8	37.0	0.0
HARVEY B	2.8	5.63	15.8	10.5	39.5	50.0	0.0
MILL	3.1	2.67	8.3	29.4	35.3	29.4	2.9
BEAR	4.6	1.38	6.3	40.0	12.0	26.0	14.0
FRANKLIN B	6.4	3.10	19.8	20.0	40.0	40.0	0.0
HARVEY A	8.2	1.99	16.3	27.5	27.5	35.0	5.0
FRANKLIN C	11.5	1.07	12.3	52.9	17.7	23.5	0.0
FRANKLIN A	14.3	1.11	15.9	57.2	11.9	16.7	9.5
TROUT C	16.0	0.84	13.4	50.0	7.1	31.0	7.1
FRANKLIN D	17.3	1.84	31.8	50.0	34.0	14.0	2.0
BUCK	3.0	2.85	8.6	54.8	0.0	23.8	21.4
FAILOR A	5.0	2.42	12.1	45.2	9.5	31.0	7.1
FAILOR B	8.1	1.56	12.6	28.1	18.8	50.0	3.1
BEAVER	9.5	1.18	11.2	34.4	9.4	53.0	0.0
DEADWOOD	14.8	0.45	6.7	46.5	21.5	17.9	10.7

Note: Power Index = Drainage Area (km^2) times Average Water Surface Slope (%)

plunge, and impoundment. Combined they made up approximately 80% of the total frequency of occurrence. Average water surface slope was the "best" independent variable (p-values <0.10) to predict the percentage of occurrence of each pool forming process. [The average p-value using drainage area as the independent variable was 0.54 .]

The percentage of plunge-caused pools increased as water surface slope increased (Figure 17). Steeper streams have greater elevation loses per unit length than those with gentler gradients and therefore would be expected to have a higher occurrence of plunge pools (more vertical movement). Similarly, Figure 18 shows the percentage of deflection-caused pools decreases with increasing water slope (more lateral movement of water in gentler gradient streams). Regression models, statistics, and OTB points are shown in Table 11 for these five pool forming processes.

High timber harvest OTB points are difficult to evaluate with regard to pool forming processes because of the wide 80% prediction bands for low timber harvest streams and low population of high harvest streams. The relationships established for plunge, underflow, and deflection-caused pools each had two high timber harvest OTB points. This may suggest a pool forming process has been altered. For example, Failor B is a positive OTB (above prediction band) in the frequency of occurrence of

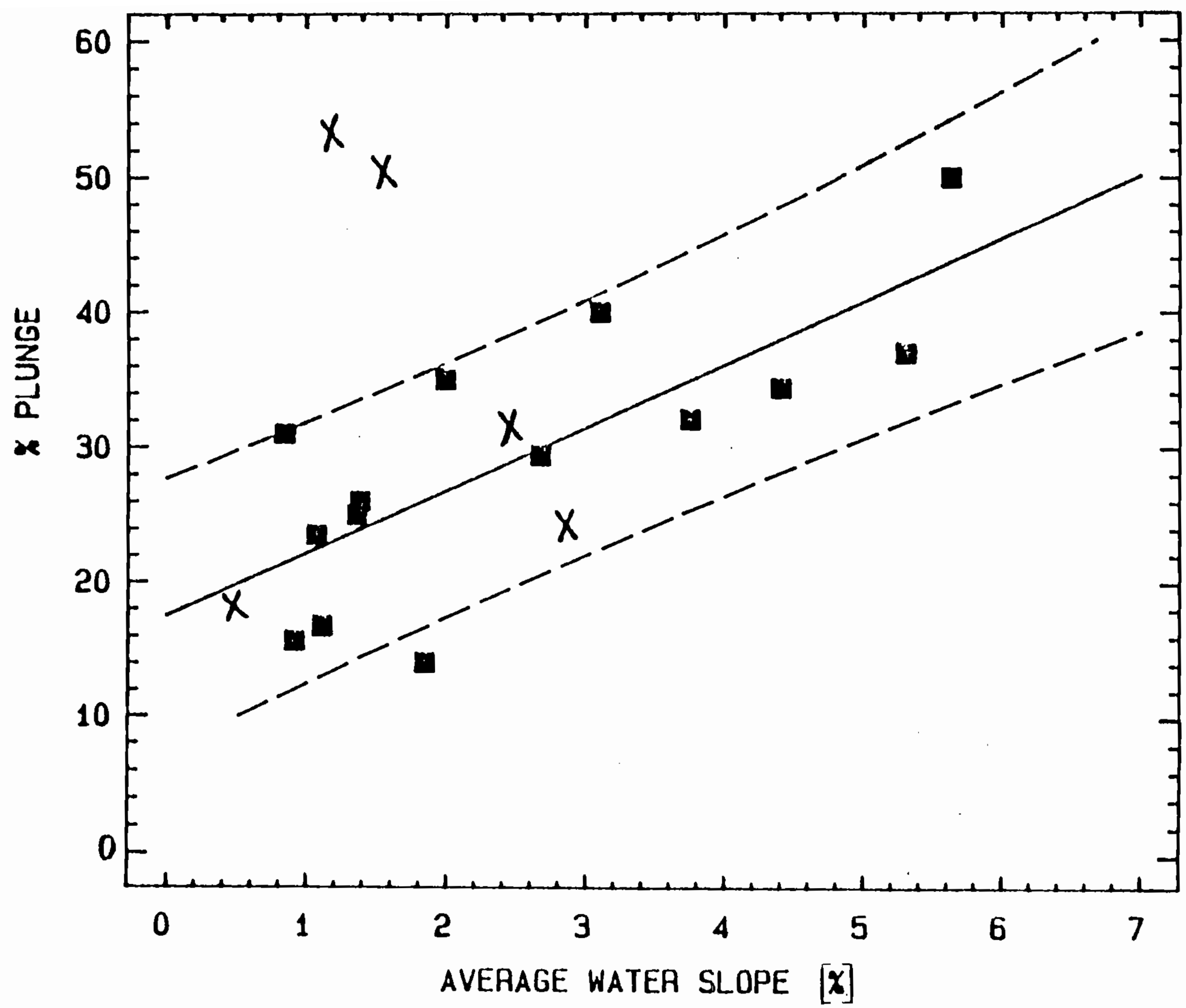

Figure 17. Percentage of residual pools caused by plunging versus average water surface slope. [■ = low, X= high timber harvest streams]

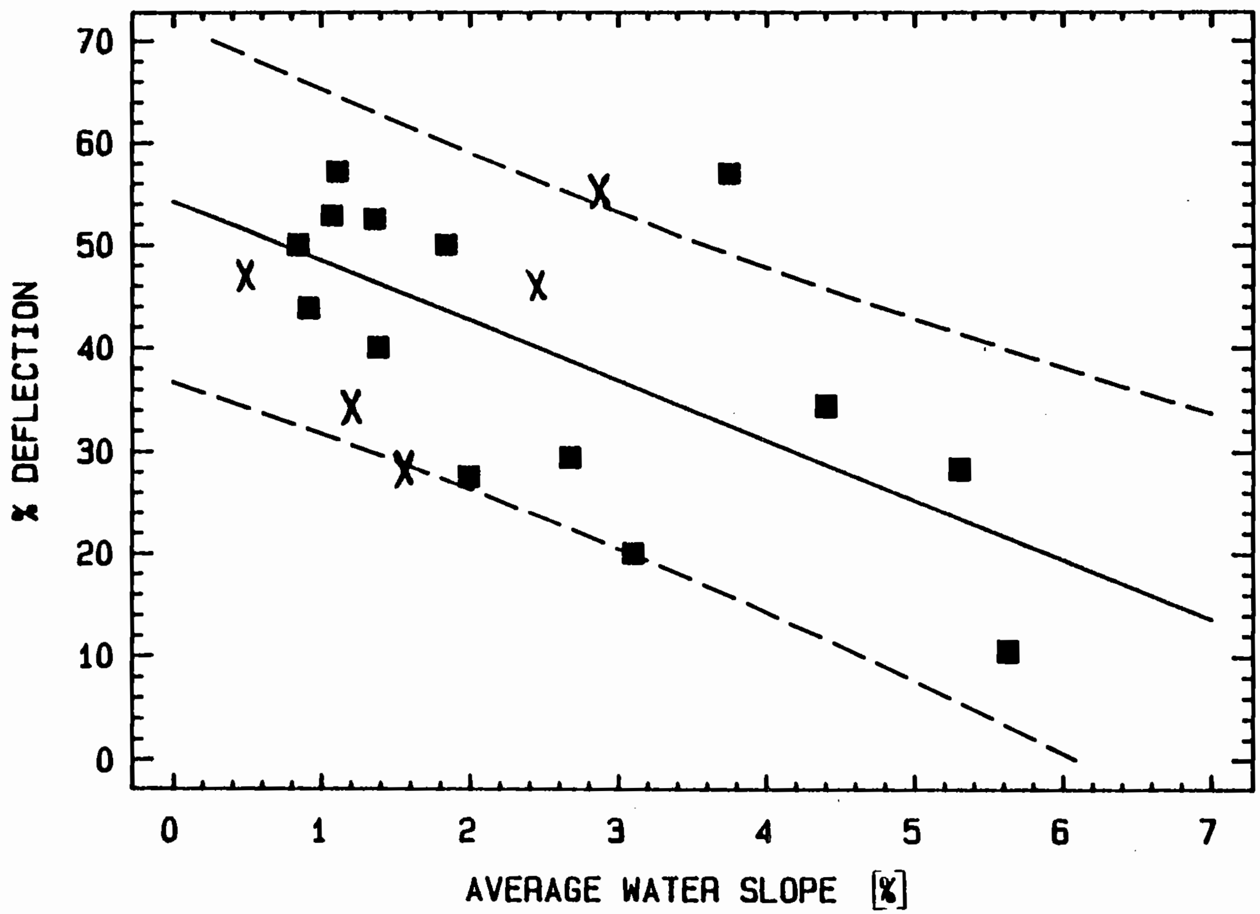

Figure 18. Percentage of residual pools caused by deflection versus average water surface slope. [■ = low, X= high timber harvest streams]

Table 11. Model equations and statistics for frequency of occurrence for pool forming processes (based on 14 low timber harvest streams). Also shown are the streams outside the prediction band for all 19 stream sections.

DEPEND VARIABLE	INDEPEND VARIABLE	MODEL* m	MODEL* b	P-VALUE	STAND. ERROR	r^2	OUTSIDE PREDICTION BAND** LOW	OUTSIDE PREDICTION BAND** HIGH
PLUNGE (%)	WATER SLOPE (%)	4.7	17.4	<0.10	6.7	0.59	FRK D(-)	FAIL B(+) BEAV (+)
UNDER-FLOW(%)	WATER SLOPE (%)	-1.7	9.3	<0.10	3.9	0.35	FRK C (-) BEAR (+)	BUCK (+) BEAV (-)
DEFLECT (%)	WATER SLOPE (%)	-5.8	54.2	<0.10	11.6	0.43	TRT A (+)	BUCK (+) FAIL B(-)
IMPOUND (%)	WATER SLOPE (%)	5.4	7.6	<0.10	11.7	0.39	TRT A (-)	BUCK (-)
FLUVIAL (%)	WATER SLOPE (%)	-2.6	11.5	<0.10	6.4	0.33	FLY A (+)	

Notes:
* All models are linear.
** (+)= above, (-)= below prediction band.

plunge-caused pools and is also a negative OTB (below prediction band) in the frequency of occurrence of deflection-caused pools. This suggests that Failor B has relatively more plunge pools and fewer deflection pools than expected. This could occur when a stream is devoid of roughness elements - a stream with a high percentage of bedrock (Failor B has 46% bedrock). This may cause less deflection (lower amounts of wood and/or boulders in channel) and more plunging (more bedrock steps or chutes). Such a change may or may not be related to management activities (e.g., a "natural" debris torrent verses stream cleaning policies). Additionally, the potential shift in pool forming processes for high timber harvest streams may not occur in the same pattern. Beaver Creek, for example, had increased plunge and decreased underflow while Buck had increased underflow and deflection, and decreased impoundment pool forming processes. Again, no definitive conclusions associated with high timber harvest streams can be stated.

Table 12 lists the frequency of occurrence in percent for the seven categories of pool forming elements in each stream section: wood, boulder, bedrock, root wad, beaver, "other" (e.g., sediment bars, small wood clusters) and endogenous. Wood and boulder elements combined usually comprised at least 50% of the total frequency. Additionally, alder pieces in the channel were not frequently observed to be associated with pools, however,

Table 12. Frequency of occurrence for pool forming elements. [19 stream sections]

STREAM SECTION	DRAINAGE AREA (km^2)	WATER SLOPE (%)	POWER INDEX (%*km^2)	FREQUENCY OF OCCURRENCE WOOD (%)	BOULDER (%)	BEDROCK (%)	ROOTWAD (%)	BEAVER (%)	ENDOG (%)	OTHER (%)
FLYNN C	1.3	1.36	1.8	70.0	0.0	0.0	5.0	0.0	10.0	15.0
TROUT A	1.5	3.75	5.6	47.9	30.0	0.0	6.5	0.0	0.0	15.6
FLYNN D	1.6	4.40	7.0	18.8	65.7	6.3	0.0	0.0	0.0	9.2
FLYNN A	1.6	0.91	1.5	31.2	0.0	6.3	3.1	0.0	28.1	31.3
TROUT B	2.2	5.30	11.7	13.0	45.7	13.0	0.0	28.3	0.0	0.0
HARVEY B	2.8	5.63	15.8	0.0	46.7	52.6	0.0	0.0	0.0	0.7
MILL	3.1	2.67	8.3	23.5	29.3	8.8	0.0	20.5	2.9	15.0
BEAR	4.6	1.38	6.3	36.0	8.0	12.0	14.0	0.0	8.0	22.0
FRANKLIN B	6.4	3.10	19.8	16.0	72.0	10.0	2.0	0.0	0.0	0.0
HARVEY A	8.2	1.99	16.3	5.0	50.0	35.0	2.5	0.0	2.5	5.0
FRANKLIN C	11.5	1.07	12.3	14.7	64.7	8.8	0.0	2.9	5.9	3.0
FRANKLIN A	14.3	1.11	15.9	19.0	57.2	2.4	14.3	2.4	4.8	0.0
TROUT C	16.0	0.84	13.4	40.5	19.1	16.7	7.2	7.1	4.8	4.6
FRANKLIN D	17.3	1.84	31.8	4.0	84.0	6.0	4.0	0.0	0.0	2.0
BUCK	3.0	2.85	8.6	54.8	14.3	9.5	9.6	0.0	0.0	11.8
FAILOR A	5.0	2.42	12.1	38.1	38.1	4.8	4.8	0.0	2.4	11.8
FAILOR B	8.1	1.56	12.6	12.5	15.6	56.2	9.4	0.0	0.0	6.3
BEAVER	9.5	1.18	11.2	3.1	31.3	62.5	0.0	0.0	0.0	3.1
DEADWOOD	14.8	0.45	6.7	32.2	21.5	0.0	10.7	32.2	0.0	3.4

Note: Power Index = Drainage Area (km^2) times Average Water Surface Slope (%).

alder root wads of living trees were more frequent.

Only boulder, wood, and "other" pool forming elements showed any significant correlations (p-value <0.10) with drainage area, water surface slope, and/or stream power. The stream power index was the "best" predictor for all three pool forming elements with an average p-value less than 0.05. [Using drainage area as the independent variable resulted in an average p-value of 0.16 for these three pool forming elements.]

The percentage of wood-caused pools decreased with stream power (Figure 19) whereas the percentage of boulder-caused pools increased with stream power (Figure 20). These graphs may infer the tendency of wood to be "floated" out of high stream power reaches whereas large boulders remain stable.

Figure 21 shows the relative frequency of "other" forming elements decreases with increasing stream power index. "Other" pool forming elements, like wood, may be unstable in high stream power reaches.

Table 13 lists the regression models, statistics, and OTB points for these relationships. OTB points occurred for both low and high timber harvest streams. No apparent shifts in pool forming elements were present.

Because no significant predictor for the frequency of occurrence of root wad, beaver, or bedrock pool forming elements was found, average values were calculated for both low and high timber harvest streams. [Endogenous

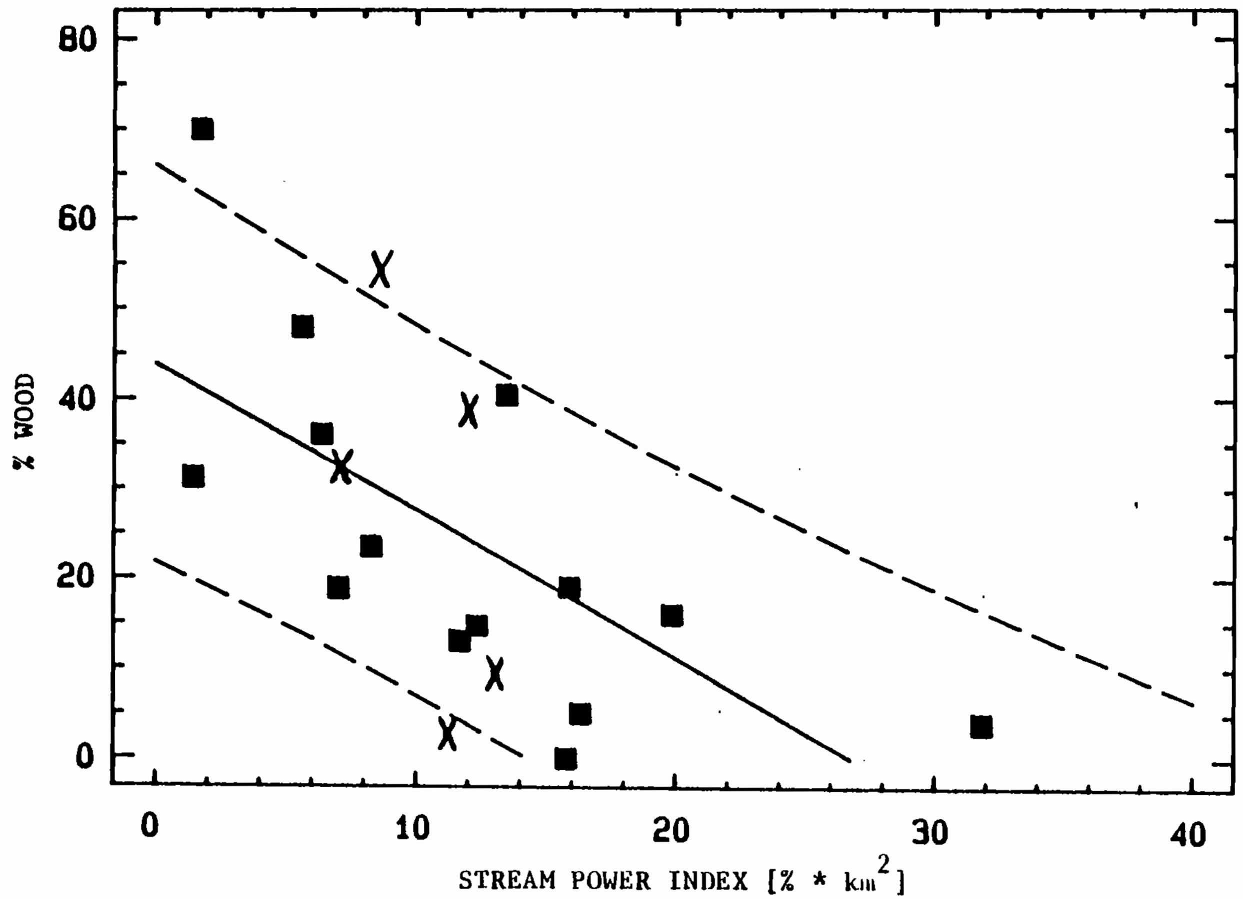

Figure 19. Percentage of residual pools caused by wood versus stream power index. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

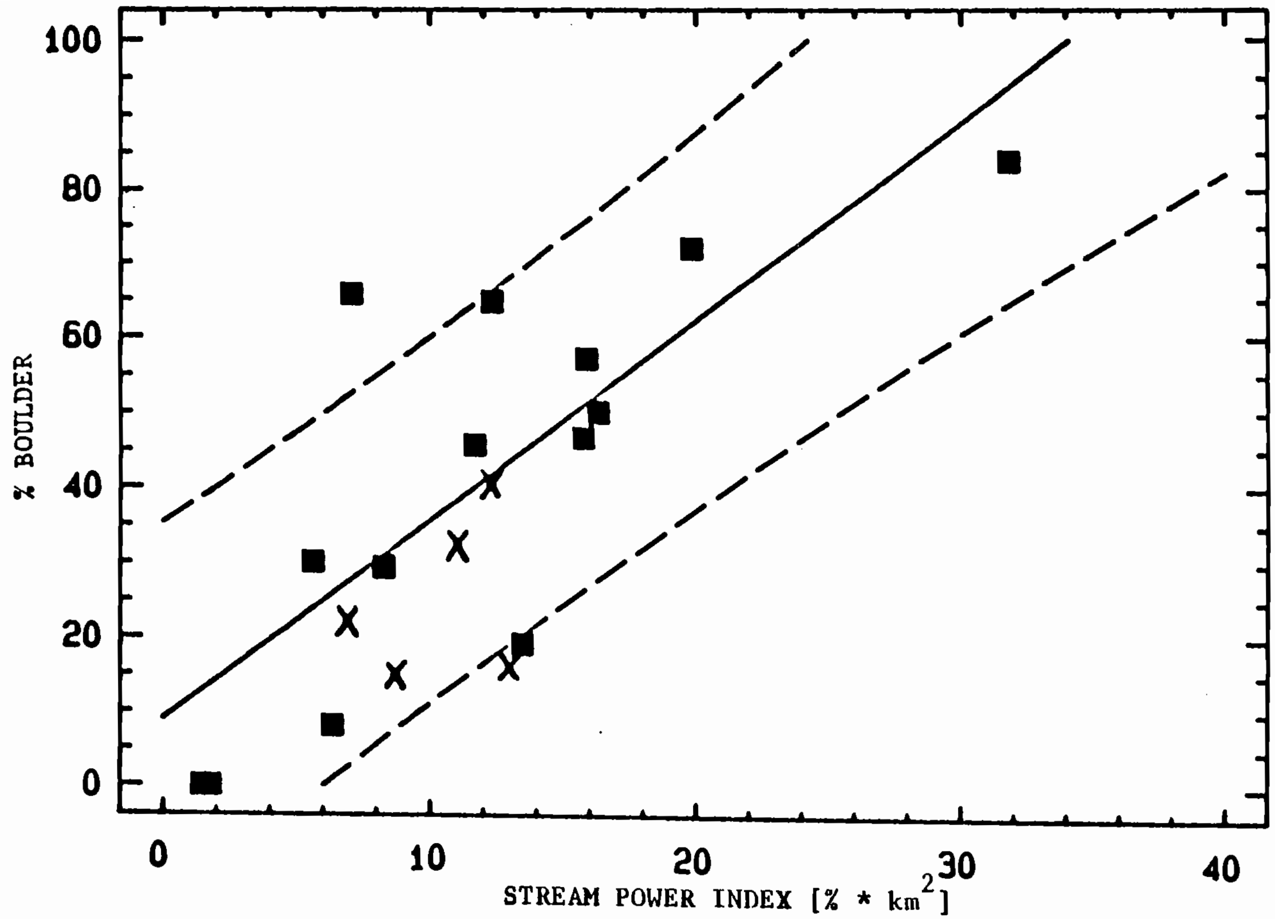

Figure 20. Percentage of residual pools caused by boulder versus stream power index. [■ = low timber harvest, X= high timber harvest, and O= high % beavers]

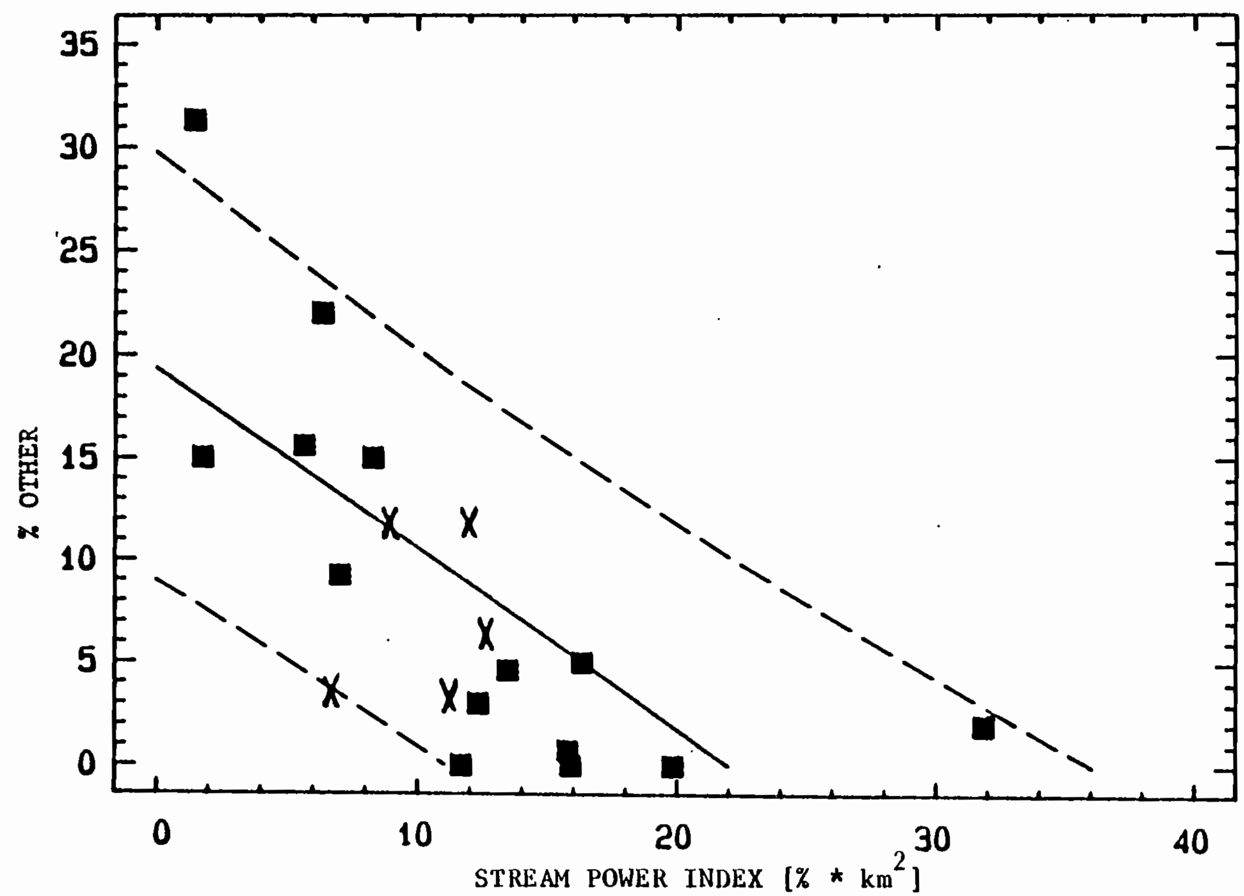

Figure 21. Percentage of residual pools caused by "other" elements versus stream power index. [■ = low, X= high timber harvest streams]

Table 13. Model equations and statistics for frequency of occurrence for pool forming elements (based on 14 low timber harvest streams). Also shown are the streams outside the prediction band for all 19 stream sections.

DEPEND VARIABLE	INDEPEND VARIABLE *	MODEL ** m	MODEL ** b	P-VALUE	STAND. ERROR	r^2	OUTSIDE PREDICTION BAND *** LOW	OUTSIDE PREDICTION BAND *** HIGH
BOULDER (%)	POWER INDEX	2.7	8.9	<0.10	17.4	0.62	FLY D(+) TRT C (-)	FAIL B(+)
WOOD (%)	POWER INDEX	-1.6	43.9	<0.10	14.6	0.47	FLY C (+)	BUCK (+) BEAV (-)
"OTHER" (%)	POWER INDEX	-0.9	19.4	<0.10	6.9	0.53	FLY A(+)	DWOOD (-)

Notes:
* Power Index = Drainage area (km^2) * Water Surface Slope (%)
** All models are linear.
*** (+)= above, (-)= below prediction band.

caused pools (i.e., fluvial) were previously found to be a function of water surface slope.] Percentage values were transformed to arc-sin values before taking averages (Snedecor and Cochran, 1980). The percentage of occurrence for root wad, beaver, and bedrock forming pools for low timber harvest streams were 2.5, 2.0, and 10.0, respectively. High timber harvest streams had average percentages of 6.0, 2.0, and 20.0, respectively. For these pool forming elements, high timber harvest streams were not significantly different (alpha=0.10) from low timber harvest streams.

Low timber harvest streams have (1) a high variability associated with the frequency of occurrence for wood, boulder, and "other" pool forming elements and (2) no significant predictors for the frequency of occurrence for root wad, beaver, or bedrock pool forming elements. This suggests that each stream may have different means for creating pools. For example, differences in soil mass movement processes (e.g., slump versus avalanches), aspect (e.g., relative susceptibility to wind storms), effects of large storms (e.g., longevity of torrent deposits), or beaver populations may affect how pools are ultimately formed. Additionally, pool forming elements may also change with time. For example, water deflects off the root wad of a stream side tree and a pool subsequently forms downstream. Over time the channel bank is undermined and the tree falls into the stream. Water then plunges over the log. The pool may persist, but the apparent cause of pool formation has changed (i.e., root wad to log). Thus, relative proportions of pool forming elements may change over time.

SUMMARY

What's a pool? There are many criteria that could be used to define pools; the choice of criteria represents an important preliminary component in classifying pools. For this study, the Rapid Bed Profile (RBP) technique provided a time efficient, flow independent, objective, and accurate means of defining residual pools.

Fourteen low timber harvest stream sections in the central Oregon Coast Range were surveyed for pools with the RBP technique. Pool morphology (i.e., size, spacing and number, and formation) for each stream section was examined to see if these morphological characteristics were correlated to total stream power. Preliminary results indicated stream sections that contained beaver dams had relatively large pool dimensions. Thus, pools caused by beaver dams were temporarily deleted from the data sets. Five high timber harvest stream sections were additionally surveyed to evaluate what effects, if any, timber harvesting had on pool morphology. All streams were underlain by sedimentary rocks, and ranged in drainage area from 1.3 to 17.3 km^2 and average water surface slope from 0.5 to 5.6%.

The factors that influenced individual pool morphology as well as the influence associated with timber harvesting and beaver dams are as follows:

Pool size

- Average residual pool size characteristics for the 12 low timber harvest stream sections with no beaver dams were positively correlated to a power function of drainage area. [Drainage area was a significantly better (i.e., lower p-value) predictor of these characteristics than total stream power.]

- Stream sections with beaver dams, especially those with at least 10% of their reach length in beaver-caused pools, typically had significantly (alpha= 0.20) higher average residual pool size characteristics.

- Average pool size characteristics for high timber harvest stream sections, without beaver dams, were not significantly (alpha= 0.20) different from low timber harvest stream sections.

Number, spacing, and percentage of pools

- The number of residual pools per 100m of channel length was negatively correlated to a power function of drainage area for the 12 low timber harvest stream sections.

- The average spacing of residual pools was positively correlated to a power function of drainage area for the 12 low timber harvest stream sections.

- The percentage of residual pools in each low timber harvest stream section was negatively correlated to average water surface slope.

- The influence of beaver dams on the number, spacing, and percentage of pools was not conclusive due to the limited number of streams with beavers.

- High timber harvest stream sections may be associated with an increase in spacing of pools and a decrease in number of pools for larger watersheds (i.e., greater than 8 km^2). However, this is not conclusive since records were limited (i.e., history of storm effects, changes in timber management practices), and the number of streams investigated was small.

Pool formation

- Stream sections with beaver dams did not alter the frequency of occurrence of pool forming elements or processes.

- The relative frequency of pool forming processes was dependent on average water surface slope for the 14 low timber harvest stream sections. As the gradient of streams decreased the percentage of pools associated with plunge and impoundment processes similarly decreased while percentages of deflection, underflow, and fluvial processes increased.

- Deflection, impoundment, and plunge were the prominent pool forming processes for the 14 low timber harvest stream sections. In combination they accounted for approximately 80% of the processes for each stream section.

- High timber harvest stream sections may be associated with a shift in the frequency of occurrence of pool forming processes. The potential shift was from impoundment and plunge to deflection or underflow processes. The shift may go in either direction but acted inversely (e.g., more plunge reduced deflection caused pools). The limited number of high timber streams precluded a definitive conclusion.

- The frequency of occurrence of wood, boulder, and "other" pool forming elements were associated with the stream power index (drainage area times average water slope) for the 14 low timber harvest stream sections. As the stream power index increased wood and "other" pool forming elements decreased while boulders increased.

- Wood and boulders combined made up approximately 80% of the total frequency of occurrence of pool forming elements for the 14 low timber harvest stream sections. Endogenous formed pools were generally less than 10%.

- The frequency of occurrence of pool forming elements associated with root wad, beaver, or bedrock showed no significant correlations (p-value > 0.10) with drainage area, average water surface slope, or the stream power index.

- The frequency of occurrence of pool forming elements was not significantly (alpha = 0.20) different between low timber harvest stream sections and high timber harvest stream sections.

IMPLICATIONS

Research

The Rapid Bed Profile (RBP) technique was efficient for defining residual pools in Oregon coastal streams. However, the limits of this technique (e.g., maximum channel gradient), reproducibility, and its correlation to current fisheries survey methods need further investigation.

Pool morphology parameters depend on drainage area, average water surface slope, or the stream power index. These factors need to be considered when determining the influence of a specific treatment between streams (e.g., logged verses unlogged). For example, the number of pools may be different because the watershed sizes are different and not the effect of the treatment. Additionally, the relationships that were devised in this study were based on summer flow conditions. Pool morphology values may change during winter flows (e.g., beaver dams may get "blown out") or may be persistent (e.g., pools maintained during high flows). Average residual pool size characteristics (e.g., volume) may differ in streams that are influenced by beaver dams during high flows.

Beaver dams changed "expected" pool morphology characteristics (e.g., increased average residual pool area) and may provide a means of increasing summer habitat. Moreover, employing beavers to improve pool habitat or rehabilitate channel processes (e.g. sedimentation) may be economically effective. However, the extent of beaver dams in a drainage system, the duration of these structures, changes in streamwater quality as well as many other variables need to be addressed, including possible adverse impacts on forest management.

Assessing changes in pool morphology via statistical methods (i.e., data points outside 80% prediction band) is difficult to determine when the "control" streams generally have high variability. Streams needed to be radically altered to be conclusively different (e.g., streams with many beaver dams). Perhaps other approaches are needed, such as examining the frequency of change (i.e., the stability of pools) or defining "change" by some other criterion (e.g., minimum pool volume to sustain a population of fish). Other pool variables may also need to be further investigated. For example, examining the amount of total pool area associated with each pool forming element and process, the quality of pools (e.g., cover, diversity, retention, shape index), or the amount of lateral habitat may provide additional insights.

Pools in two of the larger high timber harvest watersheds (Beaver and Failor B) had relatively larger spacing and fewer numbers in comparison to low timber harvest streams. However, examining more watersheds of this size is needed to conclusively establish if such changes generally occur in response to timber management.

Management

Monitoring channel morphology can be expensive. However, using the RBP technique may provide a means of reducing costs while gleaning useful pool morphology information. Periodic surveys with the RBP technique may help determine (1) the feasibility, type and number, and evaluation of stream "enhancement" structures, (2) effects of upland or riparian management activities (e.g., road building) on stream morphology, and (3) the changes in pool characteristics (e.g. average pool volume) that occur naturally over time. In addition, pool surveys may aid in establishing relationships between channel morphology and rates of aeration or chemical transport.

The drainage area, average water surface slope, and the stream power index of a stream need to be examined before fish habitat structures are installed. These characteristics may influence the ultimate outcome of a structure. For example, always using a 1:1 pool-to-riffle ratio may not be an efficient method of improving fish habitat (e.g., structures may be washed out in steep streams where the percentages of pools are typically low).

Lastly, the influence of forest management activities on pool morphology is difficult to conclusively assess. One prominent reason for this is the limited knowledge of past events (e.g., information regarding previous management practices or watershed effects due to large storms). Developing accurate historical records may help understand the present condition of a stream. For example, periodically surveying streams and hillslopes, particularly after large storms, may help resolve the affects between specific management activities and storm related changes.

LITERATURE CITED

Alig, R., D. Adams, and R. Haynes. 1983. Long range projection of forest area change: new approaches are needed. J. Forest., 81(11): 723-725.

Bagnold, R.A. 1966. An approach to the sediment transport problem from general physics. USGS Prof. Paper 422-I, 37pp.

Baker, V.R. and D.F. Ritter. 1975. Competence of rivers to transport coarse bedload material. Geol. Soc. Amer. Bull. 86:975-978.

Baker, V.R. 1977. Stream-channel response to floods, with examples from central Texas. Geol. Soc. Am. Bull., 88:1057-1071.

Baldrige, J.E., and D. Amos. 1981. A technique for determining fish habitat suitability criteria: a comparison between habitat utilization and availability. pp. 251-258. IN: N.B. Armantrout (ed.), Acquisition and utilization of aquatic habitat inventory information, Proc. Symp. Am. Fish. Soc., Portland, Oregon. 376pp.

Baldwin, E.M. 1976. Geology of Oregon, 2nd ed. Kendall-Hunt, Dubuque, Iowa. 150pp.

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

Benda, L.E., F.H. Everest, and J.R. Sedell. 1987. Influences of forest management on channel environments in the Oregon Coast Range. pp. 40-46. IN: Managing Oregon's riparian zone for timber, fish, and wildlife. NCASI technical bulletin no. 514, New York, 96pp.

Beschta, R.L. 1978. Inventorying small streams and channels on wildland watershed. pp. 104-113. IN: Proc. National workshop on integrated inventories of renewable natural resources. Gen. Tech. Rep. RM-55. USDA Forest Service, Tucson, Arizona.

Beschta, R.L. 1979. Debris removal and its effects of sedimentation in an Oregon Coast Range stream. NW Sci. 53(1): 71-77.

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

Beschta, R.L. 1983b. Sediment and organic matter transport in mountain streams of the Pacific Northwest. pp. 1-69 to 1-89. IN: D.B. Simons (ed.), Proc. of the D.B. Simons symposium on Erosion and Sedimentation. Simon, Li, and Associates, Ft. Collins, Colorado.

Bescta, R.L. and W.S. Platts. 1987. Morphological features of small streams: significance and function. Water Res. Bull., 22(3):369-379.

Bilby, R.E. 1984. Removal of woody debris may affect stream channel stability. J. Forest., 82:609-613.

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. pp. 62-73. IN: D.B. Armantrout (ed.), Acquisition and utilization of aquatic habitat inventory information. Proc. Symp. Am. Fish. Soc., Portland, Oregon. 376pp.

Campbell, A.J. and R. Sidle. 1985. Bedload transport in a pool-riffle sequence of a coastal Alaska stream. Water Res. Bull., 21(4): 579-590.

Carlson, J. (unpublished thesis [in press]) Oregon State University, Dept. of Forest Eng., Corvallis, Oregon.

Cedarholm, J. 1988. (Personal communication). Washington Dept. of Natural Resources, Olympia, Washington.

Chorley, R.J., and B.A. Kennedy. 1971. Physical Geography. A systems approach. Pitman Press, Bath, England. pp. 233-236.

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

Dolling, R. 1968. Occurrence of pools and riffles: an element in the quasi-equilibrium state of river channels. Ontario Geog., 2:3-11.

Everest, R.H. and R.D. Harr. 1982. Influence of forest and rangeland management on andromous fish habitat in western North America, 6. Silvicultural treatments. Gen. Tech. Rep. PNW-96. USDA Forest Service, PNW Range Exp. Stn., Portland, Oregon, 19p.

Everest, F.H., N.B. Armantrout, S.M. Keller, W.D. Parante, J.R. Sedell, T.N. Nickelson, J.M. Johnson, and G.N. Haugen. 1985. Salmonids. pp.199-230. IN: E.R. Brown (ed.), Management of wildlife and fish habitats in forests of western Oregon and Washington. Part 1: Chapter Narrative. Pub #:R6-F&WL-192-1985 USDA Forest Service, Portland, Oregon.

Finucane, S. 1980. A history of the Blodgett tract (1890-1846). USDA Forest Service, Siuslaw National Forest, Waldport Ranger District, Waldport, Oregon, 36pp.

Froehlich, H.A. 1986. (Personal communication). Oregon State University, Dept. Forest Eng., Corvallis, Oregon.

Grant, G.E. 1986. Downstream effects of timber harvest activities on the channel and valley floor morphology of western Cascade stream. Ph.D. dissertation, John Hopkins University, Baltimore, Maryland. 349pp.

Grette, G.B. 1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. MS Thesis, University of Washington, Seattle, Washington, 105pp.

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

Harr, D.R., W.C. Harper, J.T. Krygier, and F.S. Hsieh. 1975. Changes in storm hydrographs after road building and clearcutting in the Oregon Coast Range. Water Res. Research, 11(3):436-444.

Harr, R.D. 1979. Effects of timber harvest on streamflow in the rain-dominated portion of the PNW. IN: Proc. from workshop on scheduling timber harvest for hydrologic concerns. USDA Forest Service, PNW Forest and Range Exp. Stn., Portland, Oregon, 45pp.

Harris, D.D., L.L. Hubbard, and L.E. Hubbard. 1979. Magnitude and frequency of floods in western Oregon. USGS Open File Report 79-553, Portland Oregon, 35pp.

Hayward, J.A. 1980. Hydrology and stream sediments in a mountain catchment. Chap. 13: The character and significance of the morphology of the Torlesse stream channel. pp. 137-150. IN: Tussock Grasslands and Mtn Lands. Institute special Publication #17. Lincoln College, Canterbury, New Zealand.

Kaufmann, P.R. 1987. Channel morphology and hydraulic characteristics of torrent-impacted forest streams in the Oregon Coast Range, USA. Ph.D dissertation, Oregon State University, Corvallis, Or. 235pp.

Keller, E.A. 1971. Areal sorting of bed-load material: the hypothesis of velocity reversal. Geol. Soc. Am. Bull. 82:753-756.

Keller, E.A. and W.N. Melhorn. 1973. Bedforms and Fluvial processes in alluvial stream channels: selected observations. pp. 253-283. IN: M. Morisawa (ed.), Fluvial Geomorphology. Proc. 4th Annual geomorphology Symposia series. Publications in Geomorphology, New York, 314p.

Keller, E. A. and W.N. Melhorn. 1978. Rhythmic spacing and origin of pools and riffles. Geo. Soc. Am. Bull., 89:723-730.

Keller, E.A. and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surf. Proc., 4:361-380.

Kessel, M. 1986. (Personal communication). USDA Forest Service, Siuslaw Nat. Forest, Mapleton District, Oregon.

Kimerling, A.J. and P. Jackson, (ed.). 1985. Atlas of the Pacific Northwest (7th ed.), Oregon State University Press, Corvallis, Oregon, pp 35-38.

Klingeman, P.C. 1984. Evaluating hydrologic needs for design of stream habitat modification structures. pp. 191-212. IN: Hassler, T.J. (ed.), Proc. PNW Stream Habitat Management Workshop. Humboldt State University., Arcata, California.

Leopold, L.B. and W.B. Langbein. 1962. The concept of entropy in landscape evolution. USGS Prof. Paper 500-A, 20pp.

Leopold, L.B., M. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. W.H. Freeman & Co., San Francisco, California, 522pp.

Lisle, T.E. 1979. A sorting mechanism for riffle-pool sequence: summary. Geol. Soc. Am. Bull., 90(1):616-617.

Lisle, T.E. 1982. Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California. Water Res. Research, 18(6): 1643-1651.

Lisle, T.E. 1986. Effects of woody debris on anadromous salmonid habitat, Prince of Wales Island, southeast Alaska. North Am. J. Fish. Man., 6(4):538-550.

Lisle, T.E. 1987. Using "residual depths" to monitor pool depths independently of discharge. USDA Forest Service, Pacific Southwest For. and Range Exp. Stn., Research Note PSW-394, Berkeley, California, 4 pp.

Lucia, E. 1975. The Big Woods. Logging and Lumbering - from bull teams to helicopters in the Pacific Northwest. Doubleday and Co., Inc., New York, pp. 29-35, 80-106.

Lyons, J.K. and R.L. Beschta. 1983. Land use, floods, and channel changes: Upper Middle Fork Willamette River, Or. (1936-1980). Water Res. Research, 19(2):463-471.

MacKay, D. 1978. The Lumberjacks. McGraw-Hill Ryerson, Limited, New York, pp35-55, 265-286.

Madej, M. 1987. Residence times of channel-stored sediment in Redwood Creek, northwestern California. pp. 429-438. IN: R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds.), Erosion and Sedimentation in the Pacific Rim. Proc. of the Corvallis, Or., Symp., IAHS Publ. no. 165, Wallingford, United Kingdom, 510pp.

Marston, R.A. 1980. The geomorphic significance of log steps in forest streams of the Oregon Coast Range. Ph.D. disseration, Oregon State University, Dept. of Geog., Corvallis, Oregon, 216pp.

McHarg, I.L. 1969. Design With Nature. Natural History Press, Garden City, New York, 197pp.

McKean, J.W. 1971. Oregon's Fishery Programs and Policies in Relation to Forest Land Uses. pp. 208-210. IN: Hall, J.D. and J.T. Krygier (eds.), Forest Land Uses and Stream Environment. Proc. of a Symposium, OSU Press, Corvallis, Oregon, 252pp.

Miller, G.T. Jr. 1982. Living in the Environment (3rd ed.). Wadsworth Publishing Co., California. pp. 190-195.

Nolan, K.M., and D.C. Marron. 1985. Contrast in stream-channel response to major storms in two mountainous areas of California. Geology, 13:135-138.

Nolan, K.M., Lisle, T., and H. Kelsey. 1987. Bankfull discharge and sediment transport in Northwestern California. pp. 439-449. IN: R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds.), Erosion and Sedimentation in the Pacific Rim, Proc. of the Corvallis, Or., Symposium, IAHS Publ. no. 165, Wallingford, United Kingdom, 510pp.

O'Neill, M.P. and A.D. Abrahams. 1984. Objective identification of pools and riffles. Water Res. Research, 20(7):921-926.

Orsborn, J.F. and J.M. Stypula. 1987. New models of hydrological and stream channel relationships. pp. 375-384. IN: R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds.), Erosion and Sedimentation in the Pacific Rim, Proc. of the Corvallis, Or., Symposium, IAHS Publ. no. 165, Wallingford, United Kingdom, 510pp.

Pfankuch, D.J. 1975. Stream reach inventory and channel stability evaluation. USDA Forest Serv., Northern Reg., Missoula, Montana, 25p.

Retzer, J.L., H.M. Swope, J.D. Remington, and W.H. Rutherford. 1956. Suitability of physical factors for beaver management in the Rocky Mountains of Colorado. State of Colorado, Dept. of Game and Fish. Technical Bulletin No. 2, 33pp.

Richards, K.S. 1976. The morphology of riffle-pool sequences. Earth Surf. Proc., 1:71-88.

Robison, E.G. 1988a. Large woody debris and channel morphology of undisturbed streams in southeast Alaska. MS Thesis. Oregon State University, Dept. of Forest Eng., Corvallis, Oregon. 136p.

Robison, E.G. 1988b. Unpublished data. Oregon State University, Dept. of Forest Eng., Corvallis, Oregon.

Schumm, S.A., and Lichty, R.W. 1965. Time, space, and causality in geomorphology. Am. J. Sci., 263:110-119.

Sedell, J.R., and K.J. Luchessa. 1981. Using the Historical Record as an aid to salmonid habitat enhancement. pp. 210-223. IN: N.B. Armantrout (ed.), Acquisition and Utilization of Aquatic Habitat Inventory Information. Proc. Symp., Amer. Fish. Soc. Portland, Oregon. 376pp.

Sedell, J.R. and W.S. Duval. 1985. Water transportation and storage of logs. USDA Forest Service, PNW For. and Range Exp. Stn. GTR-186. 68pp.

Sedell, J.R. 1987. (Personal communication). USDA Forest Service, PNW Forest and Range Exp. Stn., Corvallis, Oregon.

Snedecor, G.W., and W.G. Cochran. 1980. Statistical Methods (7th ed.). Iowa State University Press, Ames, Ia., pp. 290-291.

Sullivan, K., T.E. Lisle, C.A. Dolloff, G.E. Grant, and L.M. Reid. 1987. Stream Channels: the link between forests and fishes. pp. 39-97. IN: E.O. Salo and T.W. Kundy (eds.), Streamside Management. Forestry and Fisheries interactions. Proc. of a Symposium, Univ. of Wash., Institute of Forest Resources, Seattle, Washington, Publ. no. 57, 467pp.

Swanson, F.J. and G.W. Lienkaemper. 1978. Physical consequences of large organic debris in PNW streams. USDA Forest Service, GTR, PNW-69, Portland, Oregon, pp. 12.

Swanson, F.J., Bryant, M.D., Lienkaemper, G.W., and J.R. Sedell. 1984. Organic debris in small streams, Prince of Wales Island, S.E. Alaska. USDA Forest Service, PNW Forest and Range Exper. Station. GTR-166. Portland, Oregon, 12 pp.

Swanson, F.J., L. Benda, S. Duncan, G. Grant, W. Megahan, R. Ziemer. 1987. Mass failures and other sediment sources. pp 9-38. IN: E.O. Salo and T.W. Kundy (eds.), Streamside Management. Forestry and Fishery Interactions. Proc. of a Symposium, Univ. of Wash., Institute of Forest Resources, Seattle, Washington, Publ. no. 57, 467pp.

Tschaplinski, P. and G. Hartman. 1983. Winter distribution of juvenile coho salmon (Oncorhychus Kisutch) in Carnation Creek and some implications to overwinter survival. Can. J. Fish. Aquat. Sci. 40:452-461.

Vanoni, V.A. (ed.). 1977. Sedimentation engineering: American Society of Civil Engineers. Manuals and reports on Engineering practice. No. 54., ASCE, New York, 745p.

Waldo, J.C. 1987. Timber and Fisheries - Together They Work, Divided They Decline. pp.ix-xvi. IN: E.O. Salo and T.W. Kundy (eds.), Streamside Management. Forestry and Fishery Interactions. Proc. of a Symposium, Univ. of Wa., Institute of Forest Resources, Seattle, Washington, Publ. no. 57, 467pp.

Wolman, M.G. 1954. A method of sampling coarse bed material. Transactions of the American Geophysical Union. 35:951-6.

Wolman, M.G. and J.P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology. 68:54-74.

Whittaker, J.G. and M. Jaeggi. 1982. Origin of Step-Pool Systems in Mountain Streams. Am. Soc. of Civil Eng., J. Hydr. Div. 108(HY6):758-773.

Yang, C.T. 1971a. On river meanders. Journal of Hydrology. 13:231-53.

Yang, C.T. 1971b. Formation of riffles and pools. Water Res. Research, 7(6):1567-1574.

APPENDIX

APPENDIX A: A Comparison Of Pool Defining Methods

Bathurst (1981) studied the resistance of bars by examining bed topography near zero discharge. Lisle (1986) and Kaufmann (1987) applied this idea to define pools; a channel unit is classified a pool if the unit holds water when the discharge approaches zero (i.e., residual pools). Because the method employed in this study (e.g., Rapid Bed Profile (RBP) technique) also produces residual pools, the technique used by Kaufmann and Lisle was named the Bed Elevation Profile (BEP) technique to avoid confusion. This appendix compares pool characteristics produced by each of these methods.

The BEP technique requires thalweg depth and water surface elevation at each station along a longitudinal profile to define pools. Elevation measurements were determined by using a self leveling level, tripod, and stadia rod. Subsequently, a longitudinal profile can be developed. The downstream control points on this profile are then used to define pool locations. Figure 22 graphically illustrates this technique and associated pool characteristics.

The RBP technique requires thalweg depth measurements and the average water surface slope (elevation measurements only at major slope changes (e.g., upstream end of riffles)) to define pools. The pool is defined by tilting a reference line (RBP slope) downward from peaks on a thalweg depth profile (i.e., downstream control

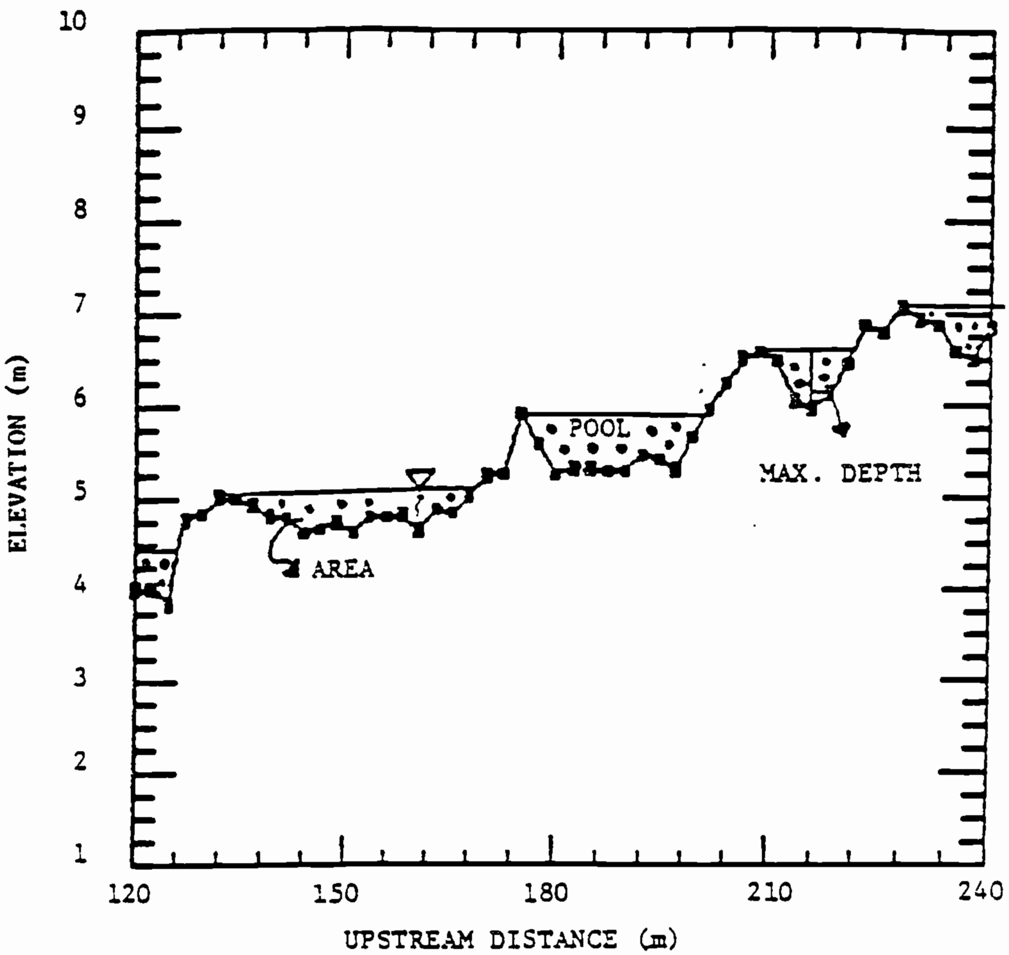

Figure 22. The Bed Elevation Profile (BEP) technique used to define pools from a longitudinal profile.

points). A thalweg depth profile is a plot of thalweg depth verses horizontal distance. Figure 2 in the Methods section illustrates the RBP technique and associated pool characteristics.

Nine stream sections were used to compare the RBP technique to the BEP technique. The streams ranged in drainage area from 1.3 - 17.3 km^2 and average water surface slope from 0.8 - 5.6%.

Both techniques generated numerous small "pools". [Residual pool areas of these pools were 1/4 to 1/3 the relative averages.] Since these pools play a minor role in hydraulics (i.e., relatively low energy dissipation) and in fishery concerns (i.e., small numbers of coho per pool) they were eliminated. The criteria used to eliminate these small "pools" was based on the standard deviation of depth (thalweg) for entire individual reaches. When the "pool" defined by either method had a maximum depth greater than or equal to its associated standard deviation of depth for the reach than this channel feature was a <u>POOL</u>. Using the standard deviation of depth criteria has three advantages: (1) objectivity, (2) independent of flow, (3) consistency with stream size (i.e., criteria used in a 4th order stream was the same as a 1st order stream). Additionally, this correlated well with channel units that looked like "pools".

The RBP slope was adjusted until the RBP total residual pool area (summation of all individual pools), for a specific stream section, equalled the BEP total residual pool area. To facilitate this calculation a computer program was used (Appendix B). For the nine streams investigated, the RBP slope showed a high correlation with the average water surface slope of associated stream sections. This relationship is shown in the Methods section, Figure 3. Therefore, to achieve a similar estimate of BEP total residual pool area, using the RBP technique, only the thalweg depths and average water surface slope are required.

To examine how well the RBP technique matched individual pools of the BEP technique, individual pool locations of both techniques were compared. The histogram in Figure 23 shows that 82% of RBP pools corresponded with similar locations of BEP pools ("match"). Where the RBP technique defined a pool while the BEP technique did not, this was called a "new" pool. Conversely, where the BEP technique defined a pool while the RBP technique did not this was called a "miss" pool. Additionally, there were "lump" pools (RBP technique lumped two BEP pools into one pool) and "split" pools (RBP technique split one BEP pool into two pools). "Lump" and "split" pools were less than 10% and were considered "match" pools. More importantly, "new" and "miss" pool had very small residual pool areas. Generally, they were 1/2 to 3/4 the average residual pool area for their associated stream section.

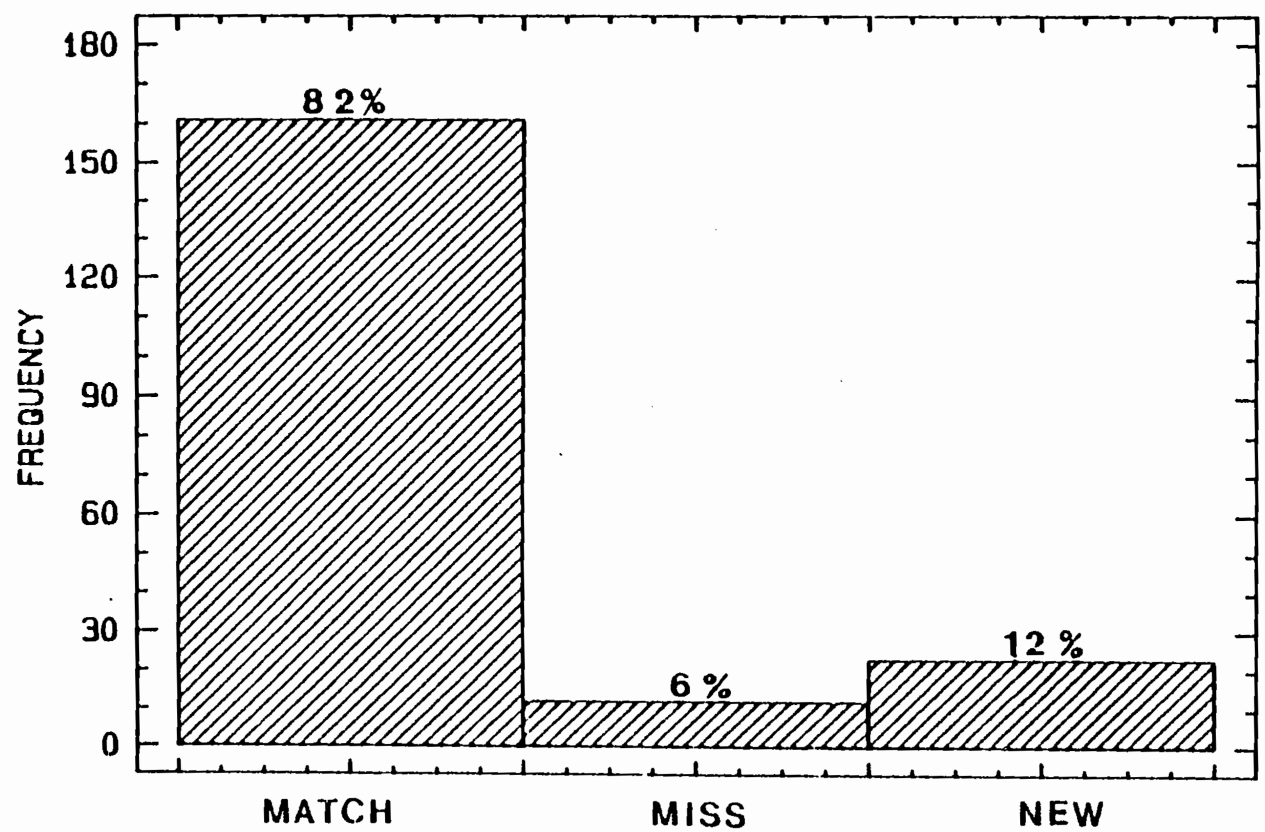

Figure 23. Histogram comparing pool location of the RBP technique versus the BEP technique. [n= 161 "match" pools]

Comparisons of pool sizes (e.g., residual pool area) indicated strong correlations between RBP and BEP techniques. Simple regression fits for residual pool maximum depth and area are shown in Figures 24 and 25, respectively. These correlations are based on 161 "match" pools. Table 14 lists the regression equations and statistics for these and other pool characteristics (e.g., length).

In summary, the RBP technique yields essentially the same trends (pool locations, numbers, and sizes) as the BEP technique. Data collection time can be reduced by approximately 1/3 by employing the RBP technique for the reach lengths studied in this report (i.e., 1/2 to 1 day). Therefore, the RBP technique was chosen as the method to define pools for the objectives of this study.

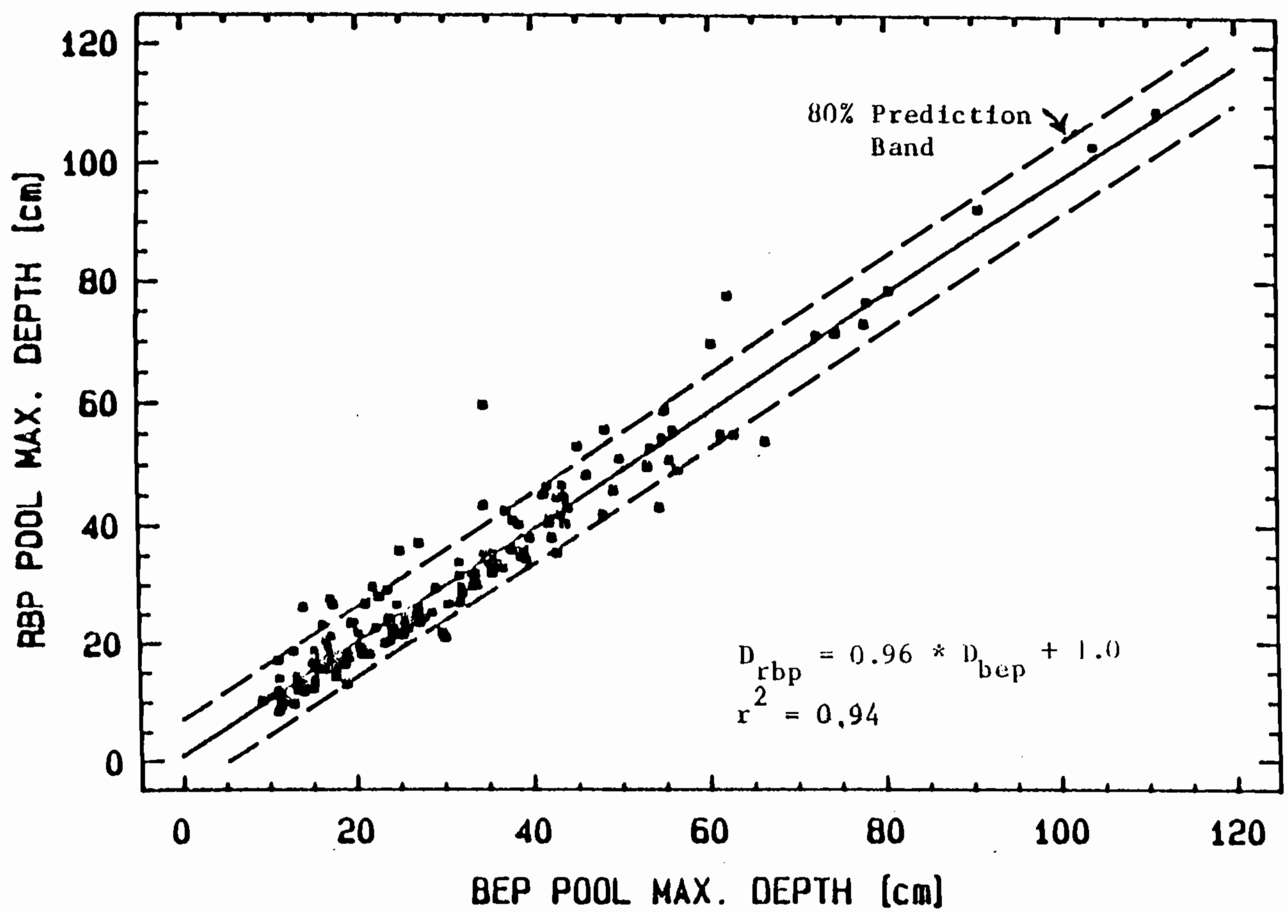

Figure 24. Residual pool depth (maximum): the RBP technique versus the BEP technique. [n= 161 "match" pools]

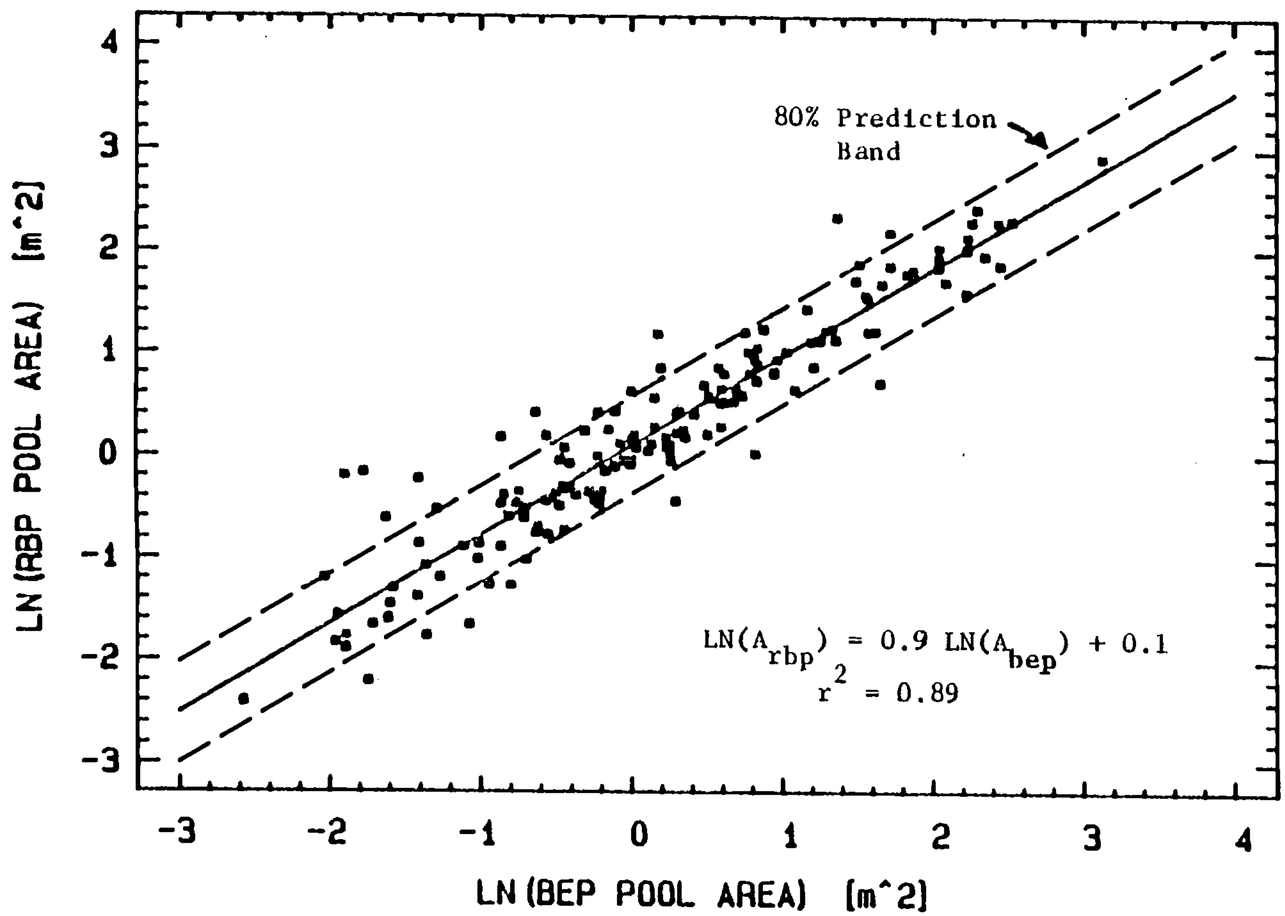

Figure 25. Residual pool area: the RBP technique versus the BEP technique. [n= 161 "match" pools]

Table 14. Linear regression models and associated statistics for pool size: RBP technique versus BEP technique. [161 "match" pools]

POOL VARIABLE	RANGE	MODEL m	COEFF'S b	P-VALUE	r^2	STAND ERROR
Length (m)	1-60	0.79	4.2	<0.10	0.80	4.6
Depth (cm)	10-110	0.96	1.0	<0.10	0.94	4.7
Area (m^2)	0.1-20	0.81	0.3	<0.10	0.88	1.0
Volume (m^3)	0.1-70	0.86	0.5	<0.10	0.91	3.1

[Note: Model form is RBP = m(BEP) + b.]

APPENDIX B: Pool Morphology Computer Programs

Two computer programs are listed in this appendix. The first program calculates pool location, spacing, and size characteristics for each pool as well as average values for the stream section by Rapid Bed Profile (RBP) technique. The second program determines the same pool characteristics but pools are defined by the Bed Elevation Profile (BEP) technique. A typical print out for either program is shown after the BEP program.

I devised the program flowcharts. Janet Cherry (Forest Engineering Research Assistant at Oregon State University) wrote the programs in quickBASIC (4.0) during the Fall of 1987.

(1) Rapid Bed Profile technique

```
DIM HOR(400), ELEV(400), DEPTH(400), LAREA(100), WP(100), DEPTH.AVE(100), SINU(1
00), LENGTH(400), SD(100), HOR.INDEX(400), POOL.MAX(400), ACT.WIDTH(400), X2(400
), DEPTH2(400), HYD.RAD(100), VOL(100), DIST(100), WIDTH.AVE(100)
INPUT "WHAT IS THE MINIMUM DEPTH FOR A POOL IN METERS"; DMIN
INPUT "WHAT IS THE SLOPE INDEX IN DECIMAL FORM"; SIA
INPUT "WHAT IS THE HORIZONTAL SPACING IN METERS"; SPACE
INPUT "ENTER INPUT FILE NAME"; FILENAM$
   OPEN FILENAM$ FOR INPUT AS #1
FOR I = 1 TO 400
   INPUT #1, HOR(I), DEPTH(I), ELEV(I), ACT.WIDTH(I), X2(I)
   IF HOR(I) = -555 THEN GOTO 5
   HOR(I) = HOR(I) / 3.281
   DEPTH(I) = DEPTH(I) / 3.281
   ELEV(I) = ELEV(I) / 3.281
   ACT.WIDTH(I) = ACT.WIDTH(I) / 3.281
NEXT I
5  CLOSE #1
   M.NUM = I - 1
Z = 1: P.COUNT = 0
FOR I = 1 TO M.NUM
   DEPTH(I) = DEPTH(I) * -1
NEXT I
```

```
MAIN:
'  FOR I=Z TO M.NUM
'     DEPTH2(I)=DEPTH(I)-DEPTH(Z)
'  NEXT I
  FOR A = Z TO M.NUM - 1
     IF DEPTH(A) > DEPTH(A + 1) THEN K = A: GOTO POOL.CHECK
  NEXT A
  IF A >= M.NUM THEN GOTO POOL.RES
7 '
POOL.CHECK:
  DEPTH2(K) = 0!
  FOR J = K + 1 TO M.NUM
    DEPTH2(J) = DEPTH(J) - DEPTH(K) + (SPACE * (J - K) * SIA)
    IF DEPTH2(J) >= DEPTH2(K) THEN Z = J: GOTO DEF.POOL
  NEXT J
  IF J >= M.NUM THEN GOTO POOL.RES
10 '
DEF.POOL:
   IF Z = K + 1 THEN GOTO MAIN
   P.COUNT = P.COUNT + 1
   POOL.MAX(P.COUNT) = 0!
20 '
   FOR I = K TO Z
    IF (-1! * DEPTH2(I)) > POOL.MAX(P.COUNT) THEN POOL.MAX(P.COUNT) = (-1! * DEP
TH2(I)): IND = I - 1
   NEXT I
   IF POOL.MAX(P.COUNT) < DMIN THEN P.COUNT = P.COUNT - 1: GOTO MAIN
25 '
   HOR.INDEX(P.COUNT) = IND * SPACE
'   IF HOR.INDEX(P.COUNT)<>144 THEN GOTO 28
28   LENGTH(P.COUNT) = (Z - K) * SPACE
30 'CALCULATE LONGITUDINAL AREA
   LAREA(P.COUNT) = 0
   FOR I = K TO Z - 1
     D = (DEPTH2(I) + DEPTH2(I + 1)) / 2!
     D = ABS(D)
     LAREA(P.COUNT) = LAREA(P.COUNT) + (D * SPACE)
   NEXT I
40 'CALCULATE LONGITUDINAL WETTED PERIMETER
   WP(P.COUNT) = 0
   FOR I = K TO Z - 1
     D = ABS(DEPTH2(I) - DEPTH2(I + 1))
     WP(P.COUNT) = WP(P.COUNT) + SQR((SPACE * SPACE) + (D * D))
   NEXT I
50 'CALCULATE AVERAGE DEPTH
   TOT.DEPTH = 0
   FOR I = K TO Z
     TOT.DEPTH = TOT.DEPTH + ABS(DEPTH2(I))
   NEXT I
   DEPTH.AVE(P.COUNT) = TOT.DEPTH / (Z - K + 1)
   HYD.RAD(P.COUNT) = 100 * LAREA(P.COUNT) / WP(P.COUNT)
52 'CALCULATE AVERAGE WIDTH
   TOT.WIDTH = 0
   FOR I = K TO Z
     TOT.WIDTH = TOT.WIDTH + ACT.WIDTH(I)
   NEXT I
   WIDTH.AVE(P.COUNT) = TOT.WIDTH / (Z - K + 1)
55 'CALCULATE VOLUME
   VOL(P.COUNT) = 0
   FOR I = K TO Z - 1
    VOL(P.COUNT) = VOL(P.COUNT) + ((1! / 2!) * (-1!) * SPACE * (ACT.WIDTH(I) + A
CT.WIDTH(I + 1)) / 2 * (DEPTH2(I) + DEPTH2(I + 1)) / 2)
NEXT I
GOTO MAIN
70 '
POOL.RES:
75 ' CALCULATE STANDARD DEVIATION FOR POOLS ONLY
    SUM2 = 0!
    FOR I = 1 TO P.COUNT
       TOT.POOL = DEPTH.AVE(I) + TOT.POOL
       TOTW.POOL = WIDTH.AVE(I) + TOTW.POOL
    NEXT I
    TOT.AVE = TOT.POOL / P.COUNT
    WLOW.AVE = TOTW.POOL / P.COUNT
```

```
    FOR I = 1 TO P.COUNT
       DIFF = DEPTH.AVE(I) - TOT.AVE
       SUM2 = SUM2 + (DIFF * DIFF)
    NEXT I
    SD.POOL = SQR(SUM2 / (P.COUNT - 1))
    DIST(1) = 0!
    FOR I = 2 TO P.COUNT
      DIST(I) = HOR.INDEX(I) - HOR.INDEX(I - 1)
    NEXT I
90 ' CALCULATE AVERAGE POOL VALUES
    DTOTAL = 0!: SUM2 = 0
    FOR I = 1 TO M.NUM
       DTOTAL = DTOTAL + ABS(DEPTH(I))
    NEXT I
    DTOT.AVE = DTOTAL / M.NUM
    FOR I = 1 TO M.NUM
      DIFF = ABS(DEPTH(I)) - DTOT.AVE
      SUM2 = SUM2 + (DIFF * DIFF)
    NEXT I
    SD.TOT = SQR(SUM2 / (M.NUM - 1))
    PM.TOTAL = 0: PL.TOTAL = 0: LAREA.TOTAL = 0: VOL.TOTAL = 0: HRAD.TOTAL = 0:
PSD.TOTAL = 0
      PDIST.TOTAL = 0
    FOR I = 1 TO P.COUNT
       PM.TOTAL = PM.TOTAL + POOL.MAX(I)
       PL.TOTAL = PL.TOTAL + LENGTH(I)
       LAREA.TOTAL = LAREA.TOTAL + LAREA(I)
       VOL.TOTAL = VOL.TOTAL + VOL(I)
       HRAD.TOTAL = HRAD.TOTAL + HYD.RAD(I)
       PDIST.TOTAL = PDIST.TOTAL + DIST(I)
    NEXT I
    PM.AVE = PM.TOTAL / P.COUNT
    PL.AVE = PL.TOTAL / P.COUNT
    LAREA.AVE = LAREA.TOTAL / P.COUNT
    VOL.AVE = VOL.TOTAL / P.COUNT
    HRAD.AVE = HRAD.TOTAL / P.COUNT
    AVE.DIST = PDIST.TOTAL / (P.COUNT - 1)
100 '
    INPUT "ENTER FILE NAME FOR OUTPUT"; FILE4$
    OPEN FILE4$ FOR OUTPUT AS #1
        FOR I = 1 TO P.COUNT
      WRITE #1, HOR.INDEX(I), POOL.MAX(I) * 100, DEPTH.AVE(I) * 100, LENGTH(I),
LAREA(I), VOL(I), HYD.RAD(I), WIDTH.AVE(I), DIST(I)
   NEXT I
 CLOSE #1
    LPRINT FILE4$
    LPRINT : LPRINT
    PRN$ = "&  #.####": PRN1$ = "&  ##.### &"
    LPRINT "        MAX    AVE                                                   LAST"
    LPRINT "LOC    DEPTH  DEPTH    LENGTH    AREA      VOL      R'      WLOW     POOL"
    LPRINT " M      CM     CM        M        M2        M3      CM        M        M"
    LPRINT "====  =====  =====    =====    ======    ======  ======  =======   ====="
    LPRINT
    FOR I = 1 TO P.COUNT
      LPRINT USING "###    ##.#    ##.#     ###     ##.##    ###.##  ###.#    ##.##
  ###"; HOR.INDEX(I), POOL.MAX(I) * 100, DEPTH.AVE(I) * 100, LENGTH(I), LAREA(I
), VOL(I), HYD.RAD(I), WIDTH.AVE(I), DIST(I)
    NEXT I
    LPRINT
    LPRINT USING "&    ##.#    ##.#     ###     ##.##     ###.#    ###.#    ##.##    #
##"; "AVE"; PM.AVE * 100, TOT.AVE * 100, PL.AVE, LAREA.AVE, VOL.AVE, HRAD.AVE, W
LOW.AVE, AVE.DIST
    LPRINT
     LPRINT USING "&                          ###.##   ####.#"; "TOTAL"; LAREA.TOT
AL, VOL.TOTAL
    LPRINT : LPRINT
    LPRINT USING "& ###"; "TOTAL NUMBER OF POOLS IS"; P.COUNT
    LPRINT USING PRN1$; "AVERAGE DEPTH FOR ENTIRE PROFILE IS"; DTOT.AVE; "METERS
"
    LPRINT USING PRN$; "STANDARD DEVIATION FOR ENTIRE PROFILE IS"; SD.TOT
    LPRINT USING PRN$; "STANDARD DEVIATION FOR POOLS IS"; SD.POOL
    LPRINT USING PRN$; "SLOPE INDEX USED IS"; SIA
    LPRINT USING PRN1$; "THE MINIMUM POOL DEPTH USED IS"; DMIN; "METERS"
END
```

(2) Bed Elevation Profile technique

```
DIM HOR(400), ELEV(400), DEPTH(400), LAREA(100), WP(100), DEPTH.AVE(100), LENGTH
(100), SD(100), HOR.INDEX(100), POOL.MAX(100), DEPTH2(400), ACT.WIDTH(400), X2(4
00), VOL(100), DIST(100), HYD.RAD(100), WIDTH.AVE(100)
INPUT "WHAT IS THE MINIMUM DEPTH FOR A POOL IN METERS"; DMIN
INPUT "WHAT IS THE POOL CONVERGENCE CRITERIA "; POOL.CON
INPUT "ENTER INPUT FILE NAME"; FILENAM$
   OPEN FILENAM$ FOR INPUT AS #1
FOR I = 1 TO 400
   INPUT #1, HOR(I), DEPTH(I), ELEV(I), ACT.WIDTH(I), X2(I)
   IF HOR(I) = -555 THEN GOTO 5
   HOR(I) = HOR(I) / 3.281
   DEPTH(I) = DEPTH(I) / 3.281
   ELEV(I) = ELEV(I) / 3.281
   ACT.WIDTH(I) = ACT.WIDTH(I) / 3.281
NEXT I
5  CLOSE #1
   M.NUM = I - 1
Z = 1: P.COUNT = 0: FLAG = 1
I = 1
X.INTERVAL = HOR(I + 1) - HOR(I)
TOT.POOL = 0!: PRO.DEPTH = 0!
  FOR I = 1 TO M.NUM
      ELEV(I) = ELEV(I) - DEPTH(I)
  NEXT I
MAIN:
  FOR A = Z TO M.NUM - 1
     IF ELEV(A) > ELEV(A + 1) THEN K = A: GOTO POOL.CHECK
  NEXT A
  IF A >= M.NUM THEN GOTO POOL.RES
POOL.CHECK:
  FOR J = K + 1 TO M.NUM
    IF ELEV(K) <= ELEV(J) THEN Z = J: GOTO DEF.POOL
  NEXT J
  IF J >= M.NUM THEN GOTO POOL.RES
10 '
DEF.POOL:
   P.COUNT = P.COUNT + 1
   POOL.MAX(P.COUNT) = 0!
   FOR I = K TO Z
      DEPTH2(I) = ELEV(K) - ELEV(I)
         NEXT I
   DEPTH2(Z) = 0!
   FOR I = K TO Z
    IF DEPTH2(I) > POOL.MAX(P.COUNT) THEN POOL.MAX(P.COUNT) = DEPTH2(I): IND = I
   NEXT I
   IF POOL.MAX(P.COUNT) < DMIN THEN P.COUNT = P.COUNT - 1: GOTO MAIN
   HOR.INDEX(P.COUNT) = HOR(IND)
   IF ABS(ELEV(Z) - ELEV(K)) <= POOL.CON THEN GOTO 30
   FLAG = 2
   XINCR = .005
   TOT.INCR = XINCR
   SLOPE = (ELEV(Z) - ELEV(Z - 1)) / (HOR(Z) - HOR(Z - 1))
   ITER = 0!
20 'CHECK TO SEE IF ELEV(Z) IS > ELEV(K)
   ITER = ITER + 1
   XELEV = (TOT.INCR * SLOPE) + ELEV(Z - 1)
      IF ABS(XELEV - ELEV(K)) <= POOL.CON THEN GOTO 25
      IF ITER > 3000 THEN GOTO 100
   TOT.INCR = TOT.INCR + XINCR: GOTO 20
25 DUMB = ELEV(Z)
   ELEV(Z) = XELEV
   DUMB3 = HOR(Z)
   XHOR = ((XELEV - ELEV(Z - 1)) / SLOPE) + HOR(Z - 1)
   HOR(Z) = XHOR
```

```
30 'CALCULATE LONGITUDINAL AREA
   LAREA(P.COUNT) = 0
   FOR I = K TO Z - 1
     D = (DEPTH2(I) + DEPTH2(I + 1)) / 2!
     W = HOR(I + 1) - HOR(I)
     LAREA(P.COUNT) = LAREA(P.COUNT) + (D * W)
   NEXT I
40 'CALCULATE LONGITUDINAL WETTED PERIMETER
   WP(P.COUNT) = 0
   FOR I = K TO Z - 1
     D = ABS(DEPTH2(I) - DEPTH2(I + 1))
     W = HOR(I + 1) - HOR(I)
     WP(P.COUNT) = WP(P.COUNT) + SQR(W * W + D * D)
   NEXT I
50 'CALCULATE AVERAGE DEPTH
   TOT.DEPTH = 0
   FOR I = K TO Z
     TOT.DEPTH = TOT.DEPTH + DEPTH2(I)
   NEXT I
   DEPTH.AVE(P.COUNT) = TOT.DEPTH / (Z - K + 1)
   LENGTH(P.COUNT) = HOR(Z) - HOR(K)
   HYD.RAD(P.COUNT) = LAREA(P.COUNT) * 100 / WP(P.COUNT)
52 'CALCULATE AVERAGE WIDTH
   TOT.WIDTH = 0
   FOR I = K TO Z
     TOT.WIDTH = TOT.WIDTH + ACT.WIDTH(I)
   NEXT I
   WIDTH.AVE(P.COUNT) = TOT.WIDTH / (Z - K + 1)
55 ' CALCULATE VOLUME
   VOL(P.COUNT) = 0
   FOR I = K TO Z - 1
     VOL(P.COUNT) = VOL(P.COUNT) + ((1! / 2!) * X.INTERVAL * (ACT.WIDTH(I) + ACT
.WIDTH(I + 1)) / 2 * (DEPTH2(I) + DEPTH2(I + 1)) / 2)
   NEXT I
   IF FLAG = 2 THEN FLAG = 1: ELEV(Z) = DUMB: HOR(Z) = DUMB3
   GOTO MAIN
70 '
POOL.RES:
75 ' CALCULATE STANDARD DEVIATION FOR POOLS ONLY
    IF P.COUNT = 0 THEN PRINT "P.COUNT=0": GOTO 100
    SUM2 = 0!
    FOR I = 1 TO P.COUNT
       TOT.POOL = DEPTH.AVE(I) + TOT.POOL
       TOTW.POOL = WIDTH.AVE(I) + TOTW.POOL
    NEXT I
    TOT.AVE = TOT.POOL / P.COUNT
    WLOW.AVE = TOTW.POOL / P.COUNT
    FOR I = 1 TO P.COUNT
       DIFF = DEPTH.AVE(I) - TOT.AVE
       SUM2 = SUM2 + (DIFF * DIFF)
    NEXT I
    SD.POOL = SQR(SUM2 / (P.COUNT - 1))
    DIST(1) = 0
    FOR I = 2 TO P.COUNT
      DIST(I) = HOR.INDEX(I) - HOR.INDEX(I - 1)
    NEXT I
80 ' CALCULATE AVERAGE POOL VALUES
    DTOTAL = 0: SUM2 = 0!
    FOR I = 1 TO M.NUM
      DTOTAL = DTOTAL + DEPTH(I)
    NEXT I
    PRO.AVE = DTOTAL / M.NUM
    FOR I = 1 TO M.NUM
      DIFF = DEPTH(I) - PRO.AVE
      SUM2 = SUM2 + (DIFF * DIFF)
    NEXT I
    SD.TOT = SQR(SUM2 / (M.NUM - 1))
    PM.TOTAL = 0: PL.TOTAL = 0: LAREA.TOTAL = 0: VOL.TOTAL = 0: HRAD.TOTAL = 0:
PSD.TOT = 0
        TOT.DIST = 0:
    FOR I = 1 TO P.COUNT
       PM.TOTAL = PM.TOTAL + POOL.MAX(I)
```

```
      PL.TOTAL = PL.TOTAL + LENGTH(I)
      LAREA.TOTAL = LAREA.TOTAL + LAREA(I)
      VOL.TOTAL = VOL.TOTAL + VOL(I)
      HRAD.TOTAL = HRAD.TOTAL + HYD.RAD(I)
      TOT.DIST = TOT.DIST + DIST(I)
   NEXT I
      PM.AVE = PM.TOTAL / P.COUNT
      PL.AVE = PL.TOTAL / P.COUNT
      LAREA.AVE = LAREA.TOTAL / P.COUNT
      VOL.AVE = VOL.TOTAL / P.COUNT
      HRAD.AVE = HRAD.TOTAL / P.COUNT
      AVE.DIST = TOT.DIST / (P.COUNT - 1)
   INPUT "ENTER FILE NAME FOR OUTPUT"; FILE4$
   OPEN FILE4$ FOR OUTPUT AS #1
   FOR I = 1 TO P.COUNT
     WRITE #1, HOR.INDEX(I), POOL.MAX(I) * 100, DEPTH.AVE(I) * 100, LENGTH(I),
LAREA(I), VOL(I), HYD.RAD(I), WIDTH.AVE(I), DIST(I)
  NEXT I
 CLOSE #1
  LPRINT FILE4$
  LPRINT : LPRINT
  PRN$ = "&  #.####": PRN1$ = "&  ##.#### &"
  LPRINT "          MAX      AVE                                                DA
ST"
  LPRINT " LOC    DEPTH   DEPTH   LENGTH    AREA     VOL      R'     WLOW     PO
OL"
  LPRINT "  M      CM      CM       M        M2       M3      CM       M
M"
  LPRINT "=====   =====   =====   ======   ======  ======   ======  ======   ==
=="
  LPRINT
    FOR I = 1 TO P.COUNT
     LPRINT USING "####     ##.#    ##.#     ###      ##.###  ###.##   ###.#   #
#.##   ###"; HOR.INDEX(I), POOL.MAX(I) * 100, DEPTH.AVE(I) * 100, LENGTH(I), LAR
EA(I), VOL(I), HYD.RAD(I), WIDTH.AVE(I), DIST(I)
      NEXT I
 LPRINT
 LPRINT USING "&     ##.#    ##.#     ###      ##.###   ##.##   ###.#   ##.##
###"; "AVG:"; PM.AVE * 100, TOT.AVE * 100, PL.AVE, LAREA.AVE, VOL.AVE, HRAD.AVE,
 WLOW.AVE, AVE.DIST
 LPRINT
 LPRINT USING "&                                  ###.##  ####.#": "TOTAL"; LAREA.TO
TAL, VOL.TOTAL
 LPRINT : LPRINT
  LPRINT USING "& ###"; "TOTAL NUMBER OF POOLS IS"; P.COUNT
  LPRINT USING PRN1$; "AVERAGE DEPTH FOR ENTIRE PROFILE IS": PRO.AVE; "METERS"
  LPRINT USING PRN$; "STANDARD DEVIATION FOR ENTIRE PROFILE IS"; SD.TOT
  LPRINT USING PRN$: "STANDARD DEVIATION FOR POOLS IS"; SD.POOL
  LPRINT USING PRN1$; "THE MINIMUM POOL DEPTH USED IS"; DMIN; "METERS"
  GOTO 500
100 '
IF ITER > 100 THEN PRINT "PICK NEW CONVERGENCE CRITERIA FOR POOLS"
500 END
```

(3) Typical output from either program

LOC M	MAX DEPTH CM	AVE DEPTH CM	LENGTH M	AREA M2	VOL M3	R' CM	WLOW M	LAST POOL M
=====	=====	=====	======	======	======	======	======	====
11	15.1	5.8	10	0.639	0.46	6.6	1.41	0
27	13.1	4.4	2	0.142	0.13	6.5	1.68	15
37	11.6	4.3	9	0.461	0.28	5.3	1.32	10
46	20.3	8.5	7	0.718	0.46	10.5	1.18	10
60	23.3	9.0	13	1.304	1.29	9.9	1.94	13
71	13.3	4.9	4	0.280	0.21	7.4	1.30	11
76	11.1	4.4	5	0.255	0.27	5.6	1.78	5
87	11.3	4.6	9	0.497	0.49	5.8	1.80	11
98	10.8	4.5	3	0.205	0.23	6.4	1.99	11
110	21.3	7.2	9	0.784	1.05	9.1	2.33	12
119	49.8	18.3	11	3.199	3.33	20.5	2.23	10
135	25.9	9.4	5	0.662	0.22	12.2	1.73	15
146	11.2	4.9	7	0.419	0.39	5.9	1.70	11
158	25.6	11.8	8	1.144	1.08	13.5	1.85	12
177	11.4	4.5	10	0.493	0.35	5.1	1.52	18
189	23.8	8.2	6	0.586	0.61	10.0	1.99	12
193	16.6	5.3	3	0.242	0.24	8.1	1.87	4
210	24.5	9.7	11	1.291	1.76	11.6	2.05	17
216	16.2	5.8	9	0.333	0.56	7.3	1.51	5
232	11.1	5.1	8	0.473	0.27	6.1	1.09	15
AVG:	19.4	7.0	7	0.671	0.70	9.7	1.71	12
TOTAL				13.43	14.1			

TOTAL NUMBER OF POOLS IS 20
AVERAGE DEPTH FOR ENTIRE PROFILE IS 0.1256 METERS
STANDARD DEVIATION FOR ENTIRE PROFILE IS 0.0815
STANDARD DEVIATION FOR POOLS IS 0.0346
THE MINIMUM POOL DEPTH USED IS 0.0820 METERS