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An approach to effectiveness monitoring of floodplain channel aquatic habitat: salmonid relationships

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Abstract

Rivers and streams that support anadromous salmonids are an important part of land management planning in southeastern Alaska and the Pacific Northwest of North America. Land managers and planners require a consistent set of protocols that include both the physical and biological aspects of the stream for effectiveness monitoring procedures to evaluate management activities in forested watersheds. We apply a quantitative method to estimate salmonid populations and link these estimates to a set of physical variables used in an assessment of channel condition at the reach scale. We are able to obtain precise estimates of juvenile salmonid populations at the habitat and reach scale; however, we find a lack of strong relationships between channel condition variables and salmonid densities. Nonetheless, a few trends appear, such as relationships between coho salmon and both pools and large wood. A significant and positive relationship exists between coho salmon fry density and two measures of pool frequency. Our results suggest that the response of fish populations to changes in the amount and quality of habitat can be measured by using the tested procedures. Complexity in habitat use, seasonal effects, and external factors tend to mask close relationships between fish populations and physical variables. We also discuss the implications for trophic status for fish populations and how this information may provide a more robust evaluation of land management activities on the aquatic biota in managed watersheds.

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1. Introduction

1.1. Background

Anadromous salmonid populations are a significant economic and social resource throughout the Pa-

cific Northwest and particularly so in southeast Alaska where sustainable salmon populations are the rule rather than the exception (Baker et al., 1996; Nehlson, 1997; Halupka et al., 2000). As a result, various statutory regulations (i.e., Endangered Species Act and water quality standards) are in place to prevent habitat degradation and species decline. Within the USDA Forest Service, Tongass National Forest, standards and guidelines intended to protect aquatic habitat and to maintain salmonid populations are included in forest

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land and resource management plans and the current land management plan for the Tongass National Forest (TLMP) in southeastern Alaska calls for “the maintenance or restoration of the natural range and frequency of aquatic habitat and stream channel and bank conditions.” Therefore, managers need the means to evaluate the effectiveness of fish and riparian standards and guidelines designed to maintain or improve fish habitat (USDA Forest Service, 1997).

Measuring habitat response to disturbance is the first step in evaluating the effectiveness of standards and guidelines; however, the response of the aquatic biota is the “bottom line,” and economically important salmonids provide a measure of success of effective land management guidelines. Linking habitat structure to habitat utilization by aquatic biota is important in establishing the causal link between disturbance and biological response, but links among channel condition, fish populations, and land use are complex and often not easy to measure (Minns et al., 1996).

1.2. Context

Several recent syntheses address factors that affect salmonid abundance and the decline of salmonid populations throughout the Pacific Northwest (Salo and Cundy, 1987; Poff and Ward, 1990; Meehan and Bjornn, 1991; Bisson et al., 1997; Gregory and Bisson, 1997; Nehlson, 1997; Hughes et al., 1998; Naiman and Bilby, 1998; Halupka et al., 2000; McCormick et al., 2001). As a result of these concerns, considerable effort has been given to monitoring stream habitat and salmonid populations. Johnson et al. (2001) review 112 documents containing 429 monitoring protocols that are relevant to salmonids, primarily in Washington, Oregon, British Columbia, and the northern Rocky Mountains. These range in scale from the reach through watershed and are reviewed by Woodsmith et al. (this issue). The focus of nearly all of these efforts to develop an effectiveness monitoring plan to evaluate the effects of land management is on the physical habitat and does not include measurement of fish populations. This is due, in part, to the difficulty of obtaining reasonably precise and accurate estimates of fish abundance and growth and the interpretation of such data at large scales.

In contrast to the much larger scale efforts, we apply our effort to reach-scale measurements that may be

applied to the watershed scale. We focus on a limited number of geomorphic indicator variables that are (1) known to be sensitive to land use effect, (2) can be measured efficiently (see Woodsmith et al., this issue), and (3) target salmonid populations within these reaches. We also emphasize measurement precision in the selection of variables, recognizing the need for confidence in statements of actual change in habitat, the effect size of the treatment being monitored, variation inherent in the sample, and measurement error (MacDonald et al., 1991; Conquest and Ralph, 1998; Bryant et al., in press) and direct our attention to low-gradient, floodplain channels that we believe are more sensitive to land management perturbations that occur adjacent to them or upstream.

1.3. Objectives

Our goal is to develop an approach and evaluate procedures that incorporate both precise measurements of selected physical variables and estimates of salmonid populations in low-gradient, floodplain channels that can be used in a protocol to monitor land management activities in forested watersheds. Our objectives include:

1. Develop and apply methods that can be used to rapidly estimate fish populations in stream reaches of second to third-order floodplain streams of south-east Alaska.
2. Analyze the relationships between salmonid densities and channel condition at the reach scale.
3. Discuss other potential biological and ecological responses to changes in channel condition and their relevance to aquatic habitat quality and broader issues such as productivity and biodiversity.

We include this discussion because analysis of physical habitat structure alone does not address the availability of food resources and other processes and elements that allow streams to function effectively to support fish and other biota. We suggest directions for research to further understanding of aquatic habitat and interactions with riparian ecosystems.

1.4. Previous studies

Woodsmith et al. (this issue) review the numerous studies that evaluate indicators of channel condi-

tion and response variables that have been applied to describe or measure the physical response of lower-gradient (less than about 0.025 m/m) alluvial streams. Several studies evaluate or review methodologies and protocols to assess the effects of land use on channel condition (Sullivan, 1986; Chamberlin et al., 1991; Montgomery et al., 1995; Bisson et al., 1997). These studies address the physical effects of land use on channel condition. Other studies have examined the effects of land use on multiple habitat quality indicators and fish populations. For example, Murphy et al. (1986) examined relationships among salmonid population densities in old-growth, buffered, and clearcut channels in southeastern Alaska. Their results were mixed among treatments, but generally higher densities of juvenile coho salmon (*Oncorhynchus kisutch*) were associated with more abundant large woody debris. Studies at Carnation Creek, British Columbia, from 1970 to 1987 evaluated the effects of timber harvesting and associated roading at three levels of intensity (Hartman and Scrivener, 1990). Treatments included clearcutting to the stream bank with significant in-channel felling and yarding, clearcutting to the stream margin with virtually no in-channel activity, and a variable-width (1–70 m) buffer strip treatment. Salmonid population responses were mixed and varied among species, life history stage, and through time. For example, as temperature increased coho salmon alevins emerged earlier and migrated to the ocean as larger smolt than those emerging later. These, in turn, apparently exhibited greater marine survival; however, variability in smolt abundance increased more than threefold. Juvenile coho salmon remaining in the logged section for a second summer generally showed lower survival. Coho abundance also decreased as large wood abundance decreased and off-channel habitat was lost.

Other studies have examined the effects of habitat features such as large wood and pools on salmonid populations. They provide a statistical relationship among fish populations and selected physical variables and form a reasonable basis for using them as a monitoring tool (Beechie and Sibley, 1997; Harvey, 1998; Solazzi et al., 2000; Roni and Quinn, 2001). Relationships of fish abundance with other variables, such as cover, undercut banks, and water depth and velocity have been demonstrated with varying degrees of statistical rigor (McMahon, 1983; Heifetz et al., 1986; Marcus et al., 1990). Many of these variables are difficult to measure

consistently and tend to be subject to observer interpretation and require a substantial investment of time. Study results are often based on intensive study of a small number of streams and tend to use habitat measurements at the habitat unit scale.

An alternative to establishing relationships between habitat and fish abundance is to measure biological communities and community structure. Karr (1981) proposed the use of biological communities (index of biological integrity) as a metric of ecosystem condition. He and others proposed that community structure, either fish or invertebrate, will provide a means of determining the function or health of an ecosystem (Karr, 1987). Although these metrics can show qualitative changes in a biological community, usually the effects must be large (e.g., severe depletion of dissolved oxygen) to effect a change in the community structure. Recent studies suggest, however, that in some cases more subtle stresses can affect community structure (Hughes et al., 1998; McCormick et al., 2001). A variety of measures of species diversity also may have some utility or may be adapted to evaluate a range of environmental effects (Pielou, 1965; Gorman and Karr, 1978; Cousins, 1991). There is considerable debate on this issue (Hughes et al., 1998), however, and their application in a species-poor environment, such as most salmonid streams in southeastern Alaska, may be limited.

2. Methods

2.1. Approach

Our study sites are located throughout southeast Alaska in a set of spatially distributed sample of reaches. A reach is a length of stream channel with homogenous morphological, sedimentological, and hydrological features (Hogan and Church, 1989). Woodsmith et al. (this issue) discuss the rationale for the scale used in this study for the physical assessment of channel condition. Bisson et al. (1997) argue for scales that are large enough to encompass the freshwater life cycles of salmon. We estimate populations at the habitat and reach scales and use a large geographic distribution range, more than 450 km north to south, of watersheds located along the southeast Alaska island archipelago.

We limit our studies to a well-defined and relatively narrow section of the watershed defined by a floodplain channel type. This limited range of sampled channel type restricts the interpretation of results, which may not apply to specific disturbances in channel types higher in the drainage network. However, a broader approach would require a very large increase in sampling effort and resources. Floodplain channels with depositional, rather than erosional or transportational, characteristics are more likely to respond to disturbance by aggradation, degradation, or other measurable changes in channel morphology or substrate. Their typical location low in the drainage network makes them likely to integrate cumulative effects of disturbances occurring throughout the watershed. These channel types also support anadromous salmonids that may respond to habitat perturbations (Bryant et al., 1991).

2.2. Variable selection

The most direct way to represent freshwater salmon production is to measure the number of smolt emigrating from the watershed. This is not as straightforward as it might appear. Smolt production integrates the combined effects of background disturbance as well as past and present land use that may be dispersed throughout the watershed. Therefore, changes in number of smolt are likely to be insensitive to less intrusive riparian management practices. Random fluctuations in environmental variables resulting in summer droughts, fall floods, or winter temperature extremes may be unrelated to land use, yet affect juvenile salmon populations in freshwater (Hicks et al., 1991). Salmon populations are also affected by events outside and often independent of freshwater conditions. In the marine environment, fishing pressure, predation, and ocean productivity substantially affect returns to freshwater and recruitment of fry to freshwater habitats.

We used juvenile coho salmon as our primary response variable to measure fish response. Coho salmon spend a substantial amount of their life cycle in freshwater and use small-order streams broadly distributed throughout the channel network. Numerous studies have demonstrated that coho are sensitive to the habitat variables that we selected (see studies cited in Bisson et al., 1987; Meehan and Bjornn, 1991). We also measured Dolly Varden (*Salvelinus malma*), cutthroat trout

(*O. clarki*), and steelhead (*O. mykiss*) that were also captured.

In addition to the reach-scale variables used by Woodsmith et al. (this issue), we included several measures of large wood. Most of these variables have been used in other studies to measure habitat suitability for juvenile salmonids (Reeves et al., 1989; Fausch, 1993; Nass et al., 1996; Nickelson and Lawson, 1998). Many quantitative measures of large wood are subject to observer variability, but counts of well-defined pieces tend to be less variable among observers (Roper et al., 2002). We used counts of whole trees (>30 cm diameter, >10 m length), rootwads, rootwads with >10 m of tree attached, key logs, and key rootwads. Key pieces of large wood were defined as pieces that were >0.30 m diameter and >3.0 m long. Key rootwads were >2 m in diameter.

2.3. Site selection and characteristics

Woodsmith et al. (this issue) used reach lengths that were approximately 20 channel widths. Reaches were wadable and generally single-thread channels without major (>20% of total discharge) tributaries or significant tidal, bedrock, or upstream lake influence. Reaches were located in one of three land use categories (see Woodsmith et al., for details) identified as pristine (P), moderate (M), or heavy (H). Pristine watersheds had no timber harvesting or roads or management intensity was unambiguously trivial. At least one of two conditions was required for a designation of H: (1) the product (% watershed area clearcut) $\times$ (% riparian area cut) $\times$ (road density (m/ha)) > 0.25, or (2) % riparian area cut > 0.25. A number of pristine reaches were included to measure background central tendency and variation in response variables.

2.4. Sample methods

Woodsmith et al. (this issue) sampled 66 floodplain (Dunne and Leopold, 1978) stream reaches distributed across the landscape of southeastern Alaska. For this study we required that our entire sample reach have access for anadromous salmonids. Juvenile salmon were sampled in 21 of the 66 surveyed reaches. Within each reach, fish sampling units (FSUs) were identified, measured to determine area, depth, and width, and used to estimate fish populations. A FSU was defined

as a discrete habitat unit with slow and generally deep water and a riffle (water depth less than 10 cm) or a feature such as a log drop at its upstream and downstream ends that would restrict short-term fish movement during the 6 h sample period. FSUs were equivalent to pool habitat units as commonly applied in many fish habitat inventories. Fish population estimates were made in at least 50% of the FSUs within each sampled reach. FSUs within each reach were selected at random (numbers were drawn out of a hat). Fish populations in each FSU were sampled to estimate abundance, species composition, and size (fork length). Fish were captured in minnow traps baited with salmon eggs packaged in perforated whirlpaks¹ (Bryant, 2000). Traps were set on the stream bottom parallel to the flow next to suspected habitat of juvenile salmonids such as debris accumulations, rootwads, or undercut banks. Each FSU was saturated with traps for complete sampling. Distance between traps depended on habitat complexity, but generally traps were separated by about 2 m. Between 40 and 50 traps were set for each removal experiment and two or more FSUs were usually sampled concurrently. Traps were left undisturbed for 90 ± 10 min, after which time they were picked up in the same order in which they were set and fish were removed. Fresh bait was placed in the trap, and the trap was reset in the same location. This procedure was repeated three to four times depending upon the desired number of capture occasions. Fish from each FSU and capture occasion were segregated and processed separately. Fish from each capture occasion were placed in a holding pen (or blocked minnow traps) until the last capture occasion was completed, and then all fish were returned to the area where they were captured.

2.5. Analysis

We used a removal method to estimate salmonid populations by species in each FSU (White et al., 1982). Coho salmon were separated into fry (age 0) and parr (age 1+) on the basis of length frequency distribution. Coho salmon captured in June were considered to be fry if they were <55 mm; those captured in July were

considered to be fry if they were <55 mm; and those in August if they were <60 mm. If four sample occasions were used, then the generalized removal method was used. It provided population estimates using both equal probabilities of capture (P_c) among occasions and unequal P_c between the first and subsequent occasions. If three occasions were used, then the Zippin method, which assumes equal probabilities of capture, was used. Both methods were computed by using the Capture Program (White et al., 1982).

The estimated salmonid population in each FSU was divided by FSU area to compute the density of each species and age group. The densities in all FSUs sampled in the reach were summed and divided by the number of FSUs that were sampled to compute the mean density in each reach. Mean density was used as the dependent variable in the analysis of the relationship of fish to the channel condition variables. The relationships between salmonid density and channel condition measurements for the reach were examined by using a series of independent linear regressions for each salmonid species and each channel condition variable (SAS Institute Inc., 2001). Differences among treatments were tested with a one-way ANOVA for the density of each species at the reach scale. We used the estimated probability of capture to evaluate the precision of the estimate of the population for each sample unit (Bryant, 2000) and used estimates only if the probability of capture exceeded 0.30 for the sample occasion.

3. Results

3.1. Population densities

All streams regardless of land use intensity supported coho salmon (Table 1). All streams were accessible to anadromous salmonids. Dolly Varden were found in all of the streams except Duckbill Creek, which was classified as moderate land use intensity. All species were found in the pristine streams except for Trap Creek. Steelhead and cutthroat were not captured in Trap Creek; however, cutthroat trout were captured in Trap Creek and its tributaries in another study (Bryant, 1984a). Steelhead was not captured in one of the moderate land use streams and two of the heavy land use streams. Cutthroat trout were not captured in any of the heavy land use streams (Table 1).

¹ The use of trade names in this paper is for the information and convenience of the reader. Such use does not constitute and official endorsement by the U.S. Department of Agriculture of any product to the exclusion of other that may be suitable.

Table 1

The presence of species in streams sampled for fish (number of streams where each species occurred/total number of streams sampled)

Species	Land use intensity		
	Heavy	Moderate	Pristine
Coho salmon fry	4/4	4/4	4/4
Coho salmon parr	4/4	4/4	4/4
Dolly Varden	4/4	3/4	4/4
Steelhead	2/4	3/4	3/4
Cutthroat trout	0/4	2/4	3/4

Large differences in densities of all fish were observed among streams (Figs. 1–5). Coho salmon fry densities ranged from less than 0.1 fish/m² to more than 3.0 fish/m² in several streams (Fig. 1). Coho parr were less abundant than fry and densities in all streams were less than 0.7 fish/m² (Fig. 2). Dolly Varden densities were highly variable among all streams. Observed densities were more than 2.5 fish/m² in one of the reaches in Maybeso Creek (MBS6), a heavy land use reach; however, densities of less than 0.5 fish/m² were observed in other reaches (Fig. 3). Steelhead was observed in 14 of the 21 sampled reaches. They were found in low den-

sities except for two reaches in Maybeso Creek where densities were 0.5 and 1.5 fish/m², respectively (Fig. 4). Cutthroat trout were found in nine streams and ranged from less than 0.02 to about 0.15 fish/m² (Fig. 5).

Painted Creek was the only stream that was sampled for salmonids for more than 1 year. All three reaches were sampled in 1997, and two were sampled in 1998 and 2000. Substantial differences in densities were observed among the 3 years for coho salmon; differences were not as pronounced for cutthroat trout and Dolly Varden (Fig. 6). Year-to-year trends for coho salmon were reasonably consistent between reaches. The density of coho salmon fry was highest in 2000 in both sampled reaches; coho parr densities were highest in 1997 in all reaches. Relative densities of Dolly Varden were similar for all 3 years. However, for cutthroat trout, densities were lowest in reach 1 and highest in reach 3 in 1997. In 2000 those relative densities were reversed (Fig. 6).

3.2. Habitat relationships

We did not observe statistically significant differences in fish densities among treatments for any species

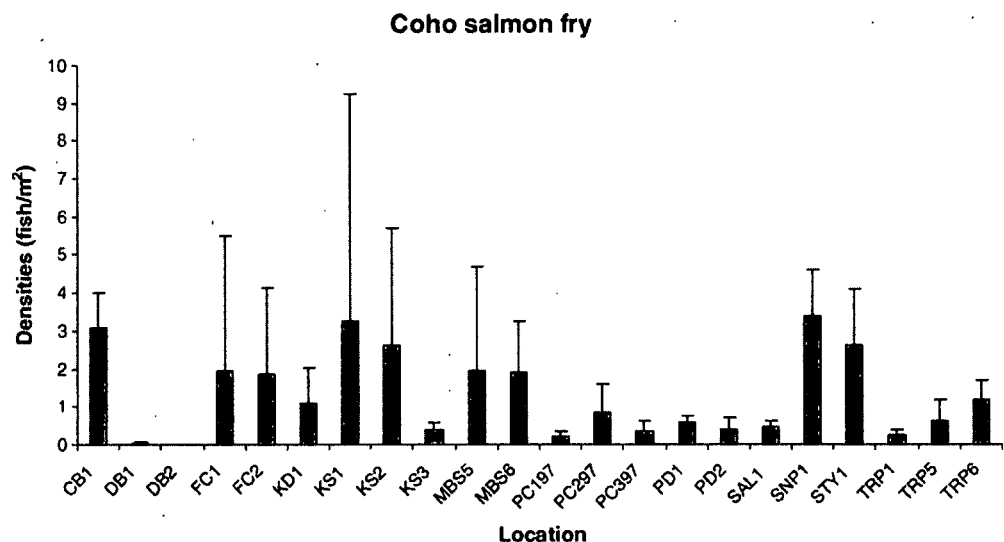


Fig. 1 The mean densities and one standard deviation of coho salmon fry in sampled reaches. CB: Cable CK, CCA reach 1; DB1: Duckbill CK, CCA reach 1; DB2: Duckbill CK, CCA reach 2; FC1: Fowler CK CCA reach 1; FC2: Fowler CK, CCA reach 2; KD1: Kadake Ck, CCA reach 1; KS1: Kadashan River, CCA reach 1; KS2: Kadashan River, CCA reach 2; KS3: Kadashan River, CCA reach 3; MBS5: Maybeso CK, CCA reach 5; MBS6: Maybeso CK, CCA reach 6; PC197: Painted CK 1997, CCA reach 1; PC297: Painted CK 1997, CCA reach 2; PC397: Painted CK 1997, CCA reach 3; PD1: Piledriver CK, CCA reach 1; PD2: Piledriver CK, CCA reach 2; SAL1: Sal Creek, CCA reach 1; SNP1: Snipe CK, CCA reach 1; TRP1: Trap CK, CCA reach 1; TRP5: Trap CK, CCA reach 5; TRP6: Trap CK, CCA reach 6.

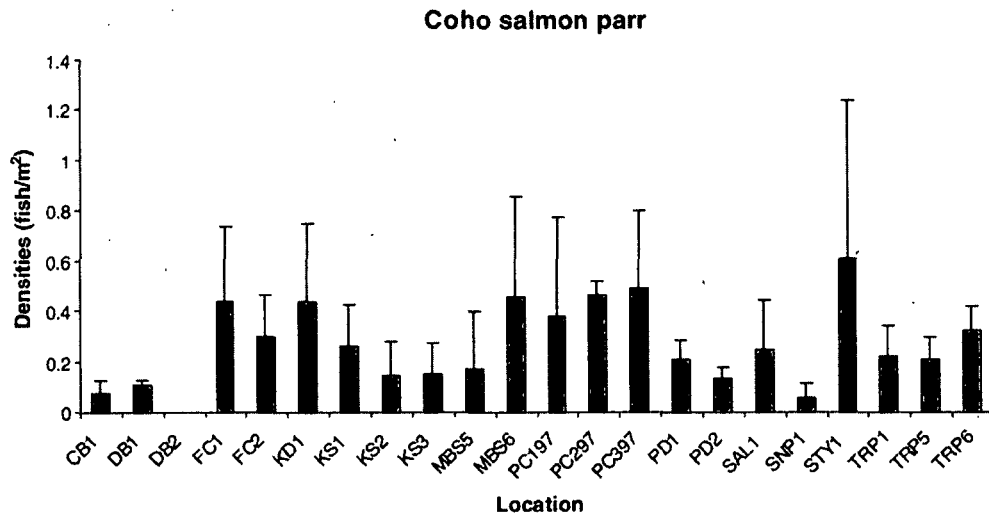


Fig. 2. The mean densities and one standard deviation of coho salmon parr in sampled reaches, 1997 (for abbreviations see Fig. 1).

at the reach scale. This result was expected given the variation in density among streams and the low sample size. Furthermore, relationships between the density of fish and each of 10 channel condition variables were weak and most coefficients of determination (R^2) were less than 0.25 (Table 2). We observed few statistically significant ($\alpha = 0.05$) relationships between fish density and most channel condition variables. Positive and significant ($\alpha = 0.05$) relationships were observed be-

tween coho salmon fry and number of pools and pool density. Although few other significant relationships appeared, a few relationships with $P < 0.10$ were observed. These included positive relationships between coho fry and average bankfull depth and average cross-sectional area (A_{xs}). For Dolly Varden, a negative relationship with median substrate size and substrate size scaled by predicted size, and a positive relationship with number of pools was observed.

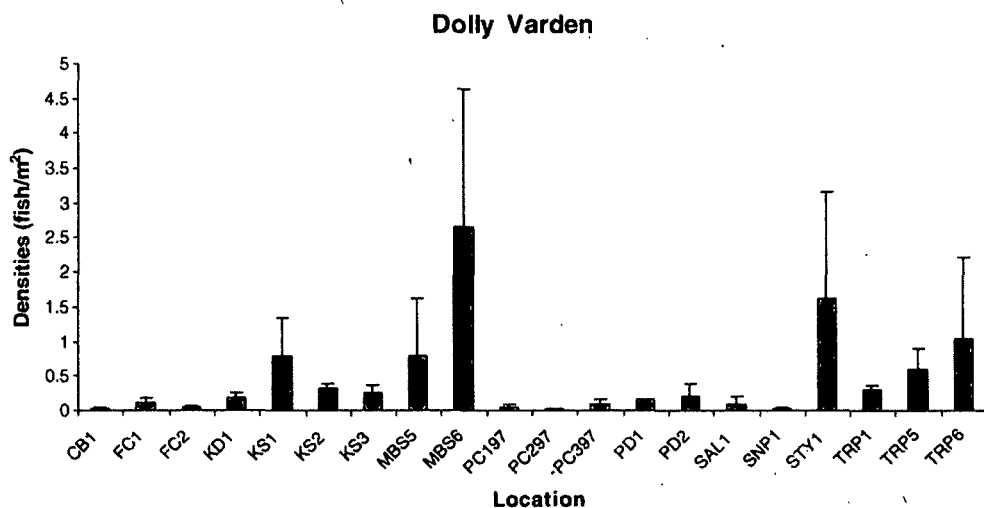


Fig. 3. The mean densities and one standard deviation Dolly Varden in sampled reaches, 1997 (for abbreviations see Fig. 1).

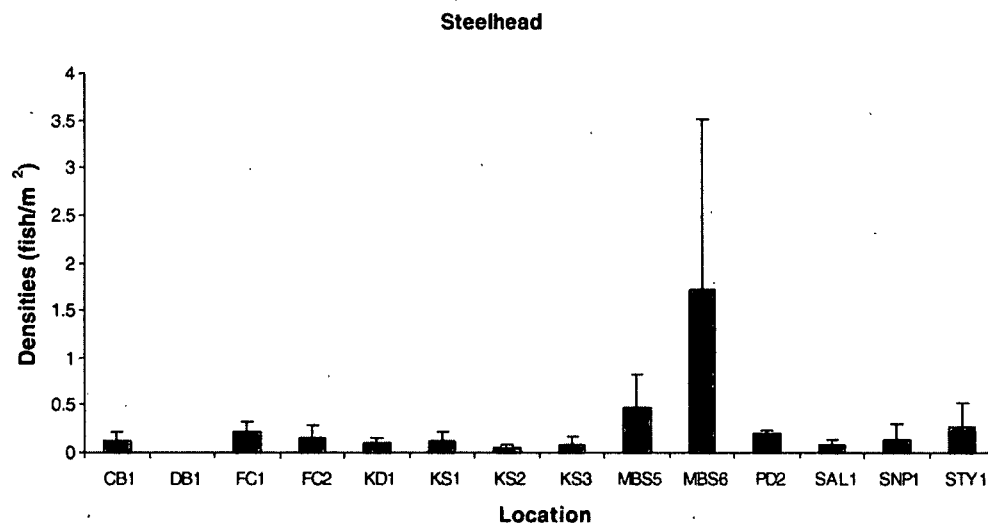


Fig. 4. The mean densities and one standard deviation of Steelhead in sampled reaches, 1997 (for abbreviations see Fig. 1).

Large wood is a common measure of habitat quality and although not used here for assessment of channel condition, five variables characterizing large wood were regressed against fish density by species (Table 3). Key pieces were large pieces that collected and maintained large wood debris jams. No debris jams greater than 50 pieces were observed in any reach. The relationships were weak for all measures and only one,

the relationship between coho salmon parr and tree-size wood was positive and significant at $\alpha < 0.05$. Significant relationships were observed for densities of coho salmon, Dolly Varden, and cutthroat trout with several measures of large wood (Table 3). Weak negative relationships were observed between coho salmon fry and key logs and key rootwads. Other positive relationships were observed between coho salmon parr

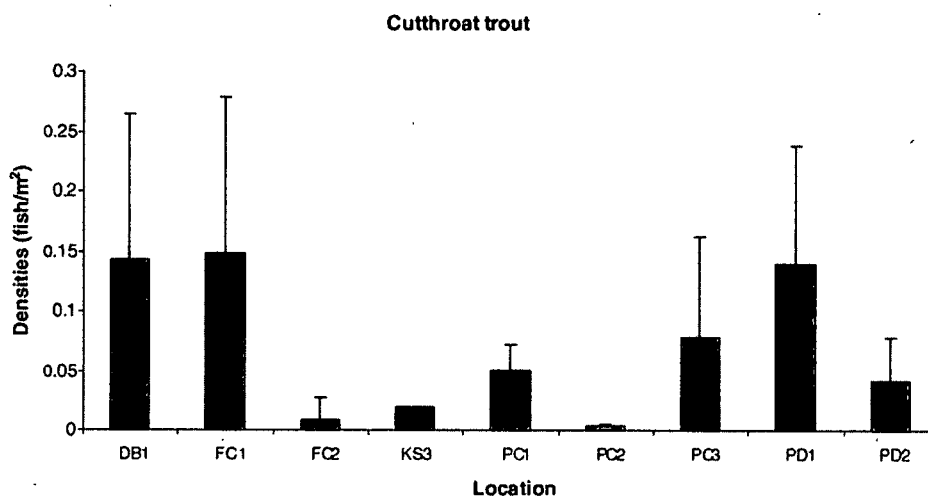


Fig. 5. The mean densities and one standard deviation of cutthroat trout in sampled reaches, 1997 (for abbreviations see Fig. 1).

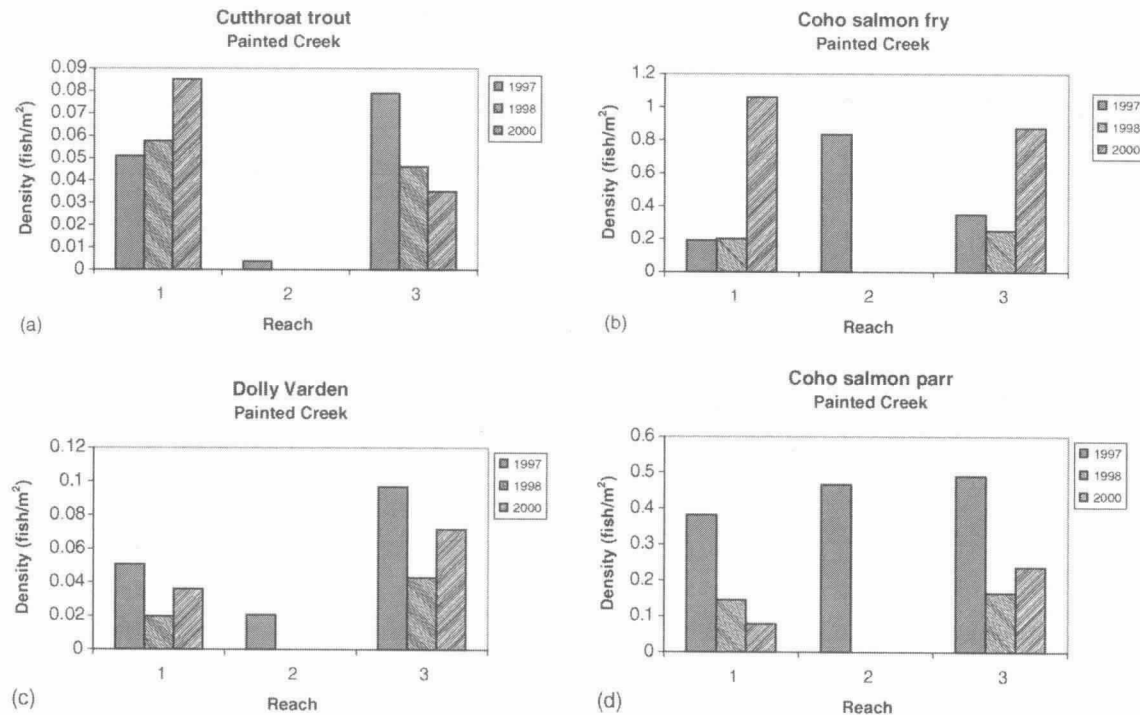


Fig. 6. Density of cutthroat trout, coho salmon fry, Dolly Varden, and coho salmon parr for 1997, 1998, and 2000 in Painted Creek.

and tree-size pieces of wood and trees with attached rootwads. Dolly Varden and cutthroat trout densities were positively related with rootwads and key logs, respectively. Although, in general, these relationships

were not strong and the variation in density among sites was large, results are in concordance with other studies relating large wood with higher densities of salmonids.

Table 2

The relationship between salmonid densities and channel condition variables expressed as R^2 values for regressions

Variable	Coho salmon fry	Coho salmon parr	Dolly Varden	Steelhead	Cutthroat trout
D_{50}	<0.001	<0.0001	0.09* (–)	0.069	0.114
W_{bed}	0.066	<0.0001	0.013	0.095	0.03
d_{bf}	0.125*	0.076	0.043	0.044	0.009
W_{bed}/d_{bf}	0.5623	0.015	<0.002	0.034	0.039
A_{xs}	0.117*	0.017	0.041	0.124	<0.001
Pools	0.242**	0.005	0.013*	0.028	0.013
d_r	0.0173	<0.0001	0.013	0.085	0.028
$Pools \times W_{bed}/L$	0.247**	0.002	0.001	0.008	<0.001
d_r/d_{bf}	0.101	0.08	0.006	0.005	0.014
D_{50}/D_{50p}	0.094	0.086	0.156* (–)	0.062	0.158

Variables are defined as— D_{50} : median grain size of the stream bed surface; W_{bed} : average stream bed width; d_{bf} : average bankfull water depth; W_{bed}/d_{bf} : average width-to-depth ratio; A_{xs} : average reach stream cross-section area; pools: number of pools in the reach; d_r : average residual pool depth; $pools \times W_{bed}/L$: pool spatial density—the number of pools per area of channel equal to $(W_{bed})^2$, L is the reach length; d_r/d_{bf} : average residual pool depth scaled by bankfull depth; D_{50}/D_{50p} : d_{50} scaled by d_{50} predicted for bankfull discharge.

* Significant at $\alpha = 0.10$.

** Significant at $\alpha = 0.05$.

Table 3

The relationship between salmonid densities and large wood variables (per meter) expressed as R^2 values for regressions

Large woody debris variable	Coho fry	Coho parr	Dolly Varden	Cutthroat trout	Steelhead
Trees	0.014	0.454**	0.105	0.001	0.008
Rootwads	<0.001	0.053	0.322**	0.025	0.138
Rootwads with boles	<0.001	0.153*	0.0831	0.008	0.005
Key logs	0.311* (–)	0.007	0.097	0.405*	0.002
Key root wads	0.159* (–)	0.001	0.045	0.043	0.171

Variables are defined in the text.

* Significant at $\alpha=0.10$.** Significant at $\alpha=0.05$.

4. Discussion

4.1. Salmonid populations

Complexity in habitat use, seasonal effects, and ocean conditions can mask close relationships between densities of salmonids and physical variables; therefore, lack of strong relationships between channel condition variables and juvenile salmonid densities is not surprising. Such relationships require that one or more of the variables have significant limiting influence (i.e., less wood-fewer fish, more wood-more fish) (Platts and Nelson, 1988). These relationships are also affected by the degree of fish recruitment into the reach. Limiting factors for juvenile coho salmon may differ seasonally and by location (Reeves et al., 1989). The same applies to the other species that we examined.

The significant and positive relationships between coho salmon fry density and two measures of pool frequency suggest ample seeding of the reaches for coho fry. This may not be the case for other species. Cutthroat trout and steelhead are generally found at low densities in this study, as are Dolly Varden in most streams. The lack of significant relationships between any of these species and physical variables may be attributable to their low densities. The abundance of juvenile coho salmon parr is often a function of over-winter survival of fry, and severity of conditions during the winter affects the number of fish that are observed during the following summer. Generally, mainstem habitats are not preferred by juvenile coho salmon during the fall and winter, and higher over-winter survival is commonly observed in off-channel habitats such as sloughs, backwaters, and beaver ponds (Bustard and Narver, 1975; Bryant, 1984b; Sedell et al., 1984; Hall et al., 1987;

Swales and Levings, 1989). Therefore, season and location of refuge habitats may influence the number of fish we observe in a reach. Although mainstem habitats may be important during the summer for juvenile coho salmon and steelhead (Bramblett et al., 2002), a wider array of habitats and seasons than are included in this study would likely improve the ability to detect changes and management effects on salmonid populations, thereby improving a monitoring plan.

The presence of coho salmon in all sampled streams is not surprising, as they are widely distributed in streams accessible to anadromous salmonids. However, the absence of cutthroat trout in the heavy land use streams is unexpected because they are widely distributed and are found in heavily impacted streams in Oregon (Hall et al., 1987). Lack of detection does not necessarily imply absence; in fact cutthroat trout may be present in other habitats in the watershed such as tributaries and headwater streams, as is the case for Trap Creek (Bryant, 1984a). However, their absence in the mainstem habitats of the heavy land use streams may indicate a treatment effect particularly when another species—steelhead also occurs at low densities in all sampled streams. Species that occur at low densities may be more susceptible to perturbations and less likely to recover than more abundant species (Ricker, 1954).

4.2. Links to productivity and biodiversity

Significant progress has been made in linking channel and habitat structure to habitat use, although there are obvious challenges in sorting out cause and effect in the presence of natural variation. Aquatic habitat quality can be measured by using channel geometry, pool

density and size, water depth, substrate size distribution, and other physical variables, but structure alone does not reflect other habitat qualities such as food supply or productivity. Having located a suitable physical habitat that provides appropriate temperature, flow, and cover, organisms must also find a supply of appropriate food that can meet their basal metabolic needs and provide energy and material for growth and reproduction. In conjunction with questions about stream habitat structure, we must also ask whether the habitat or reach contains the full complement of intact processes that allow it to function effectively. Assessment of habitat function requires some new methodological approaches the development of which lags behind structural assessments.

An important intermediate step in establishing the causal link between disturbance and biological response is the production of food supplied to a given habitat type. The abundance of food supplied to a stream reach is controlled by processes occurring both within the reach itself and in the adjacent and upstream riparian zone. The relationships between physical habitat structure and processes that produce food such as nutrient cycling and retention, and primary and secondary production are poorly documented. Although it can be assumed that key physical properties such as pool density, water depth and slope, extent of cover, and a varied range of local water velocities are correlated to the processes that occur within habitats, those relationships have received little attention. In the case of stream habitats recovering from an extensive disturbance, for example a debris flow, most research has focused on the postdisturbance recovery of large woody debris (LWD) loading and associated habitat structural complexity. It is usually assumed (without being articulated) that as physical structure recovers, associated processes also recover. The exact nature of the relationship between structural recovery and biological process recovery is unknown. Fig. 7 illustrates a variety of relationships that could exist, but there are few studies to suggest which are actually occurring.

Another often unstated assumption is that stream habitats within old-growth watersheds represent the range of structural and functional attributes that maximize habitat quality, but there is evidence that not all undisturbed habitats are equal in their ability to support production even when they are structurally quite similar. Research has shown that additions of inorganic

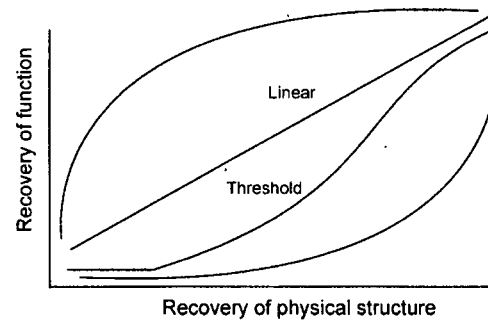


Fig. 7. Range of possible relationships between the recovery of physical habitat structure and the recovery of associated ecosystem processes.

fertilizers can increase standing stocks of periphyton, benthic invertebrates and increase growth rates of fish (Perrin et al., 1987; Johnston et al., 1990; Mundie et al., 1991). Increases in fish production following logging, in response to increased light and nutrient leaching, have also been reported (Bilby and Bisson, 1992). Currently, it is widely believed that the reduction in salmon returns has reduced the input of allochthonous nutrient and carbon inputs to streams with resulting decreases in ecosystem productivity (Gresh et al., 2000). Finally, introduction of salmonids to previously inaccessible stream reaches through fish pass construction has resulted in widely varying fish production in streams whose habitats were surveyed and considered to be good potential salmon spawning and rearing habitat.

These observations, although not often widely or rigorously tested, suggest that factors other than physical structure also influence the productivity of a given habitat and that failure to understand other factors has compromised some management actions. Understanding which attributes determine the carrying capacity or production of fish requires consideration of function as well as structure. If these observations indicate that not all physical habitats are equivalent from a process perspective, then it also stands to reason that the relationship between postdisturbance processes recovery and structural recovery may also vary with stream characteristics at a variety of scales. Little is known about what factors control the rate of postdisturbance recovery of function or how it relates to the variables that influence structure.

Within streams and rivers, the food web structure depends upon two primary sources of organic matter

and energy: plant growth within the channel referred to as autochthonous inputs and organic matter (leaf litter, dissolved organic matter in groundwater, fine and coarse woody debris, terrestrial insects, etc.) delivered from the adjacent riparian zone, referred to as allochthonous inputs. Current ecosystem theory holds that the ratio of the importance of autochthonous versus allochthonous inputs varies with position within the drainage network (Vannote et al., 1980). In small headwater streams where light penetration to the stream surface is limited by the overlying canopy, primary production by stream plants is restricted, and much of the organic matter and energy supporting the trophic structure is allochthonous. As stream channels widen downstream, the amount of light reaching the channel increases, and concentrations of plant nutrients such as nitrogen and phosphorus also tend to increase, resulting in increased autochthonous production.

These two classes of organic matter input differ in their overall food quality. In general, autochthonous production in the form of diatoms and green algae is considered to have higher food value than dead leaves and branches. Thus, even in small headwater streams where light is limiting, the higher food value of algae may increase the importance of the relatively small amount of primary production. However, through the processes of “conditioning,” leaves and branches are decomposed by fungi and bacteria and converted to microbial biomass, which increases their overall food quality (Suberkropp et al., 1976). Different litter types (e.g., alder versus conifer needles) differ in their inherent food quality, their capacity to support microbial growth, and the length of time it takes to become conditioned to higher quality food (Webster and Benfield, 1986). Intermediate prey species such as stone flies, caddis flies, or various crustaceans specialize in eating various food types, converting autochthonous and allochthonous material into food for fishes and other organisms. The abundance of plant material and detritus for consumers is controlled by primary production rates, litterfall rates, and the capacity of the stream to retain those inputs in the face of baseflow discharge and floods, which tend to wash the material downstream. Thus the productivity of a stream reach is controlled by the type and amount of organic matter entering its overall food quality and by the presence of retention structures that increase its residence time.

There are opportunities to more clearly link habitat structural variables to productivity. Some of the measurement variables used in this study to characterize habitat structure and channel morphology also address known aspects of channel productivity, although the quantitative nature of those relationships is not well established in southeastern Alaska. For example, the amount and size of LWD are related to habitat quality by providing cover for fish and creating critical pool habitat, but also give a measure of abundance of structures capable of retaining organic matter for consumption in detrital food pathways. As discussed later, LWD also relates to the frequency and extent of key subsurface water flows with important functional implications. Channel width, a fundamental descriptor of the physical state of the channel, is also related to the light penetration allowed by the canopy and could yield information about potential autochthonous productivity. Channel surveys based on methods described within this report could be combined with surveys of food abundance and production patterns to add an important link in the disturbance-effect chain.

Other variables, however, relate to channel productivity but are not commonly considered in physical habitat surveys and have received relatively little study within the Tongass National Forest. Some of those variables could provide important information in the context of current management debates. For example, there is currently much interest in understanding the effects of nutrients transported by spawning salmon on the productivity of spawning streams (marine-derived nutrients or MDN). It is thought that nitrogen and phosphorus produced by decomposing salmon stimulate primary production within the channel and increase the production of invertebrates and fish, including salmonids. Central to this phenomenon is the assumption that southeastern Alaska streams are nutrient limited because nitrogen and phosphorus are present in low concentrations, and are consequently oligotrophic (have low primary production rates). However, virtually no research has been done to (1) describe the abundance of inorganic plant nutrients in southeastern Alaska streams, (2) quantify the rates of primary production within Alaskan streams to verify the low productivity assumption, or (3) determine what nutrients, if any, limit primary production within the region. Studies from other locations suggest that the response of streams to salmon-derived inputs varies with the

nutrient context of the receiving watershed (Thomas et al., 2002). Background nitrate concentrations, for example, vary with the type of watershed vegetation, which in turn varies with geography and management history (O'Keefe and Edwards, 2001). Thus, for managers to determine the potential importance of MDN in any given location, they need an understanding of the distribution of other factors that control primary productivity within the Tongass National Forest. It stands to reason that since virtually nothing is known about these variables, there is also little known about how these aspects vary within the Tongass National Forest in response to variation in climate, geology, rainfall, and vegetation, in short, among the various ecological subsections recognized by the recent publication of Nowacki et al. (2001).

Because of its higher food quality, primary production by stream algae and other plants may be very important to stream food webs even in shaded headwater streams (Bilby and Bisson, 1992), but particularly within alluvial, fish-bearing reaches such as those described in this report. The lack of a broad understanding of how stream primary productivity varies with stream size and over the range of ecological subsections within the Tongass National Forest is an obvious impediment to a comprehensive approach to gauging effects of land use. An important fundamental element in predicting the cumulative effects of disturbances (timber harvest, climate change, flooding, etc.) is knowing how productive rivers are, what critical processes and patterns determine that productivity, and how sensitive those factors are to various disturbance types. From first principles, we can predict that the supply of limiting inorganic nutrients will vary with basin lithology, surrounding vegetation, and riparian and wetland processes that transport, transform, and retain nutrients. However, except for a study of karst streams (Wissmar et al., 1997), little effort has been made to relate productivity to location. This remains an important knowledge gap. Further research in nutrient availability and cycling and primary production is warranted.

Because the relative importance of autochthonous and allochthonous inputs varies so widely with stream physical structure, studies of primary production should be pursued as part of an integrated attempt to characterize the entire productivity base of stream reaches. Research into the patterns of secondary production (the creation of new biomass at trophic levels

above plants) and its major controls is complementary to studies of primary production. Because secondary production is supported by both primary production and exploitation of detritus derived from riparian zones, it will vary with physical conditions within the channel and with riparian condition. Therefore, an integrated understanding of productivity and its controls can build on the existing database of channel condition, but will require additional insight into variables not currently emphasized. For example, pools figure prominently in assessment of habitat conditions for fish, and LWD interaction with sediment is an important control on pool frequency and morphology. Pools are also a dominant zone of organic matter deposition, so it is possible that the loading of organic matter within a reach can be described to some extent by the same data used to describe physical habitat structure. However, the bulk of studies on primary production within streams focus on riffle communities. This is because riffles, by definition, are shallower and contain faster water velocities than pools during nonflood conditions. Light can penetrate to the bottom better in riffles than in pools, and the faster flow of water and dissolved plant nutrients over riffle substrates ensures a greater supply of limiting nutrients to periphyton than in pools. Thus the emphasis on pools created by an emphasis on physical habitat structure for fish needs to be broadened to a consideration of the state of riffles, where high-quality food is being generated. A reasonable speculation is that the processes supporting production of invertebrates and fish in pools include both secondary production on detritus contained within pools and behind debris dams, and primary production within riffles upstream of the pools. Although a simplified dichotomy, it is possible that in alluvial reaches, pool productivity is determined in part by the riffles connecting them.

4.3. *Hyporheic processes*

Because of the continuous downstream flow of water in streams, organic matter and nutrients are continually being removed from a given reach. When the supply of new material in litterfall and transport from upstream is high, downstream losses are compensated and productivity may be unaffected. However, in southeastern Alaska streams, where high rainfall, discharge, and relatively low nutrient concentrations exist, processes that retain and recycle

nutrients within a reach become critical in controlling production. Debris dams formed by LWD are a well-studied example of important retention zones. An emerging understanding of subsurface habitats points to the hyporheic zone as another important location for retention and recycling. Hyporheic zones are the water-saturated sediment beneath and beside the wetted stream channel that contain some water that originated within the surface channel (Edwards, 1998). In streams that contain porous, hydraulically conductive gravels (e.g., all salmonid streams) water continuously moves into the subsurface for periods ranging from minutes to months, where it interacts with groundwater and the extensive community of bacteria, fungi, and protozoans within the organic film coating the sediment particles (known as the epilithon). This temporary storage of water outside of the surface channel, known as transient storage, is an important physical mechanism by which the downstream transport of materials suspended and dissolved within that water is retarded. Epilithon is biologically and chemically very active, and it rapidly removes material from water passing through the sediment (Bott et al., 1984), decreasing downstream material transport and making it available for biological production over a longer interval.

Extensive hyporheic exchange in streams dramatically alters the rate of uptake of plant nutrients and dissolved organic matter, reduces stream temperatures, creates zones of nutrient-enriched upwelling water that increase surface algal biomass, and provides a large habitat volume for invertebrates. Our understanding of the ecosystem effects of hyporheic zones within the Pacific Northwest and southeastern Alaska is relatively poor, but ample evidence exists to hypothesize that hyporheic processes are an important influence on overall stream productivity and the spatial distribution of essential processes within reaches. Hyporheic zones are potentially important storage zones for allochthonous material as well as for plant-limiting nutrients. A large percentage of the organic matter passing through a stream may be discharged in dissolved form (Fisher and Likens, 1973). This dissolved organic matter (DOM) comes from several major sources: groundwater inputs, leaching from litter inputs, exudates from stream algae, and transport from the extensive surrounding wetlands that feed streams. In dissolved form, organic matter is generally not available as food for higher trophic levels, but when taken up by microbes it can move into the

food web when invertebrates feed on bacteria, fungi, or protozoans that reside in epilithic biofilms. Because the surface area of sediments and associated biofilms is so large in hyporheic zones, it is likely that they are a major habitat for DOM retention. Thus hyporheic zones serve to integrate the two source classes of energy and material inputs described in the earlier discussion.

Hyporheic zones are sensitive to the same disturbances that affect channel condition, and measurement variables used to characterize channel condition also contain information relevant to understanding hyporheic exchanges. Hyporheic flows are affected by substrate texture and are driven by changes in channel topography and its influence on water surface elevation and hydraulic head. Elements such as boulders, logs, meander bends, or reach morphology all create changes in water surface elevations that drive subsurface flows of different lengths and residence times. One of the most heavily studied classes of hyporheic exchange is that created by pool-riffle topography. Water moves into the subsurface at pool tails and riffle heads and travels downstream where it upwells in the tail of the riffle and head of the pool (Fig. 8A).

These flows also generate arcuate flowpaths of water that move laterally into the riparian zone and emerge downstream at roughly the same distance as the pool-riffle spacing (Fig. 8B). Clearly the same processes and patterns that control pool frequency and size (LWD size and frequency, slope, shear stress, sediment supply, etc.) also affect the frequency, volume, and velocity of hyporheic exchange and all the processes affected by them.

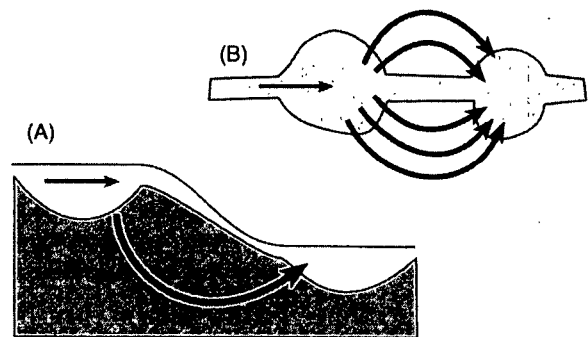


Fig. 8. (A) vertical flow section through a pool-riffle-pool sequence illustrating downwelling of water in upstream pool tail and upwelling in downstream pool head; (B) lateral arcuate subsurface flowpaths generated by pool-riffle sequences.

4.4. Watershed context and connections

Studies of habitat pattern and ecosystem processes yield an understanding of how important stream traits respond to background disturbance and management activities. The details of that response, however, will differ among the wide variety of landforms that exist within the Tongass National forest. The susceptibility to disturbance and the trajectory of recovery is influenced by lithology, rainfall patterns, temperature regime, vegetation, and a host of other variables that characterize a given watershed. In the heavily glaciated areas of southeastern Alaska, well-drained soils intersect with wetlands to form a mosaic of soil and vegetation environments. This mosaic of soil types promotes dynamic interactions between soils and water with important effects on the delivery of carbon and plant nutrients to streams. In areas of steep terrain and high precipitation such as southeastern Alaska, movement and transformation of elements from uplands to wetland environments and then to streams is significant. Wetlands are the critical link for the transport and transformation of elements and compounds between terrestrial and aquatic environments.

The physical and chemical processes occurring in wetland and riparian soils and the interaction of waters passing through each system largely determine the amount and form of material inputs from watershed to stream (Hedin et al., 1998) and the timing of their delivery. Linking hillslope hydrologic models with studies of the nutrient pools, transformations, and availability can aid in predicting the response of streams to upland management actions. Terrestrial hydrologic links to streams are well established in other regions. However, there are few landscapes in the world that contain as large a percentage of wetlands as southeastern Alaska, and the movement of elements and compounds through wetlands is very poorly understood. Wetlands can provide substantial DOM to streams (brown water streams) and lower pH levels. Isotopic analysis of stream acidification has shown that wetlands contribute to stream acidity (Wels et al., 1990).

In general, it is believed that wetlands contribute to flow stability in river systems, but streamflow responses to wetland hydrology may be very different depending on the type of wetland (Verry, 1997). Generally, peat soils are very retentive systems with low mineralization, high nutrient affinity in the microbial

community, and plant adaptations that internally recycle nutrients. As with other factors related to peatlands, there is little information related to southeastern Alaska. Initial research has shown that the peat characteristics in southeastern Alaska differ from those in the upper Midwestern States where most of the research has been conducted (D'Amore and Lynn, 2002). Nutrient cycling and stream productivity research in southeastern Alaska has focused on the marine influence and the allochthonous riparian nutrient supply. Linkages of hillslope water movement, soils, and weathering have not been extensively studied on an array of geomorphic settings except for south Chichagof Island (Stednick, 1981).

5. Conclusions

Woodsmith et al. (this issue) show that well-trained personnel are able to collect, analyze, and interpret relative effects of various land use practices on channel condition. Our results show that estimates of associated fish populations made by using removal estimate protocols can be included in the measurement of channel condition (Bryant, 2000). These results can then be used to interpret potential response of fish populations to the physical measurements of stream channel condition. Similar caveats with respect to sample size, sampling power, and a sufficient period of time to determine temporal variation also apply to the measurement of fish populations. Our results also demonstrate that the links between salmonid abundance and physical measurements may be difficult to determine and many may not show statistical significance. However, nonsignificant results in monitoring studies should be interpreted with caution (Bryant et al., in press).

Despite complexities in habitat use, seasonal effects, and external factors that mask close relationships between densities of salmonids and physical variables, a few trends are apparent, such as the relationships between large wood and coho salmon parr, Dolly Varden, and cutthroat trout. These relationships are consistent with numerous other studies that have shown close relationships with similar variables. The relationships that we did observe suggest that large wood measurements and measurement of pool abundance are important components of stream habitat monitoring protocols.

5.1. Future research directions

Various types of disturbance, including debris flows, channel scour, channel aggradation, and others largely control the movement of water, sediment, and wood through catchments and result in alteration of critical habitats for fish and other fauna (Benda et al., 1998). The apparent, measurable physical structures that we see result from processes that are inferred and modeled largely from their resulting forms. However, the structure that water and sediment transport processes create also impacts a multitude of ecological processes that play out within the physical template and alter the quality of habitats produced in ways that are less obvious. Food abundance, food quality, productivity, and biological diversity are all-important biological properties that are influenced by physical habitat in ways that are not well understood. Thus, an important addition to monitoring concerned with detecting the influence of land use practices would be an investigation of disturbance effects on the processes that create these important biological properties.

Within this perspective, there are several avenues for research that would fill in knowledge gaps and lead to an improved foundation for management decisions. As with all new lines of inquiry, some of the questions are more general in nature and do not directly answer specific management questions. Physical habitat has been emphasized in the past in part because it is more apparent and easier to measure than process. As difficult as it may seem to quantitatively describe physical habitat structure, pool dimensions are more easily measured than many stream processes. Thus some proportion of the research described below is too expensive or laborious to be included in routine management procedures such as those described within this manuscript. However, some processes will lend themselves to routine measure, and once quantified, many of the processes too expensive to repeat will be understood well enough to provide a useful context for more focused decisions. Another useful approach to limiting the number of expensive studies is to model the relationship between physical habitat characteristics and processes that are influenced by them so that those more easily measured characteristics can be used as surrogates for the processes that occur within them. In this way, the measures of physical habitat structure can be used as metrics of important functions.

Important insight into the biological/ecological response of streams to changes in physical habitat condition and their relevance to salmonid habitat quality would be gained by research in these general areas:

- Nutrient cycling and retention.
- Primary production.
- Secondary production.
- Wetland-stream interactions.

More specifically, research directions could be guided by the need to understand:

- What factors control the productivity of Tongass National Forest streams.
 - How physical and chemical variables control primary production.
 - The range of magnitude and distribution pattern (time and space in three dimensions) of secondary productivity and what variables influence it.
- What role surface/subsurface interactions play in influencing stream productivity, stability, and diversity.
- How background disturbances and management decisions influence these key processes.
- How the widespread wetlands that characterize southeastern Alaska influence carbon and nutrient inputs and stream process.

5.2. Key questions

Initial research could focus on the following key questions:

- What are the rates of stream primary production within Tongass watersheds and how do they differ with ecoregion and location within the watershed?
- How do nutrient inputs and fluxes differ with ecoregion and land use?
- What nutrients limit primary production in a particular context?
- What is the distribution of biomass and secondary production between surface and subsurface communities?
- How do hyporheic flows (volume, discharge, velocity, residence time) vary with channel condition and in response to background and anthropogenic disturbances?
- How does the distribution of hyporheic zones differ among major landforms, within catchments, and in

response to background and human-induced disturbances?

- Do hyporheic zones act to store nutrients from the watershed or marine-derived sources?
- Do nutrients stored within hyporheic zones re-enter the stream during the growth season and thereby increase primary productivity?
- What is the relationship between ecosystem (primary and secondary) production and abundance and growth of salmonids and resident fish within stream reaches?
- What are the major flow pathways from watershed to streams and what role do major wetlands play in mediating water and nutrient inputs?

5.3. Approaches

Several opportunities exist to use the history of management activities and the large naturally occurring range in landform and climate within the Tongass National forest to detect ecosystem responses at various scales. Combining studies of stream processes and chemistry with concurrent studies of upland water sources and chemistry will build toward an understanding of the watershed-stream continuum and offer a mechanistic approach to understanding how upland forest practices influence stream processes via subsurface linkages. Because the landscape context is critical in regulating stream processes, the recently completed ecological subsection compilation (Nowacki et al., 2001) could be very valuable as a hypothesis-generating tool to study endpoint watersheds that bracket the extremes of variability across the Tongass to better detect broad differences in stream productivity.

Other opportunities exist to use variation in the response of fish to habitat condition to better understand ecosystem productivity-fish productivity relationships. Stream reaches within the Tongass differ widely in the density of resident fish populations, and little is known of what habitat traits are responsible (Dick Aho, USFS, pers. commun.). Likewise, the response of salmonids to introduction to new habitats by the construction of fish passes around waterfalls and other obstructions has differed widely with little explanation as to what factors besides habitat structure might be involved. Fundamental questions about the correlations of reach nutrient stocks, allochthonous inputs, primary production, and

ecosystem metabolism with fish densities and growth rates should be pursued. Initial observations on how these variables co-vary in space and time would suggest more detailed experimental approaches to sorting out the different influences.

Ecosystem-level primary production can be measured with oxygen meters and data loggers deployed in a variety of stream types to monitor diel changes in oxygen concentration. With appropriate corrections for diffusion, gross primary production, net primary production, and community respiration can be calculated. Diel oxygen measurements have the advantage of averaging values over a reach, avoiding problems with the known high spatial variability in algal biomass distributions and photosynthetic rate. Concurrent measures of community respiration allow for the calculation of total community metabolism, which addresses the combined metabolic balance between autotrophic and heterotrophic metabolism. In conjunction with measurements of allochthonous inputs (upstream import, leaf litter, groundwater DOM inputs, etc.) the energy and organic matter base for the reach trophic structure can be quantified.

Combining metabolic budgets with measures of stream nutrient chemistry provides insight into which variables control primary production. To understand how reach characteristics affect nutrient retention, transient storage injections of conservative tracers and various inorganic nutrients can be added to characterize the hydrologic and biologic capacity of the reach to retain critical nutrients. Surface tracer injections combined with well and piezometer grid installations and subsurface tracer injections can be used to understand the role hyporheic processes play in the retention, transformation, and release of critical materials such as inorganic nutrients and carbon.

Research in these proposed areas could build on the existing and growing database. For example, models relating the extent, volume, and velocity of hyporheic flows to simple measures of channel morphology show great promise. With relatively little effort we could test the usefulness of our existing cross-sectional data for incorporation into groundwater flow models and begin to tie our understanding of the distribution of hyporheic flows to processes influencing habitat quality. Another example is to use nutrient releases and transient storage models to quantify the tightness of nutrient spirals in reaches with different distributions of LWD, thereby in-

tegrating an understanding of pool-forming processes and nutrient cycling.

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