Fish Habitat Rehabilitation Procedures

Fish Access

Stream Banks

Large Woody Debris Complexes

Boulder Clusters

Pool-Riffle Reconstruction

Fertilization

Off-channel Habitats

Watershed Restoration Technical Circular No. 9

BRITISH COLUMBIA

Watershed Restoration Program
Ministry of Environment, Lands and Parks
and Ministry of Forests

Fish Habitat Rehabilitation Procedures

Editors

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Preface

Recent reviews of the status of anadromous salmonid stocks of the western United States and British Columbia indicate that in less than a century, wild stocks have gone from a pristine state to one of numerous extinctions, threatened status or uncertain status (Nehlsen et al. 1991; Slaney et al. 1996). The causes of the declines are linked (as described by Cederholm et al. in Chapter 8) to various impacts dominated by overharvesting of weaker stocks, problems associated with hatcheries, hydroelectrical developments, and habitat loss. Nehlsen et al. (1991) concluded that for many stocks to survive and prosper in the next century, there is a need for a major shift to restore habitats and ecosystem function, rather than rely on artificial production.

There is little doubt that past industrialized forest harvest practices have played a key role in habitat losses because most watersheds in the province have had some level of forestry activity, which has altered drainage patterns, increasing erosion with greater sediment delivery to fish-bearing streams. Over the past decade, hillslope failures from roads and gullies have become much more evident as logging has shifted to steeper slopes and old roads have failed from overloaded side-casts that frequently incorporated decaying woody debris. Historically, most streams were logged to the stream banks (at almost all coastal streams until 1988, but less often at larger interior streams), leaving a legacy of bank erosion and a major deficit in the resupply of large mature wood to stream channels, the primary structuring element for juvenile fish habitat for summer rearing and overwintering. Although the role of wood in streams in providing habitat was established earlier, the linkage to its long-term recruitment was not well-recognized until the 1980's. Past fisheries legislation that promoted wood removal, and past practices by fisheries and water management agencies that resulted in removal of wood, especially of log jams, has compounded the problem further. Channelized or uniform sections of streams are also common where streams have been aligned or diverted to protect logging roads, crossings, log sorting and milling sites. Adult fish passage at road culverts has been a long-standing concern, but most culverts are likely impassable to juveniles, which often require off-channel refuges to successfully overwinter. Oligotrophication, resulting from combined impacts of industrial forestry and commercial fishing, is a more subtle impact that is receiving greater recent attention as declining trends in escapements of salmon become more evident; recent stable isotope studies (e.g., Bilby et al. 1996) demonstrate the key role of marine-derived nutrients in the smallest of salmon streams. Earlier forestry practices also favoured natural restocking of trees, which resulted in a dominance of deciduous trees, promoting damming activity by beavers of small streams utilized by migrant fish species.

The lack of any mechanisms to ensure the rehabilitation or offsetting measures for adversely impacted hillslopes, riparian areas and streams resulted in B.C.'s Watershed Restoration Program (WRP), which was implemented in mid-1994. In combination with recent forest practices legislation in B.C. (Forest Practices Code), there is an opportunity to reverse habitat losses associated with past and new forest harvesting. Both restoration and the Code are based on several decades of research on watershed processes, limitations to salmonid production in streams, and habitat rehabilitation techniques described in Chapters 5 through 15. These provide the technical basis for a suite of integrated restorative measures to accelerate natural recovery processes in forested watersheds impacted by past practices that would otherwise require decades, even centuries to recover naturally. Success will be closely associated with training and skills development initiatives, as well as effectiveness monitoring, which is needed to refine predictive biostandards (as described by Koning and Keeley in Chapter 3), to capture innovations and to facilitate adaptive management.

Clearly a watershed focus is required for such a program to be successful, as emphasized in Chapter 2 in this guide, as well as elsewhere (Slaney and Martin 1997). The "River Continuation Concept" (Vannote et al. 1980, modified by Triska et al. 1982) is a useful ecological template for such a holistic approach, in recognition that fluvial geomorphic processes, within a drainage from its headwater gullies to the stream mouth, largely regulate biological processes involving energy input, nutrient spiralling, organic matter transport, storage, and use by aquatic biota including invertebrates and fishes; functioning of downstream communities is contingent on upstream contributions of materials. Thus, hillslope stabilization is typically a requisite in advance of stream restoration, with the exception of protected off-channel habitats located along floodplains. Accordingly, in addition to the 15 stand-alone chapters in this guide, there are eight published guides (or technical circulars) that provide the technical standards for aquatic ecosystem restoration in B.C.'s integrated Watershed Restoration Program. [An expanded terrestrial ecosystem focus, with greater incorporation of wildlife values, may be incorporated as technical standards are developed.] These circulars include: (1) guidelines for planning integrated projects, with flow charts for the implementation sequence in watersheds, for shifting from assessment to implementation phases, and a decision strategy for shifting from restoration to rehabilitation to mitigation (see Johnston and Moore 1995; Figs. 1, 2 and 3); (2) watershed assessment procedures (now a Code guidebook); (3) road rehabilitation standards; (4) forest site rehabilitation; (5) gully assessment procedures (now a Code guidebook); (6) riparian assessment and prescription procedures; (7) channel condition assessment and prescriptions; (8) fish habitat assessment procedures; (9) fish habitat rehabilitation procedures; and (10) monitoring and evaluation protocols (in preparation). About the same time in 1993-1994, the National Forests of Washington and Oregon developed a remarkably similar integrated watershed program, the Aquatic Conservation Strategy of the Northwest Forest Plan, although some hillslope and considerable stream restoration had been underway for at least a decade.

It is assumed throughout this guide that recovery of structural diversity and nutrient sources (often salmon carcasses) will eventually restore aquatic communities or the biodiversity of disturbed aquatic ecosystems. The loss of the large old-growth trees in stream channels with their massive rootwads as anchors, is the type of structure that cannot be easily duplicated, which is the rationale for cable anchoring of woody complexes to streamside trees and instream boulders, at least on the first pass. Salmon spawners, in particular, are keystone species as the vital link between aquatic and terrestrial communities, especially within the riparian zone (see Ashley and Slaney, Chapter 13).

Most of the procedures in this guide are focused on the short term (20-50 years). For the long term, riparian protection and restoration needs to be implemented and maintained to recover riparian functions, to provide future desired conditions for fish and wildlife resources and to provide shrubs and deciduous trees for leaf litter mixed with mature coniferous trees for large wood recruitment and fluvial-resistive root systems. Finally, although practitioners of restoration have little control over fish harvest rates or ocean (or lake) conditions that cause shifts in migrant survivals, it is assumed that wise stock management in the fishery will ensure sufficient spawning escapements to these streams.

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Table of Contents

Part I. Planning Stream Restoration Projects

Chapter 1

Planning Fish Habitat Rehabilitation: Linking to Habitat Protection

Pat A. Slaney[1], Alan D. Martin[2]

INTRODUCTION: SETTING THE STAGE FOR STREAM RESTORATION

It is widely recognized that past land management practices have degraded water quality and fish habitat in western Canada and the northwestern United States (Slaney et al. 1977a, b; Cederholm et al. 1980; Tripp and Poulin 1986; Hall et al. 1987; Hartman et al. 1987; Hartman and Scrivener 1990; Koski 1992; Murphy 1995). In most instances there were no mechanisms in place to ensure rehabilitation of degraded or threatened aquatic resources in forested watersheds in British Columbia. Although it is becoming more accepted that habitat protection measures, such as riparian buffer zones, are more cost-effective than habitat rehabilitation (Koski 1992), there is a large province-wide legacy of impacted hillslopes and streams in British Columbia. This necessitates a long-term initiative to rehabilitate impacted areas, where feasible, to environmental standards consistent with the new Forest Practices Code of British Columbia, and thereby accelerate natural recovery processes in forested watersheds. Furthermore, it was also evident that the efficacy of new forest practices regulations and the effectiveness of restoration of watershed areas impacted by practices of the past are co-dependent, and need to be implemented simultaneously. The effectiveness of these measures will also depend on practicing risk-averse, sustainable fisheries resource management by fish harvesters and fisheries management agencies.

The purpose of an introductory chapter on planning stream restoration, linked closely to habitat protection under the policy of **no-net-loss** of habitat, is to set the stage for several technical habitat rehabilitation chapters that follow. For ease of reference, the contents of this chapter are summarized as:

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SUSTAINABILITY: WATERSHED RESTORATION AND THE FOREST PRACTICES CODE

In the absence of simultaneous implementation of both a watershed restoration program (for "old logging") and advanced forest practices regulations (for "new logging"), there would be significant risks to the sustainability of the provincial fisheries resources, which can be summarized (from the section on impacts of past forest harvesting practices) as:

- an increasing incidence of landslides and debris flows to streams on the coast, and surface erosion and sediment transport to streams from expanding road systems in the interior;
- an increasing incidence of eroding stream banks, and sediment-infilled stream channels;
- a high frequency of culverts, many passable to adult fish, but blocking or impairing passage of juvenile fish into seasonal off-channel refugia (tributaries, groundwater channels and alcoves, side-channels, ponds, wetlands and lakes) from severe winter conditions;
- an increasing loss of riparian functions, resulting in a declining recruitment of large woody debris (LWD) to stream channels, and stream bank instability on floodplains as old-growth root-masses decay;
- continuing loss of large woody debris (LWD) in stream channels, causing a substantial loss of fish habitat until resupply of LWD over a duration of 100-200 years;
- declining trends in salmon carcass-derived marine nutrient and carbon influxes to most anadromous fish streams, resulting in oligotrophication, with depression of fish growth and size-dependent survival in freshwater and saltwater (from both land-use and overfishing impacts).

Greater than 40% of the Provincial Forest has been harvested under logging practices of the past, and most of the productive low-land streams have been logged to their stream banks. After several decades of research, case studies and audits of practices, it is now evident that many of the past practices resulted in impacts that would require decades to two centuries to recover. Some hillslope sites were also left at risk of failure with downstream consequences of debris torrents and flows. In the remaining Provincial Forest, resource values of streams, wetlands and riparian areas should be protected by new forest practice regulations (Forest Practices Code or FPC) that make use of knowledge gained over the past several decades on the processes leading to such impacts. Without the FPC, there are potential impacts from new logging on restored areas situated downstream, and also without restoration, the intended results of applications of the FPC may not be achieved, or may be lost. For example, maintenance of habitat resource values in a FPC-regulated reach of a valley can be impaired by debris torrents from gullies causing debris-sediment flows, in turn caused by failure to restore natural drainage patterns and restore road slopes on blocks logged in the past. Similarly, the new FPC may result in maintenance and protection of key spawning habitat for salmonids in an upper reach. In a lower reach after several decades of loss of LWD without recruitment, as well as a loss of bank stability and the cut-off of overwintering refugia, protection of the upper reach under the new regulations of the Code will have negligible benefits to salmonids dispersing downstream for rearing. Either restoration or legislation can be of limited effectiveness without coordinated implementation at a watershed scale. Clearly, the Forest Practices Code and Watershed Restoration Program are a **"package deal"**.

It may require at least a decade for the benefits of watershed restoration to be detectable in returns of resident or anadromous fish from rehabilitated stream channels and connected hillslopes. Stabilization of hillslope impacts reduces sediment-debris transport to streams, which increases fish survivals but results in only modest increases in habitat capacity from less infilling. Rehabilitation of degraded, lost or cut-off fish habitat in streams restores habitat capacity as well as improving survival rates. In combination, increases in **stock productivity** — by improving freshwater and marine survival rates, and **habitat capacity** — by restoring or offsetting losses in the quantity of habitat — will result in potentially much higher sustainable yields of fish (Fig. 1-1). However, to realize such benefits more rapidly, lower stock harvest rates may be required in the interim, as "risk-averse fisheries management practices".

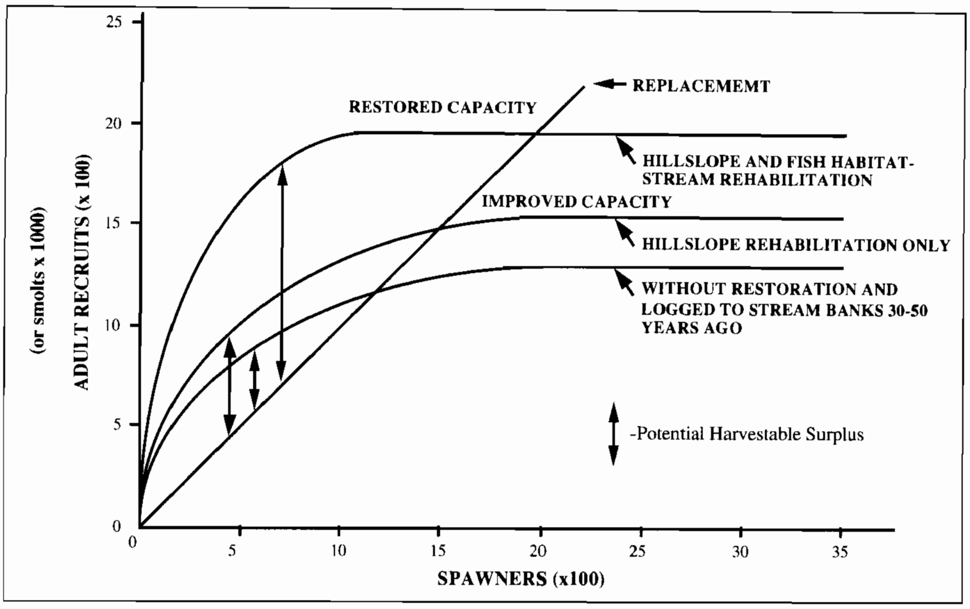

Figure 1-1. Theoretical effects of watershed restoration on the stock recruitment relationship of stream-rearing salmonids, as (1) hillslope restoration only, and (2) hillslope plus stream restoration. Note that both hillslope and stream-riparian restoration provide a greater increase in stock productivity and habitat capacity, resulting in much greater potential resource benefits.

GOALS OF B.C.'s WATERSHED RESTORATION PROGRAM (WRP)

The Watershed Restoration Program, a provincial initiative under the Forest Renewal Plan and funded through a crown corporation, **Forest Renewal BC**, was founded in April, 1994. It is a strategy to implement a program of rehabilitative and preventative measures, accelerating natural recovery processes, by:

- **restoring, protecting and maintaining fisheries, aquatic and forest resources adversely impacted by past logging practices, which would otherwise require several decades to recover naturally;**

- **providing community-based employment, training and stewardship opportunities throughout the province; and**
- **providing a mechanism to bridge historical forest harvesting practices and the new standards established by the Forest Practices Code (FPC), diversifying jobs in the forest sector.**

The provincial Ministry of Environment, Lands and Parks (MELP), and the Ministry of Forests (MOF) manage the stream and hillslope components, respectively. The federal Department of Fisheries and Oceans is also cooperatively involved in stream and off-channel projects. The Program is largely "proponent driven" by the forest industry, First Nations, conservation societies, community groups, and government agencies, typically in partnerships of stakeholders who have vested interests in rehabilitating resource values, targeting on small- to moderate-sized watersheds. Funding for the Forest Renewal Plan was made available by an increase in stumpage fees, in recognition that there was a compelling need for reinvestment in stewardship of resource values of our provincial forested watersheds, as well as in the stability of logging-dependent communities throughout the province.

To achieve substantial resource benefits, an integrated watershed approach is the fundamental principle of the Program, in recognition of the interconnections between physical and biological processes within impacted watersheds, where streams are either functioning at risk or have become non-functional. Projects are cooperatively developed and implemented by stakeholders and resource management agencies, using a sequence of condition assessments of watershed components, followed by prescriptions, restoration and monitoring (Johnston and Moore 1995; Slaney and Martin 1997).

HISTORICAL IMPACTS OF LOGGING ON AQUATIC RESOURCES

Logging activities potentially alter all the primary environmental components that affect the productive capability of fish habitat as well as the food chains upon which fish depend. Logging impacts have been difficult to document because of the large natural variability associated with natural stream systems and multiple activities affecting watersheds, including overfishing (Larkin 1975). Case studies, such as the Alsea Watershed study (Hall et al. 1987) and the Carnation Creek study (Hartman et al. 1987) have assisted in the understanding of the functioning of stream ecosystems. Shorter-term investigations including the Slim Creek study in the interior of B.C. (Slaney et al. 1977a, 1977b), the Clearwater River study on the Olympic Peninsula (Cederholm et al. 1980), comparisons of streamside logging practices in S.E. Alaska (Murphy et al. 1986) and the Fish-Forestry Interaction Program on the Queen Charlotte Islands (Tripp and Poulin 1986) have also added to our knowledge of how logging activities affect fish habitat. These and related hydrologic studies have made predictions of the effects of logging on fish production more reliable, albeit incomplete. Other examples, more striking, but less well documented, have also demonstrated that impacts can be severe; e.g., substantial losses (80-90%) of important stocks of summer-run steelhead (*Oncorhynchus mykiss*) and coho salmon (*O. kisutch*) at Deer Creek, in northwest Washington (Doyle et al. in press). Estuarine back-channels and eel grass areas have also been historically impacted by accumulations of organics associated with marine log sorting. Any benefits of logging, such as improved growth rates of juveniles in cool salmonid rearing streams (Slaney et al. 1977b), can be offset by cumulative impacts (Murphy et al. 1986; Cederholm et al. 1980).

There are several primary alterations that are evident as a result of forest harvesting to the stream bank, which was the common practice in much of B.C. until the introduction of the

Coastal Fisheries-Forestry Guidelines in 1988, superseded by the Forest Practices Code in 1995. There are changes in solar radiation, water temperature, forest canopy and stream bank vegetation, stream bank stability, suspended solids, fine woody debris, coarse woody debris, channel morphology, substrate sediments, streambed stability, nutrient supply, and stream flows. Some effects are transient or fluctuate (nutrients can increase then decrease), some recover in decades (stream temperature) and some require over a century (large woody debris from mature or old-growth windfalls) (Koski 1992). Negative changes are diverse and interactive, but there is little argument that the more restrictive logging practices of the Forest Practices Code are necessary to protect what is remaining in watersheds still dominated by old growth, as well as those watersheds that will be logged in the near future as second growth forests.

Landslides and increased peak flows that impact water quality, fish habitat and forest sites have become more evident, especially on steeper slopes in the coastal regions. "Torrenting" of debris-loaded gullies on the coastal regions have been well documented (Cederholm et. al 1980; Hogan 1986). Moderate rates (>25 %) of deforestation are known to increase peak stream flows, especially as a result of rain-on-snow events (Harr and Fredriksen 1979). These two processes cause an increase in sediment transport from hillslopes and stream banks, with bedload sediments moving through less stable channels of unconfined, and frequently logged, floodplains. The resultant widening of mainstem channels, infilling of coarser substrates, and blocking of side-channels, has caused declines in salmon and steelhead stocks, such as that documented at the San Juan River on southern Vancouver Island where 428 landslides were recorded in logged terrain by Northwest Hydraulic Consultants in 1994. Also, 495 landslides have been documented by the Ministry of Forests in the Gordon River watershed on southern Vancouver Island, which were mainly caused by overloading fill-slopes of logging roads. Similarly, failures of 20-year-old logging roads above a gully on Jones Creek in south coastal B.C. have eliminated a spawning channel utilized by pink (*O. gorbuscha*) and chum salmon (*O. keta*), and caused chronic sedimentation of fish habitat in the stream since 1993. Accordingly, both spawning and overwintering substrates are frequently degraded, and thereby the productivity of fish stocks declines, increasing the risk of overharvest of weakened stocks in mixed stock fisheries. Although the use of Coastal Fisheries-Forestry Guidelines since 1988 have improved protection of fish habitat, slope failures and debris flows from logged gullies persisted from past practices on steeper slopes (Tripp 1994).

Chronic surface erosion from logging roads can degrade water quality, resulting in impacts on both domestic water supplies and fish habitat. Suspended solids in some community water supplies increased as a result of road slope failures and surface erosion (e.g., Chapman and Mashiter Creeks in the Sechelt and Squamish Forest Districts). Also, studies in the central interior of the province have demonstrated that transport of fine sediments from logging roads and skid trails, located in terraced lacustrine soils, can impair water quality, fish spawning gravels, rearing areas and aquatic insect abundance (Slaney et al. 1977a, b). In May to July, mean suspended sediment concentrations were 37 $mg{\cdot}L^{-1}$ (peak, 257 $mg{\cdot}L^{-1}$) in upper Centennial Creek (logged), 75 $mg{\cdot}L^{-1}$ (peak, 467 $mg{\cdot}L^{-1}$) in Centennial Creek (logged with terraced lacustrine road settings) versus 14 $mg{\cdot}L^{-1}$ (peak, 60 $mg{\cdot}L^{-1}$) in the adjacent unlogged Donna Creek. Amounts of fine sediment deposition (clays, silts and fine sands < 0.3 mm diameter) in simulated spawning redds were a function of suspended sediment loading (or dose) from May to July (Slaney et al. 1977a). Revegetation of erodible road slopes by hydroseeding is necessary to retard sediment transport from the silty side-slopes of logging roads.

There is also recent evidence of a more subtle and insidious negative impact of past logging and overfishing practices because a lower abundance of spawner carcasses reduces the availability of nutrients that support the salmonid food chain (Schuldt and Hershey 1995). Coastal and many interior streams in British Columbia are oligotrophic, with dissolved inorganic phosphorus concentrations less than or near detection limits of 1 $\mu g \cdot L^{-1}$ (Slaney and Ward 1993). Recent studies of the nutrient and carbon movement in food chains of a small coho salmon stream have demonstrated that returning salmon spawners provide 30-40% of the nitrogen and carbon to juvenile salmonids (Bilby et al. 1996). Because survival of salmonids through freshets is strongly correlated with fish size reached by fall in streams (Scrivener and Brown 1993), or size at migration to a larger waterbody, the abundance of fish carcasses is potentially crucial to maintenance of fish populations that rear in streams (i.e., trout and char species, chinook salmon (*O. tshawytscha*) and coho salmon). Runs of adult fish may continue to decline as logging impacts increase, returning less nutrients and carbon to streams, which are already nutrient-carbon deficient. The problem is exacerbated when combined with overfishing of a (now) less productive stock (Larkin and Slaney 1996).

Past practices of logging of mature and old-growth trees to the stream bank of both small and large streams have probably had the greatest impact on the habitat of stream-rearing and resident fish. This is because of the reduction in availability of large woody debris (LWD) from mature conifer windfalls, but also results from reductions in stream bank stability within the floodplain of streams (Murphy 1995; Koski 1992). During the 1950's to 1970's many fisheries managers believed that introductions of woody debris in streams impaired fish production by creating impassable jams or scouring channels, and a previous section of the Canadian Fisheries Act promoted its removal from streams during the 1960's to 1970's. Clearance of log jams was widely practiced in the Pacific Northwest. However, more recently it has been clearly demonstrated that the loss of LWD in stream channels (versus small organic debris) results in a serious long-term decline in the complexity and diversity of aquatic ecosystems including fish habitat (Fig. 1-2; from Koski 1992).

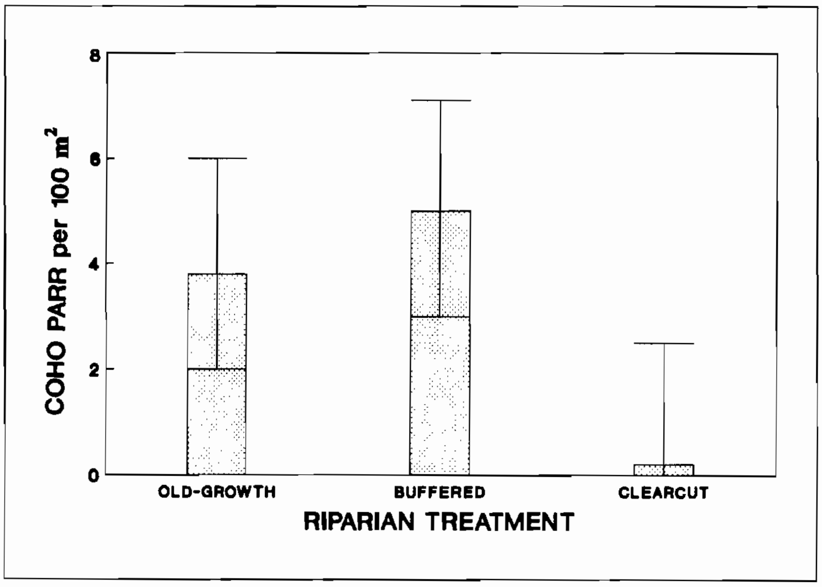

Figure 1-2. Relationship between coho salmon parr density in winter and different logging treatments of stream reaches. Coho parr density was much greater in old-growth reaches than in clear-cut reaches; bars are 95% confidence intervals (from Murphy et al. 1986 and Koski 1992).

Because almost half of the provincial forest has been logged, including the riparian zone of most of the salmonid streams at lower elevations, a serious LWD deficit continues to worsen. The effects of stream bank logging at Carnation Creek on the production of coho smolts has been initially moderated or offset by the remaining old-growth LWD in the mainstem and by the preservation of off-channel overwinter habitat (logging roads were excluded from the floodplain), and also by modestly elevated stream temperatures. Regardless, since logging (1976-81) both the average coho fry abundance in late summer and the average return of mature coho adults per smolt have declined, suggesting a significant decline in stock productivity, from a stock-recruitment perspective. Although there was no external control (unlogged) for the Carnation Creek case study, a gradual declining trend in coho smolt production from the mainstem can be predicted in the long term because only very limited mature large wood is recruitable from the logged riparian zone. Moreover, the abundance of chum salmon and steelhead trout have been depressed because of impacted spawning and overwintering habitat in the mainstem of Carnation Creek, respectively (Scrivener and Brown 1993).

Streamside logging to the banks seriously impacts overwintering habitat, reducing the abundance of juveniles that survive winter freshets (Fig. 1-3; from Koski 1992). A buffer strip or riparian management zone provides much of the future supplies of large woody debris by bank erosion and from mature tree windfalls, but the zone also provides deciduous leaf litter, and protects other overwintering areas as side-channels, alcoves, off-channel ponds, as well as access to small tributaries. Buffer strips of mixed vegetation types also moderate excessive increases in stream temperature, especially in southern latitudes and most lake-headed streams. Logging to the stream banks has left most low-land banks with deciduous canopies, some up to 50 years old, or with immature conifer forests at higher elevations. Deciduous trees provide little permanent large woody debris as windfalls, and also encourage beaver damming activity on small streams. Although summer habitat may be initially maintained by deciduous (alder) canopies, as the old-growth wood in the channel decays or shifts, the habitat becomes simple and monotypic, resulting in much fewer fish overwintering successfully to the smolt stage (Fig. 1-3; from Koski 1992). This impact is most severe for species that expend a year or more in streams, including steelhead trout, coho salmon, bull trout (*Salvelinus confluentus*), Dolly Varden (*S. malma*), rainbow trout, cutthroat trout (*O. clarki*), Arctic grayling (*Thymallus arcticus*) and some chinook salmon stocks.

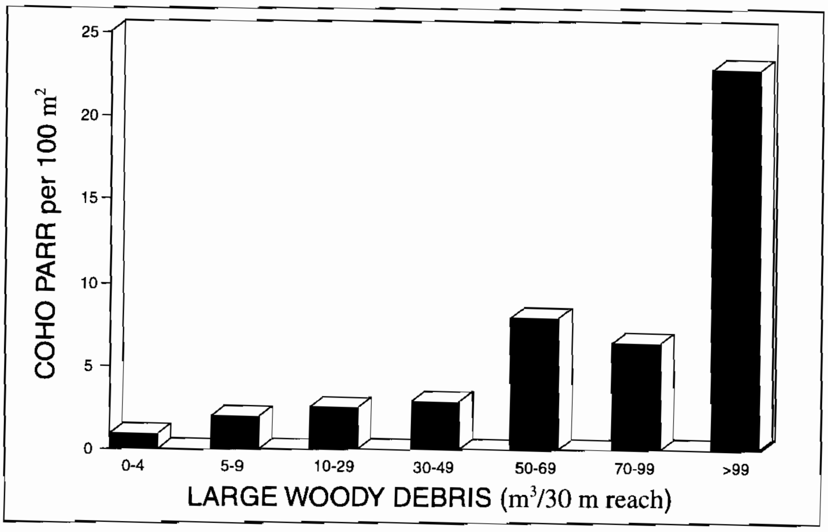

Figure 1-3. Relationship between volume of large woody debris (LWD) in streams and the density of coho parr in winter (from Koski 1992).

in deciding if a more detailed channel assessment is advised to assess risk of instream prescriptions (Barrett et al. 1995).

Restoration practitioners need to ensure that the assessment phase is thorough but not excessive, thereby adding a burden on cost effectiveness of the project (see economic screening criteria; Chapter 4). Clearly, if habitat impacts are obvious, overzealous recording of habitat or channel or riparian conditions and applications of diagnostics is neither cost-effective nor wise spending. The assessment phase is based on standards that are repeatable, but need to be efficiently conducted, to shift rapidly to the detailed prescriptive and restorative phase.

The Fish Habitat Assessment Procedures (Johnston and Slaney 1996) provide diagnostics for assessing limiting factors related to past logging impacts, and thus provide direction towards preliminary options and opportunities as restorative or mitigative measures. The Fish Habitat Rehabilitation Procedures (WRP Tech. Circ. 9) then provide a guide for prescriptions of rehabilitative measures including decision charts for the types of prescriptions suitable to various geomorphic settings (Figs. 8-2A, 8-2B). In the planning-prescriptive phases the use of biostandards (Chapter 3) and a basic benefit-cost analysis (Chapter 4) will rapidly indicate whether a project is cost effective, or its ranking compared to other project options in the watershed. **Regardless, the key to success will be use of natural instream and off-channel templates, plus advice or "mentorship" from "seasoned" practitioners of fish habitat rehabilitation.**

OPERATIONAL PRINCIPLES OF RESTORING STREAM ECOSYSTEMS

Sequencing Hillslope and Stream Rehabilitation

As a general principle, watersheds impacted by past practices need to be treated holistically to minimize risks to instream rehabilitative works. As an example, during the mid-1980's LWD was restored in 14 km of Fish Creek, a fifth order steelhead and coho stream situated in a steep valley in northern Oregon (Shively and Hickman 1996). As at Carnation Creek in B.C., fish abundance evaluations at Fish Creek were constrained by a lack of a paired external control (to adjust for a coincident decline in the coast-wide status of salmon stocks). Also, only minor hillslope stabilization was undertaken and a watershed analysis was not completed until 1994. After almost 10 years of stability, a 100-year flood event in February, 1996 resulted in severe landsliding (236) causing extensive debris torrenting (24 km), resulting in considerable channel changes and adjustments in Fish Creek. Substantial numbers of LWD attached to boulders were exported (53% of pool transects lost) as a result of debris-sediment flows, followed by a substantial depression in fish survival and smolt production in 1996 (Shively and Hickman 1996). Although durability of structures in this productive stream was maintained for a decade before the 100-year flood, in hindsight, a watershed analysis with identification of at-risk drainages and slopes could have been used to reduce hillslope failures and prevent much of the impacts to restored habitat.

Although instructive, such a graphic example does not lead to the conclusion that rehabilitative works cannot ever be undertaken until completion of hillslope rehabilitation, nor does it infer that instream restoration can be safely conducted after restoring natural hillslope drainage patterns and stabilizing slopes and roads. Historical logging of floodplains can destabilize streams for several decades as a result of loss of root stability and woody armouring of banks (Kellerhals and Miles 1996). Where channel instability is evident or at risk, "seasoned" judgement would direct stream rehabilitation prescriptions to low risk off-channel habitat mitigation, especially where fish stocks are at risk (e.g., Jones Creek). Similarly, there is little risk to improvement of fish access, or selective riparian treatments in advance of most hillslope rehabilitation.

Thus, operational principles in sequencing stream rehabilitation are:

- **as a general principle, undertake hillslope stabilization first (see "flow charts" in Johnston and Moore 1995), but not exclusively;**
- **examine the biological need for off-channel mitigation before or simultaneously with hillslope work to maintain or salvage fish stocks at risk from destabilized channels;**
- **as a priority, focus restoration on sub-watersheds that are less highly impacted to ensure more rapid recovery and watershed-level benefits to fish stocks. (A strategy endorsed in Aquatic Conservation Strategy for watershed restoration in the National Forests of Oregon and Washington);**
- **emulate nature by use of natural templates or analogues within undisturbed reaches of streams as the key to a successful stream restoration strategy.**

Emulating Natural Processes in Stream Rehabilitation

A hierarchical restoration strategy is consistent with the federal Habitat Management Policy, which is supported in principle (as a no-net loss provision) in the Ministry of Environment, Lands and Park's 5-year Fisheries Program Strategic Plan. This strategy is largely outlined in Fig. 3 of "Guidelines for Planning Watershed Restoration Projects" (Johnston and Moore 1995) (the terms restoration, rehabilitation and mitigation are defined in the glossary of this guide):

- **assess if the resource (channel and fish habitat) is impaired and to what extent;**
- **estimate the time to recovery without managed restorative actions;**
- **if more than a few years to recover naturally, assess if restoration is feasible;**
- **where restoration is not feasible examine rehabilitative options as a second priority;**
- **examine and document all restorative and rehabilitative options and opportunities to maintain and recover resource losses to habitat and its productivity;**
- **as a last recourse, search for and identify feasible mitigative options, first at the impact site, then elsewhere in the watershed, and if necessary in an adjacent watershed.**

Clearly, watershed restoration, or specifically fish habitat restoration, is directed at wild fish habitat. However, habitat impairment in highly destabilized streams can be severe, and even after replacement of instream and off-channel habitat, fish populations may be at or near depletion. Cautious and very limited short-term use of fish culture using stronger native stocks from the same watershed may accelerate recovery of depleted stocks from degraded sub-watersheds. Use of native early-fry to restock depleted rehabilitated habitats should be beneficial initially because selective juvenile mortality will result in near-wild progeny. Some fish culturists may take an active role in habitat rehabilitation projects, particularly during seasonal ebbs in hatchery activities. For example, hatchery salmon carcasses originating from within the same watershed have been transported to rehabilitated local streams and mitigative off-channel projects to accelerate the restoration of nutrients and carbon and to stimulate biological productivity (Larkin and Slaney 1996).

DESIGN TARGETS AND COSTS OF STREAM REHABILITATION PROJECTS

A design target to withstand a "one in 50-year" flood event has a reasonable probability of 10-20 years of functional durability, a time frame that has economic support in fish habitat improvement and restoration projects (Ward and Slaney 1979). Although a 50-year event is a useful design target, there are instances where lesser protection is more cost effective and should be considered. For example, dyking necessary to protect an off-channel restoration project from overwash from a 50-year flood event can make some projects extremely costly, with a negative economic appraisal using the screening criteria and method outlined in Chapter 4 in this guide, as well as confining the natural functioning of the floodplain. However, past experience in south coastal B.C. has demonstrated that most flood impacts are usually only temporary, and with minor maintenance costs, most off-channel projects can be re-operational within a few days of an extreme storm event (M. Foy, Department of Fisheries and Oceans, Vancouver, B.C., pers. comm.).

Costs of fish habitat restoration can increase substantially with the degree of engineering design detail. For example, at Porter Creek in southern Washington, large wood structures were installed in the stream channel by two approaches in two reaches: (1) detailed engineering design drawings with engineering control surveys at each site, and (2) on-site placements and attachments of local large wood by forest workers. The cost of the former was four times the cost per km, adjusted for differences in pieces of LWD placed (Table 1-1), or prohibitive from an economic perspective. Alternatively, most instream restoration treatments require only a set of **conceptual designs**, such as LWD configurations. An experienced individual undertaking prescriptions simply selects the best alternative design concept and specifications for the specific geomorphic site. Then the site is flagged in the field according to the selected concept code. This approach has been used very successfully in the Pacific Northwest and more recently in British Columbia in a Squamish River tributary (Shop Creek) and at the Keogh River near Port McNeill. Costs were considerably lower, or about $50,000-65,000 per km. Similarly at a 5th order stream in Oregon, LWD was increased to historical frequencies at a cost of about $50,000 per km over 14 km, using design concepts (D. Heller, USDA Forest Service, Portland, OR, pers. comm.). Note that a second pass is usually required the next year to refine and selectively add structures after a seasonal freshet.

The **design concept** approach is appropriate for LWD and lateral LWD complexes (with boulder ballasts), boulder cluster and simple weir prescriptions, minor fish access improvements, and groundwater-fed alcove channels. However, more conventional engineering design surveys and drawings are typically required by regulatory agencies for major stream bank armouring and dykes, major groundwater channel and pond excavations, and water intake structures, and larger-scale channel reconstructions or reconfigurations. The proximity of structures located downstream including bridges and structures on private property can influence requirements for engineering design drawings. Instream restoration of LWD using design concepts for lower gradient habitat within smaller 2nd and 3rd order coastal streams has had very low failure rates in Washington and Oregon (Heller et al. 1996).

REGULATORY APPROVAL PROCESS FOR B.C. STREAM RESTORATION PROJECTS

There are four main Acts and Legislation that apply to WRP fish habitat restoration and off-channel projects within the riparian management area. Project managers and supervisors must be well aware of requirements of these regulations, and the advance timing (minimum of 60 days) necessary to provide notifications, obtain approvals or permits. They are as follows:

- **Canadian Fisheries Act and Habitat Policy;**
- **B.C. Water Act - Section 7 Regulation (revised to Section 9);**
- **B.C. Forest Practices Code;**
- **Navigable Waters Act.**

In addition, if the stream is in a municipality, there are usually municipal bylaws that may restrict access to, alterations to, or work in and around a watercourse. Approvals may be required from the Municipal Engineering Department.

Table 1-1. Estimated costs (1996 $C) per km of instream and off-channel fish habitat rehabilitation projects, funded by various sources in the USA and BC. (More detailed costs by area and km are presented in the technique chapters; geometric mean cost = $ 70,000 per km).

Stream and Location	Year	Rehabilitation Prescription	Cost per km ($C)
Upper Keogh R., BC Ward and Slaney 1979	1977-80	Various boulder designs; clusters, small LWD bundles: 1 km.	30,000
Confederate Creek, MN from Koski 1992	1986	Log sills and step dams.	76,000
Fish Creek, OR D. Heller, pers. comm.	1986	Attached LWD: 14 km "Spider" and epoxy method.	50,000
Porter Creek, WA J. Cederholm pers. comm.	1991-92	Attached LWD: 0.5 km "Loggers Choice Section" (120 pieces per km).	18,000
Porter Creek, WA J. Cederholm pers. comm.	1992	Attached LWD: 0.5 km "Engineered Section" (444 pieces per km).	224,000
Shop Creek, BC D. Duff, pers. comm. (donated time: add 20 %)	1994-95	Log V-weirs, large LWD, boulder clusters, pond and 2 small groundwater side-channels.	60,000
Coquitlam R. Mainstem, BC M. Rosenau, pers. comm.	1993	Opposing wing deflectors pool and run reconstruction (2 structures = $20,000).	90,000
Or Creek, BC R. Finnigan, pers. comm.	1995	Intake pond, side channel and woody pond (phase 1).	75,000
Coquitlam R., BC R. Finnigan, pers. comm.	1994-95	Side channel and pond-channel complexes: 1.5 km.	80,000
Slesse Creek, BC R. Neuman, pers. comm.	1995-96	Groundwater-side-channel and pools-alcoves: 1 km (with dyke protection and repairs).	200,000
GEOMETRIC MEAN COST per km			**$70,000**

Canadian Fisheries Act and Habitat Policy

The Fisheries Act contains provisions to prevent:

- the harmful alteration (removal) of fish habitat (Section 35);
- the obstruction of fish passage (Sections 22 and 26);
- the deposition of deleterious substances to fish including sands, silts and clays; fuels and oils; and toxic preservatives.

The Act is administered by two agencies:

- Department of Fisheries and Oceans Canada (DFO),
  - from district offices by habitat management and enforcement (fisheries officer) staff,
  - focus on salmon habitat in freshwater & all marine fish;
- B.C. Ministry of Environment, Lands and Parks; Habitat Protection Section,
  - focus on all freshwater fish. (Key contacts are Fisheries and Habitat Protection staff.)

Both agencies subscribe to a "no net loss" of habitat policy (DFO handbook), which requires that habitat management and protection staff support restoration projects that result in a "net gain" of fish habitat.

Action Required: notification and request for approval from MELP and DFO is advised to ensure fisheries agencies support the rehabilitative habitat measures (including fertilization) of the WRP project and also approve, by letter, measures to minimize and mitigate temporary alterations. (Note that approval letters are needed at the work site to inform agency staff, as environmental monitors, of the conditions of approvals.)

B.C. Water Act: Section 7 Regulation (Section 9 in revised Water Act)

B.C. Water Management Branch licenses and regulates water under the Water Act. Section 7 Regulation (recently revised to Section 9) contains provisions to ensure that changes in and about a stream meet provincial standards for the protection of water quality, aquatic habitat and private property, such as:

- prevention of sedimentation and deposition of deleterious substances into streams;
- timing instream operations to least sensitive periods;
- maintaining minimum flows;
- salvage of fish if at risk; and
- ensuring private property is not adversely impacted by sedimentation, erosion or channel shifts related to works in and about a stream.

Action Required: Notification and approval in writing is required for all instream and off-channel projects.

Section 9 notification requirements vary by activity as:

(1) WRP projects requiring both notification and Section 9 approval:

- constructing side-channels and off-channel ponds;
- reconfiguring the channel morphology of a stream section;
- installing mainstem structures for restoring or rehabilitating fish habitat; and
- constructing fish screens, permanent counting weirs and intakes.

(2) WRP projects requiring notification but not Section 9 approval:

- restoration work to existing works; and
- routine channel and fish habitat maintenance.

(3) projects not requiring notification:

- emergency repair of dykes and erosion control structures;
- emergency clearing of an obstruction from bridges and culverts; and
- work carried out by a person authorized under the Forest Practices of British Columbia Act, Forest Act or Range Act. (Consult with district staff.)

Also, all WRP projects proposing to divert or store water normally require a water license, and a longer processing time. For a diversion, plan on 60 days, and for a storage dam, plan on six months to a year depending on the complexity of the WRP project. Minor diversion, where a portion of stream is diverted and returned within the same adjacent section of stream, may not require a water license because of non-consumptive water use, but is subject to a site-specific decision by the Water Management Branch who may refer the proposal to federal and provincial fisheries agencies in the region and district.

Notification procedures vary by region and therefore local contact of district staff or regional staff is advised. An applicant completes an application for an environmental review including the following information:

- name of applicant;
- location of works (or fertilization treatment, e.g., nutri-stones);
- specification of who is doing the work and supervising it;
- description of proposed works or treatment;
- site plan, map area, and engineering drawings where applicable (restoration of large woody debris typically requires only conceptual drawings);
- proposed timing of project activities from start to completion;
- any fish and wildlife restrictive covenants including mitigative measures to avoid impacts, thus complying with site conditions related to land ownership, water quality, habitat protection, other water users, public safety, and legal requirements.

This information is sent (by registered mail or equivalent delivery by courier) to both the regional/district habitat officer (or via a regional officer of the Water Management Branch, depending on regional protocols) of the B.C. Ministry of Environment, Lands and Parks, and the Department of Fisheries and Oceans. Currently, under subsection 40(2) of Section 7 of the Water Act, if no response is received within 45 days, the WRP-related works may proceed, but this does not apply to Department of Fisheries and Oceans where a response is made available at the local level. Responses typically specify restrictions and conditions that must be adhered to, including timing and mitigative measures to minimize impacts to fish and fish habitat such as isolating the work site or capture and temporary relocation in complex projects. Note that in the recently revised Water Act there is a 45-day time limit for an environmental review, but no time limit for a Section 9 approval. Water Management will assess if a Section 9 approval is required, based on the project description.

Forest Practices Code (FPC) and Related Land Approvals

WRP project supervisors typically undertake several activities, which require approval under the Forest Practices Code, and these are:

- cutting of or damage to trees;
- use of trees as large woody debris;
- access of equipment through the riparian area (there is an allowance in the FPC for access to undertake fish habitat projects);
- constructing a new side-channel in the riparian management area.

The project supervisor should contact the local WRP Habitat Officer for advice and assistance (or contact local forest tenure holders, and then obtain an approval from the MOF District Manager or designate) and habitat protection staff for the activities listed above.

Watershed restoration projects proposed on B.C. Crown lands require approval by the regulatory agency; provincial Ministry of Forests, or Ministry of Environment, Lands and Parks (Parks Branch) for B.C. parks, or Lands Branch (Crown lands not within the provincial forest). On federal lands, such as airports and military lands, the local federal agency must be contacted to obtain permits. On private lands, where a stream project has been approved, the provincial Land Titles Office can provide the name and location of the land owner, from whom a letter of covenant is required by Forest Renewal BC to ensure rehabilitative instream or off-channel works are protected against damage or removal. Municipal bylaws also may apply and approvals may be required from the Municipal Engineering Department.

Navigable Waters Act

The Navigable Water Protection Act of Canada regulates any activity in and around and over navigable waters (related to commerce, transportation and recreation) in the province. The Act is administered by the Canadian Coast Guard of the Department of Fisheries and Oceans Canada. Approvals are required for WRP projects that require works below the high water mark or above a navigable water, including dredging, placement of bank armouring, boulders or large woody debris at streams of a sufficient size for navigation by boats including canoes. Bridge and major culvert replacements require a referral. Provided the proposed restoration measures do not impede navigation, approval is routine, especially for structures associated with stream banks where natural woody structures are common features in streams utilized for navigation. A copy of a Section 7 Application for Environmental Review is an acceptable notification form, and a conditional approval can be processed efficiently.

A "Fast-Track Guide" to the Regulatory Referral Process

A referral review process has evolved historically to ensure stream-related projects provide a net gain in habitat, and that risks to other resources and landowners is minimized or negligible. A flow chart is included that provides a recommended procedure for WRP applicants or supervisors to streamline the approval process (Fig. 1-5). Note that involving either the Ministry of Environment, Lands and Parks, or the federal Department of Fisheries and Oceans as a resource restoration partner in a WRP project may facilitate the agency acting as the applicant, thus carrying the approvals and permits, and associated liabilities under conditions of due diligence by the project operators. A protocol is being developed in the near future to streamline the federal and provincial review process for WRP applications to ensure unnecessary delays and duplications are minimized, but the onus is on the applicant to allow sufficient "lead time" for review of the proposal (i.e., a minimum of 60 days). The key is contact of agency staff early in the process and on-site.

COUPLING FISH HABITAT REHABILITATION WITH RIPARIAN RESTORATION

It will require one to two centuries to re-establish large mature conifer windfalls from the riparian zone, and therefore, rehabilitation of fish habitat in mainstems and side-channels will be required in the short term to bridge the lengthy time-gap for natural resupply of large woody debris. Prior to the B.C. Coastal Fisheries-Forestry Guidelines of 1988, there was no provision for leaving strips of mature or old-growth trees to contribute to LWD, to maintain fish habitat and aquatic biodiversity, and to provide windfalls as coarse woody debris for wildlife biodiversity. Similarly, in the interior of the province, protective "leave strips" were only left on streams and lake shores with higher salmon and/or recreational fishery values. The abundance of fish in streams, (and probably lake shores) is closely related to habitat complexity provided by large woody debris (Figs. 1-2, 1-3) (Koski 1992; Scrivener and Brown 1993). Replanting of rapidly growing cuttings of deciduous species on stream banks will reduce bank erosion and supply carbon and nutrients to the stream, yet, short- and long-term benefits as structural elements providing fish habitat are usually not significant except in very small streams. Much of this type of work has been done in agricultural settings in the Pacific Northwest and Europe by community environmental groups, but it is not a sound alternative to stream ecosystem restoration where recovery of instream structures is also a primary objective.

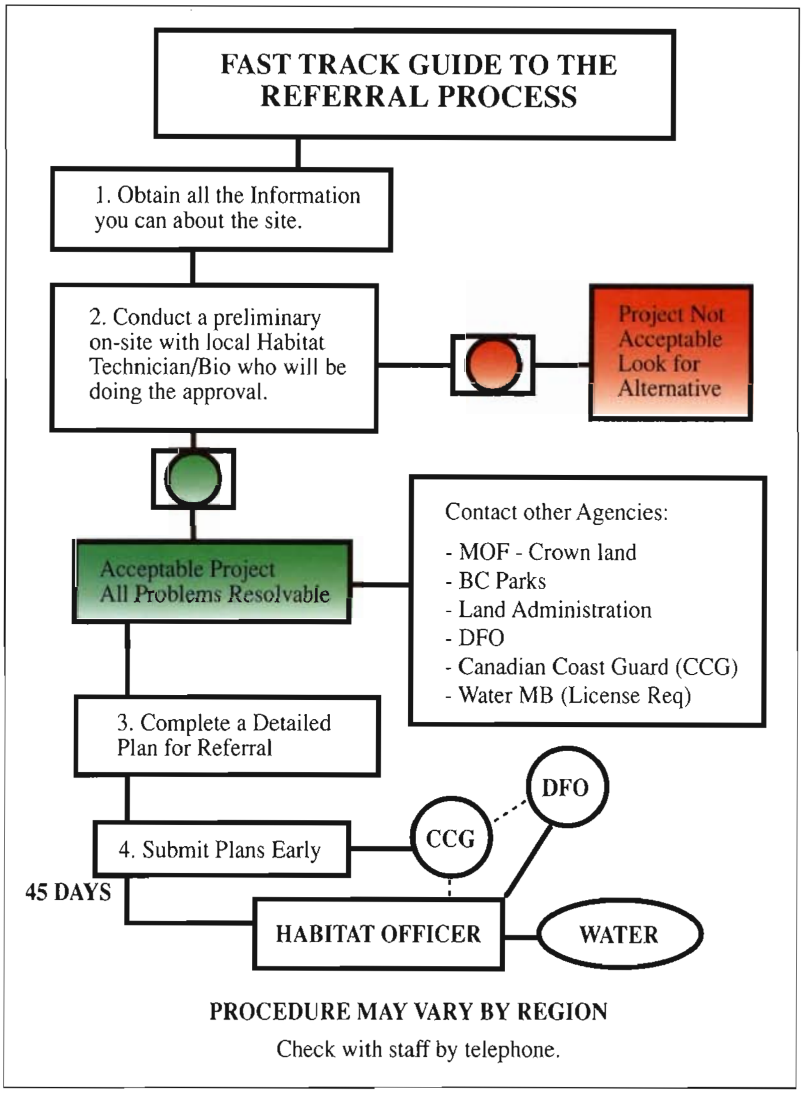

Figure 1-5. A "streamlined" procedure to facilitate rapid review and approval of stream restoration projects by regulatory agencies. Note that submission of an application or notification is required well in advance of the target date for implementation (minimum 60 days; preferably 90 days).

To achieve success in the long term, riparian restoration must be implemented aggressively, and where the riparian reserve zone is comprised solely of hardwood stands (a common condition), stewardship will be required to accelerate recovery of mature conifers for bank stability and the recruitment of large wood to the channel (WRP Technical Circular No. 6;

McLennan and Johnson 1996). Riparian selective spacing, replanting and tending will greatly accelerate ecologically balanced native mixes of deciduous and conifer trees (roughly 40:60%), as well as shrubs, to provide, in the long term, natural riparian functions. Deciduous stands of alder and poplar, in particular, are a challenge because after thinning and replanting of the spaces with advanced young conifers, several years of seasonal tending and protection from browsing is required, thus requiring a continuing stewardship role by licensees or conservation groups. The key aquatic function is to provide streamside sources of mature trees as large woody debris that provide both summer and winter fish habitat. Other key aquatic functions are large root masses from mature conifers and deciduous trees for bank stability, provision of deciduous leaf litter at the stream bank, nutrient supply from nitrogen-fixing vegetation (e.g., red alder, (*Alnus rubra*)), and in some settings, rapidly growing deciduous trees on the banks for temperature moderation or erosion control. Riparian assessment and restoration specialists are a fish habitat biologist and a silviculturist, but advice of other technical specialists including forest ecologists, wildlife biologists and geomorphologists should be sought where possible. Forest workers including fallers, spacers, planters, trained equipment operators and manual labourers undertake prescribed restorative works to achieve a "future desired condition". As a critical interface, the riparian zone may require special treatments because fish habitat, both in the mainstem by LWD and off-channel in overwintering areas, are within a sensitive fish and wildlife zone, which is well-recognized in the Forest Practices Code. Restoration of the riparian zone provides an opportunity to integrate forestry and fisheries, striving for both aquatic and terrestrial biodiversity (Barrett et al. 1995).

SUMMARY OF COMMON FISH HABITAT REHABILITATION TECHNIQUES

Restoring Fish Access as a Priority

Past logging access practices typically resulted in considerable road building on floodplains in fish bearing watersheds, which also frequently cut off fish producing side-channels and ponds as well as smaller water courses that are utilized as overwintering refuges. As a first priority in habitat assessments, all culverts and crossings are assessed for the passage of fish, and especially overwintering juveniles. Steep extended culverts are typically impassable to migrant fish, particularly juveniles, and these are replaced, or baffles installed to facilitate migration. Perched or elevated culverts are a common problem and fish passage is restored by backwatering, installing stable drop-structures, or by replacing the culvert. Similarly, historical side-channel refuges isolated by roads or debris flows are re-opened to fish access as overwintering refugia.

Restoration specialists, in their eagerness to restore habitat, can easily overlook numerous blockages to fish passage, especially culvert slopes and velocities that have historically eliminated access of juvenile salmonids to overwintering refuges from anchor ice and floods, including lakes, ponds and groundwater-fed wall-based channels and ponds.

Large Wood and Stream Bank Restoration

Fish habitat in stable streams can be restored by replacing pieces of LWD and "log jam" complexes in suitable geomorphic settings. In many streams, large woody debris (LWD) was removed from the channel by forestry-fisheries "practices of the day", and logs and rootwads were typically left on stream banks or nearby. The number of pieces of large wood in streams logged to the stream banks is typically reduced to <1 piece per channel width, whereas at least three pieces per channel width is common in unlogged streams (Johnston and Slaney 1995). (This equates to <100 (logged) and >300 (unlogged) pieces per km, in 2nd-3rd order streams.)

Stream rehabilitation crews can rewinch some of the more preserved logs and log-rootwads into the channel and secure them as outlined in Chapters 8 and 9 to provide prime fish habitats. Where required, excavators are utilized to build small streamside access trails or tote-roads and to install instream structures including log-rootwad-boulder complexes. Where access is difficult or there are environmental risks, helicopters are frequently used to sling in 500-700 kg boulders and logs. Costs can be similar to tote-road access (Ward and Slaney 1979), but can be several-fold greater with larger capacity helicopters for larger logs and rootwads. Large woody debris restoration in small- to medium-sized streams has been demonstrated by the U.S. Forest Service to withstand 35-75 year floods of 1990 in the Mt. Baker Snoqualmie National Forest (Doyle 1991; loss rate of structures, 12%).

Stream bank and channel stabilization is undertaken selectively as outlined in Chapter 6. Boulder and boulder-secured log armouring, brush matting, geotextiling, cut-tree staking, and planting of deciduous cuttings and rooted tree stock on upper stream banks are employed to reduce bank erosion and restore ecological riparian functions at the stream bank interface. Larger excavator and earth moving equipment is used to reroute and restore diverted channels, where logging-induced bedload aggradation has rerouted streams into riparian forest lands on historically logged floodplains. Stream bank and bar reconfiguration or stabilization of stream reaches, using boulder-secured LWD within unstable logged-over floodplains, is a geomorphic technique in its infancy, but holds promise because there are many templates in unlogged moderate-sized streams. Applications of these techniques on anything but a small scale requires the advisory and design input of a highly experienced fluvial geomorphologist and hydraulic engineer, respectively, as inferred from Chapter 2 on watershed geomorphology and fish habitat.

Salmonid smolt production is dependent on near-natural LWD structures, as was recently demonstrated by a six-year intensive study at Porter Creek near Olympia. Coho smolts in Porter Creek increased about four-fold by systematically securing large wood in the channel, but the benefits to salmonid abundance were not detectable until post-winter, as described in Chapter 8. Similarly, numbers of coho migrants at two streams in Oregon were increased 3 to 5-fold by restoration of large wood in the channel (Solazzi 1992 in Murphy 1995). "Mentorship" and on-site training of workers is necessary to assure that the most successful techniques are repeated with precision, and that less reliable techniques such as cross-stream structures (V-logs) are generally avoided unless the stream is small or very stable (Frissel and Nawa 1992; Ward and Slaney 1993b).

Restoration of fish habitat with LWD has been less successful in medium to larger streams, which have not been "storm proofed" or are naturally unstable (Doyle 1991; Ward and Slaney 1993b; Olson and Doyle 1996). Inspections of 400 LWD structures were conducted after record storm flows in 1996 in central coastal Washington (post >50-year events of mid-winter) in restored tributaries of the White River. Percentages of functional structures (in-place including 10% moved) were 80, 78 and 86% in West Fork White, Huckelbury and Greenwater Creeks, respectively. Failed structures (lost or buried) were mainly log deflectors and log cover secured within larger depositional channels, and frequently associated with stream bank erosion and road failures (Olson and Doyle 1996). Recovery of fish populations in larger streams has been attributed to combined hillslope and stream restoration. Large populations of summer-run steelhead and coho salmon have recovered from near extinction at Deer Creek, Washington, to about 40% of their historical abundance (Doyle et al. in press).

As described in Chapter 9, natural templates can also be used to design and install woody debris catchers and boulder-secured log jams and reefs in stable reaches of streams that are deficient in habitat complexity. Submerged stream reefs, constructed of log rafts weighted with cobbles and boulders, and analogous to the well-proven artificial marine reefs, are a bioengineering innovation being tested in the Program.

Channel Morphology Reconstruction Techniques

Simple instream boulder structures can be used to effectively rehabilitate channel morphology and especially fish habitat, where the availability of more natural LWD is limited. LWD structures are most effective in simple shallow pools and glides, and boulder structures are most effective in riffles as well as the head of runs. Boulder clusters of 3 to 7 boulders are one of the primary techniques as described in Chapter 10. Note that in terms of fish per boulder, single boulders are not nearly as effective as clusters or as a series of several boulders angled downstream. For example, juvenile and adult brown trout avoided single boulders in a large stream, but highly utilized horseshoe configurations of boulder clusters, as well as loose boulder wings and boulder-log bank covers (Shuler et al. 1994).

In some salmonid streams that are relatively stable, more technically complex instream structures are required to accelerate recovery of fish rearing, holding and spawning sites, especially where the natural pool-riffle sequence has been lost by channelization, or there is risk of dislodgement of simple LWD structures (i.e., in larger streams). Where steeper stream sections (> 2% gradient) have been channelized or simplified, complex pool-riffle sequences are re-established by use of steep low-profile boulder ramps that are keyed well into the stream banks, and installed at a "natural frequency" of six channel widths as described in Chapter 12. Natural meander patterns can also be restored, although channelization upstream of road crossings usually precludes this option. Pools and runs can also be re-established in lower gradients with opposing wing deflectors and weirs in uniform sections of streams, as described in Chapter 11. The key to biological effectiveness of both procedures is to ensure "backwatering" that creates shallow extended "flats" is minimized. Also, installation of attached or buried LWD, especially submerged rootwads, is typically needed to maintain and enhance scour pools and cover, while providing overwintering and escape refugia for juvenile fishes.

Nutrients and Carbon Replacement

Where runs of fish (including kokanee in inland streams) are depressed and streams are oligotrophic, nutrient and carbon inputs to stream ecosystems may be limited by the availability of spawner carcasses (Bilby et. al. 1996; Schuldt and Hershey 1995), or a condition referred to as "oligotrophication" (the opposite of eutrophication). Streams in British Columbia are typically highly infertile and the base of the food chain of fish is phosphorus- and, to a lesser extent, nitrogen-limited. In highly destabilized anadromous streams that retain some overwintering habitat, there may be no option other than attempting to increase smolt production by adding low-level nutrients, provided some structural elements remain. The overwinter survival of salmonids is positively correlated with the size juveniles attain by autumn, to the degree that a 1 cm increase in size of fall-fry may double their overwinter survival (Scrivener and Brown 1993). In destabilized oligotrophic streams with depressed returns of migrant fish, seasonal low-level stream fertilization can accelerate summer growth and overwinter survival of salmon and trout, as an inexpensive interim measure to accelerate recovery. At Grilse Creek and the unstable Salmon River on Vancouver Island, the mean weights of steelhead underyearlings and parr were increased 2 to 3-fold over a distance of 15 km by adding inexpensive low-level nutrients additions (Slaney and Ward 1993). As described in Chapter 13, once-annual applications of slow-release nutrients as compressed "nutri-stones" are being applied in several streams and off-channel habitats, which is beneficial to ecosystem recovery. Similarly, the addition of salmon carcasses from hatcheries in the same watershed will accelerate recovery of stream productivity, although there is evidence its effectiveness is contingent on the availability or restoration of LWD to collect and retain carcasses.

Off-channel Habitat Restoration and Mitigation

In streams where the recovery of channel stability will require decades, off-channel habitat restoration and mitigation projects are undertaken to create stable groundwater or intake side-channels and ponds. About 100 of these have been constructed and successfully maintained with minimal maintenance over the past 15 years, mainly by the Resource Restoration Division of the federal Department of Fisheries and Oceans, including 40 groundwater channels by 1990, which were designed for production of chum and coho salmon (Bonnell 1991). Because of the higher risks of structural failure in larger unstable streams, off-channel projects are one of the most common technical options employed by the Watershed Restoration Program. These channels are very productive because of their stability, groundwater sources of nitrogen and the contributions of salmon eggs and carcasses to phosphorus and nitrogen, and to energy flow as carbon. Restored side-channels can produce 1.6 adult chum salmon per m^2. High levels of coho smolt production have been documented (0.5 to 1.0 smolts per m^2 on average from complex deep ponds and boulder lined channels resulting in 0.07-0.09 adults per m^2). Juvenile coho and some trout migrate into channel-pond complexes to overwinter as described in Chapter 7, utilizing woody refuges in the channels. Deeper areas (>2 m) of the ponds provide wintering refuges for these and other rearing species. The productivity of oligotrophic channels with surface intakes can also be improved by annual applications of slow-release nutrients (nutri-stones), until provided naturally by species such as chum salmon and sockeye or kokanee spawners. Access of fish into productive beaver impoundments can also be accomplished by working with beavers to retain or improve ponds, but also impeding beaver access by the use of floating rafts of LWD at pond outlet streams.

ESTIMATING FISH HABITAT REHABILITATION BENEFITS

The Watershed Restoration Program will protect and improve aquatic habitats of wild fish that contribute to fresh and saltwater sport, commercial and aboriginal fisheries, which generate considerable benefits annually in the province. The Program could increase freshwater survivals of wild anadromous fish in impacted watersheds by at least two-fold by improving *stock productivity*. Survival of salmon and steelhead in freshwater are typically less than 10%. Hillslope and channel restoration that substantially reduce erosion could double freshwater survival of wild fish, strengthening the productivity of weak fish stocks. Similarly, projects that restore habitat complexity in streams or improve habitat productivity can readily increase salmon and steelhead *carrying capacity* or smolt output by at least two-fold on average, and thus, combined with gains in stock productivity, can at least double the numbers of adult fish (Keeley et al. 1996). Results of instream population estimates of juvenile steelhead and coho salmon (Ward and Slaney 1979), and enumerations of coho smolts in coastal Oregon and Washington (as described in Chapter 8) provide convincing support that 3 to 5-fold improvements are achievable in smaller stream systems with sparse LWD. Catchable-sized resident fish populations, supporting highly-valued sport fisheries in British Columbia, can be re-established as well.

Stocks of wild fish "at risk" should receive greater priority to strengthen their productivity. These stocks are typically vulnerable because of the "double-barrelled" impact of overharvest in commercial fisheries targeted on more productive salmon stocks, and habitat impacts that further reduce their survival rates. A cooperative, integrated approach with fisheries management agencies and commercial and sport fishing associations will be needed to achieve *risk-averse fisheries management* to assure that sustainable benefits are generated by focusing restoration on weaker stocks of fish within a drainage basin.

Greater biodiversity of fish and wildlife will result from more diverse and complex habitats in stream channels and riparian zones, which will be an added benefit of the Watershed Restoration Program. The riparian zone, in particular, a complex and sensitive fish and wildlife area of wetlands, ponds, side-channels, groundwaters, and backwaters, provides primary benefits as overwinter refugia for fish. As well, it is a critical corridor that more than 90% of wildlife species depend upon for at least one stage in their life history.

To ensure selection of the most beneficial watershed restoration projects on a regional basis, "biostandards" have been developed for estimating and predicting the benefits derived from a large range of fish habitat rehabilitation treatments. As described in Chapter 3, these provide a first level prediction of benefits that can be used to compare projects or in advance of more intensive evaluations. Comparing the economic benefits of projects is useful as a check to be sure that projects are justified as "well within the ball park." Comparisons permit the selection of projects with the highest economic "pay-offs", beyond regional rankings of them as within priority watersheds, providing community stability and employment benefits.

TRAINING AND EVALUATION STRATEGIES FOR RESTORATION

"Mentorship" at Demonstration Training Sites

Training and education is required to implement stream restoration soundly because of the need for technical and operational expertise and the environmental sensitivity of restoration of aquatic habitats. A critical shortage of experienced stream and riparian restoration specialists will be managed over the years by emphasis on technique-focused short courses and workshops that focus on field instruction and techniques demonstrations, plus by on-site mentorship by "seasoned practitioners". Vital to meeting the aquatic employment and stewardship goal, is the rapid development of demonstration training sites, which, with the addition of monitoring, are instructive models of stream and riparian restoration. Community-based demonstration training sites, integrated where feasible with hillslope sites, are expanded in scope and diversity over that of routine projects, then coupled with trails and signage to demonstrate the full range of more than ten techniques described in this procedural guide (e.g., Upper Squamish R. tributaries, Keogh R., Chilliwack R. (off-channel), with interior sites in progress in the West Kettle and Willow R. watersheds).

Evaluation and Monitoring of the Effectiveness of Fish Habitat Rehabilitation

Project evaluation is essential to improve our effectiveness as the program proceeds, and to demonstrate Program effectiveness or "wise spending" in the long term. Monitoring and evaluation are defined according to four categories of intensity and complexity: (1) "implementation monitoring" (contract monitoring; or determining if the work is done correctly according to specified standards); (2) "routine monitoring" (simple visual site inspections and counts); (3) "project effectiveness monitoring" (more intensive monitoring of a subset of projects selected on the basis of risk and/or innovations that potentially lead to adaptive management benefits); and (4) more complex controlled (paired) evaluations. Research can determine what techniques are most effective in which settings, and can be combined with project effectiveness monitoring, to capture innovations. The overall effectiveness of the Program is best accomplished by more intensive evaluation of a subset of replicated logged watersheds established in treated and untreated (control) pairs. Alternatively, comparisons to "biostandards", as described in Chapter 3, (for streams, side-channels and ponds) or "riparian silvicultural standards" (for the riparian reserve zone) should also be utilized as benchmarks or indicators of benefits where before-and-after controlled comparisons or replicated pairs are unavailable for effectiveness evaluations.

It is anticipated that the benefits of the Watershed Restoration Program to fish abundance, as one of the key indicators, will be substantial, provided experience in effectiveness monitoring is transferred rapidly through province-wide training initiatives delivered at demonstration sites in forestry-dependent communities. The challenge to the Program's administrators, planners, prescribers, and operational workers will be to efficiently achieve a "net gain" of productive habitats on a large enough scale to benefit succeeding generations of British Columbians.

Chapter 2

Watershed Geomorphology and Fish Habitat

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INTRODUCTION

The purpose of this chapter is to consider the physical watershed factors important to fluvial geomorphology and fish habitats. Channel characteristics typical of the different locations within a watershed, the common types of disturbances and their natural recovery times are considered. The particular channel type and its natural characteristics direct salmonid distribution and habitat utilization. We discuss these issues in general terms, along with the appropriate types of fish habitat restoration activities.

Many of the physical factors that control stream channel environments are a function of processes operating at the watershed scale. That is, the channel morphology at any point along the drainage network is strongly influenced by physical processes operating in upstream catchment areas, since stream channels transfer water, sediment and debris from headwater areas downstream along the drainage network to the stream mouth. The physical shape of each channel along the network results from the interaction of sediment and debris being transferred and stored through the drainage system. Therefore, rehabilitation of stream channels should be considered in a watershed context; complex interactions between upslope catchments and downstream channel networks exist and must be understood if successful channel restoration is to be accomplished.

The nature, severity and duration of stream channel disturbances are also partially dependent upon watershed considerations. Headwater streams are often more resilient to disturbance, and recover more quickly, than larger downstream channels. Headwater channels are commonly coupled to the hillslope so the fluvial environment is directly influenced by terrestrial processes. Conversely, streams located further downstream have relatively lower channel gradients, finer textured bed sediments and alluvial banks. These channels, although not coupled to the hillslope, are prone to fluvial disturbances resulting from relatively small storms; often the damage can persist for decades.

Salmonids have adapted to B.C. streams in direct relation to the physical attributes of the coastal and interior watersheds. For example, the Fraser River remains the greatest producer of salmonid fishes of any single large river in the world. As Northcote and Larkin (1966) summarized, causes lie in its geological, morphometric and hydrological features: salmonids require clean, cold rivers with abundant cover and food. Successful restoration of salmonid habitats therefore involves the understanding of not only the many biological factors (e.g., life history traits such as fecundity, growth, size, and age at maturity, and behaviours such as migration, feeding, and spawning) and interactions (e.g., competition and predation), but also an

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equally diverse and complex set of physical factors and interactions, which must be considered and accounted for during the operational phase of habitat restoration. The correct biological-physical mix is necessary, but difficult to realize, in restoration projects. The link between salmonid habitat and geomorphology is critical to effective rehabilitation, and appropriate; trout standing crop has been related to geomorphic variables as accurately as stream habitat variables (Lanka et al. 1987).

WATERSHED AND STREAM CHANNEL MORPHOLOGY

The general physical characteristics of a stream, including its channel shape and appearance, depend on many watershed factors. Those that govern channel conditions have been summarized by Church (1992):

- the flood regime characteristics of the stream,
- the amount, timing and nature of sediment delivered to the stream,
- the nature of the materials through which the stream flows, and
- the local geological history of the area.

Several secondary factors also govern channel appearance:

- local climate,
- the nature of riparian vegetation,
- human modification of the channel (direct effects), and
- land use (indirect effects).

These factors interact to produce a wide array of different channel types, each with varying bank, bed, bar and planform pattern characteristics (Fig. 2-1). The variety of possible channel types are a function of the dynamics of channel stability and sediment supply, and thus impact the quantity and quality of the salmonid spawning and rearing habitat (Fig. 2-1).

Although the specific characteristics of a stream depend on many factors, certain generalities are evident at the watershed level. Flood regime, sediment delivery and material types vary along the drainage network. In a typical watershed, channel morphology changes with distance from the drainage basin divide (Fig. 2-2). As distance increases, the amount of water, channel size and water force increases, while bed material sizes and overall channel gradient are reduced. As a result, streams range from those with steep gradient, step-pool morphology channels to those with low gradient, meandering pool-riffle systems. Pool-riffle morphologies will not occur in steep channels (where gradients exceed 4%) and pool-step morphologies will not be found in low gradient, large channels. Therefore, habitat restoration techniques must mimic the appropriate natural setting.

The salmonid community also changes with the channel morphology as a function of distance from the drainage basin divide (Fig. 2-2, and see Sullivan et al. 1987). The area of step-pools nearer the headwaters may be devoid of salmonids or have resident fish such as cutthroat or rainbow trout, or Dolly Varden, in small populations isolated by impassable sections, unless lake-headed or in a zone that has high stream discharge for part of the year. Higher flows may allow access for juvenile or adult migrants. More typically, the area of anadromous salmonid utilization begins in the cascade-pool section, where coho, steelhead, and cutthroat may spawn and rear. Chinook salmon and sockeye salmon may be present if flows are suitable for migration and spawning, or if a large, accessible headwater lake is present. Riffle-pool habitats, lower in the watershed and at gradients of <1 to 4% have fish communities that are dominated more by salmonids that spawn in large numbers, such as chinook, chum, and pink salmon. They also

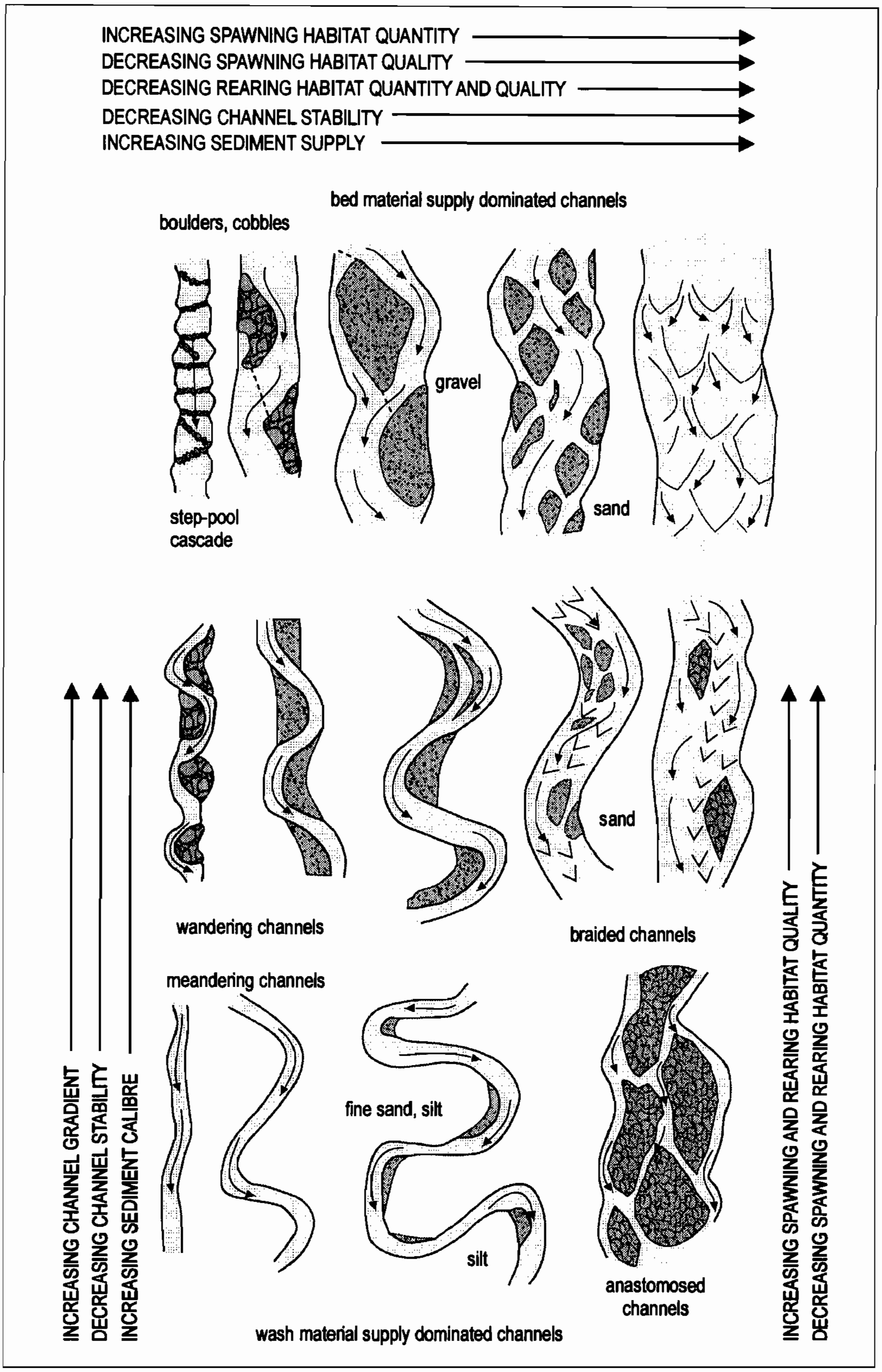


Figure 2-1. Conceptual pattern of morphological types of large channels (Church 1992, as modified from Mollard 1973 and Schumm 1977).

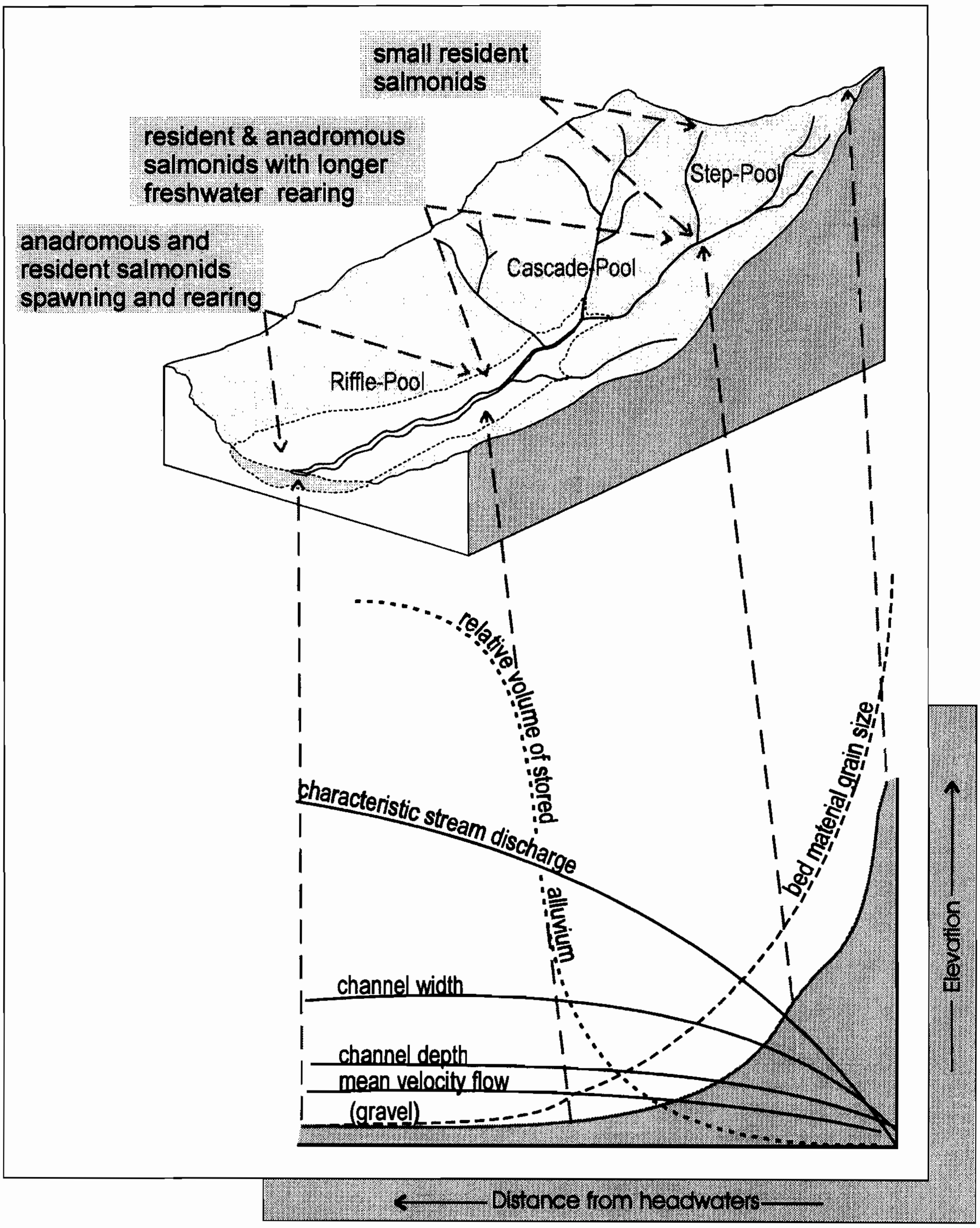


Figure 2-2. Schematic diagram of channel properties and fish use varying within a watershed (modified from Church 1992; Schumm 1977; and Anon. 1996a, b).

contain smaller fish, which require months to years of stream residence in the variety of main-stem and off-channel habitats characteristic of that area, such as juvenile steelhead and cutthroat trout, Dolly Varden, chinook and coho salmon. The transition in the salmonid community, towards increased diversity and production, from the headwaters to higher order medium-sized rivers, is connected to the change from an ecosystem dependent on terrestrial inputs to one that relies mainly on algal production and upstream leakage. Vannote et al. (1980) based this river continuum concept on the energy equilibrium theory of fluvial geomorphologists.

CHANNEL MORPHOLOGY TYPES

Stream morphology varies along the stream network, in accordance with changes in channel properties (as seen in Fig. 2-2), within all watersheds. Several of the properties that change can be used to determine the channel morphology. The relevant properties are bankfull width (W_b), bankfull depth (d_b), dominant bed sediment size (D) and channel gradient (S).

The Channel Assessment Procedure (CAP) is used operationally to classify channels into three absolute and seven relative sizes (Anon. 1996a and b). The absolute sizes (small, intermediate and large) are used commonly as general descriptors but are not as useful for morphological classification purposes. For example, a small channel is usually referred to as one having W_b less than 10 m. However, depending on S, the small channel can have a wide range of morphologies; these can vary between coarse-bedded step-pool and fine-textured, low gradient meandering morphologies. The seven relative sizes are used to describe channel morphology. There is a general relation between absolute and relative size but there are several exceptions that make the distinction between the two necessary. For instance, small channels usually have relative roughness (D/d) values greater than 1; intermediate channels usually have D/d values between 0.1 and 1.0 and large channels have D/d values of less than 0.1, commonly less than 0.01. Exceptions occur when, for example, as noted by Church (1992) "... a sand channel on a beach over which one can step with impunity would not be a 'small' channel". This channel has a small absolute size (W_b<0.5) but a large size morphology (D/d <0.1). Similarly, it is possible in very powerful systems (streams with steep gradients and large streamflow discharges) to have wide channels with a small size morphology such as boulder-controlled steps and pools.

The relation between specific channel attributes and morphological type have been considered in the literature (e.g., Grant et al. 1990; Church 1992; Schumm 1977; Mollard 1973). The relation between slope, sediment size, expressed as relative roughness, and channel width, expressed as relative width (D/W_b), is summarized in Anon. (1996b). The seven types of morphology used in CAP (Table 2-1) are based on: a) bed material size (dominant); b) channel attributes (depth, width and slope); c) bed roughness (whether individual clast or clast aggregate controlled); and d) LWD presence and function (prevalence and importance). The three basic morphologies are illustrated in Fig. 2-3a, b and c; additional details appear in Table 2-2.

Table 2-1. Channel types and associated characteristics.

Type	Morphology	Sub-Code	Bed material	LWD
RP	riffle-pool	**RPg-w**	gravel	functioning
RP	riffle-pool	**RPc-w**	cobble	functioning
CP	cascade-pool	**CPc-w**	cobble	present, minor function
CP	cascade-pool	**CPb**	boulder	absent
SP	step-pool	**SPb-w**	boulder	present, minimal function
SP	step-pool	**SPb**	boulder	absent
SP	step-pool	**SPr**	boulder-block	absent

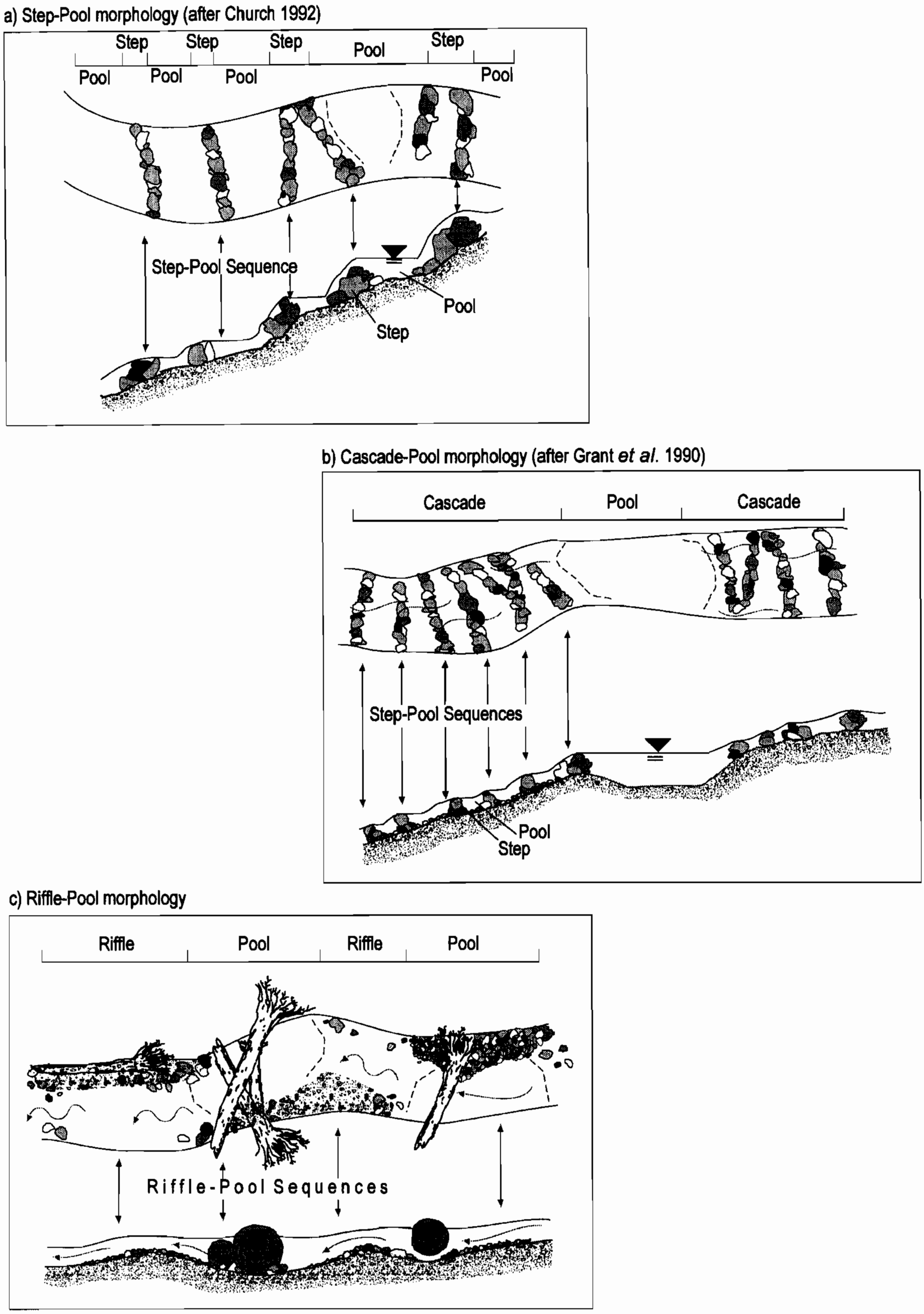


Figure 2-3. Channel morphologies of small- and intermediate-sized channels (Anon. 1996a, b).

Table 2-2. Typical channel and aquatic characteristics associated with the major morphological types.

General Characteristics	Small	Intermediate	Large
Channels:			
morphology	step-pool	cascade-pool, riffle-pool,	riffle-pool sand bed forms
bed sediment size	boulder, cobble	cobble, gravel	gravel, sand
Typically[a]			
bankfull width, W_b (m)	<10	10-30	>30
bedform spacing (W_b)[b]	1-4	3-5	5-7
channel gradient (%)	≥4	<4	<2
valley wall-channel relation	coupled	partially coupled	uncoupled
bank materials	boulder, bedrock	sand, gravel, cobble	alluvium
functional role of LWD	minor-moderate	major	minor
stream order (1:50,000)	1-2	3-5	>5
stream productivity	allochthonous	allochthonous and autochthonous	autochthonous
insect community	shredders, collectors	collectors, grazers	collectors
fish community	one or two species, small adults	three or four species, large adults	a diversity of species and life histories in a variety of habitats
principal fish use	residence, or juvenile rearing, restricted passage	incubation, juvenile rearing and spawning	spawning, off-channel rearing, passageway
dominant salmonid habitat	plunge pools with canopy cover, boulder clusters	abundant spawning gravel; LWD holds gravel, forms pools, and provides cover	large pools, off-channel creeks and ponds

Notes: [a]Typical channel characteristics are presented, exceptions occur.
[b]Bedform spacing refers to the average number of bankfull channel widths covering one bedform sequence.

The steepest and coarsest stream morphology is referred to here as block-Step-Pool (SPr). Such streams have very large boulders (with some single boulders larger than the channel is wide and deep) that form steps along the channel. The boulders do not move even during extreme flood events, but can be moved by debris flows. Pools are present between the boulder blocks, but because the boulders are not moved by normal fluvial processes, there is no regular step-pool spacing pattern. Boulder-Step-Pool (SPb) morphologies form in slightly lower gradient channels, compared to block-Step-Pool channels, and are formed by clusters of boulders that are as big as the channel is deep but only about one-third as wide as the channel ($D/d > 1$, W_b=3D). The boulders and cobbles cluster into lines that cross the channel and form stable steps with intervening pools.

Debris-boulder-Step-Pool (SPb-w) morphologies are similar to boulder-Step-Pool channels except that LWD is present, though it does not influence the trapping or scouring of bed and bank sediments to any significant extent. The stone lines (boulder steps) remain the primary stabilizing influence on the channel; the boulder and cobble clusters form most of the steps.

Such step-pool habitats are usually not accessible to fish, but small, isolated "dwarf" populations (e.g., cutthroat trout, bull trout) may be present, perhaps remnants from periods when the stream section may have been more accessible from the mouth, or through headwater capture. If present, adults may have spent several years rearing to maturity with low fecundity, along with relatively few cohorts in adjacent pools. Where block Step-Pools are accessible to anadromous salmonids, the pool area is likely highly important as a refuge for migrant adults and highly valued as a station for juveniles feeding on the abundant and large insects in the drift.

Boulder-Cascade-Pool (CPb) channels are typically steep ($6\%<S<10\%$) but are much wider than commonly expected for small-sized channels, often exceeding 10 m in width ($W_b>>10D$). The bed sediments are very large because of the steep gradients and high stream power. Debris-cobble-Cascade-Pool (CPc-w) morphologies are typically found in channels ranging in steepness from 4 to 6%, approximately. The steps in these channels are formed by clusters of cobbles, boulders and sometimes LWD. Although steps are predominant, steep-faced cascade riffles also form in these channels. Pools are large, often accounting for over two-thirds of the channel area, and have a wide range of shapes and sizes.

Salmonid spawning habitat may be limited to very few riffles with gravel substrate, but rearing habitat within the cascade-pool channel type can be plentiful. Conditions conducive to survival may be poor, however, given the high gradient and possible extremes of discharge, as well as the relatively close connection with hillslope processes, where debris slides and sedimentation may reduce productivity at times. Due to high gradient in this channel type, fish refuge in off-channel ponds and groundwater sloughs during catastrophic events may be limited. Here, and in other pool types, the nature of the seasonal discharge characteristics interacts with the channel morphology to determine suitability for salmonid spawning and rearing. Northcote (1992) presented typical hydrographs for major B.C. drainages, which indicated two general forms. Watersheds tend to be dominated by rainfall events (coastal rivers during the fall and winter; Cowichan, Keogh) or snow melt events (interior rivers; upper Fraser, Skeena). In coastal rivers, one might expect to find extensive rearing by juvenile salmonids in accessible cascade pools, riffles, and runs. However, during the spring and summer snow melt, interior rivers are likely to be uninhabitable in these sections, although it is likely that adult sockeye or steelhead may be passing through, where possible.

Intermediate-sized channels commonly consist of cobble-Riffle-Pool (RPc) and gravel Riffle-Pool (RPg) morphologies. Both types have relative roughness values of less than 0.1, but do include features that range up to $D/d=1$ (occasional large stones). Channel widths are usually between 10 m and 30 m. The fundamental morphological features are riffles (on relatively steep bed slope and composed of coarse sediment textures), pools (on flat, average bed slope and composed of finer-textured materials), and bars (accumulations of bed materials). Bars are more extensive in the RPg types. Intermediate channels include a diverse range of pool and riffle types (Sullivan 1986; Grant et al. 1990).

The riffle-pool channel morphology is likely responsible for the majority of salmonid spawning and rearing. Channel gradient, width, and bed materials, as well as stream power, discharge regime, and the associated riparian community combine to generate stream morphologies to which salmonids may gain access, find adequate water depths and velocities, rest or hide in sufficient cover, and feed on a variety of food sources that are derived from both terrestrial and aquatic sources. The four key ingredients of salmonid habitat — food, water, cover, and passageway — for all trout, salmon and char life stages may be provided by the intermediate size and nature of riffle-pool channels. Species presence or absence may be a function of their specific habitat requirements, post-glacial distribution, natural catastrophic events, and interactions with humans.

The morphology of large rivers with fine-textured beds and banks varies with discharge, but certain channel attributes, such as pattern, bar and island types and lateral stability, can be classified on aerial photographs (Kellerhals et al. 1976). Large river morphology classification and assessment for forestry operations is considered in Anon. (1996a).

Salmonid rearing in large channels is limited to stream margins and off-channel areas, due largely to velocity limitations in the mainstem. Species with short life stages in freshwater such as pink and chum salmon may use large rivers, and the mouths of rivers, for spawning in the fall, and may do so in large congregations over extensive riffle habitats. Other salmonids may appear seasonally, but the period is often critical to their overall survival (overwinter, or feeding on eggs or fry). They may hold for long periods in deep pools during spawning migrations (e.g., summer-run steelhead), or may rest briefly (a few weeks) in these areas, or off-channel, during feeding or smolt migrations.

STREAM CHANNEL RESPONSE TO DISTURBANCE

Forestry activities within a watershed directly and indirectly influence several of the factors listed above. For example, timber harvesting and road building can change flood characteristics, particularly increasing peak flows (Jones and Grant 1996), increase sediment delivery (Roberts and Church 1986; Schwab in press; Rood 1984), alter riparian vegetation (Anon. 1993) and disturb channel integrity (Tripp 1994). The importance of each factor differs regionally. For example, in coastal areas the most important influence is usually on coarse-textured sediment and debris production and delivery to the stream. Changes in flood flows and the generation of fine-textured sediments are often the main concerns in interior zones where snow accumulation and melt patterns and soil conditions can be strongly influenced by logging practices.

The expected generalized channel response to increased sediment supply and stream flow is summarized in Table 2-3. The importance of the channel type and its associated watershed position are again evident because these elements partially account for the type, extent and severity of both past and potential channel impacts. Theoretically, for example, channel width should increase with elevated sediment supply levels (Schumm 1977). However, width will not change if the channel is confined by bedrock hillslopes, as is common in headwater areas. Conversely, channels flowing through alluvial deposits can widen dramatically with increased sediment supply. Floodplains are particularly sensitive to channel change, particularly if the stream banks are disturbed (Kellerhals and Miles 1996). It is, therefore, inappropriate to expect increases in channel width, depth and gradient in step-pool or cascade-type channels, but these changes are expected in pool-riffle channels or those located farther down the drainage system. Changes to the salmonid community with stream channel disturbance are numerous and complex, and have been summarized in Chapter 1.

Table 2-3. Generalized response of erodible channels to changes in sediment supply and streamflow as a result of forestry activities (modified from Church 1992; Montgomery and Buffington 1993; and Anon. 1996b).

Stream size	Morphology	Channel Width	Channel Depth	Channel Gradient	Sediment Scour depth	Sediment Texture	Morphology Pool	Morphology Step	Morphology Bar	LWD Function
	Typically									
Small										
	Step-Pool	o	o	o	i	i	x	x	o	i
	Cascade	o	o	o	o	i	o	o	o	i
	Bedrock	o	o	o	o	o	o	o	o	o
Intermediate										
	Cascade	i	i	i	i	i	o	o	o	o
	Riffle-Pool	x	x	x	x	x	x	x	x	x
Large	Straight	x	x	x	x	x	x	x	x	i
	Sinuous	x	x	x	x	x	x	x	x	i
	Meandering	x	x	x	x	x	x	x	x	o

where:

o = unlikely change
i = possible change
x = likely change

Changes in streamflow, sediment and debris supply cause channels to undergo a sequence of morphological change; increases in supply generally lead to aggradation while decreases in supply commonly lead to channel degradation. Each aggradation and degradation cycle involves many changes in the channel, including altered bed, banks and LWD conditions. Although many channel responses are similar in each type of channel, there are also important differences between each type. The response of each channel type (RP, CP and SP) is shown schematically in Figure 2-4 and summarized in Table 2-4.

There are also cycles of degradation and aggradation within individual channel types. These cycles are initiated by various types of natural disturbances. Schwab (in press) has documented the historical rate of landslide events occurring over the last two hundred years on the Queen Charlotte Islands (Fig. 2-5). He shows that over 85% of all sediment and debris derived from hillslope areas and delivered to the stream channels by landslides occurred during four major storm events (1891, 1917, 1935 and 1978). These episodic landslide events initiate the channel changes that persisted for over half a century (Hogan et al. in press). For example, a typical deposition/erosion cycle is shown in Figure 2-6. This illustrates the progression of changes that occur along a channel reach as the result of the formation of an instream large debris jam. In this case, the channel disturbance was initiated by a landslide that delivered large volumes of sediment and debris to the channel, but similar channel processes occur in areas subject to large floods, wildfires and insect infestations, all of which generate abnormally large inputs of sediment and debris. Restoration attempts must recognize that infrequent, large magnitude natural disturbances will occur and that when they do, both restored and natural channels may be radically rearranged. However, since certain streams in a watershed are more susceptible to disturbance than others, restoration planning can target those channel types with the highest potential for long term survival.

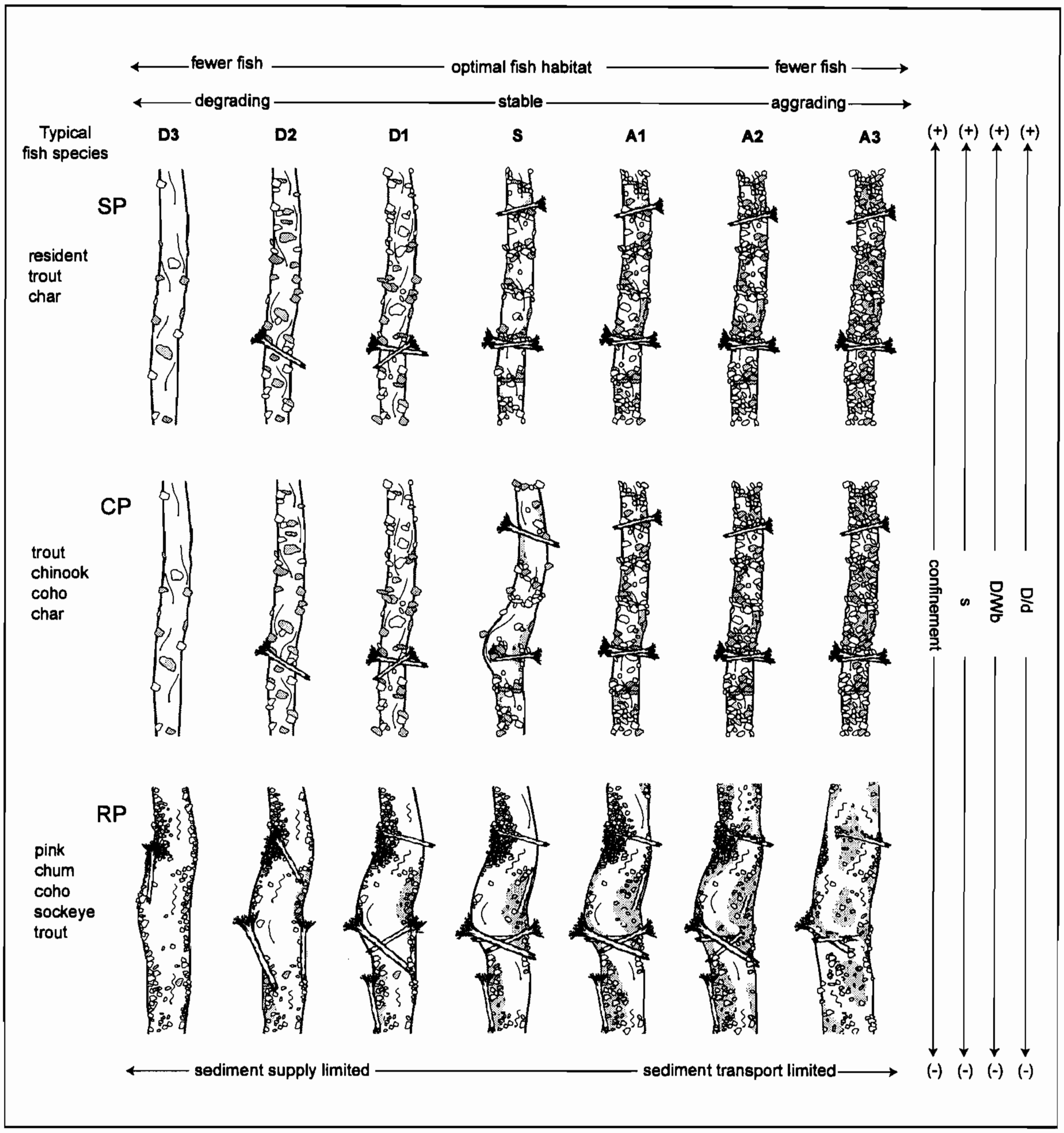


Figure 2-4. Channel morphology matrix showing levels of disturbance (modified from Anon. 1996b).

Table 2-4. General summary description of stable and disturbed channels. (Refer to Figures for typical field indicators of each.)

Channel type / *Attribute*	Degraded	Stable	Aggraded
Step-Pool			
Morphology	•No organized stone lines (due to erosional displacement)	•Intact stone lines -clast steps -intervening pools	•No organized stone lines (due to depositional infilling)
Bed sediment	•Largely bedrock	•Largely moss covered	•Not moss covered
Bank sediment	•Not eroded	•Boulder, bedrock, turf or roots	•Banks cleaned of moss but not eroded (due to bedrock)
LWD	•Not important	•Present, minimal function	•Not important
Cascade-Pool			
Morphology	•Stone line series disorganized (no recognizable pattern, due to erosional displacement)	•Series of repeating stone lines forming overall steep zone connecting lower gradient pools that are $\geq 1W_b$ in length	•Few distinct pools. Deeps infilled with sediment (both stones originally in lines and finer materials)
Bed sediment	•Large stones remaining (strewn over bed) not moss covered	•Moss covered stone steps	•All sediment along the bed devoid of moss or vegetative cover
Bank sediment	•Boulder and cobble	•Boulder and cobble	•Boulder and cobble, localized bank erosion
LWD	•LWD not present, if so it has no (minimal) functional role	•LWD present and functioning to limited extent (forms steps, traps/scours sediment and protects banks)	•LWD present but not functional (does not trap/scour sediment in any substantial way
Riffle-Pool			
Morphology	•Extensive riffles and bars	•Repeating riffle-bar-pool sequences	•Extensive riffles and runs
	•Small shallow pools (due to erosion of riffle crests)	•Diverse pool size, shape and depth	•Small, shallow pools (due to depositional infilling)
	•Channel consists of less than $^1/_4$ pool, approximately	•Channel consists of $^1/_2$-$^3/_4$ pool environment	•Channel consists of less than $^1/_4$ pool, approximately
	•One main channel (primarily single thread)	•One or two main channels	•Multiple channels on braided bed surface
	•Simple, uniform riffle and run shapes	•Diverse riffle shapes	•Simple, uniform riffle and run shapes (minimal depth variability)
	•Limited side channel bar	•Mainly diagonal and point bars	•Mainly mid-channel bars. Bars elevated to at or above elevation of surrounding bank tops. Steep downstream bar faces
Bed sediment	•Mainly cobbles and coarser textures	•Cobble and gravels	•Mainly gravel and finer textures
Bank sediment	•Mainly cobbles and gravel	•Mainly cobbles, gravel and sand.	•Mainly gravels, sand and cobbles.
	•Banks primarily sloping and/or overhanging	•Large proportion of undercut/overhanging banks	•Extensive bank erosion (commonly complete absence of undercut banks
LWD	•Limited, those present are small sized and oriented parallel to the banks	•Oriented across, and spans, the channel	• Absent or buried. LWD present are small sized and oriented parallel to the banks

Figure 2-5. Historical landslide events occurring in the Queen Charlotte Islands, 1810-1991 (Schwab, in press).

The debris jam, shown in Figure 2-6, interrupts sediment transport down the reach. This leads to the development of a large sediment wedge on the upstream side of the jam. In the vicinity of this aggradational wedge, the channel undergoes major changes. The banks erode in response to increased bar development, the channel changes from a single thread to multiple branches or braids, sediment textures are finer, pools are infilled and LWD is buried. In contrast, downstream of the LWD jam the channel is scoured away because sediment removed during floods cannot be replenished from upstream due to the jam forming a barrier to sediment transport. In this degradational zone the bed erodes, thereby removing LWD pieces, causing coarser sediment textures, loss of pool areas and more extensive riffles and runs. Over time the channel returns to predisturbance conditions as the jam deteriorates and sediment and debris previously stored upstream are released and transported downstream. The morphological adjustments to the breakdown of the jam are shown in Figure 2-6.

The influence of individual pieces of LWD is indicated in Figure 2-4. LWD pieces and accumulations provide critical structural channel elements in certain, but not all, forested watershed channels. The size and power of a stream exerts an important influence on the functional role of LWD (Anon. 1996b). While LWD controls the morphology of many intermediate-sized streams, it is often less important in both small and large channels. In small channels the bed-stabilizing elements are commonly boulders and clusters of cobbles. In large streams, LWD tends to control floodplain construction, such as development of side channels, more than the shape of the contemporary mainstem channel. Although LWD is normally critical to the morphology of intermediate-sized streams, in steep gradient channels its importance is reduced because excess stream power transports LWD downstream to lower gradient reaches.

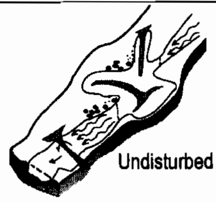
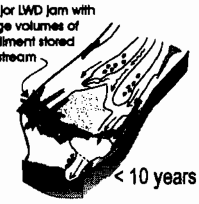
DOWNSTREAM: Channel Characteristics	DOWNSTREAM: Effects on fish habitat	Log Jam Evolution: Time since disturbance	UPSTREAM: Effects on fish habitat	UPSTREAM: Channel Characteristics
•same as upstream	•productivity, capacity for salmonid spawning and rearing in most stable condition, diversity of pool and riffle types meet habitat requirements at life stages, several species.	 Undisturbed	•same as downstream	•diverse morphology: high width, depth and sediment texture variability,pool length = riffle length, diagonal riffles,lateral scour pools •LWD primarily diagonal to streamflow, many small debris steps, infequent larger debris accumulations (jams),abundant undercut banks, LWD functions at all flow levels
•single straight channel •coarse textured bed •riffles, (slip-face & cascade), few pools •LWD parallel to channel •mainly over-hung banks rather than undercut •few LWD steps (ie. few small sediment storage sites associated with LWD)	•quantity of salmonid spawning sites reduced, or non-existent on bedrock •poor survival in redds, scour of limited gravel •access for adults & juveniles difficult, or lost at low flows •cover in pools in jam reduced and less stable elsewhere	Major LWD jam with large volumes of sediment stored upstream  < 10 years	•more spawning area, but lower survival of eggs and fry •rearing habitat reduced for pool dwelling species (ie. coho) •riffle habitat reduced for species in boulder and LWD cover (ie. chinook fry, steelhead parr) •dewatered sites & intergravel flow limit fish usability •increase in off-channel over-winter sites, but unstable, seasonally accessible and possible isolation at low flow •migration barriers or increased predation during adult, smolt & fry migrations in shallow habitats that lack cover	•braided channel •minimal undercut banks •fine texture surface layer of bed •riffle-glides, few pools (assoc. LWD) •few LWD steps •LWD jams, diagonal or perpendicular to channel •individual LWD pieces parallel to channel •major LWD jam with larger volumes of sediment stored upstream
•few channels, increased sinuosity due to debris and stone lines •bar development mainly mid channel few diagonal •bed sediment finer as sediment moves down over jam •pools associated with debris •channel usually straight riffle between lateral scour pools pieces (LWD parallel and wads)	•increasing productive spawning and rearing habitat, in larger number but smaller size of riffles and pools •unstable cover, mobile LWD, but improved rearing sites in small pools •increased bedload movement, depth of scour decreases survival for eggs & fry •access may remain difficult •deep pool habitat with cover reduced for older age classes of rearing species, spawning adults, & over-winter juveniles	 10 - 20 years	•towards more useable sites with cover for salmonid rearing •higher survival in redds as fines removed, flows through gravel improve •fewer or cut-off side channels, thus less over-wintering sites which are more stable	•reduced number of main channels, increased sinuosity due to debris •fine sediment removal leading to coarser bed •pools associated with debris (LWD parallel and wads) •channel gradient steeper overall
•one or two main channels •bed sediment finer •pools more extensive •riffles less extensive •channel gradient less steep overall	•same as upstream	 20 - 30 years	• habitat improves for salmonid spawning and rearing •habitat becoming more stable •multiple-channels decrease the magnitude of individual spawning and earing sites, but there are more of them	•one or two main channels •bed sediment coarser •pools more extensive •riffles less extensive •channel gradient steeper overall
•downcutting continues •stable diagonal riffles •pools and riffles extent approximately square •pool type more diverse (plunge, lateral scour, dammed, back water, etc (see Bisson 1982)	•same as upstream	 30 - 50 years	•habitats are becoming more accessible,more productive, and useable habitat for spawning and rearing is diversified and increasingly stable	•same as downstream
•previously buried debris uncovered and begins to function (ie.effectively traps sediment and produces scour holes and pools) leading to more diverse channel conditions	•same as upstream	 > 50 years ago	•recovery to nearly undistrubed condition assuming there is an adequate supply of stable LWD	•side channels •complex channel •same as "never" above

Figure 2-6. An example of a typical cycle of degradation and aggradation (Hogan et al., in press) and effects on fish habitat.

The importance of LWD in large and small streams to provision of salmonid habitat cannot be overemphasized, and is reflected in the frequent reference to LWD in this technical circular on stream rehabilitation, and elsewhere (reviewed in Ward and Slaney 1993a, see also Fausch et al. 1988). In large streams, salmonids are distributed near stream banks, where LWD can play a key role in the creation of suitable depth and velocity, as well as cover, for many species and life stages (e.g., chinook fry and smolts, rainbow trout in the Nechako River, Slaney et al. 1993; cutthroat trout in the St. Mary's River, Slaney and Martin 1987).

The time for recovery of disturbed channels also depends on watershed conditions. Steeper channels that have a step-pool morphology are relatively resilient to flood disturbance; large storms, with recurrence intervals exceeding 20 years, are required to alter the channel features (Church 1992). The step-pool channels can be completely altered by debris flows that can occur on a more frequent basis. Recovery of these channel types varies on the type of disturbance. If the channel is scoured then recovery is slow (10-30 years), but if it is aggraded then recovery is rapid (<10 years).

Riffle-pool morphology channels are commonly disturbed by intermediate-sized storms (recurrence intervals between 2 and 20 years) and recovery to predisturbance conditions occurs in time spans ranging from 35-50 years (Fig. 2-6). There has been no documentation of the recovery times for cascade-pool morphology channels, but the times are probably in between those required for recovery of step-pool and the riffle-pool channels.

The time of recovery of salmonid populations from major disturbance events may also require decades, and likewise increases from the headwater to the mouth. Disturbances in headwater areas may be more frequent, but less severe (clear water and clean habitat soon after), and recovery follows quickly if fish colonization is permitted. Riffle-pool channels are affected for longer periods. The differing strength of odd-and-even-year pink salmon runs may reflect past disturbances during fall spawning or winter egg incubation of one or the other of the runs, and this difference can require several generations and recruitment cycles to rebuild. Furthermore, the difference in run strength can be further maintained by subsequent events, which may continue to suppress recovery. The threatened and endangered status of some salmonid populations in British Columbia has been linked to habitat condition (Slaney et al. 1996). And the increased frequency and impact of disturbance events in the many small headwater coho streams, for example, may well explain the poor status of many coho stocks (a situation that can be made worse by overharvest in commercial and recreational fisheries and declining oceanic conditions for salmonids). Larger climatic shifts, which can increase the magnitude and frequency of channel disturbances in logged areas, may induce a major reduction, or even elimination, of a juvenile salmonid year class (Ward and Slaney 1993b), or complete blockage of the channel to access by salmonids. In many instances, disturbance events occurring in step-pool or cascade-pool areas are propagated downstream through the watershed, during subsequent storm events, such that changes in channel morphology and large woody debris impact salmonid spawning and rearing habitat throughout the drainage network (see Chapter 1).

STREAM CHANNEL RESTORATION

Restoring stream channels to a predisturbed state is a daunting challenge—one that involves an extensive procedure involving many important steps. To restore the physical features of a channel, it is first necessary to determine the level of forestry-related channel disturbance. It is then necessary to determine what the channel condition was before it was disturbed by forestry activities so that restoration activities can be designed to return it to the predisturbance state. In the absence of historical information or robust theoretical predictions, it must be assumed that the original, or undisturbed, channel state would have been the "typical" morphology for the particular stream size and type. Restoration should aim to return the "aggrading" and "degrading" conditions (Table 2-4 and Fig. 2-4) to the stable condition (Table 2-5). Estimation of the predisturbance channel state is often a problem because of the large natural variability inherent in forested streams. These channels experience episodes of natural disturbance and undergo cyclic periods of aggradation and degradation; the cycles are associated mainly with sediment supply and transport limitations interacting with LWD jams, and the morphology changes as a consequence. As a result, distinguishing between natural and forest management related factors can often be difficult. Furthermore, the time spans over which channel changes occur are sufficiently long that evaluation of restoration works is limited; it is common for evaluations to be conducted within a decade of completion of the works, but the works' proper function may not be achieved for several decades. Because of all of these considerations, stream channel restoration must be approached in a watershed context.

The watershed provides a framework within which much of the natural morphological variability can be taken into account. Several guiding watershed "rules-of-thumb" can be followed when planning fish habitat restoration works:

- determine the cause of the documented channel disturbance and ensure that it has been rehabilitated before the habitat restoration work is implemented (e.g., if bed aggradation is the concern then the cause of elevated sediment supply levels, perhaps a landslide, must be rectified);
- ensure that upstream watershed conditions that influence downstream channel morphology and the longevity of completed habitat restoration works (e.g., sediment and debris production and delivery mechanisms) are evaluated (see the CCPA, Hogan et. al. 1997);
- do not consider using LWD placements in stream types where LWD does not normally have a structural function (e.g., in steeper step-pool morphologies);
- do not consider placing large boulders in stream types where boulders do not normally have a structural function (e.g., in riffle-pool morphologies);
- do not consider using bank stabilization techniques in stream types where non-erodible banks are prevalent (e.g., in steeper cascade-pool and step-pool morphologies);
- do not consider constructing back-channels in stream types where lateral channel developments are not normal (e.g., in steeper cascade-pool and step-pool morphologies);
- in areas with floodplains that are normally characterized by abundant back and side channels (e.g., in riffle-pool morphologies), ensure that back and side channels are, in fact, limited before proceeding to develop new ones;
- even in channel types with naturally high volumes of LWD, exercise caution in the steeper lengths of channel (e.g., riffle sections) because LWD placed in these areas are more unstable than those placed in the lower gradient lengths;
- be very careful in floodplain areas with naturally active channels (e.g., broad valley-flats with riffle-pool morphologies) because the normal high rate of lateral movement will tend to undermine the longevity of instream works.

Consideration of these rules of thumb will help ensure that watershed conditions are considered and that natural conditions are recreated along rehabilitated streams.

Table 2-5. General summary of restoration objectives and actions by stream channel type (from Hogan et al. 1997). Numbers in brackets [ ] refer to chapters in this manual.

Channel type *Attribute*	Degraded	Stable	Aggraded
	Action	***Objective***	***Action***
Step-Pool			
Morphology	•Reconstruct stone lines using boulder clusters [10] Enhance sediment trapping at flow divergence sites upstream of step [10]	•Intact stone lines -clast steps -intervening pools	•Reconstruct stone lines using boulder clusters [10] Enhance sediment scouring at flow convergence sites downstream of step [10]
Bed sediment	•Increase sediment trapping with stone lines	•Largely moss covered	•Increase sediment scouring with stone lines
Bank sediment	•Not eroded	•Boulder, bedrock, turf or roots	•Banks cleaned of moss but not eroded (due to bedrock)
LWD	•Not important	•Present, minimal function	•Not important
Cascade-Pool			
Morphology	•Construct diagonally oriented stone lines using cobble clusters, LWD and/or boulders [10, 8, 11]	•Series of repeating stone lines forming overall steep zone connecting lower gradient pools that are $\geq 1W_b$ in length	•Enhance flushing of fine textured sediment by re-establishing stone lines. Promote flow convergence by placement of LWD or cobble clusters or boulders [10, 8, 11]
Bed sediment	•Increase sediment textural variability by re-establishing stable stone lines (interstitial filling) [10, 8, 11]	•Moss covered stone steps	•Rearrange stone lines for stability •Revegetate all elevated bar tops [6, RAPP (McLennan and Johnson 1996)]
Bank sediment	•Stabilize boulders and cobbles (intact steps) using cobble clusters, boulders or wood [10, 8, 11]	•Boulder and cobble	•Stabilize localized bank erosion sites with boulders [10]
LWD	•Place LWD to supplement clastic steps. Use LWD to enhance key-stones (main stone that traps other large stones ultimately forming the structural step) [10, 8, 11]	•LWD present and functioning to limited extent (forms steps, traps/scours sediment and protects banks)	•Place LWD to enhance trapping and scouring of sediment by planning flow convergence and divergence patterns
Riffle-Pool			
Morphology	•Promote pool development (e.g., LWD placement) •Increase pool size, shape, and depth diversity [8] •Reconnect or build off-channel habitats [7]	•Repeating riffle-bar-pool sequences •Diverse pool size, shape and depth •Channel consists of $^1/_2$-$^3/_4$ pool environment	• Promote pool development (e.g., LWD placement) • Increase pool size, shape, and depth diversity [8] • Build and enhance off-channel pond habitats [7]

Channel type *Attribute*	Degraded	Stable	Aggraded
	Action	***Objective***	***Action***
Riffle-Pool			
Morphology	•Interrupt long runs[8, 10, 12]	•One or two main channels	•Promote two main channel threads, cut off other branches to become flood channels [11]
	•Increase riffle variability [8]	•Diverse riffle shapes	•Increase depth variability [8, 11, 12]
	•Place LWD and cobble/boulder clusters to increase sediment storage along channel margins [8, 10]	•Mainly diagonal and point bars	•Scalp (remove) elevated, mid-channel bars.
Bed sediment	•Increase textural variability by LWD storage [8] and cobble/boulder clusters [10]	•Cobble and gravels	•Promote local downcutting to increase fluvial sorting of sediment. Revegetate elevated bar tops.
Bank sediment	•Revegetate banks to enhance over-bank sediment trapping [RAPP]	•Mainly cobbles, gravel and sand	• Revegetate banks to enhance over-bank sediment trapping [RAPP]
	•Place LWD to re-establish bank location and shape	•Large proportion of undercut/overhanging banks	• Revegetate banks to enhance bank stability [RAPP]
LWD	•LWD piece and jam placement [8, 9]	•Oriented across, and spans, the channel	•Excavate predisturbance LWD (exhume LWD). LWD piece and jam placement [8, 9]

Chapter 3

Salmonid Biostandards for Estimating Production Benefits of Fish Habitat Rehabilitation Techniques

C. Wendell Koning[1], Ernest R. Keeley[2]

INTRODUCTION

One of the main objectives of watershed restoration is to restore fish habitat (Johnston and Moore 1995; Slaney and Martin 1997). Depending on which habitat characteristics limit stream fish abundance, a variety of techniques can improve important habitat features. The addition of large woody debris (LWD), the re-establishment and deepening of pools, the addition of nutrients, and stream bank stabilization are generally thought to stabilize or increase salmonid populations in streams (Murphy 1995). A fish habitat assessment is carried out to determine the limiting factors. After the fish habitat assessment has been conducted, and as part of the stream restoration planning activities, "biostandards" (i.e., estimates of abundance or output) can be used to predict responses in terms of increases in fish numbers or biomass, due to specific watershed restoration activities. For example, if large woody debris (LWD) was added to a stream channel that is limited in this characteristic, then increases in fish yield or productivity might be expected. This potential increase could be expressed, for example, as a 2-fold increase in fish numbers, or as a specific number of fish per m^2 or length of stream. Biostandards may be specific to one species of fish (e.g., rainbow trout), a group of fish (e.g., stream-rearing anadromous salmonids), or may be limited to a specific life stage (fry, smolt or adult).

To effectively use biostandards in stream restoration, three items must be considered. First, potential upslope impacts should be addressed or accounted for prior to working within the stream channel. There is less benefit to working in the mainstem of a stream when there are still upslope stability or erosion problems. Second, there should be no other instream factors or bottlenecks that limit fish productivity (Fig. 3-1). Third, for anadromous species, best estimates of ocean survival should be incorporated.

Biostandards in this chapter will focus on B.C. salmonid fish species, divided into stream-rearing anadromous species (coho and chinook salmon, and steelhead trout), non-stream rearing anadromous species (chum, pink and sockeye salmon); and resident trout and char (rainbow, cutthroat, brook (*Salvelinus fontinalis*), brown (*Salmo trutta*) and bull trout, and Dolly Varden char).

In order to apply biostandards to specific streams, project planners must first be familiar with basic habitat requirements for the various salmonid species, and second, with which fish species or life-stage are present in the specific stream. For example, overzealous creation of pool habitat using extensive full-spanning LWD and weir structures for coho salmon could decrease spawning habitat for non-stream rearing species such as pink salmon (Murphy 1995); or may

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backwater over prime boulder habitat used extensively by juvenile steelhead in riffles (see Chapters 9 and 10). Bjornn and Reiser (1991) and Keeley and Slaney (1996) provide practical reviews of habitat requirements (e.g., ideal water temperatures, depths, velocities, redd sizes) for Pacific salmon and resident trout found in B.C. streams. Diagnostics of fish habitat quality are provided in WRP Technical Circular No. 8 (Johnston and Slaney 1996). Ideally, instream restoration work should strive to maintain or recreate the natural biodiversity of the system, in terms of fish species and other organisms native to the stream, by use of templates or analogues from undisturbed streams. A watershed-wide approach is needed, rather than single component restoration (Kauffman et al. 1997; Roper et al. 1997).

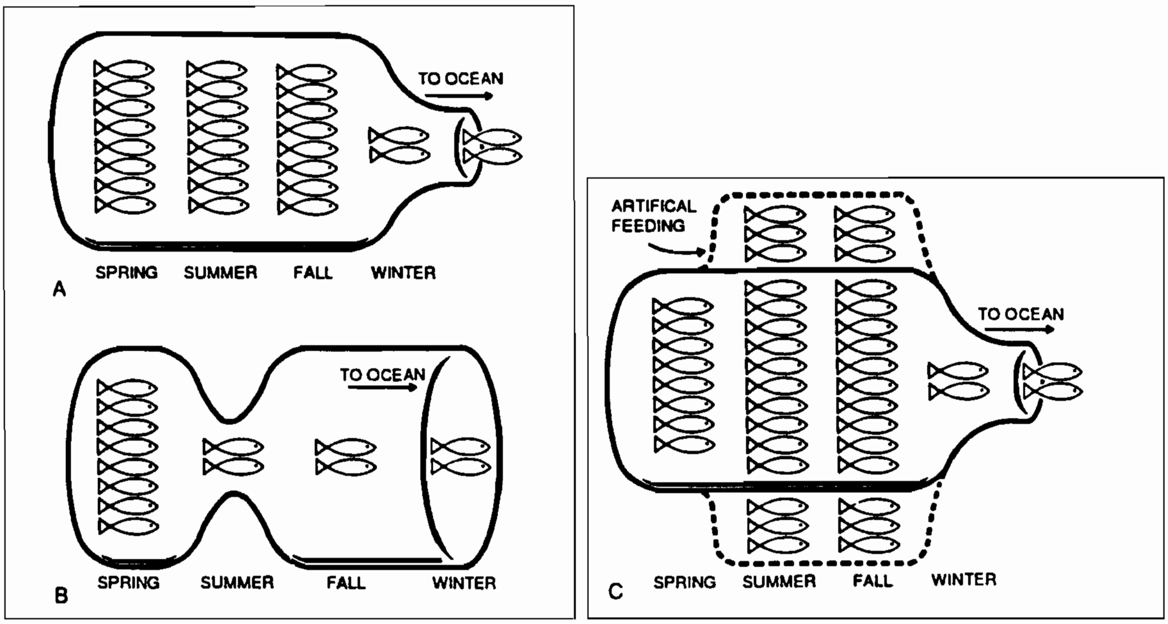

Figure 3-1. Examples of limiting factor "bottlenecks" that occur (A) during winter just before salmon smolts migrate to sea, and (B) during summer, early in the life of salmon. Attempts to increase fish abundance before a limiting factor acts on the population, such as by augmenting the food supply (C), usually fail (Mason 1976, in Reeves et al., adapted from Hall and Field-Dodgson 1981).

CURRENT BIOSTANDARDS

Keeley et al. (1996) synthesized data from documented restoration studies to provide estimated changes in salmonid production resulting from various fish habitat restoration techniques (Tables 3-1 to 3-4, and Appendix Tables 3-1 to 3-6). Average densities have been calculated for various life stages of coho and chinook salmon, and steelhead trout as a result of adding to habitat complexity in the mainstem of streams (Table 3-1); increasing the area of spawning gravels for nonstream-rearing anadromous salmon species; chum, pink and sockeye salmon (Table 3-2); for chum and coho salmon in off-channel habitat (Table 3-3); and for resident populations of brook, brown, cutthroat and rainbow trout (Table 3-4). Keeley et al. (1996) used studies that were based on paired estimates of pre- and post-restoration densities. The data must be viewed with some caution because the many projects summarized included different levels of restoration effort per area of stream, over different time periods; however, despite these difficulties, most comparisons showed significant increases in fish densities over a wide range of conditions. Hence, under most conditions, restoration has substantial positive effects on salmonid populations.

Table 3-1. Summary of estimated fish production benefits for both pre- and post-restoration of fish habitat (mainstem habitat complexing), for anadromous stream rearing salmonids (adapted from Keeley et al. 1996).

Species		Fry[a] ($no \cdot m^{-2}$)	Parr[b] ($no \cdot m^{-2}$)	Survival Rate[c]	Smolts ($no \cdot m^{-2}$)	Survival Rate[d]	Adults ($no \cdot m^{-2}$) ($no \cdot 100m^{-2}$)	Adults x-fold increase
coho	pre[f]	0.49		0.68	0.33	0.098	0.033 (3.3)	
	post[g]	0.87		0.68	0.59	0.098	0.058 (5.8)	1.8
chinook	pre	0.073		0.68	0.0496	0.041	0.00204 (0.2)	
	post	0.68		0.68	0.4624	0.041	0.0190 (1.9)	9.3
steelhead	pre	0.19	0.042	0.33	0.014	0.16[e]	0.0022 (0.22)	
	post	0.29	0.097	0.33	0.032	0.16[e]	0.0051 (0.51)	2.3

[a,b] Fry and parr values from: House and Boehne 1985, 1986; Espinosa and Lee 1991; Poulin, V. A. and Assoc. 1991; Ward and Slaney 1981, Johnston et al. 1990; Slaney et al. 1994a, Moreau 1984.
[c] For coho and chinook, based on overwinter survival rates in Crone and Bond (1976); for steelhead in Ward and Slaney (1988).
[d] For coho and chinook, based on average marine survival rates in Bradford (1995).
[e] For steelhead, based on average marine survival rates in Ward and Slaney (1988). More recent work of Ward (1996) report a mean marine survival of steelhead as 12% rather than 16%; in recent years the percentage is still lower; rates over the past 20 years have fluctuated between 3 to 25% (B.R. Ward, Min. of Envir. Vancouver, pers. comm.).
[f] Pre, fish values pre-restoration.
[g] Post, fish values post-restoration.

Table 3-2. Summary of estimated fish production benefits for both pre- and post-restoration of fish habitat (increase in spawning gravel area per 100 linear m of stream), for anadromous non-stream rearing salmonids (adapted from Keeley et al. 1996).

Species		Fry[a] ($no \cdot m^{-2}$)	Freshwater Survival Rate[b]	Migrating Fish ($no \cdot m^{-2}$)	Marine Survival Rate[b]	Adults ($no \cdot m^{-2}$) ($no \cdot 100m^{-2}$)	Adults x-fold increase
chum	pre[c]	129.30	0.069	8.92	0.007	0.062 (6.2)	
	post[d]	1106.05	0.069	76.32	0.007	0.53 (53)	8.5
pink	pre	143.45	0.070	10.04	0.028	0.28 (28)	
	post	1227.04	0.070	85.89	0.028	2.39 (239)	8.5
sockeye	pre	123.80	0.093	11.51	0.073	0.84 (84)	
	post	1059.00	0.093	98.49	0.073	7.19 (719)	8.6

[a] Fry values are based on species-specific redd area and average fecundity values.
[b] Based on average life-stage survival rates from Bradford (1995).
[c] Pre, fish values pre-restoration.
[d] Post, fish values post-restoration. Restoration methods were log weir and deflector installations for spawning gravel enhancement in: Buer et al. (1981); Moreau (1984); West (1984); and House and Boehne (1985) (1986).

Table 3-3. Estimates of fish production benefits from side-channel and pond construction (adapted from Keeley et al. 1996).

Species	Fry[a] (no·m^{-2})	Survival Rate[c]	Smolts[b] (no·m^{-2})	Survival Rate[c]	Adults (no·m^{-2}) (no·100 m^{-2})
			Side channels		
chum	225	0.007	-	-	1.58 (158)
coho	-		0.67	0.098	0.066 (6.6)
			Off-channel ponds		
coho	1.01	0.68	0.69	0.098	0.068 (6.8)

[a,b] Fry and smolt values from: Bustard and Narver (1975), Lister et al. (1980), Peterson (1982a), King and Young (1986), Swales et al. (1986) (1988), Beniston et al. (1987), (1988), Cederholm et al. (1988), Swales and Levings (1989), Lister and Dunford. (1989), Sheng et al. (1990), Cederholm and Scarlett (1991), M. Foy (unpubl. data).
[c] Based on marine survival rates from Bradford (1995).

Table 3-4. Estimates of fish production of salmonid fry and catchable size trout (≥ 15 cm) for both pre- and post-enhancement of fish habitat (mainstem habitat complexing), for resident salmonids (adapted from Keeley et al. 1996).

Species		Total fish[a] (no·m^{-2}) (no·100m^{-2})	x-fold increase	Catchable-sized fish[b] (≥ 15 cm; no·m^{-2}) (no·100m^{-2})	x-fold increase
brook	pre[c]	0.30 (30)		0.054 (5.4)	
	post[d]	0.44 (44)	1.5	0.074 (7.4)	1.4
brown	pre	0.20 (20)		0.14 (14)	
	post	0.29 (29)	1.4	0.18 (18)	1.3
cutthroat	pre	0.061 (6.1)		0.035 (3.5)	
	post	0.14 (14)	2.3	0.058 (5.8)	1.7
rainbow	pre	0.036 (3.6)		0.12 (12)	
	post	0.097 (9.7)	2.7	0.16 (16)	1.3

[a] References: Riley and Fausch (1995); Binns (1994); Saunders and Smith (1962); Binns and Remmick (1994); Burgess and Bider (1980); and Hunt (1988).
[b] Catchable-sized fish data for brook, brown and rainbow trout are from Hunt (1988). Rainbow trout densities are based on overall responses in salmonid fish densities due to a paucity of data for rainbow trout. Cutthroat trout densities are based on data from Binns and Remmick (1994).
[a,b] Total fish data in [a]-column are not correlated to catchable-sized fish data in [b]-column.
[c] Pre, fish values pre-restoration.
[d] Post, fish values post-restoration.

Estimates of fish survival differ between salmonid species and life stage. For example, while the fry-to-smolt survival for coho and chinook are similar (0.68), the smolt-to-adult survival rate for chinook (0.041) is less than half that of coho (0.098) (Table 3-1). Adult salmon production estimates in Keeley et al. (1996) are based on fry and smolt survival rates of Crone and Bond (1976). The adult salmon data is based on total adult returns (catch plus escapement) in Bradford (1995). The steelhead smolt-to-adult survival rate in Keeley et al. (1996) is estimated to be 0.16 (16%) based on the work of Ward and Slaney (1988).

Keeley et al. (1996) provide the following anadromous salmonid productivity increases (biostandards) due to mainstem restoration techniques (Table 3-1): a 1.8-fold increase in number of coho, 9.3-fold increase in chinook salmon numbers, and 2.3-fold increase in steelhead. Summarizing all the stream-rearing anadromous salmonid data in Appendix Table 3-1 provides an average 2.2-fold increase in salmonids due to increasing complexity of habitat in the mainstem, and this value can be used as a general "rule-of-thumb" in initial project planning. Biostandards for resident trout (Table 3-4) range from 1.3 to 2.7-fold increases due to mainstem complexing, and up to 9-fold in the earlier summary of White (1975a) (Table 3-5). Summarizing the resident salmonid data (Appendix Table 3-4) provides an average 1.9-fold increase in resident salmonids due to increasing complexity of habitat in the mainstem.

Adams and Whyte (1990) (Appendix Table 3-6) provided a summary of anadromous fish productivity biostandards for the following habitat restoration methods: minimum flow control; fishway construction; obstruction removal; colonization of new habitat; gravel placements; incubation boxes; off-channel developments; overwintering ponds; rearing habitat complexing, and supplemental feeding. Adams and Whyte (1990) only provide anadromous fry and smolt densities, and do not provide adult fish densities or standards for resident salmonids. However, the anadromous fry and smolt densities they cite are quite similar to the values more recently reported in Keeley et al. (1996).

Specific biostandards have been summarized here, where possible, for the following 10 techniques, following the order in Chapters 5-14:

- restoring fish access and rehabilitation of spawning sites (Chapter 5);
- rehabilitating stream banks (Chapter 6);
- rehabilitating off-channel habitat (Chapter 7);
- rehabilitating stream channels and fish habitat using large woody debris (Chapter 8);
- accelerating the recovery of log-jam habitats: large woody debris-boulder complexes (Chapter 9);
- using boulder clusters to rehabilitate juvenile salmonid habitat (Chapter 10);
- rehabilitating mainstem holding and rearing habitat (Chapter 11);
- restoring habitats in channelized or uniform streams using riffle and pool sequences (Chapter 12);
- accelerating recovery of stream and pond productivity by low-level nutrient replacement (Chapter 13), and
- augmenting minimum streamflows in sediment deposition reaches (Chapter 14).

These restoration techniques are currently being used successfully in stream restoration in many streams (primarily 2nd to 4th order) in the Pacific Northwest region of the USA and Canada. An introduction to these techniques and their associated biostandards are provided in the following subsections.

Restoration of Fish Access and Rehabilitation of Spawning Sites

Past logging and related practices can create obstructions to fish passage as a result of road construction, slope destabilization, excessive instream debris and altered hydrology (see Whyte et al., Chapter 5). Upstream access may be restricted for all fish species and life stages (total obstruction), or may be restricted to salmonid fry and juvenile stages, the latter condition being a more difficult impact to assess. Access may be restricted in the stream mainstem at all flows or during high or low flow events, in off-channel areas, or in overwintering refuges and wetlands.

Table 3-5. Effect of stream restoration techniques on resident trout abundance, midwestern and eastern USA (adapted from White 1975a).

Stream; wild trout species: reference	Primary management	Schedule of population inventories	Effects on trout populations and angling yield
1. Lawrence Creek. Wisconsin; brook trout: Hunt (1971)	Bank cover deflectors in 1.7 km of stream (compared with 1.4 km control)	3 years before, 3 years after managment	141% rise in age 2+ biomass from better overwinter survival; 156% more fish over 20 cm in April; 200% greater anglers' catch
2. Big Roche-a-Cri Creek. Wisconsin; brook and a few brown trout: White (1972; 1975b)	Bank cover deflectors in 6 km of stream (compared with 5 km of interspersed control areas): cattle fenced out; beaver dams removed	3 years before, 2 years during, 5 years after management	200% rise in numbers of age 2+ fish (3 pre- versus 3 post-management years of similar flow regime) in the 3 km section of most intensive alteration; greatest effect was improvement of drought (low water) abundances of fish; 36% increase in catch per angler-hour
3. West Br. Split Rock River. Minnesota; brook trout: Hale (1969)	Deflectors, bank covers, low dams in 1.6 km of stream (compared with 1.6 km control area)	3 years before, 3 years after managment	9-fold increase in numbers of age-0 fish; 2 fold increase in numbers of age-1+ fish; angler success increased from 0.58 to 0.89 fish/ angler-hour in managed area, decreased in control.
4. Hayes Brook, Prince Edward Island; brook trout: Saunders and Smith (1962)	Low dams. deflectors. cover of poles and brush in 0.4 km of stream (no control area)	5 years before, 1 year after managment	Number of age-1+ fish in year after construction was highest on record, nearly double the previous 5 year average
5. Hunt Creek, Michigan; brook trout: Shetter et al. (1949)	Deflectors in 0.5 km of stream (no control area)	1 year before, 3 years after (creel census 3 years before, 5 years after) management	35% increase in catch per angler hour; little change in standing crop
6. Pigeon River, Michigan; brook and brown trout: Latta (1972)	Deflectors in 2 km of stream (compared with 2 km control)	5 years before, 5 years after management, then 5 years after dismantling	Trout abundance in managed section (in terms of fall population plus anglers' catch in previous summer) originally lower than in control but increased to equality after management, then decreased when devices were intentionally dismantled
7. Kinnikinnic R., Wisconsin; brook and brown trout: Frankenberger (1968)	Rock deflectors, rock revetments, fences along 2.2 km of stream (compared with an unmanaged control)	5 years before, 3 years after managment	400-500% rise in numbers of brook trout over 14 cm and 150-200% rise in numbers of brown trout over 14 cm; populations in control area remained essentially static
8. Bohemian Valley Creek, Wisconsin; brown trout: Frankenberger & Fassbender (1967)	Floodwater detention dams, rock deflectors, rock revetments, low dams, fencing in 4.3 km of stream (cf to 1.2 km control)	6 years before, 4 years after management	Originally negligible brown trout abundance (sometimes fewer than 5/km) increased to about 250/km
9. McKenzie Creek, Wisconsin; brown trout: Lowry (1971)	Deflectors, bank covers, brush covers, low dams in 5 km of stream (compared with 0.6 km control)	2 years before, 6 years after management	10-15% increase in total biomass (25% increase for age 1+, 100% increase for age 2+ fish): inconclusive changes in numbers of fish larger than 15 cm
10. Black Earth Cr., Wisconsin; brown trout: White (1975a)	Fencing, dam removal, few deflectors, bank revetments in 8 km of stream (control: Mt. Vernon Creek)	3 years during, 5 years after management	3-fold increases in age-0 fish, total biomass, and anglers catch per hour of wild trout: 5-fold increase in spring (pre-angling) numbers of fish >15 cm
11. Mt. Vernon Cr., Wisconsin; brown trout: White (1975a)	Unmanaged control for Black Earth Creek (adjoining drainage basin); dam removed	Concurrent with Black Earth Creek	Relatively minor increases in age-0 fish, total biomass, and anglers' catch per hour of wild trout: 2-fold increase in spring number of fish > 15 cm, attributable to hydrologic events

- Table was prepared for publication and referenced in White (1975a) but omitted from publication by editorial error, instead appearing in Reeves et al. (1991).
- A+ sign means "the given age and older"; for example, age-2+ fish means age 2 yr and older fish.
- Original references have not been seen.

Activities involved in restoring fish access include excavating gravel bars, removing barriers (debris jams, poorly installed culverts), restoring dewatered reaches, creating velocity refuges, and by adding or cleaning spawning gravel. Restoring fish access to upstream fish habitat results in corresponding increases in fish carrying capacity.

Spawning habitat restoration can benefit non-stream rearing salmonids, such as chum, pink and sockeye salmon. Activities to rehabilitate habitat include gravel cleaning or addition, creation of gravel catchment structures (spawning platforms), use of full or partial spanning weirs and wing deflectors, and creation of off-channel spawning habitat. On average, increases in spawnable gravel area per given length of stream (Appendix Table 3-5), due to addition of log weirs and deflectors provide a 8.5-fold increase in chum, pink and sockeye salmon densities (Table 3-2) based on the work of Buer et al. (1981), Moreau (1984), West (1984), and House and Boehne (1985) (1986).

Stream Bank Rehabilitation

Past logging practices can affect stream bank erosion and subsequent channel responses through increases in total yield, intensity and timing of delivery of water, sediment and woody debris to the channel from adjoining hillslope and riparian areas (see Babakaiff et al., Chapter 6). Loss of a "proper functioning condition" (Barrett et al. 1995) in riparian vegetation due to logging to the stream bank may further alter sediment loading to the stream channel. Impacts of bank erosion include loss of protective cover, reduced nutrient inputs, increased stream temperatures, infilled pools and smothered spawning gravels.

Bank stabilization techniques include rock methods (rock toe keys, deflectors, revetments, turning rocks, and tie-backs), vegetative methods (brush mattresses, facines, live cuttings, herbaceous ground cover) and integrated methods using rock, logs, soil and plants (vegetated geogrids, live cribwalls, tree revetments) (Babakaiff et al., Chapter 6). Planted trees and shrubs, besides establishing root systems that stabilize the banks and reduce sediment input, also provide shade, input of organic debris and food materials, and overhanging cover for fish. Bank armouring with riprap boulders reduces sediment input, and if large boulders are placed instream at the toes, also provides habitat for juvenile stream rearing salmonids (e.g., coho and resident trout); however, excessive smooth armouring reduces habitat complexity. Bank armouring with riprap in the past has frequently been the "first option of choice" due to its simplicity of design and effectiveness; however, critics of the method argue that rip-rapped stream banks permanently separate the stream channel from riparian habitat without allowing for any future natural recovery or dynamic change in the stream system.

Reduction of sediment input due to stream bank rehabilitation is not easy to measure. Based on laboratory studies, Bjornn and Reiser (1991) provided egg-to-fry survival in relation to percent fine sediment in spawning gravel (up to 60% fines). They found that the relationship was not linear. A reduction in fine sediments (in spawning gravel) from 60 to 40% resulted in increased egg survival from approximately 5 to 10 percent; from 20 to 0% fine sediment in spawning gravel resulted in increased egg survival from 10 to 80%. Thus, in streams subject to significant erosion, a 50% decrease in input of fines due to erosion control mechanisms could result in increased egg survival from 2 to 8-fold, assuming that post-restoration flushing flows are able to remove the accumulated fines from the impacted reaches. Similarly, Bjornn and Reiser (1991) provide the relationship between winter habitat use by juvenile steelhead and embeddedness of the stream by fine sediment. Fine sediment can reduce the amount of cover available in the streambed by filling interstitial spaces. A reduction in embeddedness of 50%

may result in an approximately 1.5 to 2.5-fold increase in juvenile steelhead numbers per m^2 of streambed.

As a "rule-of-thumb", Keeley et al. (1996) provided a general estimate of a 2.2-fold increase in stream-rearing anadromous salmonids and a 1.9-fold increase in resident salmonids due to increases in mainstem habitat complexity, provided the stream bank project is designed to integrate both bank protection (erosion control) and restoration of fish habitat.

Off-channel Habitat Rehabilitation

Off-channel habitats (overwintering pools, protected alcoves, groundwater channels, stream intake channels and channel pond complexes) can provide highly productive fish habitat for certain species and life stages of salmonids, especially for chum and coho salmon (with minor numbers of steelhead, chinook and Dolly Varden). Where appropriate, they provide cover for rearing juvenile salmonids, protection from peak flows and stable overwintering habitat. Off-channel habitat development and rehabilitation is an attractive option for high-energy coastal streams where extreme flows and channel instability make it impractical to rehabilitate the mainstem river, and in the interior, where winter conditions, in combination with degraded habitat in the mainstem may be too severe (Lister and Finnigan, Chapter 7). Groundwater-fed off-channel habitat projects are best constructed in floodplains along low gradient streams. Surfacewater-fed off-channel projects are best located on a bench or in the upper floodplain, and the water supply must be reliable, year-round (Lister and Finnigan, Chapter 7).

Keeley et al. (1996) provided predictions of 158 adult chum and 6.6 adult coho salmon per 100 m^2 side-channel habitat, and 6.8 coho per 100 m^2 off-channel pond (Table 3-3). Narver (1978, Carnation Creek) reported that overwinter survival of juvenile coho in a natural side-channel tributary averaged 74% over four winters, while comparable survival in the main channel was 23%. Everest et al. (1986) in Fish Creek, Oregon constructed an off-channel pond where the pond represented less than 1% of the basin's habitat but contributed 50% of the coho salmon smolts 3 years after construction. In addition, overwinter survival of the coho salmon juveniles exceeded 50% in the pond but was less than 30% in other areas. Beaver ponds are considered to be a special type of off-channel habitat (Finnigan and Marshall, Chapter 15).

The number of salmonid fish that can be held in a pond increases with pond size (Fig. 3-2); however, the slope of the line (Fig. 3-2) is less than one and thus smaller ponds are relatively more productive. For example, in Appendix Table 3-3, Lister et al. (1980) report a total of 268 coho per 100 m^2 in an off-channel pond of 0.056 ha, and Cederholm and Scarlet (1991) report 288 coho per 100 m^2 in a 0.018 ha pond. The time of year at which ponds are sampled may affect fish density estimates (Lister and Dunford 1989); values reported in Appendix Table 3-3 are from winter months.

Similar to off-channel pond size and fish densities, the number of chum fry migrating from side-channel habitat increases with increasing density of spawning females (Fig. 3-3); however, density of migrating fry reaches a maximum of about 500 fry per m^2 when female spawner density reaches about 1 spawner per m^2 (Keeley et al. 1996).

Rehabilitation of Stream Channels and Fish Habitat Using Large Woody Debris

Instream large woody debris (LWD) abundance has been greatly diminished in the past due to logging of stream banks and stream clearance practices (Cederholm et al., Chapter 8). LWD is defined as wood pieces greater than 10 cm in diameter and 2 m in length. Normally, LWD enters the stream channel from stream bank undercutting, windthrow and slope failures. Adding large woody debris (which includes whole trees, logs and rootwads) provides shape and stability to the stream channel, stores sediment, creates pools, dissipates stream energy, and provides diverse habitat for either fish spawning or rearing (Murphy 1995). The LWD is typically focused on shallow pools and glides or runs that historically were well-recruited with large wood.

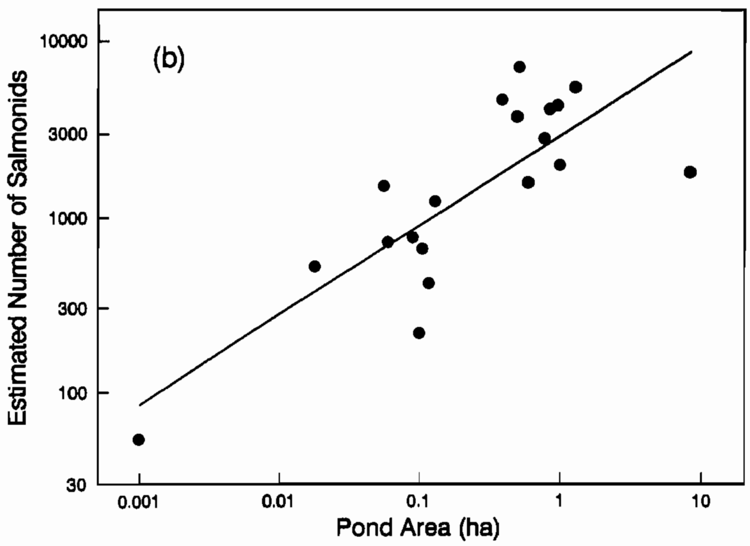

Figure 3-2. The relationship between surface area of off-channel ponds and estimated number of salmonid fish present. Equation of the line is Log_{10} fish number = 0.51 $\log_{10}$ pond area (ha) + 3.47, n = 19, r^2 = 0.64, P<0.001. (Data are from Bustard and Narver 1975; Lister et al. 1980; Peterson 1982a; Swales et al. 1986; Beniston et al. 1987; Beniston et al. 1988; Swales et al. 1988; Cederholm et al. 1988; Swales and Levings 1989; Cederholm and Scarlett 1991; M. Foy, Department of Fisheries and Oceans, Vancouver, B.C., unpublished data. Figure after Keeley and Slaney 1996).

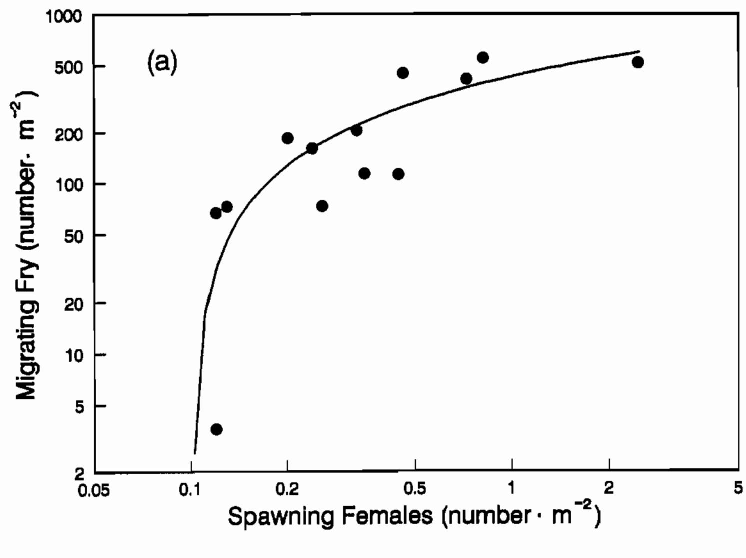

Figure 3-3. Relationship between the numbers of spawning female chum salmon and spring migrating chum salmon fry from side channel habitat (from Keeley et al. 1996).

Keeley et al. (1996) provided a general estimate of a 2.2-fold increase in stream-rearing anadromous salmonids and 1.9-fold increase in resident salmonids due to increases in mainstem habitat complexity. Other studies have shown similar or higher increases. Cederholm et al. (in press) reports coho smolt production increases of 4 to 6-fold after LWD was added. Solazzi and Johnson (1994) report increases of approximately 3-fold and 25-fold in coho smolt output after experimental addition of large woody debris (conifer logs) to debris-poor streams in two basins in western Oregon. Riley and Fausch (1995) (see Appendix Table 3-4) installed drop logs in six small Rocky Mountain streams in Colorado. They found no increase in fish growth rates or survival for brook, brown, rainbow and cutthroat trout, and attributed the increase in fish abundance (in 250 m sections), from roughly 2-fold to 7-fold increases over control reaches, to immigration from other parts of the stream (based on low recaptures of marked fish, high captures of unmarked fish). Regardless, the end result was still an increase in the overall carrying capacity of the stream.

Accelerating the Recovery of Log-jam Habitats: Large Woody Debris-boulder Complexes

Large woody debris catchers are normally employed in moderate gradient mainstem sites in rivers, and not in tributaries because the former transport woody debris. They provide juvenile and adult fish rearing habitat for anadromous and resident stream rearing salmonids. Large woody debris catchers have been used with some success within the province of B.C. Slaney et al. (1994a) reported mean numbers of juvenile chinook in debris catchers (pipe and rail types) at 277 and 522 fingerlings per catcher in May and June, respectively. On the West Kettle River, one of four catchers (V-log type) successfully trapped woody debris floating downstream, and in the process, created a large lateral scour pool. At this catcher, 18 rainbow trout (15 - 30 cm lengths) and 50 mountain whitefish (*Prosopium williamsoni*) (20 - 35 cm lengths) were observed by underwater counts during early September 1996 (P.A. Slaney and W. Koning, unpublished data). Fish were not observed elsewhere in the vicinity. The other three catchers were unsuccessful in capturing debris and therefore were not successfully functioning. Debris catchers in use on the St. Mary River, once completed with collected debris and when sited properly, provided habitat for a mean of 8 adult cutthroat per structure (Oliver 1994). Properly locating debris catchers has been found to be a crucial component of their success, based on the work in the West Kettle and St. Mary Rivers (P.A. Slaney, B.C. Ministry of Environment, Lands and Parks, Vancouver, pers. comm.).

More recent design and installations of debris catchers incorporates the use of logs and cabled (or epoxy fastened) boulders (e.g., Keogh River) in a lateral jam design (Chapter 9), which is more "natural" than the pipe and rail types. This is quite a recent trend and thus little data is available, but positive results (in fish productivity) are reported when adding wood to boulder clusters (Chapter 10) and boulder deflectors (Chapter 11).

Artificial fish reefs constructed of log cribs and sunk with boulders are being experimentally installed in Shovelnose Creek (R. Finnigan, British Columbia Conservation Foundation, Surrey, pers. comm.). Fish reefs provide a combination of LWD and boulder habitat. They are easy to construct and of low cost materials (Chapter 9), and they are expected to provide habitat for juvenile coho and steelhead. Similar to the lateral jam design described above, little in the way of monitoring data is currently available and therefore there are no biostandards at this time, but fish densities should be higher than those provided by boulders or large wood alone.

Boulder Clusters to Rehabilitate Juvenile Salmonid Habitat

Boulder clusters provide rearing habitat for juvenile salmonids. Ward and Slaney (1993b) reported up to 0.1 steelhead parr per m^2 (about 8 parr per 100 m^2, or 1 parr per boulder in a cluster) and 0.3 coho fry per m^2 (about 3 fry per boulder in a cluster) in areas of a coastal stream that were almost completely absent of fish previously. Most boulder clusters had a small amount of woody debris attached. Mean survival of 1+ parr to smolt was estimated at 65% (Ward and Slaney 1993b), and therefore each treated site could increase returns by 0.5 adult steelhead (based on 3-4 wild smolts per cluster of 5-7 boulders). Where scour occurred below the boulder clusters, coho fry increased by 4-fold and 3-fold after 1 and 2 years, respectively, post-placement. After 12 years post-placement, steelhead parr were still at 6 parr per site, compared to zero parr pre-placement, although many of the boulder clusters had lost their woody attachments. Espinosa and Lee (1991) report 10 steelhead parr per 100 m^2 due to boulder cluster installations and 65.3 chinook underyearlings per 100 m^2 of treated habitat in an interior stream system of Idaho. Griffith (1982) reported a 3-fold increase in abundance of steelhead parr in a boulder treated section.

Deflectors and Weirs to Rehabilitate Mainstem Holding and Rearing Habitat

In destabilized watersheds, excessive bedload combined with higher than normal peak flows may result in infilling of deep runs and pools. Opposing wing deflectors and weirs are structures that can be constructed at natural pool-riffle sequences to encourage streambed scour, thus restoring lost deeper water habitat in uniform channels (see Chapter 5 for use of weirs and deflectors to create spawning habitat). Log weirs or sills cause water to plunge downward and thus encourage streambed scour; deflectors narrow the channel, increasing stream velocity and subsequently encouraging downstream scour (Allan and Lowe, Chapter 11). Opposing wing deflectors simulate obstructions that constrict streamflow, and thereby create pools and cover by narrowing and deepening the stream; weirs create plunge pools downstream and dammed pools upstream (Murphy 1995). Care must be taken to ensure excessive backwatering is not created at stream gradients of less than 2%.

In two southern Alberta streams, up to 68 juvenile and 62 adult rainbow trout, and 16.7 juvenile and 13.9 adult bull trout were found per 100 lineal meters of V-weir run. Up to 11.8 juvenile and 2.4 adult rainbow trout, and 2.4 juvenile and 2.4 adult bull trout were found per 100 lineal meters of opposing deflector run (see R.L.&L. data in Chapter 11). At the Keogh River, Vancouver Island, Ward and Slaney (1993b) compared boulder deflectors with and without large wood added. Deflectors with large wood carried about twice as many juvenile steelhead parr and coho young-of-year. Keeley et al. (1996) provide a general estimate of a 2.2-fold increase in stream-rearing anadromous salmonids and a 1.9-fold increase in resident salmonids due to increases in mainstem habitat complexity.

Restoring Habitats in Channelized or Uniform Streams Using Riffle and Pool Sequences

Restoring habitat that has been previously channelized or made uniform (for example, to align logging roads) creates additional meanders, pools and riffles, and thus reduces stream gradient, stream velocities and adds depth (Newbury and Gaboury 1993). Restoring channelized habitat rebuilds diverse hydraulic conditions that would otherwise naturally be present (based on a natural pattern of a pool approximately every 5-7 channel widths). Properly designed, rock-riffles enhance pools, recruit gravel, re-aerate flows, and assist fish passage; they increase the availability of spawning habitat, assist in fry passage, and provide overwintering habitat, especially in steep coastal streams (Newbury et al., Chapter 12). Similar to the less structurally stable upstream V-weirs, care is required to avoid use in gradients less than 1.5 to 2% to minimize backwatering of existing habitat (see exception below).

Positive results are reported from reconstruction of channelized habitat in both low gradient (0.3%) and higher gradient (3%) streams (Chapter 12). In the low gradient stream (Mink Creek in Manitoba), egg viability of walleye (*Stizostedion vitreum*) spawning in the reconstructed section was slightly higher than for the channelized reach, averaging 73 and 68%, respectively, for the samples taken over a 6-year period, post-rehabilitation. The effect of walleye eggs being scoured off of spawning substrates was reduced by 150% in the reconstructed section, in comparison to the channelized section. Low gradient examples such as Mink Creek are only appropriate in B.C. to the northeast section of the province where walleye are present; in other parts of the province low gradient work could create undesirable cyprinid habitat. In the higher gradient stream (Oulette Creek, Howe Sound, south coastal B.C.), productive pool habitat increased 450% (4.5-fold) from pre-restoration levels, with a subsequent increase in age 1+ steelhead and cutthroat trout of up to 5.4-fold over pre-restoration levels (Chapter 12).

Accelerating Recovery of Stream and Pond Productivity by Low-Level Nutrient Replacement

In certain B.C. streams, primary production is limited by nutrient deficiencies (Slaney et al. 1986; Johnston et al. 1990; Slaney and Ward 1993). In some streams, low nutrient conditions are the natural oligotrophic condition; in others, these conditions are due to habitat impacts (including past timber harvesting practices) or overharvest of fish (primarily anadromous fish). Nutrient addition as a stream restoration technique involves the addition of nitrogen (N) and phosphorous (P) to obtain an in-river target concentration of approximately 5 μg per liter P and 20 μg per liter N. This stimulates the food chain (algae-to-invertebrates-to-fish) resulting in increases in fish biomass and densities. Studies in S.E. Alaska established a strong positive correlation between algal standing crop and coho abundance (see Murphy 1995, Fig. 5.14). Increased food abundance may also result in decreased feeding territory sizes thereby increasing stream carrying capacity, e.g., with juvenile coho salmon, in Dill et al. (1981).

An alternative to addition of inorganic nutrients is the addition of salmon carcasses. Bilby et al. (1996) added coho carcasses to a western Washington state stream with the hope of doubling returning coho adults. Bilby's prediction of a 2-fold increase is based on the added food source increasing the size of individual juvenile coho with a resultant increase in instream overwintering survival and increased ocean survival, based largely on studies at Carnation Creek, Vancouver Island (Scrivener and Brown 1993). Larger coho fry are found to have higher freshwater overwintering survival rate, and larger smolt size increases their ocean survival rate (Scrivener and Brown 1993; Quinn and Petersen 1994).

Fertilization of the Keogh and Salmon Rivers resulted in up to 2 to 3-fold increase in the average weight of juvenile steelhead trout after only 2 to 3 months of fertilization (Slaney et al. 1986; Johnston et al. 1990; Slaney and Ward 1993). Slaney and Ward (1993) report that the mean weights of age 1+ and 2+ steelhead parr were 55 and 24% larger within the treated reach compared to the untreated reach after approximately 10 weeks of nutrient treatment. Steelhead fry densities in the control reach were 86, and 77 fry per 100 m^2 (1985); and were 116, 108, and 120 fry per 100 m^2 in the treated reaches (Slaney and Ward 1993). An increase in steelhead parr length of 10 mm, from 50 - 60 mm, was associated with a doubling of survival to the smolt stage (from 25-50%). There was a 65% increase in steelhead smolts and adults (2-2.5 fold in one year), with less impact on coho since they reared in the tributaries and not in the fertilized mainstem (Ward and Slaney 1993). Steelhead and rainbow trout size increased 2 to 3-fold in the Salmon River due to nutrient addition (Slaney et al. 1994b); and steelhead parr and smolt trapping numbers exhibited a strong positive trend (Chapter 13, Table 13-2).

With only a 6-week growth window in the Kuparuk River in northern Alaska, age 0+ Arctic grayling showed a 1.4 to 1.9-fold increase in size, and adult grayling an increase of up to 1.5 to 2.4-fold in weight gain as a result of stream fertilization (Deegan and Peterson 1992). Fish in the fertilized reach gained up to three times as much length as fish in the control reach (0.9 cm versus 0.3 cm, respectively), but not in each year of fertilization (Deegan and Peterson 1992). Preliminary results in the Mesilinka River (northern B.C.), in year two of nutrient addition suggest that the weight of adult rainbow trout, age 4+, were up to 34% greater in the fertilized reach compared to the control reach (Koning et al. 1996).

Nutrient addition should only be used as a stream restoration technique where food is limited (oligotrophic streams) and all other habitat factors are suitable; however, where habitat is not limiting overwinter survival and influx of nutrients from salmon carcasses is depressed (Larkin and Slaney 1996), nutrient addition (replacement) is a viable option, and in fact may be the only option. In streams that are naturally oligotrophic and in pristine condition, adding nutrients would be inappropriate.

Augmenting Minimum Streamflows in Sediment Deposition Reaches

Past forest harvesting practices have created hydrological changes in watersheds such that in some highly disturbed systems the entire streamflow subsurfaces at much higher flows in the sediment accumulation zone in comparison to the steeper gradients upstream (Wood, Chapter 14). Potential impacts include a reduction in rearing area for anadromous juvenile salmonids and resident fish populations, higher summertime water temperatures, and delayed adult migrations. One of the primary risks to chinook salmon from flow reduction in the Nechako River was a possible decrease in cover (Slaney et al. 1994a).

Summer low flows can be augmented in lake-headed streams by construction of low dams with a small fishway between the lake and the stream below, provided there is sufficient water storage capacity in the lake (Chapter 14). Base summer flows can also be augmented by increasing the groundwater component and intercepting subsurface flows; replacement of the main channel by excavation of side-channels is another option.

Flow augmentation increases the wetted area of stream. An increase in summer base flows of 50% may increase effective pool and riffle area by 30% with a corresponding increase in fish production, in particular coho, steelhead and resident trout (Chapter 14). Where flow augmentation results in additional availability of spawning gravels per unit area of stream, Keeley et al. (1996) predicted an average 8.5-fold increase in chum, pink and sockeye salmon production.

OCEAN SURVIVAL

Productivity estimates for anadromous adult salmonids are highly dependent on ocean survival rates, and these rates may vary between streams and regions, and over time. In comparison to the ocean survival rates cited in Bradford (1995) and used in Tables 3-1 to 3-3 (one average number per species), ocean survival rates provided in Lucchetti and White (1995) (synthesizing the data of others), are separated into "high", "low" and "mean" values - the actual rate chosen would depend on the specific project. Survival rates ranged from 4 to 23% for sockeye salmon, 0.1 to 1% for chinook, 10 to 20% for coho, and from 5 to 15% for steelhead. A mean ocean survival value of 28% was provided for anadromous cutthroat trout. High, low and mean values are an appropriate alternative to the Bradford averages when comparing different streams where, for example, stream temperature and nutrient status are quite variable, since temperature and nutrient availability have a significant effect on the size of smolts, and larger smolts have higher ocean survival rates (Ward and Slaney 1988; McGurk 1996). Ocean survival rates are also affected by changing ocean temperatures (Welch et al. 1995; Minns et al. 1995), commercial and sport fishery harvest rates, and by changes in bi-catch values. Ocean survival rates of hatchery-produced fish can be significantly less than for wild stocks, as reported in the case of coho and chinook salmon (Cross et al. 1991) and steelhead trout (Ward and Slaney 1990). In addition, steelhead survival rates differ between summer and winter run populations because winter steelhead runs are solely a sport fishery harvest, while summer runs are often caught as a bi-catch in commercial fishing activities.

CONCLUSIONS

We conclude with a few notes of caution. Bisson et al. (1992) question the untested assumption that often underlies habitat restoration programs, namely that fish populations increase proportionally with the amount of rearing habitat. This assumption is not always correct as was already alluded to in earlier parts of this chapter. Increases in habitat area do not always result in proportional increases in fish abundance or biomass. Larger fish require larger territories, rearing space is known to fluctuate with food availability, and the presence of competitors and predators further increases the difficulty of realistically relating rearing area to population density. Hopefully, some of these difficulties will be overcome as we learn more about life history components that are currently not completely understood, such as nocturnal habitat preference, use of winter refuges and ocean survival.

A final cautionary note for biostandards of fish habitat restoration productivity concerns the supporting data reported in the scientific literature. These data may already have an inherent bias towards success, since researchers may be less likely to submit work reporting a "no increase in fish productivity" data (non-successes), than a "positive increase". A systematic evaluation of watershed restoration projects is essential to determine their biological effectiveness (Koning et al. 1997).

Despite the limitations noted in generating biostandard values, the data presented in this chapter indicate that for the average mainstem restoration project, one can expect an approximate 2-fold increase in both resident and anadromous fish numbers. In exceptional projects or in streams with highly favorable growing conditions, and for specific salmonid fish species, one might expect substantially larger increases; in other projects, a less than 2-fold increase will be achieved. Side-channels and off-channel ponds have also been shown to provide substantial fish habitat, especially for coho and chum salmon.

With additional research and project evaluations the accuracy and predictive ability of salmonid productivity biostandards will improve. Biostandards should not take the place of field-based assessments and monitoring. They are, however, a very appropriate tool to use when developing project targets in the planning stage, and as standards against which to compare post-restoration results.

APPENDIX

Appendix Tables 3-1 to 3-6 follow with supporting data.

Appendix Table 3-1. Pre- and post-treatment anadromous salmonid densities (stream rearing species) (adapted from Keeley et al. 1996).

		Density ($no \cdot m^{-2}$)													
Reference[a]	Stream	Treated Coho-0+	Untreated Coho-0+	Treated Stlh-0+	Untreated Stlh-0+	Treated Stlh-parr	Untreated Stlh-parr	Treated Chinook-0+	Untreated Chinook-0+	Treated Dolly V	Untreated Dolly V	Tot. fish Treated	Tot. fish Untreated	% diff.	x-fold increase
1	Tobe Cr, OR	0.49	0.18	0.11	0.07	0.02	0.06	.	.	.	.	0.62	0.31	100	2
2	E Fork Lobster Cr., OR	0.90	0.45	0.34	0.41	0.04	0.05	.	.	.	.	1.28	0.91	40.4	1.4
3	Squaw Cr., ID	.	.	0.21	0.16	0.08	0.02	0.08	0.05	.	.	0.37	0.24	54.7	1.5
3	Papoose Cr., ID	.	.	0.42	0.28	0.17	0.07	0.17	0.06	.	.	0.76	0.40	88.3	1.9
3	E Fork Papoose Cr., ID	.	.	0.49	0.26	0.16	0.02	.	.	.	.	0.65	0.28	133.3	2.3
3	Lolo Cr., ID	.	.	0.11	0.12	0.11	0.02	0.41	0.14	.	.	0.63	0.28	127.9	2.3
3	Pete Cr., ID	.	.	0.42	0.20	0.16	0.04	0.01	0.03	.	.	0.59	0.27	120.0	2.2
4	Sachs Cr., BC	1.5	0.89	0.35	0.09	0.11	0.09	.	.	.	.	1.96	1.07	83.5	1.8
4	Macmillian Cr., BC	0.93	0.57	.	.	.	.	.	.	0.20	0.03	1.12	0.60	86.5	1.9
4	Southbay Dump Cr., BC	0.99	0.69	.	.	.	.	.	.	.	.	0.99	0.69	43.5	1.4
4	Bonanza Cr., BC	1.51	0.47	.	.	.	.	.	.	0.21	0	1.72	0.47	266.0	3.7
5	Keogh R., BC	0.28	0.38	.	.	0.09	0.03	.	.	.	.	0.37	0.41	-9.8	0.9
6	Keogh R., BC	0.34	0.28	0.2	0.15	.	.	.	.	0.07	0.014	0.61	0.44	37.4	1.4
7	Nechako R., BC	.	.	.	.	.	.	2.71	0.09	.	.	2.71	0.09	2878.0	29.8
8	Hurdygurdy Cr., CA	.	.	.	.	0.03	0.025	.	.	.	.	0.03	0.03	20.0	1.2
	Average:	0.87	0.49	0.29	0.19	0.10	0.04	0.68	0.07	0.16	0.02	0.96	0.43	271.3	**2.2**
	x-fold increase:	1.8		1.5		2.3		9.3		10.4					

[a]Reference: 1, House and Boehne (1986); 2, House and Boehne (1985); 3, Espinosa and Lee (1991); 4, Poulin V.A., and Associates (1991); 5, Ward and Slaney (1981); 6, Johnston et al. (1990); 7, Slaney et al. (1994a); 8, Moreau (1984).

Stlh-0+ refers to steelhead trout age 0+; Dolly V are Dolly Varden char; % diff. refers to percentage difference between pre- and post-restoration fish densities.

Average - the arithmetic mean. In some cases the median value may be a better measure of the mean.

Appendix Table 3-2. Side-channel habitat salmonid production estimates (adapted from Keeley et al. 1996).

Reference[a]	Channel	Area (m^2)	Chum total	Chum total /100 m^2	Coho smolts	Coho smolts /100 m^2	Resident trout	Resident trout /100 m^2	Coho age 0+	Coho age 0+ /100 m^2	Chinook	Chinook /100 m^2	Dolly Varden	Dolly Varden /100 m^2	Total fish	Total fish /100 m^2	Total stream rear.fish	Total stream rear. fish/100 m^2
1	Maple Glen	1621	182285	11245	326	20.1	259	16.0	41688	2571.7	.	.	.	.	224558	13853	42273	2608
1	Kelsey	1754	199597	11380	809	46.1	14	0.8	9756	556.2	.	.	.	.	210176	11983	10579	603
1	Creamer	2331	430624	18474	628	26.9	31	1.3	662	28.4	27	1.2	.	.	431972	18532	1348	58
1	Simpson	385	159395	41401	5	1.3	7	1.8	58001	15065.2	13	3.4	.	.	217421	56473	58026	15072
1	Upper Schafer	361	199228	55188	584	161.8	187	51.8	9588	2656.0	.	.	.	.	209587	58057	10359	2870
1	Low Schafer	2418	177751	7351	371	15.3	230	9.5	10493	434.0	15	0.6	.	.	188860	7811	11109	459
2		850	.	.	411	48.3	.	.	.	.	.	.	.	.	411	48	411	48
2	Upp.Paradise	2625	.	.	5280	201.1	.	.	17220	656.0	.	.	.	.	22500	857	22500	857
2		2000	.	.	2678	133.9	.	.	.	.	.	.	.	.	2678	134	2678	134
2	Deadman	1753	.	.	.	.	3141	179.2	8596	490.4	.	.	.	.	11737	670	11737	670
3	Nicola 1	500	.	.	.	.	.	.	1397	279.4	.	.	.	.	1397	279	1397	279
3	Nicola 2	500	.	.	.	.	.	.	1188	237.6	.	.	.	.	1188	238	1188	238
4	Hopedale	4000	1251572	31289	688	17.2	732	18.3	41603	1040.1	.	.	.	.	1294595	32365	43023	1076
4	Kitwancool	1355	.	.	.	.	248	18.3	201	14.8	.	.	248	18.3	697	51	697	51

[a]Reference: 1, King and Young (1986); 2, Sheng et al. (1990); 3, Swales et al. (1986); 4, M. Foy, DFO, Vancouver, unpublished data.

Appendix Table 3-3. Off-channel ponds habitat salmonid production estimates (adapted from Keeley et al. 1996).

Reference[a]	Area (ha)	Total fish	Total fish/ha	Total fish /100 m²	Total coho smolts	Total coho smolts /100 m²	Total coho	Total coho /100 m²	Total stlh	Total stlh /100 m²	Total Dolly V	Total Dolly V /100 m²	Total chinook	Total chinook /100 m²
1	0.85	4100	4824	48.2	3613	42.5	4100	48.2	.	.	.	.	.	.
1	1.29	5430	4209	42.1	1534	11.9	5430	42.1	.	.	.	.	.	.
2	1	1979	1979	19.8	.	.	1954	19.5	.	.	.	.	25	0.3
2	0.1	214.5	2145	21.5	.	.	171	17.1	.	.	.	.	43.5	4.4
2	0.13	1233.5	9488	94.9	.	.	1017.5	78.3	.	.	.	.	216	16.6
3	0.97	4300	4433	44.3	.	.	4024	41.5	.	.	.	.	37.2	0.4
3	0.06	714	11900	119.0	.	.	706.5	117.8	.	.	.	.	7.5	1.3
4	8.3	1802	217	2.2	.	.	1459	1.8	.	.	343	0.4	.	.
5	0.001	54	54000	540.0	.	.	54	540.0	.	.	.	.	.	.
6	0.056	1500	26786	267.9	11	2.0	1500	267.9	.	.	.	.	.	.
7	0.018	519	28833	288.3	503	279.4	519	288.3	.	.	.	.	.	.
8	0.5	3715	7430	74.3	4805	96.1	3715	74.3	.	.	.	.	.	.
9	0.39	4649	11921	119.2	.	.	2585	66.3	2064	52.9	.	.	.	.
9	0.09	761	8456	84.6	.	.	623	69.2	138	15.3	.	.	.	.
9	0.52	7064	13585	135.8	.	.	5831	112.1	1233	23.7	.	.	.	.
9	0.6	1563	2605	26.1	.	.	330	5.5	1233	20.6	.	.	.	.
10	0.1053						652	61.9						
10	0.777						2794	36						
11	0.118						414	35.1						

[a]Reference: 1, Peterson (1982a); 2, Swales and Levings (1989); 3, Swales et al. (1986); 4, Swales et al. (1988); 5, Bustard and Narver (1975); 6, Lister et al. (1980); 7, Cederholm and Scarlett (1991); 8, Cederholm et al. (1988); 9, M. Foy, DFO, Vancouver, unpublished data; 10, Beniston et al. (1987) (1988); 11, Lister and Dunford (1989).

Appendix Table 3-4. Pre- and post-treatment resident salmonid densities in mainstem habitat complexing (adapted from Keeley et al. 1996).

		Density(no•m^{-2})														
Ref.[a]	Stream	Treated Brook-0+	Untreated Brook-0+	Treated Brook-1+	Untreated Brook-1+	Treated Brook-2+	Untreated Brook-2+	Treated Brown-1+	Untreated Brown-1+	Treated Brown-2+	Untreated Brown-2+	Treated Rnbw-1+	Untreated Rnbw-1+	Treated Rnbw-2+	Untreated Rnbw-2+	Treated Cutts<15
1	North Fork Cr.	.	.	0.036	0.007	0.217	0.149	.	.	.	.	.	.	.	.	.
1	Walton Cr.	.	.	0.388	0.256	0.215	0.193	.	.	.	.	.	.	.	.	.
1	Colorado Cr.	.	.	0.376	0.318	0.537	0.401	.	.	.	.	.	.	.	.	.
1	Jack Cr.	.	.	0.031	0.020	0.156	0.114	.	.	.	.	.	.	.	.	.
1	Beaver Cr.	.	.	.	.	.	.	0.160	0.111	0.327	0.225	.	.	.	.	.
1	St.Vrain Cr.	.	.	0.059	0.020	0.056	0.024	0.039	0.035	0.048	0.031	0.002	0.005	0.049	0.033	.
2	Beaver Cr.	0.095	0.059	0.115	0.060	0.100	0.024	.	.	.	.	.	.	.	.	.
3	Hayes Cr.	1.198	1.098	0.652	0.312	0.114	0.025	.	.	.	.	.	.	.	.	.
4	Huff Cr.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.080
5	Un-named	0.457	0.214	.	.	.	.	.	.	.	.	.	.	.	.	.
6	Compendium	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Average:	0.583	0.457	0.237	0.142	0.199	0.133	0.099	0.073	0.188	0.128					
	x-fold increase:	1.3		1.7		1.5		1.4		1.5		0.4		1.5		3.1

		Density(no•m^{-2})														
Ref.[a]	Stream	Untreated Cutts<15	Treated Cutts>15	Untreated Cutts>15	Total treated brook	Total untreated brook	Total treated brown	Total untreated brown	Total treated rnbw	Total untreated rnbw	Total treated cutts	Total untreated cutts	Total salmonids treated	Total salmonids untreated	% diff	x-fold increase
1	North Fork Cr.	.	.	.	0.252	0.156	.	.	.	.	.	.	0.252	0.156	62.2	1.6
1	Walton Cr.	.	.	.	0.603	0.449	.	.	.	.	.	.	0.603	0.449	34.3	1.3
1	Colorado Cr.	.	.	.	0.913	0.719	.	.	.	.	.	.	0.913	0.719	26.9	1.3
1	Jack Cr.	.	.	.	0.187	0.135	.	.	.	.	.	.	0.187	0.135	39.3	1.4
1	Beaver Cr.	.	.	.			0.487	0.336	.	.	.	.	0.487	0.336	45.0	1.5
1	St.Vrain Cr.	.	.	.	0.116	0.045	0.087	0.066	0.051	0.039	.	.	0.254	0.150	69.0	1.7
2	Beaver Cr.	.	.	.	0.310	0.143	.	.	.	.	.	.	0.310	0.143	117.5	2.2
3	Hayes Cr.	.	.	.	1.964	1.435	.	.	.	.	.	.	1.964	1.435	36.8	1.4
4	Huff Cr.	0.026	0.058	0.035			.	.	.	.	0.139	0.061	0.139	0.061	127.1	2.3
5	Un-named	.	.	.	0.457	0.214	.	.	.	.	.	.	0.457	0.214	113.3	2.1
6	Compendium	.	.	.	.	.	.	.	0.144	0.034	.	.	0.144	0.034	327.9	4.3
	Average[b]:				0.600	0.412	0.287	0.201	0.097	0.036	0.139	0.061			**90.9**	**1.9**
	x-fold increase:		1.7		1.5		1.4		2.7		2.3					

[a]Reference: 1, Riley & Fausch (1995); 2, Binns (1994); 3, Saunders and Smith (1962); 4, Binns and Remmick (1994); 5, Burgess and Bider (1980); 6, Hunt (1988).
[b]Average - the arithmetic average. In some cases the median value may be a better measure of the mean.
Density(no•m^{-2}) - refers to density of fish per square meter of stream area. Hunt (1988) Compendium - refers to a compendium of streams.
Brook-0+ - refers to brook trout age 0+; brown, brown trout; Rnbw, rainbow trout. Cutts<15 - refers to cutthroat trout less than 15 cm.

Appendix Table 3-5. Spawning gravel increases per 100 linear meters of stream due to restoration efforts (adapted from Keeley et al. 1996).

Reference[a]	Gravel area (m^2) Pre-treatment	Gravel area (m^2) Post-treatment	Section length (m)	m^2 gravel per 100 lin. m stm. Pre-treatment	m^2 gravel per 100 lin. m stm. Post-treatment
1	0	278	(not stated)	.	
2	185.8	557.4	1219.2	15.2	45.7
3	0	1366.8	1340	0	102
3	0	53.6	1340	0	4
4	26	296	150	17.3	197.3
5	33.5	158	183	18.3	86.3

[a]Reference: 1, Buer et al. (1981); 2, West (1984); 3, House and Boehne (1985); 4, House and Boehne (1986); 5, Moreau (1984).

Increase in spawnable gravel area per given length of stream - due to installation of log weirs and deflectors.

Appendix Table 3-6. Biostandards for fish habitat enhancement projects (adapted from Adams and Whyte 1990).

Project type/ Species[a]	Number emergent fry /100 m²	Number smolt /100 m²	Assumptions[b]	References[c]
1. Minimum flow control.				
CO		40	a	1
CN-C		30	b	2
CN-I		45	c	2
ST-C		2	d	2
ST-I		10 .	e	2
2. Production in previous non-salmonid habitats: fishways; obstruction removal; colonization; gravel placements in non-gravel streams; CO, CN, and ST incubation boxes.				
CO		40	f	1
CN-C		30	g	2
CN-I		45	h	2
ST-C		2	i	2
ST-I		10	j	2
PK-Fr	26000		k	3
PK-C(odd)	18000		l	3
PK-C(even)	20000		i	3
CM	17000		m	3
SK-Fr	40000		n	3
SK-C	30000		o	3
3. Off-Channel development: side channels with river intakes and gravel placements.				
CO		40	p	1
CN-C		30	q	2
CN-I		45	r	2
ST-C		2	s	2
ST-I		10	t	2
PK-Fr	63000		u	4
PK-C(odd)	63000		v	4
PK	63000			4
CM	45000		w	5
SK-Fr	75000		x	6
SK-C	75000		y	6
4. Off-Channel development: side channels with river intake and native gravels.				
CO,CN,ST			z	1,2
PK-Fr	34000		aa	7
PK-C(odd)	34000		bb	7
PK	34000			7
CM	24000		cc	8,9
SK-Fr	67000		dd	10
SK-C	67000		ee	10
5. Off-Channel development side channels with river intakes, for coho rearing (pools and riffles).				
CO		(3000/km)	ff	1
CO		133	gg	11
ST-C		(382/km)	hh	2
ST-C		10	ii	2
6. Off-Channel development: groundwater-fed side channels with gravel placements.				
CO		40	jj	1
CM	45000		kk	5
7. Off-Channel development groundwater-fed side channels with native gravels.				
CO		40	ll	1
CM	27000		mm	5
8. Coho over-wintering ponds.				
CO		120	nn	1
9. Rearing habitat complexing.				
CO		(2800/km)	oo	12
ST-C		7	pp	12
10. Instream supplementary feeding.				
CO		240	qq	13

[a]Abbreviations: CM, Chum; C, Coastal; F, fry; CN, Chinook; I, Interior; S, smolts; CO, Coho; K, Catchment; A, adults; PK, Pink; E, Escapement; SK, Sockeye; Fr, Fraser River; ST, Steelhead.
[b]Assumptions: see following page.
[c]References: 1, Marshall and Britton 1980; 2, Slaney et al. 1980; 3, DFO 1981; 4, Cooper 1977; 5, Lister et al. 1980; 6, Ginetz 1977; 7, McNeil 1969; 8, Sandercock and Minaker 1975; 9, Minaker et al. 1979; 10, West 1978; 11, Mundie 1969; 12, Ward and Slaney 1980; 13, Mason 1976. (Original references not seen).

Appendix Table 3-6 continued: (the "Assumptions" supporting stated fish production values: a through qq)(adapted from Adams and Whyte 1990).

1. Minimum flow control.
(a) for coho, CO[a]: a-1, Enhancement increment is determined by difference in minimum wetted area of stream before and after flow control. a-2, Overwintering capacity of stream or river system is adequate to accommodate increased fall standing crop of juveniles. (b) for coastal chinook, CN-C: Same as a-1 but flows are probably not a limiting factor on most coastal streams for juvenile production. For (c) interior chinook, (d) coastal steelhead,and (e) interior steelhead: same as a-1 and a-2.

2. Production in previous non-salmonid habitats: fishways; obstruction removal; colonization; gravel placements in non-gravel streams; CO, CN, and ST incubation boxes.
(f) Production is determined by additional length/area of stream at low flow periods accessible to fish; (g to j) Same as (f) but small streams and headwater streams should not be included in estimates of suitable rearing habitat; (k) PK-Fr: Production is determined by additional area of spawning gravel accessible to adults; (l) PK-C Production is derived by assuming at least 1 female per m^2 and back calculating from S.E.P. biostandards; (m) same as (k) and assuming spawning densities of at least 1 female per 1.5 m^2; (n) SK-Fr, same as (k) and (m), but assuming spawning densities of at least 1 female per 1.5 m^2; (o) SK-C, same as (k) and (m) but assuming spawning densities of at least 1 female per 1.5 m^2.

3. Off-Channel development: side channels with river intakes and gravel placements.
(p to t) Production is similar to natural streams; (u and v): Fry production per 100 m^2 is similar to Upper Seton River spawning channel at high spawning densities (1963); (w) CM Fry production per 100 m^2 is similar to groundwater-fed side channels with gravel placement; (x and y): Fry production per 100 m^2 is similar to Fulton River spawning at high spawning densities.

4. Off-Channel development: side channels with river intake and native gravels.
(z), same as (p-t); (aa, bb) Fry production per 100 m^2 is similar to Sashin Cr., Alaska, at densities of at least 1 female per m^2 and above average survival rates (1940, 1958, 1960, 1962 brood years); (cc) CM Fry production per 100 m^2 is similar to Big Qualicum mainstem after flow control; (dd, ee) Fry production per 100 m^2 is similar to Fulton River mainstem after flow control.

5. Off-Channel development side channels with river intakes developed for coho rearing ponds and riffles.
(ff) Smolt production per km is similar to Big Qualicum mainstem after flow control; (gg) Smolt production per 100 m^2 is derived from (ff) assuming an optimum channel width of 4 m; (hh) Smolt production per km is similar to Big Qualicum mainstem after flow control; (ii) Smolt production per 100 m^2 is derived from (hh) assuming an optimum channel width of 4 m.

6. Off-Channel development: groundwater-fed side channels with gravel placements.
(jj) Smolt production per 100 m^2 is similar to natural streams; (kk) Fry production per 100 m^2 is similar to Worth and Railroad Creeks at spawning densities greater than 0.5 females per m^2.

7. Off-Channel development groundwater-fed side channels with native gravels.
(ll) Same as (jj); (mm) Fry production per 100 m^2 is similar to Lower Paradise Channel at spawning densities of at least 0.5 females per m^2.

8. Coho Over-wintering Ponds.
(nn) Smolt production per 100 m^2 is similar to Rotary Park, Bible Camp and Cowichan Side Channels, Cowichan River.

9. Rearing Habitat Complexing.
(oo, pp): Keogh River studies indicate 2-fold increase over natural levels.

10. Instream Supplementary Feeding.
(qq) Coho, CO studies by Mason (1976) indicate a 6-fold increase in natural levels. Assumes overwintering capacity of stream or river system is adequate to accommodate increased fall standing crop of juveniles.

[a]Abbreviations: CM, Chum; C, Coastal; F, fry; CN, Chinook; I, Interior; S, smolts; CO, Coho; K, Catchment; A, adults; PK, Pink; E, Escapement; SK, Sockeye; Fr, Fraser River; ST, Steelhead.

Chapter 4

Screening Criteria for Restoration Projects

Brian L. Scarfe[1]

PREFACE

Watershed Restoration Program proposals have been evaluated for funding according to several criteria, including (prioritized) resource benefits, community stability, employment, and partnerships. In addition, resource management agencies have ranked watersheds by historical aquatic resource values and degree of perceived impact from past logging practices, thereby attempting to focus proposals on the more historically important, but degraded, aquatic ecosystems. The primary purpose of the screening criteria described in this chapter is to facilitate rankings of aquatic restoration projects **within** a watershed, although the methodology could be applied to compare the merits of proposal submissions. The menu of potential aquatic restoration projects within a moderately-sized watershed are typically numerous (20-50) as an outcome of condition assessments that identify restoration needs and feasible opportunities with preliminary prescriptions. Decisions on which of these projects should proceed and in what time sequence can be made with the assistance of the project screening criteria outlined in this chapter. Cost-benefit analyses can be arranged and compared on a spreadsheet, then weighted according to urgency in returning the condition to an acceptable environmental standard, and by estimates of community employment benefits. Thus, decisions on implementing annual sets of projects within a watershed can be more systematic and effective, generating greater resource benefits per expenditure in both the short and long term.

INTRODUCTION

This chapter outlines a practical methodology for the assessment of environmental restoration projects from the perspective of their value to society. Essentially, the chapter provides a user-friendly approach to the implementation of a multiple account evaluation framework for screening watershed rehabilitation projects. The framework relies upon an environmental standards filter that is consistent with the rehabilitation goals of Forest Renewal BC's Watershed Restoration Program to provide the necessary condition for project approval, an economic benefits filter to provide the sufficient condition for project support, and an employment generation and community stability filter to provide the "supporting cast" that resolves judgment calls when the economic benefits filter provides uncertain results.

In addition, the chapter outlines the economic values that are relevant to the overall assessment of the integrated fisheries, forestry, recreation, and other benefits of rehabilitation projects in a manner that allows these benefits to be balanced against the costs of such projects. An appropriate "social rate of discount" is identified for the present value calculations that may be needed to assess restoration projects with multi-faceted, time-dependent and uncertain environmental benefits.

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The chapter has six major sections, relating to:

- evaluation criteria for rehabilitation projects,
- the environmental standards filter,
- the economic benefits filter,
- the employment benefits and community stability filter,
- improving cost effectiveness through iterative risk assessments and adaptive management strategies, and
- composite guidelines for screening rehabilitation projects.

A final section containing a brief summary appears at the end of the chapter.

EVALUATION CRITERIA FOR REHABILITATION PROJECTS

The fundamental rehabilitation goal of the Watershed Restoration Program (WRP) is to restore, protect and maintain fisheries, aquatic and forest resources that have been adversely impacted by logging operations and that would otherwise require several decades, if not centuries, to recover naturally. Funding is to be provided by Forest Renewal BC (FRBC) to successful applicants in support of rehabilitation proposals that are consistent with this fundamental FRBC/WRP goal. Proposals are evaluated on the basis of four underlying criteria, each of which has a weighting factor attached to it. These four criteria are prioritized as resource benefits, community stability, employment generated and partnership development. Under the fundamental criterion of resource benefits, watershed rehabilitation proposals are evaluated on their technical feasibility and on their project costs in relationship to their potential benefits, measured from the perspective of fisheries, aquatic and forest resource rehabilitation.

From this criteria, it follows that FRBC/WRP funding should only be made available for projects that make a positive contribution towards the restoration and improvement of the ecological health of a particular watershed. Eligibility for funding, therefore, requires that an appropriate environmental standards filter be met. However, as a necessary condition for project eligibility, the environmental standards filter will, in most instances, be multi-faceted because of the variety of resources that are affected by the ecological health of a watershed.

Before funding is provided to a watershed rehabilitation project that passes the necessary environmental standards filter, it also needs to be demonstrated that there is a reasonable probability that the project would also pass a cost-benefit filter. Since the economic and environmental benefits to society of many restoration projects are likely to be both time-dependent and uncertain, it will often be difficult to assess whether or not these projects pass the sufficient condition for funding, namely that their net present value from a societal perspective is positive. Nevertheless, in principle, the economic benefits criterion of positive net present value ought to be used to provide the sufficiency test, which permits one to choose those projects to be funded from among all projects that satisfy the necessary environmental standards criterion.

When the economic benefits criterion only provides ambiguous results, the balance may be tipped in one direction or the other by considering a community stability/employment generation/partnership development filter. The greater these potential social benefits are, the less likely will it be that major allocative mistakes will occur when judgment calls are made to provide funding to rehabilitation projects for which the positive net present value or economic benefits criterion cannot be demonstrated to have been met.

In summary, the project screening criteria for watershed rehabilitation projects that are being articulated in this chapter are hierarchical in structure. First, a necessary condition for funding eligibility is that the project pass an environmental standards filter. A necessary and sufficient condition for funding approval is that the project pass both an environmental standards filter and an economic benefits (positive net present value) filter. In cases where the potential economic benefits are too uncertain for one to be able clearly to demonstrate that the project passes the cost-benefit filter, additional consideration should be given to the potential social benefits that the rehabilitation project may provide. The environmental, economic and social benefits of watershed rehabilitation projects may overlap in various ways. In particular, some of the social benefits may also classify as economic benefits. However, as further articulated in the following sections, there is considerable merit in taking a hierarchical decision-making approach to the evaluation of watershed rehabilitation projects. A logical decision-making process is thereby imposed on the multiple account evaluation framework.

THE ENVIRONMENTAL STANDARDS FILTER

Watershed rehabilitation projects should be assessed within an environmental standards framework that encompasses the complete ecological health of the watershed. The restoration of aquatic resources involves improvements to the quality of stream flows, fish-rearing habitats, riparian forest lands and associated wetlands. It also involves the reduction in hillslope erosion through road-bed restoration, the restoration of forest cover with appropriate species selection and, wherever possible, the re-establishment of natural drainage networks. Improvements to tributary streams and off-channel habitats as well as to the mainstem will often be involved. Although restoration of forest resources and of aquatic resources are ordinarily interdependent, aquatic restoration is usually a necessary condition for the restoration of fisheries resources, independent of whether the focus of concern is with the commercial, aboriginal or recreational fisheries. Aquatic restoration and forest restoration are often required together for the restoration of recreational values, including values that relate to the abundance and variety of wildlife and birds.

It will often not be possible (nor always desirable) to restore watersheds that have been impacted by logging operations to a pristine, as-it-was, state of nature. Nevertheless, the environmental standards filter should ensure that eligible rehabilitation projects satisfy "best-practice" techniques for restoring ecosystem health to the watershed. No resource values should be ignored in this process. In particular, the restoration of fish habitat and riparian lands adjacent to the streambed must be considered along with forestry values, even though their impact on fisheries, wildlife and recreational values is indirect. (Compare Iverson and Alston 1994.)

Several other chapters in this volume identify and illuminate the "best-practice" techniques that are available for resolving particular situations of fish habitat degradation. Individual rehabilitation projects should be evaluated in relationship to known "best-practice" techniques by appropriate technical assessors. Technical feasibility and project cost, in particular, should be reviewed in this light. Where appropriate, technical assessors should recommend modifications to project proposals that would bring their actual implementation closer in line with known "best-practice" techniques.

It is not the purpose of this chapter to elaborate upon the nature of the "best-practice" techniques that are to be used in the restoration of the various components of degraded watersheds. Nevertheless, project proposals should be evaluated from the perspective of how closely they implement "best-practice" techniques. Indeed, such proximity should be a required element of the environmental standards filter, and only projects that pass this proximity test should be eligible for FRBC/WRP funding.

THE ECONOMIC BENEFITS FILTER

The economic and environmental benefits that are associated with watershed rehabilitation projects are multi-faceted, time-dependent and uncertain. There may be potential benefits to fisheries resources that accrue only gradually over time in response to water quality and fish habitat improvements. There may be aquatic and recreational resource improvements that also accrue gradually. Finally, there may be enhancements to forest resource values, which could take a century or more to achieve their full maturity. Because all of these potential benefits accrue at various times in the future, it is essential to convert all future values into the present so that they can be compared with current project costs. In addition, it is appropriate to evaluate all costs and benefits in dollars of constant purchasing power. Project evaluation should be undertaken by bringing all costs and benefits into present values, measured in equivalent dollars of today's purchasing power. Accordingly, future values should be expressed in constant dollars of today's purchasing power and then discounted back to the present using an appropriate real (or inflation-adjusted) rate of interest.

The appropriate real rate of interest for discounting the future benefit stream that may be associated with watershed rehabilitation projects combines additively a basic time-preference element with a specific risk-premium. However, a case can be made for setting at least one of these two elements equal to zero. The reason for this is that, in a general sense, the value to society of a sound ecosystem ought to increase gradually over time in a way that offsets the effect of discounting on the present value of the future stream of benefits, which may accrue from investments in ecosystem restoration that are made today. In particular, there may be a general gain in the form of a "public good externality" that accrues from these investments through their potential to preserve and/or enhance the biodiversity of the environment. Put differently, there is a general ecosystem risk to society if watershed restoration investments are not made and the environment is allowed to deteriorate. This general risk may be accommodated in present value calculations by either dropping the time-preference element or the specific risk-premium.

Nevertheless, specific investments in ecosystem restoration made today all have outcomes that not only accrue in the future but also are to some degree uncertain. Accordingly, a real discount rate that reflects their future orientation and their basic uncertainty should be applied to these investments, but one that takes into account the offsetting general riskiness of not undertaking investments in ecosystem health or, alternatively, the increasing value of ecosystem health to society. Thus, it would be appropriate to apply a real discount rate of perhaps 3% per annum to the present value calculations that necessarily underlie the application of a cost-benefit filter to the evaluation of watershed rehabilitation projects. The application of significantly higher real discount rates would not be appropriate in this context. (Compare Pearce and Turner 1990, Chapter 14, and Zerbe and Dively 1994, Chapter 13.)

The economic and environmental benefits that enter the determination of net present value using the suggested 3% real discount rate are likely to be multi-faceted in the case of watershed rehabilitation projects. There may be a potential gain from the recovery of the fish stocks available to the commercial, aboriginal and/or recreational fisheries. There may be a potential gain from the renewed availability of clean water, from both instream use and consumptive use perspectives. Recreational values may be enhanced by an increased abundance and variety of the flora and fauna of the particular watershed. Forest values may also be enhanced, if harvestable timber is enabled to regenerate more quickly through watershed restoration activities. For each relevant future time period, each of these potential gains should be aggregated into a single time-specific sum before the whole stream of time-specific sums is discounted back into net present value terms. Since the costs associated with the watershed rehabilitation project may also be incurred in various time periods, the net present value (NPV) calculation involves the following discounted sum:

$$NPV = B_0 - C_0 + \frac{B_1 - C_1}{1 + r} + \frac{B_2 - C_2}{(1 + r)^2} + \ldots + \frac{B_T - C_T}{(1 + r)^T},$$

where B_l represents the aggregated benefits made available by the project in year 1, 1 = 0...T. C_l represents the costs incurred with respect to the project in the same year, and r is the real discount rate, recommended herein to be set at 3% per annum. Projects that pass the economic benefits filter will have an NPV that is greater than or equal to zero. (An example is presented in Appendix 4-1.)

Fisheries benefits should ordinarily be estimated in the following way. Let S be the kilometric length of streambed in which habitat improvements are likely to occur; let *K* be the likely impact per kilometer of upgraded streambed in the particular watershed on the relevant fish stocks (measured in terms of adult fish); and let Y be the average weight in kilograms of an adult member of the relevant fish species. Then *"SKY" is* the estimated growth in the biomass of the relevant fish species that potentially may result from the watershed improvements, which are undertaken.

The economic value of this potential biomass growth will depend upon the particular fish species in question. It is recommended that the following prices be used for various fish species in estimating the economic value of biomass restoration, so that *"SKY"* should be multiplied by these suggested price parameters for each period in which the additional potential biomass is available:

anadromous salmonid fish resources		*other freshwater fish resources*	
steelhead	$\$4.50 \cdot kg^{-1}$	kokanee	$\$3.00 \cdot kg^{-1}$
chinook	$\$5.00 \cdot kg^{-1}$	trout	$\$2.50 \cdot kg^{-1}$
sockeye	$\$5.00 \cdot kg^{-1}$	other sport fish	$\$2.00 \cdot kg^{-1}$
coho	$\$4.00 \cdot kg^{-1}$		
chum	$\$2.50 \cdot kg^{-1}$		
pink	$\$2.00 \cdot kg^{-1}$		

The suggested price parameters given above are intended to represent the intrinsic value to society of marginal additions to fish biomass, regardless of whether the associated fish become part of the annual catch of a particular fishery. They are therefore intended to represent an amalgam of commercial fishery values, recreational fishery values, aboriginal fishery values and spawner values. However, it is known that sockeye, chum and pink are mostly of importance to the commercial fishery; steelhead and the various freshwater fish resources are mostly of importance to the recreational fishery; and chinook and coho are of importance to both these fisheries. The aboriginal fishery draws variously upon all of these fish resources in different areas of the province. Fish left uncaught and free to spawn are obviously of importance to the survival of any particular fish species.

Although these price parameters are all intended to represent the intrinsic value of fish, they are nevertheless based upon estimates of commercial fishery values provided in two recent reports published by the ARA Consulting Group Inc. The prices for chinook and coho rest upon the firmest analytical basis, since they are the 1994 all-B.C. short-term marginal values to the commercial fishery provided in the 1996 ARA report, rounded to the nearest whole dollar. The prices suggested for the other salmonids (except steelhead) are based upon all-B.C. estimates averaged for 1991-93 that were provided in the earlier 1994 ARA report, appropriately adjusted to reflect the approximate degree of augmentation measured in the commercial values of chinook and coho between the two ARA Consulting Group Inc. reports. The values placed upon steelhead and resident freshwater fish resources are essentially "best guesses" derived from the commercially-based intrinsic values of the various salmonids, since these fish are essentially not part of the B.C. commercial fishery.

These intrinsic price parameters should be applied in any cost-benefit analysis regardless of whether the additional potential biomass is expected to be harvested in a particular fishery or left to regenerate under the constraints of natural attrition. However, in cases where the watershed rehabilitation project also increases the value of a recreational fishery, an additional benefit equal to the estimated increase in angler-days per year multiplied by a pricing factor of $40 per angler-day should be specified, consistent with the 1996 ARA report finding that the marginal values of chinook and coho resources in the recreational fishery exceed those found for the commercial fishery. More generally, the same $40 per adult-visitor-day could be used in assigning amenity values to other recreational benefits that may result from the watershed rehabilitation project. This $40 figure seems consistent with current practice in the Pacific Northwest, and B.C. in particular. (For further discussion, see Fortrends Consulting Inc., et al. 1991.)

Forest resource values may also be enhanced and brought forward towards the present by successful watershed rehabilitation projects. However, if earlier timber harvesting is made feasible, the harvests that are thereby foregone at a later date need to enter the net present value calculation in an offsetting way. What is important to measure is the incremental net value generated from timber harvests as they accrue over time, where the incremental net value in any particular year is derived by deducting from the estimated value of the additional timber harvested all associated harvesting, silviculture and management costs, not including stumpage payments made to the Crown since these payments represent part of the incremental net value.

Species, quality and locational differences are all of considerable importance in assessing the economic value of timber harvests. Nevertheless, it is recommended that only species differentials be recognized in assessing enhancements to timber values that may incidentally arise from associated watershed rehabilitation projects. The following price parameters, all measured in dollars per cubic meter ($\$ \cdot m^{-3}$), are suggested for use, where appropriate, in assessing the incremental net value generated from B.C. timber harvests:

Cypress	$\$135 \cdot m^{-3}$	Fir	$\$110 \cdot m^{-3}$
Cedar	$\$100 \cdot m^{-3}$	Spruce	$\$100 \cdot m^{-3}$
Hemlock	$\$\ 80 \cdot m^{-3}$	Pine	$\$\ 75 \cdot m^{-3}$

Alternatively, a simple average net value of $\$100 \cdot m^{-3}$ could be used. Improvements in water quality should also be appropriately valued from an instream use and/or consumptive use perspective, as appropriate.

Given these basic resource values, it should be possible to form an aggregated estimate of the potential value of the resource benefits accruing in each future year, and from this stream of benefits and associated costs obtain an estimate of the net present value of the rehabilitation project. Of course, for most watershed rehabilitation projects, one will at best be able to provide a gross estimate of the overall resource benefits for comparison with overall project costs. Nevertheless, it is important to attempt this, even if implicitly, in assessing the relative merits of proposed watershed rehabilitation projects. An example of the use of the net present value approach to the assessment of a fictitious, but typical, watershed stream restoration proposal involving fish habitat rehabilitation at Trout Creek, B.C., is provided in Appendix 4-1.

THE EMPLOYMENT BENEFITS AND COMMUNITY STABILITY FILTER

The economic benefits filter outlined in the previous section made no mention of possible employment benefits or benefits to community stability that might result from the allocation of FRBC/WRP funding to watershed rehabilitation projects. These indirect spill-over benefits may well be important from a social perspective, and should be weighted into the complete evaluation process whenever the economic benefits filter gives uncertain results. However, they should not be added together with the direct economic and environmental benefits that enter the net present value calculation.

The reason is that similar employment impacts and community stability impacts could alternatively be obtained by spending the same amount of public money directly in the communities adjacent to the proposed watershed rehabilitation project, instead of allocating this funding to the project itself. Accordingly, positive impacts on employment generation and/or community stability (and/or, for that matter, partnership development) should not be counted as direct gains from the expenditure of FRBC/WRP funds on particular watershed rehabilitation projects. Rather, emphasis should be placed on the question of whether or not funding allocations from FRBC/WRP to the particular project are the best way of achieving these positive impacts, in comparison with other ways of using the same amount of public funding to meet these ends.

Indirect gains to employment generation and/or community stability should only be given a "supporting cast" role in the overall assessment of proposed watershed rehabilitation projects. Their presence or absence should only be used to tip the balance towards funding or away from funding when the economic benefits filter fails to indicate a strong probability of either positive or negative net present value as a result of the uncertainties involved in measuring project benefits and, in some instances, project costs. This is not to say that employment generation and community stability (along with partnership development) are unimportant objectives. It is simply that these objectives should not be considered to be the primary ones when FRBC/WRP funding is being contemplated.

IMPROVING COST EFFECTIVENESS THROUGH ITERATIVE RISK ASSESSMENTS AND ADAPTIVE MANAGEMENT STRATEGIES

Many watershed rehabilitation projects will involve an element of "learning-by-doing". For this reason, it will be valuable to approach watershed restoration in the province through the funding of manageable-sized projects. Pooling the knowledge gained from the effective monitoring of such manageable-sized projects will be helpful in reducing the uncertainties associated with watershed rehabilitation projects that are to be developed in the future. This is particularly important on the benefits assessment side, but it also relates to the technical effectiveness of project design. The pooling of the knowledge obtained from effective monitoring also provides for the evolution over time of "best-practice" techniques in a manner that responds to up-to-date scientific and practical experience.

Cost effectiveness can be improved by the use of iterative risk assessments and adaptive management strategies. Manageable-sized projects provide the flexibility for frequent reassessment of the risks associated with the adoption of specific mitigation and rehabilitation measures in various watersheds. They also provide project and program managers with the opportunity to reconsider their restoration strategies at frequent intervals. "Learning-by-doing" is less likely to occur as effectively when indivisible large-scale rehabilitation projects are undertaken, since these projects may well become locked into the use of yesterday's "best-practice" techniques. Wherever possible, therefore, it is useful to approach mitigation and rehabilitation programs in a sequential manner, which allows at least the preliminary environmental outcomes from each individual project to be assessed before the next related project is fully underway. As a result, the cost effectiveness of the whole program is likely to be enhanced.

Training is also an important component in environmental restoration work. Although considerable knowledge can be imparted through formal training programs, there is no ready substitute for "on-the-job" training. Cost effectiveness for the whole watershed restoration program will be well-served if representative rehabilitation projects are selected to provide the apprenticeship training venue for new rehabilitation workers.

COMPOSITE GUIDELINES FOR SCREENING REHABILITATION PROJECTS

The multiple account evaluation framework outlined in this chapter essentially uses the environmental standards filter to provide the necessary condition for a proposed watershed rehabilitation project to be eligible for FRBC/WRP funding; it uses the economic benefits filter (the positive net present value criterion) to provide the sufficient condition for funding approval for each project proposal; and it uses the employment benefits and community stability filter to provide the "supporting cast" when it is unclear whether or not the economic benefits filter is satisfied. The decision matrix proposed here is, therefore, the simple one illustrated in Fig. 4-1.

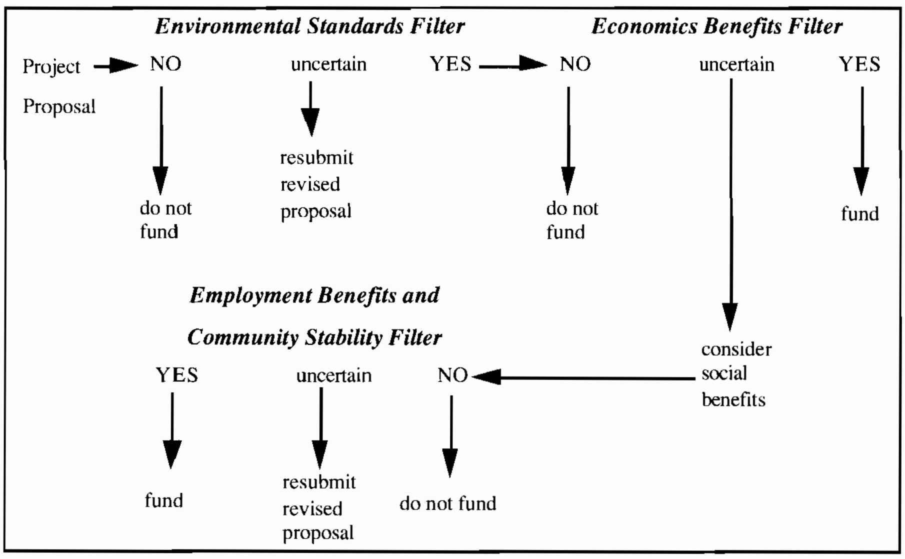

Figure 4-1. Proposed decision matrix for screening watershed restoration projects involving fish habitat rehabilitation.

It should be noted that at two points in this diagram the project applicants could be invited to resubmit their proposal after suitable revisions have been made. The first of these occurs if eligibility is questionable because the necessary environmental standards filter gives uncertain results. The second of these occurs if the economic benefits filter and the substitute employment benefits and community stability filter both give uncertain results. Projects that pass the environmental standards filter but fail the economic benefits filter should not be approved for funding. Moreover, projects that pass the environmental standards filter, but for which the economic benefits filter gives uncertain results, should only be approved for funding if they also pass the substitute employment benefits and community stability filter. This third filter should not be used as a substitute for the economic benefits filter if this second filter indicates failure by generating a negative net present value.

SUMMARY

This chapter has outlined a user-friendly approach to the implementation of a multiple account evaluation framework for screening watershed rehabilitation projects. This approach has three components. An environmental standards filter provides the necessary condition for project approval, while an economic benefits filter involving the usual cost-benefit criterion of positive net present value provides the sufficient condition. In cases in which it is unclear whether or not the sufficient condition has been met, an employment benefits and community stability filter may be used to break the uncertainty.

The use of a 3% real discount rate is recommended for the calculation of net present value in the assessment of the economic and environmental benefits of watershed rehabilitation projects. Also recommended are certain resource values to be used for assessing the fisheries, aquatic, recreational and forest resource benefits that may accrue to watershed rehabilitation projects. The project screening criteria outlined should be of considerable value to both the applicants and the reviewers who are involved in the project evaluation process for environmental restoration project proposals.

Appendix 4-1. An Example of Net Present Value Estimation for a Proposed Fish Habitat Rehabilitation Project.

This appendix sets out a numerical example of the net present value calculation on which the economic benefits filter outlined earlier in this chapter is based. The numerical example is based upon the Trout Creek Fish Habitat Rehabilitation proposal, a fictitious proposal which has been used by the Watershed Restoration Program to illustrate the nature of the applications that the program managers expect to receive.

The Trout Creek Fish Habitat Rehabilitation proposal requests two inputs of funding, $30,800 in year zero, and $10,000 in year one, with co-funding contributions amounting to $5,000 in each of these two years. Although the co-funding contributions are in large part volunteer labour, they should still be included as part of the real costs of the project. The estimated long-term resource benefits from the project involve coho recovery/restoration of 305 adults per year, beginning in year four, and steelhead recovery/restoration of 35 adults per year, beginning in year five. These gains are expected to continue to accrue for twenty years after these adult returns commence. No other specific resource benefits are identified.

Since Trout Creek is in the Harrison Lake watershed adjacent to the lower Fraser Valley, the average weights of these incremental adult coho and steelhead are conservatively estimated to be

3.2 kg and 5.0 kg, respectively. All of the incremental steelhead are assumed to be counted as available to the recreational fishery. Accordingly, an estimated 70 angler-days per year are likely to be created, at an estimated recreational value of $40 per angler-day, given the basic assumption that the existence of one steelhead generates two angler-days. On the other hand, it is also assumed that all of the incremental coho are counted as being available to the commercial fishery. As a result, the overall estimate of 70 additional angler-days per year should be considered a reasonably conservative one, because some of the coho would probably be available to the marine and freshwater recreational fisheries. Although the actual harvest rate should not exceed 60% if sufficient fish numbers are to survive for spawning, all fish biomass restoration should be counted on the "fish have intrinsic value" assumption. This assumption renders it unnecessary to estimate harvest rates for the purpose of net present value calculations.

Using the suggested biomass prices cited earlier in this chapter, the costs and benefits related to the proposed rehabilitation project are as follows:

Year 0	$35,800, basic cost outlay
Year 1	$15,000, basic cost outlay
Year 2	0
Year 3	0
Year 4	$3,904, annual coho value ($305 \cdot 3.2$ kg $\cdot$ \$4.00 $\cdot$ kg^{-1})
Year 5	$3,904
	+ $787.50, annual steelhead value ($35 \cdot 5.0$ kg $\cdot$ \$4.50 $\cdot$ kg^{-1})
	+ $2,800, annual recreational value ($70 \cdot$ \$40 per angler-day)

Years 6 through 24, inclusive, are the same as Year 5.

At a 3% real discount rate, the value in Year 6 of one dollar received in each of the ensuing 19 years is $14.32. (See Appendix 4-2 for alternative number of years other than 19.) Thus, the value in Year 6 of the future benefit stream of $7,491.50 per annum is $14.32 x $7,491.50 = $107,278. Accordingly, the net present value (NPV) of the Trout Creek Fish Habitat Rehabilitation Project is:

$$\text{NPV} = -\$35{,}800 - \frac{\$15{,}000}{(1+.03)^1} + \frac{\$3{,}904}{(1+.03)^4} + \frac{\$7{,}491.50}{(1+.03)^5} + \frac{\$107{,}278}{(1+.03)^6}, \text{ or}$$

$$\text{NPV} = -\$35{,}800 - \$14{,}564 + \$3{,}469 + \$6{,}462 + \$89{,}845, \text{ or}$$

$$\text{NPV} = \$49{,}412.$$

Given the assumptions made, the net present value of the rehabilitation project is greater than zero. Accordingly, the project would pass the economic benefits filter on these assumptions. Put differently, a reasonable margin is available to offset unforeseen costs and/or the possibility that somewhat smaller resource benefits might accrue over time. The benefit-cost ratio for the rehabilitation project is approximately 2:1.

Appendix 4-2. Present Value Calculations: Years 1 to 25

The following numbers give the present value of $1.00 received T years in the future, and the present value of $1.00 received in each year for the next T years, given a 3% discount rate.

Year	Present Value of $1.00 $\frac{1}{(1+r)^T}$ with r = 0.03	Present Value of $1.00 Per Year $\frac{1}{r}\left[1 - \frac{1}{(1+r)^T}\right]$ with r = 0.03
1	0.9709	0.97
2	0.9426	1.91
3	0.9151	2.83
4	0.8885	3.72
5	0.8626	4.58
6	0.8375	5.42
7	0.8131	6.23
8	0.7894	7.02
9	0.7664	7.79
10	0.7441	8.53
11	0.7224	9.25
12	0.7014	9.95
13	0.6810	10.63
14	0.6611	11.30
15	0.6419	11.94
16	0.6232	12.56
17	0.6050	13.17
18	0.5874	13.75
19	0.5703	14.32
20	0.5537	14.88
21	0.5376	15.42
22	0.5219	15.94
23	0.5067	16.44
24	0.4919	16.94
25	0.4776	17.41

Given the 3% discount rate, it is possible to ascertain from this table the present value of a stream of payments of $1.00 per year, which start in year N and last for T years, by multiplying the appropriate number for T years from the right hand column by the number for N years from the left hand column. Thus, the present value of $7,491.50 per year commencing in year six and lasting until year 24 (for 19 years in total) is

$7,491.50 x 14.32 x 0.8375 = $89,845.

Part II. Applying Rehabilitation Techniques

Chapter 5

Restoring Fish Access and Rehabilitation of Spawning Sites

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INTRODUCTION

The Watershed Restoration Program was initiated to address the adverse impacts of past logging practices on fish populations and their habitats throughout British Columbia. Among the most detrimental impacts logging practices have had on fisheries resources are the elimination of migratory access and degradation of spawning habitats. This chapter describes the nature of these two impacts, criteria for assessing the magnitude of their effect on fisheries resources, and techniques to offset their effects. Because impacts to spawning areas are largely caused by hillslope disturbances through mass wasting and erosion, spawning habitat rehabilitation is generally contingent upon hillslope reclamation. Accessibility and spawning habitat are presented together in this chapter as these issues are closely related (restoration of access is perhaps the most cost-effective approach to re-establishing spawning production).

SEASONAL HABITAT REQUIREMENTS OF FISH

Small streams, rivers and lakes of British Columbia provide important habitats for anadromous and resident salmonid populations, including salmon, trout, char, grayling and whitefish. A brief description of the life history and habitat requirements of each species is presented below. For more detailed information refer to Bjornn and Reiser (1991).

Anadromous salmon return to their natal freshwater streams to spawn, generally between late summer and early winter. Chum and pink salmon fry emigrate from their natal streams to the sea shortly after hatching. In northern regions of the province, coho salmon rear in natal and non-natal streams and rivers for up to two years, while chinook salmon may rear in freshwater rivers and streams for up to one year. Further south, where water temperatures are higher, coho salmon typically rear for only one year and chinook salmon rear for only three to four months prior to migrating to the sea. Unlike the other Pacific salmon that spawn only in fluvial habitats, sockeye salmon also spawn in lake littoral areas. Sockeye salmon may also spend up to two years rearing

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in mainly freshwater lakes. Kokanee salmon are the landlocked race of sockeye salmon that reside in lakes through most or all of their life history. They spawn in the lower reaches of small lake tributaries, or within the lake littoral zones.

In coastal areas, cutthroat trout, rainbow trout and Dolly Varden char may exhibit either anadromous or resident life history patterns. Sea-run or coastal cutthroat are widespread in coastal systems and spawn in small streams between December and June. They typically rear in small streams but may also be found in larger rivers staying in freshwater from one to five years before migrating to the sea. Resident cutthroat trout spawn between February and May, and may spend their entire life cycle in their natal stream or river. Anadromous rainbow trout, or steelhead, spawn in coastal rivers and streams as well as tributaries to major inland river systems in late winter to late spring. Juveniles rear between one to five years (two and three years are most common) in streams and rivers prior to seaward migration. Resident rainbow trout also spawn in streams and rivers, where they may reside for their entire life cycle. Resident rainbow trout often migrate to lakes as juveniles in favour of greater food availability. They return to their natal streams where spawning typically occurs in the spring. Dolly Varden char usually migrate to the sea in the spring and return between August and September, while residents migrate to lakes at about the same time. They spawn during the fall in streams and rivers with medium to large gravels. Dolly Varden char may spend three to four years in their natal streams prior to emigrating to a lake or the sea. Bull trout display two distinct life history strategies, resident and migratory. Resident populations tend to spend their entire life history in small headwater streams, while migratory forms move downstream to larger rivers or lakes after spending several years in smaller streams. Migratory forms will return to the smaller streams to spawn after spending several years in the river or lake. Bull trout prefer cold water streams for spawning and rearing and often hybridize with Dolly Varden and brook trout. Brook trout are indigenous to northeastern North America, but have been introduced to a few streams in B.C. as a result of their appeal as a sport fish, as have brown trout to a few streams on Vancouver Island. Brook trout typically spawn in late summer or fall. Spawning occurs in the cool water of small headwater streams, although spawning may also occur in gravelly shallows of lakes.

Arctic grayling prefer the clear water of cool rivers, rocky creeks, and lakes. They migrate from these habitats to spawn in small streams at about the time of ice breakup, generally between April and June. Mountain whitefish are distributed throughout British Columbia, with the exception of coastal areas (except the Fraser Valley) and Vancouver Island. Mountain whitefish utilize a wide range of habitats for spawning. Some populations migrate from large rivers or lakes to spawn in smaller streams. Gravels within lake littoral zones are also utilized. Mountain whitefish generally spawn during the fall and the young emerge in early spring.

IMPACTS OF LOGGING PRACTICES ON FISH AND FISH HABITATS

Loss or Restriction of Fish Access

Logging and related practices have caused obstructions to fish passage as a result of road construction, instream activities, slope destabilization and altered hydrology. Perhaps the most common and widespread problem has been the improper culverting of streams during road construction. From a drainage perspective, culverts are hydraulically efficient conduits of water that tend to have a much smaller cross-sectional area than the natural stream in which they are installed. Consequently, water typically flows at a greater velocity and/or at a shallower depth through the culvert than in the natural stream, often resulting in conditions that restrict or prevent the upstream movement of fish. The relatively high velocity of water exiting the downstream end of a culvert can also cause the erosion and downcutting of the stream, resulting in the formation of a vertical drop that may prevent fish from accessing the lower end of the culvert. Culverts not designed to accommodate the passage of debris may become partially blocked at the upstream end, preventing fish from moving out of the culvert. The most underestimated impact is prevention of access for salmonid fry and parr to off-channel overwinter refuges of ponds, wetlands and small creeks that are often dry during summer.

Road construction in steep terrain often occurs at valley bottoms, within riparian or streamside areas. Roads constructed in close proximity to streams may interfere with their natural lateral movement and lead to erosion of the road fill material. In narrow valleys, roadways may force the stream into a narrower corridor, resulting in a stream reach characterized by a steeper gradient and higher velocities that may restrict or prevent fish passage. Road fills often isolate seasonally-flooded areas that are important off-channel and overwintering habitats.

Logging activities on hillsides above streams may contribute to slope destabilization and increased rates of runoff. The destabilization of slopes caused by forest harvesting operations and road building contributes to mass wasting and debris accumulation in streams. Coarse rock and debris may enter the stream channel and create a migration barrier. While large woody debris (LWD) in streams is generally considered a beneficial component of stream habitat, excessive debris resulting from past cross-stream or instream falling or yarding, excessive bank erosion or debris slides may result in impassable barriers. The accumulation of bedload within and/or upstream of a debris/log jam may render the jam impassable. A careful assessment of all debris/log jams is required to determine whether or not a passage problem exists since most log jams are beneficial in terms of their role in the creation of spawning, rearing and overwintering habitat.

Degradation of Spawning Habitat

The distribution of substrates within a stream is a reflection of various hydraulic, hydrologic, geomorphic and geologic characteristics. The particular combination of conditions that provide for clean, loose, suitably-sized spawning gravels can be disturbed by activities related to logging and road construction practices.

Removal of forest cover increases both the volume of water that is shed from an area and the rate at which it runs off. Consequently, peak flows in streams adjacent to or downstream of cleared areas tend to be greater, with impacts that include erosion of channel banks and floodplain areas, sedimentation of downstream habitats, and scouring of gravels. Fine sediments that settle out in spawning habitats cause decreased spawning success by filling the interstitial spaces between gravels, thereby "cementing" the substrates and impeding redd construction and fry emergence. Interstitial flow of water may be decreased, leading to depressed dissolved oxygen concentrations for developing eggs and alevins. Infilling of gravels with finer sediment also displaces the habitats of aquatic invertebrates, the primary food source for salmonids.

Sedimentation in streams may occur as a result of chronic soil washing from disturbed surfaces, or more abruptly in mass wasting events such as landslides or debris torrents. Instream activities such as operation of equipment within a stream channel or yarding of logs through a channel damage habitats directly. While causing sedimentation and bank erosion, such activities can also displace spawning fish, damage spawning redds, and cause egg mortality as a result of vibration during sensitive developmental stages. Clearing of riparian vegetation typically results in destabilization of the channel banks, loss of cover, and elimination of the primary source of large woody debris, which in many streams is critical for entrapment of spawning gravels.

HABITAT ASSESSMENT CRITERIA

Fish Access

The assessment of migration barriers is best performed during the period of migration. The primary migrations of concern are the upstream movement of adult fish to their spawning habitats, and the movement of juvenile fish into off-channel habitats. Most juveniles migrate to overwinter areas (lakes, ponds, wetlands, tributaries, larger rivers, groundwater discharge areas, etc.) in late summer to fall (an increase in flow or decrease in temperature may provide the cue for migration). The most direct means of assessing a potential migration barrier is to determine, by observation and/or sampling downstream and upstream of the potential barrier, whether or not fish movement is impeded. Obstructions to fish migration should be evaluated at various flow conditions since many obstructions prevent or restrict fish movement during only some flows. As the majority of migration barriers are those associated with either high water velocities or vertical drops, the swimming capabilities of the target species and lifestage (see Table 5-1) can be applied to assess potential access barriers.

Table 5-1. Swimming and jumping capabilities of some salmonids (adapted from Dane 1978).

Species and Lifestage		Maximum Swimming Speed ($m \cdot s^{-1}$)			Maximum Jump Height (m)
		Sustained	Prolonged	Burst	
coho/chinook:	adults	2.7	3.2	6.6	2.4
	juveniles (120 mm)		0.6		0.5
	juveniles (50 mm)		0.4		0.3
sockeye:	adults	1.0	3.1	6.3	2.1
	juveniles (130 mm)	0.5	0.7		
	juveniles (50 mm)	0.2	0.4	0.6	
chum/pink:	adults	1.0	2.3	4.6	1.5
steelhead	adults	1.4	4.2	8.1	3.4
cutthroat/rainbow:	adults	0.9	1.8	4.3	1.5
	juveniles (125 mm)	0.4	0.7	1.1	0.6
	juveniles (50 mm)	0.1	0.3	0.4	0.3
Arctic grayling	adults	0.8	2.1	4.3	1.0
whitefish	adults	0.4	1.3	2.7	1.0

Sustained swimming speeds are the swimming velocities that can be maintained for extended periods of time. Prolonged speeds are swimming velocities that can be maintained for passage through difficult areas. Burst speeds are for escape and feeding. In addition to a species' maximum jump height, the ability to jump a vertical obstacle is also related to the depth of water from which a fish can leap. A pool depth of at least 1.25 times the height of the obstacle provides for ideal leaping conditions.

Spawning Habitat

The occurrence of spawning habitat is primarily a reflection of prevailing hydrological conditions. Since features such as water depth and velocity can be calculated based on hydraulic analyses, it is not necessary to conduct the assessment of spawning habitat during the spawning period. However, assessments of spawning habitat (or potential spawning habitat) can be aided by observations of spawners (utilizing nearby sites, avoiding subject site, etc.). The assessment should include a review of site conditions during typical spawning season flows and peak flows (to assess habitat stability). Assessment of (potential) spawning areas generally involves evaluation of at least the following conditions: water depths, velocities, substrate composition, channel gradient, site accessibility, and space. Some of these criteria are presented in Table 5-2.

Table 5-2. Water depth, velocity and substrate size criteria for some salmonids.

Species	Minimum Depth (m)	Velocity ($m \cdot sec^{-1}$)	Substrate Size (mm)	Mean Redd Area (m^2)	Req'd Area per Spawning Pair (m^2)
fall chinook salmon	0.24	0.30 - 0.91	13 - 102	5.1	20.1
spring chinook salmon	0.24	0.30 - 0.91	13 - 102	3.3	13.4
summer chinook salmon	0.30	0.32 - 1.09	13 - 102	5.1	20.1
chum salmon	0.18	0.46 - 1.01	13 - 102	2.3	9.2
coho salmon	0.18	0.30 - 0.91	13 - 102	2.8	11.7
pink salmon	0.15	0.21 - 1.01	13 - 102	0.6	0.6
sockeye salmon	0.15	0.21 - 1.07	13 - 102	1.8	6.7
kokanee	0.06	0.15 - 0.91	13 - 102	0.3	0.15
steelhead	0.24	0.40 - 0.91	6 - 102	4.4 - 5.4	
rainbow trout	0.18	0.48 - 0 91	6 - 52	0.2	
cutthroat trout	0.06	0.11 - 0.72	6 - 102	0.09 - 0.9	

METHODS FOR RESTORING FISH ACCESS

There are four common types of naturally occurring obstructions to fish movement, of which two may be associated with logging-related activities: log/debris jams and blockages resulting from rapid mass movements. Two other types of obstruction, falls/inclines and beaver dams, are not generally related to logging activities, although the latter may be promoted by the conversion of coniferous forest to deciduous forest, such as red alder in the coastal lowlands. Falls/inclines are addressed in this chapter as they offer a means of mitigating logging impacts. Beaver dams are treated in a separate chapter. Providing fish passage at impassable culverts is discussed.

Log/Debris Jam Removal

Log and/or debris jams occur where trees and other woody debris accumulate in stream channels, often trapping sediment within and upstream of the jam. Most log and debris jams do not block fish passage completely or degrade habitat significantly. In fact, habitat quality for rearing species are typically improved by the jam and, therefore, it is critical that modification of a jam be undertaken only after it has been **proven** to prevent fish passage, degrade habitat, or pose a risk to public safety. Several techniques may be applied to remove log and debris jams. Small jams can be selectively opened manually employing tools such as chainsaws, winches, or a block and tackle equipped with a choker or grapple hook. Larger jams may be selectively adjusted with a commercial log yarder, skidder or an excavator equipped with a "thumb". Debris should be transported to a disposal site above the flood level of the stream. In extreme cases, such as large jams in locations where there is no access for machinery, blasting may be appropriate. This approach is dangerous (requiring specially trained personnel) and may be expensive. A fish salvage must be undertaken prior to blasting. Current practices leave some log jam components intact and secured to large boulders (see Chapter 9) as cover and refugia for fish.

Debris and Rockslide Removal

Rapid mass movements such as debris flows, rock slides and avalanches may introduce coarse material into the stream channel and decrease passage area. Resultant changes in the hydraulic geometry such as increased channel gradient or water velocity may prevent or limit fish passage. As rapid mass movement events typically occur without warning, prompt action may be required, particularly if the event occurs during a fish migration period. The sediment and debris introduced into the channel must be removed to re-establish a pathway for the fish. The recommended slide removal technique is dependent on the accessibility of the site to work crews and/or machinery, and the volume and size of material to be removed. Manual removal of material may be possible for small slides consisting of predominantly non-bouldery sediment. Useful tools include shovels and crowbars. Large rocks can be fragmented with explosive or non-explosive fracturing agents, and moved with a winch, or block and tackle. If machinery access is available, a bulldozer or excavator may be employed to shift debris and open the channel. Sediment and debris may also be loaded into a sling and moved with a helicopter. Slide removal should be avoided during spawning and incubation periods as the detrimental impacts of fine sediment washed downstream during the operation may outweigh the positive benefits of obstruction removal. Alternatives include construction of a bypass route for the fish, or capture and transport of the fish past the slide.

Falls and inclines occur on bedrock-controlled stream reaches. A fall occurs where the stream gradient increases abruptly to near vertical. An incline is a steep reach with water velocities that exceed the maximum swimming capabilities of the target species. Falls and inclines may be rendered passable by altering the stream geometry to create hydraulic conditions within the swimming and jumping capabilities of migrating salmonids. Such morphologic changes typically require the selective removal of bedrock by blasting or breaking and, therefore, generally require personnel with specialized training. Obstruction removal at a fall may be achieved by decreasing the height of the jump or increasing the depth of the plunge pool (employ the guideline of jump height-to-pool depth ratio of 1-to-1.25, subject to maximum jump height for target species). Incline passage may be accomplished by blasting a series of pools and steps into the streambed to increase the roughness of the channel and to create areas of lower water velocities. In the Watershed Restoration Program, making bedrock falls passable would be supported as a mitigation alternative where habitat elsewhere in the watershed has been degraded beyond rehabilitation.

Restoring Access at Culverts

Culverts may hinder or prevent passage of adult fish due to high water velocity, insufficient water depth, elevated outlet or debris accumulation. Hydraulic criteria that should be adhered to in culvert design and construction include the following for the fish migration period. For adult salmon migration, average water velocity should not exceed 1.2 m·sec^{-1} and 0.9 m·sec^{-1} for culverts less than and greater than 24.4 m, respectively (see Table 5-1). Water depth should not be less than 0.23 m at any point within the culvert. Any sudden drop in the water surface profile should not exceed 0.31 m. During the period of upstream migration, the length of time during which the foregoing conditions are not met at the culvert site should not exceed three consecutive days in an average year. Culverts that do not achieve these conditions can be either reconstructed or modified to provide unobstructed fish passage. Baffles can be installed within culverts (either at the time of construction or retrofitted) to decrease water velocities and increase water depths within the culvert (see Fig. 5-1). Tailwater control devices can be installed to create a resting pool at the downstream end of the culvert, backflood the culvert (thereby increasing depths and decreasing velocities), and control erosion downstream of the culvert. All new culverts should be installed 0.30 m below the natural grade line of the stream (to allow for natural substrates to line the culvert bottom) and should be sized to accommodate the 100-year flood. Structures that preserve the natural streambed, such as clear-span bridges and open-bottom arch culverts (see Fig. 5-2), are optimal in terms of preserving both habitat values and fish passability. Culverts should be designed and installed to prevent scouring and downcutting of the streambed, thereby preventing the formation of an access obstruction. Many restoration projects focus on addressing the damage caused by this. Trash racks should be installed at the upstream end of the culvert, or additional culvert capacity should be provided for passage of debris.

Figure 5-1. Baffles in this culvert alter hydraulic conditions to improve fish passage.

Figure 5-2. This culvert has addressed fish passage by providing a semi-natural streambed throughout.

Culverts also hinder or prevent passage of fry and other juvenile (parr) fish, which must relocate to more stable or warmer (groundwater) overwinter habitats and refugia to survive through the harsh flood or winter conditions. Culverts linking main channel habitats with overwinter (off-channel) habitats should be designed and installed to provide low velocities required by juvenile fish including fry. Access to overwinter habitats for juvenile coho and trout is particularly critical at larger creeks and rivers destabilized by logging activities. The culverts in Figure 5-3 prevent juvenile fish from accessing important overwintering areas, while the timber bridge in Figure 5-4 provides for unrestricted access of all fish. Estimated costs for access restoration projects are provided in Table 5-3.

SPAWNING HABITAT REHABILITATION

Streambed composition at any site is a function of local and regional factors, including geologic, geomorphic, hydrologic and hydraulic parameters. Where spawning habitat exists naturally, these factors work in concert to provide a supply of gravels and conditions that maintain both the quantity and quality of those gravels. Where degradation of spawning habitat has occurred, the primary objective is to re-establish the conditions that provide for ideal spawning habitat. Typically, it will be necessary to precede instream restoration works with hillslope restoration techniques, as outlined in WRP Technical Circular No. 3 (Moore 1994) and Ministry of Forests Land Management Handbook 18 (Chatwin et al. 1994). Stream bank stabilization techniques may also need to be applied prior to commencement of spawning habitat rehabilitation. Similarly, spawning habitat can be developed at sites where it did not naturally occur, as an approach to offset losses and degradation elsewhere.

Figure 5-3. Juvenile fish are generally incapable of entering and/or swimming through poorly installed culverts.

Figure 5-4. This timber bridge retains the natural streambed and provides for passage of juvenile fish.

Table 5-3. Approximate costs for selected access restoration projects.

Project Type	Approximate Costs	Comments
log/debris jam removal - small jams	\$50-100 per m^3 debris	• manual labour and equipment • debris disposed of on-site
log/debris jam removal - large jams	\$5-10 per m^3 debris	• excavator (or heavy machinery) • debris disposed of on-site
rockslide removal	\$15-30 per m^3 rock	• bulldozer and/or excavator • trucks used to haul off-site
fall/incline modification	\$25-50 per m^3 rock	• performed by certified blaster • manual removal of fragments
culvert replacement - circular pipe	\$450-700 per linear m	• 1600 mm ∅ corrugated steel pipe • moderate depth below road grade • not including headwalls
culvert modification - tailwater control	\$30-100 per linear m	• excavator and manual labour • small (<1600 mm) ∅ culverts • using materials available on-site

Fish with extended rearing phases, such as steelhead and coho, tend not to be limited by the quantity of spawning habitat unless highly degraded. Therefore, the rehabilitation of spawning areas would rarely be directed at these and other species with stream rearing periods of one year or more.

Potential rehabilitation sites must be assessed carefully by appropriately skilled personnel, as improperly designed or constructed works will typically fail and result in further degradation of habitat. Situations that should be avoided include channels that are laterally or vertically unstable, streams that carry large volumes of bedload, and streams with steep gradients (over 2 - 4%). Structural designs that tend to fail least often include those that involve minimal modification of the pre-existing conditions. Factors that must be considered in the siting and design of spawning habitat improvement projects include stability and size of material used, structural durability, and stream characteristics (bed and bank stability, sediment load, gradient, and discharge regime). Ideally, any rehabilitation of spawning areas would be located in areas of natural upwelling, which are typically dictated by variations in streambed elevation. Methods for improving the quality and quantity of existing spawning habitats, and the creation of additional spawning habitat, are described below.

A relatively high degree of success can be achieved in increasing the productive capacity of a stream by stabilization of historically valuable spawning habitat and by reducing sediment transport from degraded hillsides to spawning areas. The accumulation of fine sediments and the scouring of gravels are the two primary causes of spawning habitat degradation. Sites that have been degraded by accumulation of fine sediment over spawning gravel can be restored by either cleaning or replacing the gravels, although use of these techniques is rarely recommended because they will not be maintained by natural processes. In either case, however, it is critical to ensure that the recruitment of fine sediment from upstream is curtailed by either slope or channel stabilization.

Gravel Cleaning

Cleaning of gravels at potential or historic spawning sites is only conducted during periods of moderate to high streamflow such that the stream will sort the gravels and promote the downstream transport of fines. The most frequently used techniques for cleaning spawning gravels include large-scale mechanical scarification using bulldozers or excavators, and small-scale manual scarification using hand tools or high pressure jets to expose subsurface gravels to the streamflow and force fines up into the current (Adams and Whyte 1990). Gravel cleaning projects should be initiated at the upstream limit of spawning areas and proceed downstream. All cleaning projects should be monitored for future maintenance requirements.

Gravel Placement

Placement of gravel should be limited to extended stable reaches that lack a natural source of gravel, display characteristics that are conducive to gravel retention (see Figs. 5-5 and 5-6) and have little or no sediment transport from hillside impacts. The greatest success has generally been achieved at sites downstream of lakes and reservoirs, and at groundwater-fed channels, where streamflow is relatively stable. In other stream settings it may be necessary to install instream structures such as control weirs to prevent the downstream transport of the placed gravels.

Spawning substrates should be consistent with the optimal substrate size for the target species. For most species of salmonids, the general guideline is approximately 80% of 10 to 50 mm gravel with the remaining 20% made up of 100 mm gravel and a small portion of coarse sand (2 to 5 mm). Tractive force calculations should be performed to determine whether the placed gravels would be stable.

Figure 5-5. Gravels placed at this site were not suited to the energy regime of the stream and, as a result, have been washed downstream.

Figure 5-6. The gravels placed in 1995 at this site are stable and free of sediment as a result of proper planning and site assessment.

Gravel Catchment Structures

Salmonids typically spawn in riffles where particular substrate and flow characteristics occur. With gravel catchment structures or "spawning platforms", emphasis should be on designs that emulate the hydraulic conditions that cause riffles to develop. Riffles are features that generally occur in association with pools, therefore, instream structures should address the natural pool-riffle (or scour and deposition) sequencing. A variety of full spanning and partial spanning structures have been successfully employed to create these sequences.

Full spanning structures can be used to re-establish natural pool-riffle sequences and/or trap gravels in reaches where they have been washed away. A simple full spanning rock weir involves a row of large diameter rocks placed across the stream to accumulate smaller substrates on the upstream side. A riffle template (Fig. 5-7) is a more stable structural design. Created in series, riffle template spacing should reflect the natural pattern within the stream and generally range between one and six times the bankfull width. An example of a stable riffle template is shown in Figure 5-8; a riffle template destabilized due to improper construction is shown in Figure 5-9. Refer to Chapter 12 for further information on riffle construction. On smaller stable streams, logs may be used in place of rock to construct a full spanning weir. However, full-spanning structures are generally not recommended owing to risks to long-term stability and the potential for creation of stagnant backwater areas upstream (slopes < 15%).

Partial spanning structures can be used to create spawning habitat on a more localized basis (Frissell and Nawa 1992). Examples include wing deflectors (single or paired on opposing banks) and groynes. These structures can be constructed with either large rocks or logs extending outwards from the stream bank in an upstream direction, and located at a low profile relative to the streambed (see Figs. 5-10 and 5-11). Failure has often resulted from deflectors being set too high in the water column, or at angles that direct flow towards the opposite stream bank (Fig. 5-12).

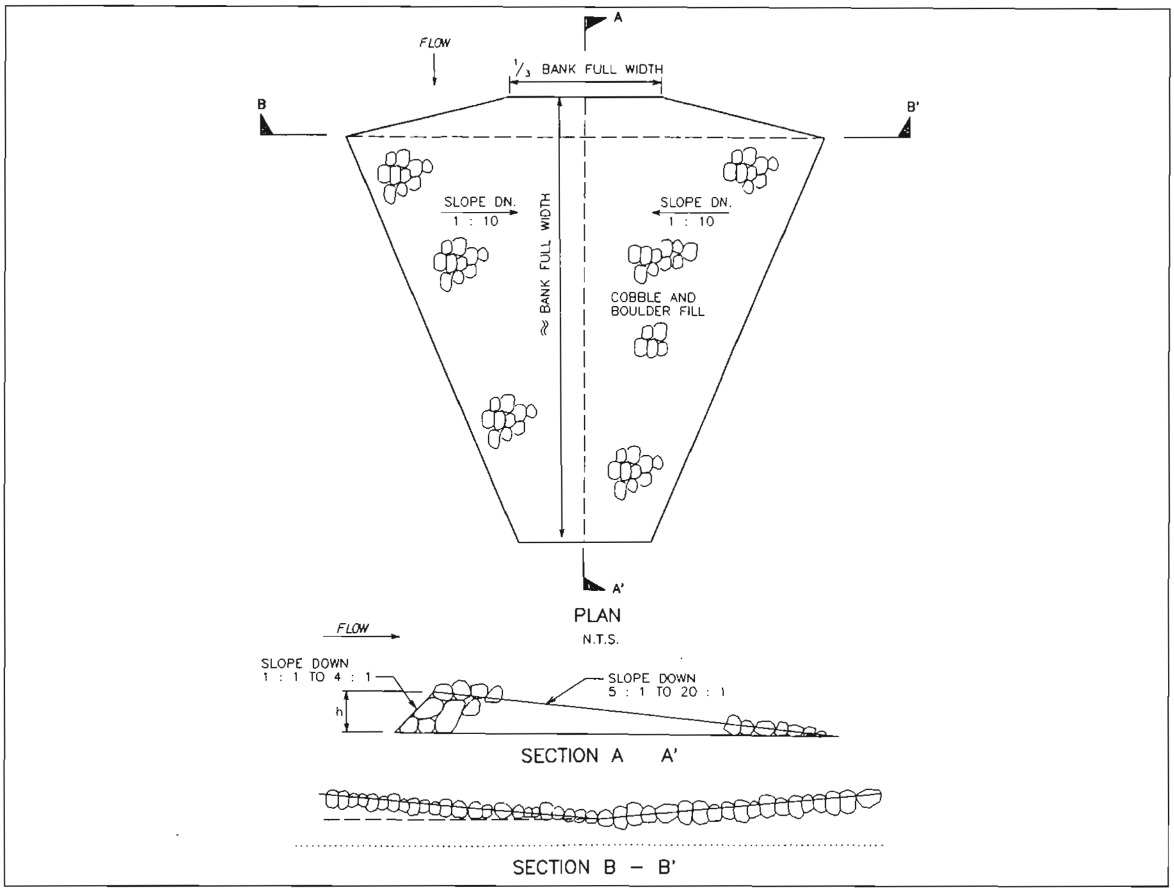

Figure 5-7. Design characteristics of a riffle template.

Figure 5-8. Aerial view of a riffle template to create spawning habitat. Large boulders are located at the crest of the riffle to provide stability.

Figure 5-9. Movement of undersized boulders from the crest of a created riffle template resulting in the loss of downstream spawning habitat.

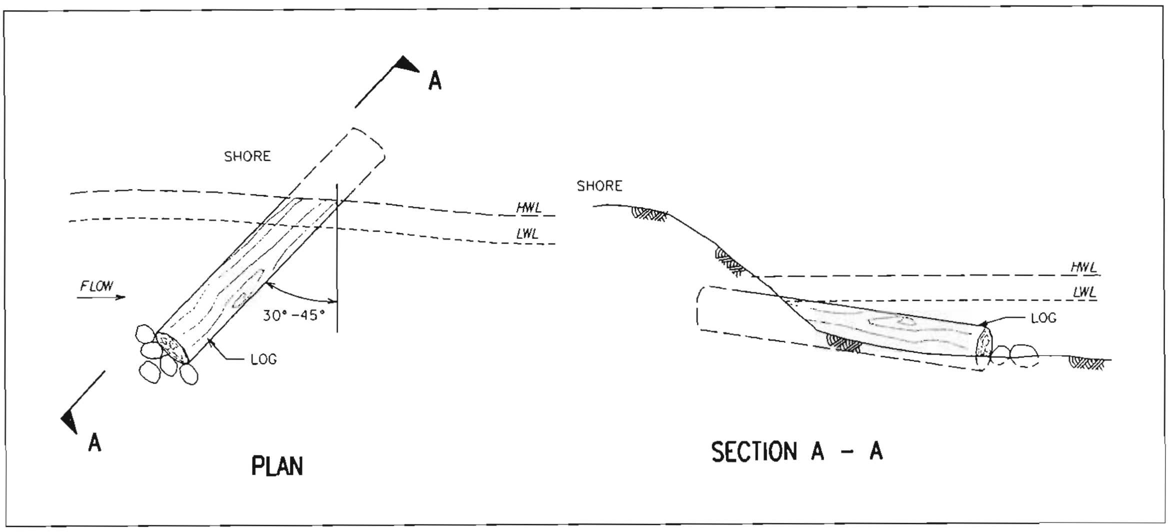

Figure 5-10. Design characteristics of a log deflector.

Figure 5-11. Log deflector extending halfway across channel. A pool has formed downstream of the deflector, with gravels accumulating upstream of the deflector and at the tail of the pool.

Figure 5-12. Log weir that has been seriously undermined as a result of being installed perpendicular to the bank and too high in the water column.

Creation of Side-channel Spawning Areas

Bank erosion, bed scour and sediment transport often limit the economic feasibility of in-channel structures due to high maintenance costs. In many streams, the most effective habitat rehabilitation projects may be the creation or re-establishment of side-channel and back-channel habitat. Candidate project sites should have an adequate water supply, provide the opportunity to construct a channel with sufficient gradient to allow creation of a diversity of habitat types, and be located in proximity to existing spawning areas. Ideal sites are often located on alluvial fans or near valley wall edges where groundwater percolation may be expected. Groundwater studies should always be completed as an initial step to ascertain that a consistent flow would be available during critical periods. Additional details on site selection are provided in Chapter 7.

Development of side-channels that are open to the main channel at their upstream end must be planned and constructed with care in order to minimize maintenance problems. Accumulation of sediment or debris at the upstream end is a common difficulty. Debris screens and modified water intakes at the upstream end have proven successful, but site-specific design is critical.

Costs of Spawning Habitat Rehabilitation

Estimated costs for example spawning habitat rehabilitation projects are provided in Table 5-4. To reiterate, hillslope rehabilitation is a requisite to undertaking these measures and their application is site-specific.

Table 5-4. Approximate costs for selected spawning habitat rehabilitation projects.

Project Type	Approximate Costs	Comments
Gravel cleaning - mechanical scarification	$5-20 per m^2	• bulldozer working instream • streams over 10 m wide
Gravel cleaning - manual	$20-50 per m^2	• high pressure hose • small, shallow streams
Gravel placement	$50-70 per m^3 gravel	• washed/sorted gravel supplied • limited delivery distance • machine placed • not incl. control structures
Riffle template construction	$20-50 per m^3 rock	• natural source of rock available • rock transported a limited distance • excavator placed
Log deflector installation	$50-100 per linear (instream) m	• logs available at no cost • excavator placed and backfilled
Side-channel development	$50-150 per m^2	• shallow/moderate excavation depth • excavated material disposed on-site • water supply not included

APPROVALS

All aspects of instream work require an environmental approval issued by the Ministry of Environment, Lands and Parks. Approvals include a list of conditions that must be adhered to, typically including seasonal restrictions and requirements to perform fish salvages and site dewatering. Refer to Chapter 1 on habitat protection and approvals for further information.

Chapter 6

Rehabilitating Stream Banks

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INTRODUCTION

Bank erosion is a natural process that may be considered beneficial or detrimental, depending upon the associated environmental or socioeconomic concerns. Stream channels respond to inputs of water, sediment and woody debris, forming dynamic links between hillslopes and riparian areas in the watershed. Anthropogenic activities such as forest harvesting may affect channel processes through changes in the intensity, timing of delivery and total yield of sediment and water from the hillslopes. Impacts to riparian vegetation from streamside forest harvesting, farming and ranching practices have further altered sediment loading and woody debris structure within channels. Bank erosion may lead to a degradation of fish habitat through loss of protective cover, reduced channel depths, increased stream temperatures, infilled pools and smothered spawning gravels. In some instances, rehabilitation of stream banks may positively contribute to the rehabilitation of fish habitat and, in turn, fish populations.

This chapter describes the rehabilitation of stream banks that have been impacted by historical logging practices. It includes a section on the assessment of a site-specific need to stabilize eroding stream banks, and describes the most suitable stabilization techniques as a function of the fluvial environment. Central to the techniques presented is the need for a multiple objective treatment approach that simultaneously addresses bank stabilization and fish habitat requirements.

FLUVIAL PROCESSES

Alluvial channels accommodate variability in water and sediment discharge through adjustments in cross-sectional area and shape, slope, channel pattern, bed structure or bed material characteristics. Non-alluvial channels are not discussed because, as described in the Channel Assessment Procedures (CAP) (Anon. 1996a,b), "land management practices cannot affect either the bed or the banks of the channel". In many reaches, bank erosion is discontinuous and short-term erosion rates are based on interdependent processes such as sediment deposition adjacent to eroding banks. Width is typically the most adjustable component of channel geometry, but adjustments in width or planform are highly dependent on the resistance of channel banks to erosion.

Natural bank erosion may be initiated or accelerated by many processes including:

- increased sediment load within a reach,
- higher than average floods, particularly extreme discharges which follow several years of sub-average flows (pioneer vegetation may have provided short-term bank stabilization),

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- migration of river forms or channel avulsions,
- increased woody debris,
- bank failures unrelated to fluvial processes (e.g., freeze-thaw),
- local flow deflection (e.g., woody debris),
- wave action.

Similarly, anthropogenic activities such as logging may initiate or accelerate bank erosion by:

- increasing sediment or water discharge,
- increasing magnitude and flashiness of extreme sediment or water discharges,
- decreasing bank strength through removal of riparian vegetation or altering groundwater regimes,
- increasing current speeds or turbulence by encroachments or channel realignment,
- increasing the angle of thalweg impingement onto banks by channel realignment,
- increasing current speeds as a result of increased slope following channel realignment,
- reducing present and future sources of large woody debris which stabilize channel beds.

Although there are numerous causes of bank erosion, the actual failure of bank material is typically a result of hydraulic and/or geotechnical processes. **Hydraulic failure** occurs if water flow in a channel exerts a stress that exceeds the critical shear stress for sediment transport. This occurs where current speeds along the bank are high, particularly along the outside bank of a river bend where secondary flow directs water downward towards the toe of the bank. **Geotechnical failure** occurs if gravitational forces acting on the bank material exceed the strength of the resisting forces. This process commonly occurs during recession of flood waters as saturated banks collapse due to diminished soil strength.

Most bank failures are associated with a combination of hydraulic and geotechnical factors (e.g., undermining by hydraulic forces leading to slumps or block-type geotechnical failures), but the type of failure is often related to the characteristics of the bank material. **Noncohesive** banks are made primarily of sand and gravel, and erosion is controlled by the direction and magnitude of flow velocities at the bank, particle characteristics, gravitational forces and turbulence (i.e., hydraulic failure). In contrast, **cohesive** banks contain clay minerals, which produce strong chemical and electrochemical bonds between the particles, and geotechnical failure is more common. **Interbedded** cohesive and noncohesive layers within a stream bank are fairly common, and these heterogeneous banks may be eroded by hydraulic or geotechnical processes. Typically, the erodability of interbedded banks is controlled by the thickness and position of the noncohesive layers.

Several studies have shown that the average rate of erosion for alluvial streams is roughly proportional to the drainage basin area. The potential or normal rates of erosion for a particular bank or bend have been related to several factors, such as bank vegetation, the ratio of width to radius of curvature, bank height and material. Unfortunately, no general formulae relating these factors to relative erosional resistance exist because of the strong dependence on transient conditions such as antecedent moisture levels or the presence of protective basal accumulations.

GUIDELINES FOR ASSESSING STREAM BANK REHABILITATION NEEDS

The likelihood of formulating a successful[4] stream bank rehabilitation prescription will be increased by carefully considering the geomorphic and hydrologic setting. Several parameters may be used to help identify the cause of bank erosion and to assess the probability of channel recovery[5] following bank stabilization. If rehabilitation of fish habitat is not the prime objective (i.e., protection of built structures, transportation corridors or human lives), channel recovery may not be an implicit goal. However, assuming that fish habitat rehabilitation is the prime objective, prioritization within a watershed should depend upon the type of channel instability present and the potential benefits to fish habitat.

An assessment of the geomorphic and hydrologic setting is usually required to:

- determine the history and spatial extent of bank erosion,
- determine the cause of bank erosion, as related to the state of stability,
- predict the likelihood of channel recovery and habitat benefits following bank stabilization.

Field inspections utilizing channel assessment techniques (Anon. 1996a, b; Hogan et al. 1997) will often indicate the geomorphic setting and recent channel responses. It is necessary to examine the stream bank in a number of spatial perspectives and place the erosion into a historic context. This should begin by determining the planform changes as documented by air photos, maps and anecdotal information. Visibility of historic channel response from air photos will depend on the channel size, photo scale and riparian cover. For typical 1:20,000 scale air photos, identification of river morphology may be limited to channels exceeding 20 m in width. Prioritization techniques described in this chapter are typically appropriate for fluvial systems having stream classes of third-order or greater, based on 1:50,000 scale maps. The general principles also apply to smaller channels, but the impacts of forest harvesting relating to changes in sediment and water delivery to small[6] channels usually manifest as changes in bed morphology, rather than bank stability. Planform changes should be analyzed over at least three reaches upstream and downstream of the erosion site; reach differentiation is described in the CAP. The parameters to be documented include:

- bankfull width: the width of the channel as measured during the bankfull discharge, often statistically defined as the 1.5 year recurrence interval discharge. Field determination of the bankfull width is described in the channel assessment.

- channel sinuosity: ratio of stream length to valley length; also described as the ratio of valley slope to channel slope.

- bank erosion rates: the migration of a river bank may be determined by comparing the relative locations of the bank line over time, or by comparing the position of the bank line to a point fixed in space over the period of comparison. If photo coverage allows, the erosion rates should be calculated at approximately 5 to 10-year intervals over the period of air photo coverage. Short-term migration rates calculated from one or two intervals are often not representative of long-term averages.

[4] The "success" of a fish habitat rehabilitation program should include physical and biological components. Structures should form the desired stream habitat feature, persist over the intended lifespan and be utilized by the targeted fish species or age class (Hartman and Miles 1995).
[5] Channel recovery or restoration to a predisturbed state is discussed in Chapter 2.
[6] Small channels typically have bankfull widths less than 10 m, with individual clasts constituting significant form elements on the channel bed.

Consideration of these three factors will allow the stream response through time to be classified as dynamic stability, localized instability or long-term instability. A stream reach displays a state of **"dynamic stability"** if its energy is at a level that allows sediment loads entering the reach to equal those leaving it, and if there are no long-term net changes in hydraulic geometry. It should be expected that bank erosion rates, sinuosity and bankfull width will have remained approximately constant, or have not shown progressive increases or decreases over the inspection period. Dynamic stability may also be examined by assessing the cross-sectional form factor, or ratio of bankfull width to depth. If the percentage of silt and clay in the banks (B) exceeds 5%, a stable form factor will be less than 10-15. However, if B is less than 5%, stable form factors will be greater than 10, and will often exceed 40. A bank that maintains a form factor out of the expected range indicates a lack of dynamic stability. Examination of channel bar form as described in Hogan et al. (1997) may also elucidate these relations.

Often, accelerated bank erosion or progressive increases in bankfull width or sinuosity occur as a result of increased sediment load or discharge. If the stream response is restricted to specific banks or reaches, it is termed a **localized instability**. For example, a slug of coarse sediment introduced into a stream channel by a landslide may take decades to be flushed through the fluvial system. As it passes through downstream reaches, bank erosion will be atypically high in magnitude or different in nature than erosion experienced at the site in the recent past. This may last for several years as the sediment load is redistributed and the cross-sectional parameters respond to localized slope or velocity changes, but erosion rates should return to "normal" levels following passage, and re-occupation of the floodplain by pioneer vegetation.

By contrast, if sinuosity, bankfull width or bank erosion rates have been highly variable for several decades over an extensive stream length, the stream reaches may display a more general **long-term instability**. It is typical of stream reaches that include structural elements such as gradient breaks or highly erodible non-alluvial banks. It may also be expected if a channel has been impacted by several significant variations in sediment load or discharge.

In order to prioritize the rehabilitation of stream banks, it is necessary to consider the expected future lateral activity of the channel, the channel recovery following bank rehabilitation and the potential habitat benefits. These factors are represented by the planform changes, the entrenchment ratio and the bank material, respectively.

The expected channel activity may be ascertained from the planform changes based on the inspection of air photos and maps. **Regular** lateral activity displays orderly lateral and/or downvalley meander progression, often combined with neck cutoffs (Fig. 6-1). However, **irregular** lateral activity displays an apparently chaotic pattern of channel activity dominated by avulsions and formation of chutes, side-channels and sloughs (Fig. 6-2). Attempts to stabilize banks, which have displayed regular lateral activity, are typically not recommended. Manipulation of channel parameters will often produce an undesired response as the channel attempts to attain a new post-manipulation equilibrium. Associated changes in the magnitude and direction of current speeds or the water surface slope may have adverse impacts on reaches upstream or downstream of the rehabilitated site. Stabilization of banks with irregular instability pose a lower risk to inducing morphologic adjustments elsewhere, but the design should include structures to minimize the risk of flows outflanking the bank rehabilitation (e.g., tiebacks).

As a general guide, the recovery of a channel is related to its vertical containment or degree of incision[7]. This "entrenchment" distinguishes whether the flat adjacent to the channel is a contemporary floodplain, or if it has been inherited (i.e., non-alluvial) or abandoned due to incision. Rosgen (1994) defines the entrenchment ratio as the ratio of the width of the flood-prone area to the bankfull width. The flood-prone area is defined as the width measured at an elevation, which is determined at twice the maximum bankfull depth. If the entrenchment ratio is less than approximately 1.4, the channel does not have a large overbank area to accommodate flood flows, and the natural recovery (once the cause of instability is corrected) will be fair to poor. However, entrenchment ratios exceeding approximately 2.2 indicate a greater likelihood of channel recovery. Entrenchment ratios over the lifespan of the bank stabilization project may change if the channel aggrades or degrades; this likelihood must be considered during prioritization.

Figure 6-1. Regular lateral activity - North Thompson River, B.C. (1:31,700).

Figure 6-2. Irregular lateral activity - Chilliwack River, B.C. (1:9,100).

Lastly, the potential habitat benefits of bank stabilization are related to the type and amount of material added to the stream. Stream banks composed of well-sorted cobbles and gravels are good sources of spawning and rearing substrates. However, inputs of fine sand, silt and clay may adversely affect fish habitat by filling pools and smothering spawning gravels. For the purpose of the risk ranking provided, it is assumed that cohesive banks include materials that will have an adverse impact on fish habitat, while non-cohesive banks do not. This is a generalization that must be considered carefully, depending upon the volume and rate of sediment delivery to the channel, the type of habitat, which may be impacted and the relative proportions of fine sand and silt in the bank.

The following table incorporates these three parameters and relates them to the type of instability in order to provide a relative prioritization for stream bank rehabilitation (Table 6-1). This table should serve as an assessment tool to assist preliminary investigations; it is not

[7] Factors such as the future magnitude and frequency of extreme inputs of water or sediment discharge to the channel are also important, and should be considered if air photo analyses or field observations allow reasonable extrapolation of future events (e.g., location of sediment wedges relative to potential rehabilitation site).

intended to provide recommendations that supercede site-specific review by individuals with training and field experience in assessing river forms and processes.

If the bank erosion has direct adverse impacts upon fish habitat, particularly if the habitat affected has been identified as a limiting factor, the priority should be elevated. A similar adjustment should be made if the bank erosion will have a significant impact on the overall sediment load in the stream, or on the proportion of bedload versus suspended load transported by the stream.

Table 6-1. Prioritization of bank stabilization for habitat rehabilitation.

Bank Material	Planform Changes	Entrenchment Ratio	Type Of Instability		
			Dynamic Stability	Long-term Instability	Localized Instability
cohesive	irregular	1.4 - 2.2	L	M	H
cohesive	irregular	<1.4	L	M	H
cohesive	regular	>2.2	L	M	M
cohesive	regular	1.4 - 2.2	L	L	M
cohesive	regular	<1.4	L	L	M
non-cohesive	irregular	>2.2	L	L	M
non-cohesive	irregular	1.4 - 2.2	L	L	M
non-cohesive	irregular	<1.4	L	L	L
non-cohesive	regular	>2.2	L	L	L
non-cohesive	regular	1.4 - 2.2	L	L	L
non-cohesive	regular	<1.4	L	L	L

Note: L, M, H = Low, Medium and High Priority.

BANK STABILIZATION TECHNIQUES

There are many techniques that may be employed to control bank erosion. Selection of the most appropriate approach requires careful consideration of project objectives, habitat issues, site conditions, and budgetary constraints. To clarify descriptions of the bank protection methods, stream banks have been differentiated into three general zones (Fig. 6-3). The **Toe Zone** is that portion of the bank normally inundated, located between the ordinary high water (OHW) and low water levels. This zone is often quite erosion-prone due to exposure to river currents, debris and repeated wet-dry cycles. The **Bank Zone** is that portion of the bank inundated for short periods annually, located between the OHW and the bankfull level. In addition to exposure to river currents and debris, these sites may also be subject to impacts from human and animal traffic. The **Overbank Area** is that portion of the bank inundated when the stream exceeds bankfull levels. During dry periods, soil moisture is primarily dependent upon rainfall.

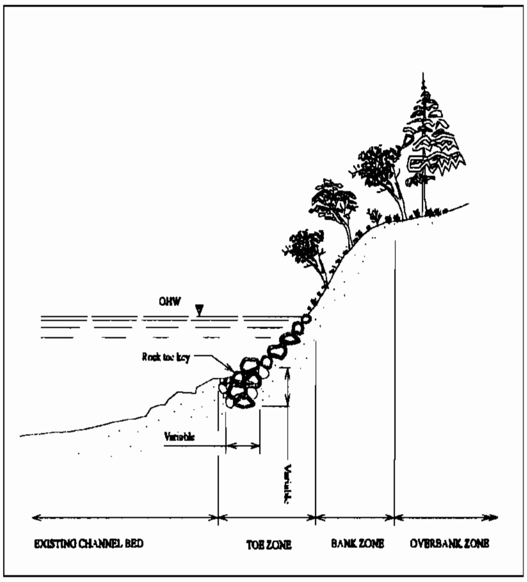

Figure 6-3. Stream bank zones.

Bank stabilization techniques may be classified as one of three structural types:

1. Rock methods employ large boulders or riprap to armor the bank or redirect flows. Types include: rock toe keys, groynes, rock revetments, turning rocks and tie-backs.

2. Vegetative methods utilize plants or plant cuttings for bank stabilization. Types include: herbaceous ground cover, rooted stock, live cuttings, fascines, brush mattresses and brush layers.

3. Integrated methods incorporate a variety of materials such as rock, timber, soil or plants, and may also include fabrics such as jute or coir mesh. Types include: joint planting, vegetated geogrids, live cribwalls, tree revetments and large woody debris.

For all three types, design criteria must include the following, at a minimum:

- design flows (WRP uses a 1 in 50-year event) to determine the associated design stage and bank velocity,
- maximum slope angle, current speeds or water surface slopes,
- use of filter materials to prevent loss of underlying fines,
- toe protection or suitable foundation treatments to guard against undermining,
- protection to reduce the risk of overtopping or outflanking,
- incorporation of habitat features for fish,
- access and right-of-way areas,
- source areas for rock or vegetative materials,
- proposed areas of cut and fill.

Rock Methods

Rock methods have been employed to stabilize eroding banks for many decades in British Columbia and elsewhere; the design concepts and criteria are well-established. The methods can be costly, but proper design and careful construction followed by regular inspection and maintenance provide effective protection for eroding banks in a wide range of fluvial environments. The possibilities for habitat enhancement include placement of large rocks at a mean annual flow depth or construction of rock benches to induce eddies or shear zones, which may be utilized by fish as resting and rearing sites. Vegetative enhancements such as planting of live stakes between riprap to increase shading and drop-in nutrients are discussed later.

Rock toe keys involve excavation of the channel bed in the toe zone and placement of large, hard, angular rock below the expected level of scour to protect from undercutting. This technique should be employed at all sites where toe erosion has been identified as a primary mode of bank failure. Common prescriptions include toe key placement at least 1 meter below the lowest recorded thalweg elevation within the reach. Several methods are available for sizing the toe key and determining maximum scour depths (see Richardson et al. 1990). For use with riprap, the minimum width of the key should be 1.5 times the thickness of the riprap blanket at the base of the slope. Toe aprons have been used as an alternative to toe keys where construction of a toe key is limited by site layout or environmental constraints. However, toe aprons require larger rock, greater volumes and more careful placement to ensure a compact, interlocking structure.

Groynes (including spurs, spur dykes or deflectors) are structures that are attached to one bank and protect erodible areas by directing the flow towards the middle of the channel (Fig. 6-4). Critical design parameters include the location, deflector shape, orientation angle, effective length, crest height, construction material, spacing between multiple deflectors, and expected scour. They should not be utilized in energetic streams that are entrenched, steeper than 2%, or where the risk of undermining or scour at the toe is high. Groynes are often cheaper than continuous riprap, but should not be utilized in streams less than 10 m wide. For stream bank protection, an upstream-pointing (repelling) groyne oriented at 100° to 120° to the flow is recommended. If the floodplain elevation is less than 1 m above normal flow levels, the groynes should be built no higher than the floodplain elevation, and should slope downward to the tip at approximately 50H:1V (2%). If the risk of flood damage to adjacent features is high, groynes should be designed to be submerged at high flows so that they do not catch debris. In general, the recommended distance (S) between multiple groynes is related to river width (w) or deflector length (L) as $S \cong 0.5$ to $2w \cong 1$ to $6L$. A more thorough discussion of design criteria is provided by Przedwojski et al. (1995).

Rock revetments or riprap is a layer of large angular rock placed in the bank zone to limit fluvial erosion. It is a popular technique, but has been criticized for impacts to fish habitat and riparian vegetation, and negative aesthetic values. Other factors that may prevent its use include site access, availability of suitably-sized rock, and construction costs. The effectiveness of riprap depends upon proper selection of rock type (density and strength), size and shape, gradation, and placement. Critical design factors for riprap placement include slope, thickness, alignment, lateral extension, filter layer specifications, and toe scour protection. Design velocities are typically derived from equations of open channel hydraulics; detailed recommendations are described by Woods (1982).

Figure 6-4. Rock revetment with groyne at Thompson River, B.C.

Angular rock, which is well graded, allows the particles to interlock and minimize voids within the structure. Eddies and crevices formed by the large rocks on the surface layer are utilized by fish for shelter. The likelihood of riprap instability due to undersizing or soil failure in the bank increases as the slope of riprap placement is increased. On slopes shorter than 3 m, riprap has been placed as steep as 1.5H:1V, but it is recommended that rock should not be placed on slopes steeper than 1.8H:1V. This will often require substantial sideslope grading if the bank is near vertical. If there is potential for the underlying bank material to become saturated, the revetment face slope must not exceed the angle of repose of the bank material. Most riprap is placed on a filter layer of well-graded angular rock or geotextile fabric to minimize the loss of fines from the bank through the riprap. A properly graded filter layer having a uniform thickness greater than 20 cm is often adequate to minimize the loss of fines from the bank through the riprap, but a geotextile fabric is recommended if the bank is predominantly silt or clay. The riprap layer thickness will vary depending on the application, but a typical range is 1.5 to 2 times the median rock size used in the riprap. For stabilization projects consisting solely of rock revetment, the riprap should include a "freeboard" allowance for wave overtopping and a means of access for maintenance.

An extension of this concept is the "safe-fail" dyke design employed at Shovelnose Creek in the upper Squamish River watershed. The structure limits the amount of cold, silty Squamish River water, which is able to flow into valuable fisheries habitat of lower Shovelnose Creek (Fig. 6-5).

Turning rocks are boulders placed in a diagonal row across a river bend, starting at the outside bank and extending downstream towards the inside bank. The boulders serve to diminish erosion along the outside bank by dissipating energy and disrupting the generation of secondary currents. The longest axis of each rock should be positioned slightly askew to the flow to direct the current away from an unstable bank. Typically, several rows of 5-10 turning rocks are required, and other structures such as deflectors or rock toe keys may be necessary in particularly energetic or deep flows. However, turning rocks are not recommended for use in steep (>5%) streams, which transport large volumes of bedload, or have bankfull widths exceeding 20 to 30 m. The turning rocks also serve to enhance habitat by creating eddies and providing cover for fish.

Figure 6-5. "Safe-fail" dyke at Shovelnose Creek, B.C.

Tie-backs are lengths of rock revetment that are placed perpendicular into an eroding bank to protect a straight reach from lateral migration of the thalweg. They are often utilized in association with vegetative methods or rock toe keys to minimize disturbance within the bank zone. Tie-backs are most effective when placed at the end points of the protection to link rehabilitated sections to stable bank, and to reduce the risk of erosion control structures being outflanked during floods. They are not recommended for use in steep, highly sinuous, actively migrating streams, which are dynamically stable. Potential damage to existing riparian vegetation during construction may also limit its application.

Vegetative Methods

Vegetation can introduce a cost-effective, self-maintaining mechanism for improving bank stability, but the species selected and techniques employed must meet site and project-specific requirements. The applicability of a plant species at a particular site depends on several factors: soil moisture, available sunlight, competitor species, elevation and potential for animal browsing or foot traffic. The first step in the application of vegetative methods must be to identify the local plant communities. Plant species selected for use must be derived from sites with similar ecological conditions, including moisture requirements and tolerance levels. Soil characteristics must also be considered: critical parameters include drainage, compaction, texture, strength, nutrients and pH. For example, soils with high gravel and sand content are well-drained and easily penetrated by roots, but are easily eroded, compacted and are very droughty. Soils with high clay content resist hydraulic erosion, but may restrict root development. Vegetative methods alone do not provide fish habitat; components such as boulders, woody debris or undercut banks must already be present. However, vegetative methods often serve to improve the aesthetic qualities of the riparian zone.

Over time, the structural integrity of a bank will be enhanced as the root systems develop, but the initial benefits may be limited to a reduction in surface erosion. Willows (*Salix spp.*) are a popular choice for bioengineering projects due to their robust nature and adaptation to saturated conditions in the bank zone. Associated species that will provide more shade such as alder (*Alnus spp.*) and cottonwood (*Populus balsamifera spp.*) are recommended further upslope in overbank areas. Fencing is often required to minimize damage from animal browsing and foot traffic.

For maximum success, plants should be installed while dormant and should coincide with cool, moist weather in either spring or fall. Spring planting with supplemental irrigation is recommended if the river is likely to experience autumnal flooding. Sites subject to vernal snowmelt-related floods may be planted in late spring or early summer. Plant stress is greater under these latter conditions but can be effectively managed by overplanting and including soil moisture amendments, rooting hormone and supplemental irrigation as needed during the plant establishment period. However, work in or near the stream may not be permitted outside of operational periods dictated by agency regulations. Project managers may be able to extend construction seasons by completing instream, toe and bank zone work during the fisheries window and completing work in the overbank zone afterwards.

There have been many applications of bioengineering techniques in British Columbia, but success rates have been less than expected. The use of unsuitable plant species has been identified as a critical fault in such bank stabilization programs, as well as inappropriate site selection. Vegetative methods alone will not restore fish habitat, but supplementary techniques such as boulder clusters or anchored large woody debris will often prove valuable.

Vegetative methods have been effective in low gradient streams where riparian vegetation has been removed or damaged by livestock, but these techniques are not recommended for steep, entrenched coastal streams with flashy discharges. In cases where removal of large streamside trees has resulted in extreme channel widening, it is typically unrealistic to anthopogenically replace the large woody debris that served as the stabilizing features. More appropriate and holistic prescriptions include:

- instituting a riparian buffer zone,
- examining the utility of bar stabilizing treatments,
- aggressively pursuing source control measures for elevated sediment and water inputs from upstream,
- replanting riparian forests.

Details regarding species and site selection, planting and maintenance requirements are not included in this manual; excellent references include Schiechtl (1980) and Johnson and Stypula (1993).

Herbaceous ground cover includes grasses and forbs that provide temporary erosion control and ground cover on bare soils in the bank and overbank zones prior to establishment of shrubs and trees. Ground covers are not effective as a single vegetative treatment for stream bank rehabilitation.

Live cuttings consist of woody plant material often taken from first or second year growth of species, that will root from cuttings (Fig. 6-6). Native species such as willow (*Salix spp.*) and red-osier dogwood (*Cornus stolonifera*) that root easily provide a quick means for controlling soil erosion and shallow sliding. Even under unfavorable conditions, these pioneer species will often survive long enough to allow successional vegetation to establish. Recommended sites depend on species selection, but in general, moist, well-drained banks, which are not subject to direct erosive attack, will be most successful. Live cuttings are an inexpensive method of improving bank stability and vegetative cover to a stream. Cuttings may be fashioned and installed as live stakes, posts or whips for other projects. Live cuttings are the most common vegetative practice in riparian restoration projects conducted in the Pacific Northwest, and are typically planted in late autumn after buds have set or in spring after snowmelt when moisture stress is low. Planting densities are based on desired frequency (e.g., 1 m by 1 m spacing in a grid pattern).

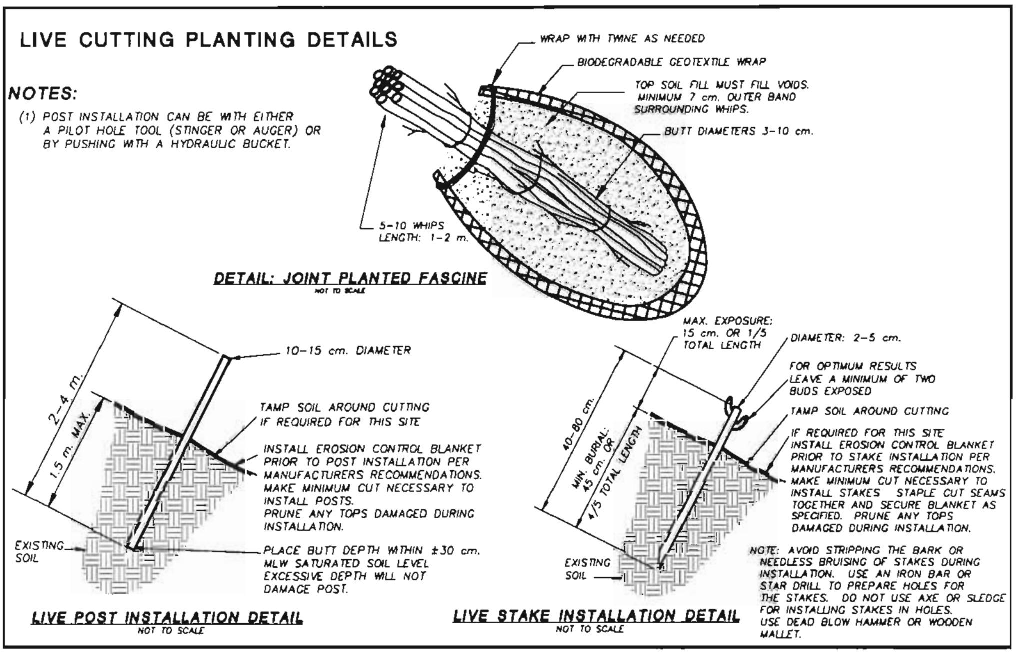

Figure 6-6. Live cutting planting details.

Rooted stock may be employed if rapid establishment of root support is required. However, materials and operation and maintenance costs are considerably higher than other vegetative methods and its use is recommended only for the restoration of buffer zones.

Live cuttings that are tied into bundles and secured in the bank or toe zones with stakes have been termed **live fascines** or **wattles**. Trenches are dug parallel to the stream in the bank zone at a spacing dictated by the slope and type of materials; typical values are 1.0 to 1.5 m. The bundles are placed into the trenches and covered with a thin layer of soil (Figs. 6-7 and 6-8). This method provides immediate erosion control, but is usually limited to slopes flatter than 1H:1V. It is recommended in areas of general scour or to control surface erosion, but should not be used in steep entrenched streams that are sinuous and have displayed long-term instability. It is used primarily in association with other bioengineering techniques such as brush mattresses and vegetated geogrids, but may be installed by itself or with live stakes or posts.

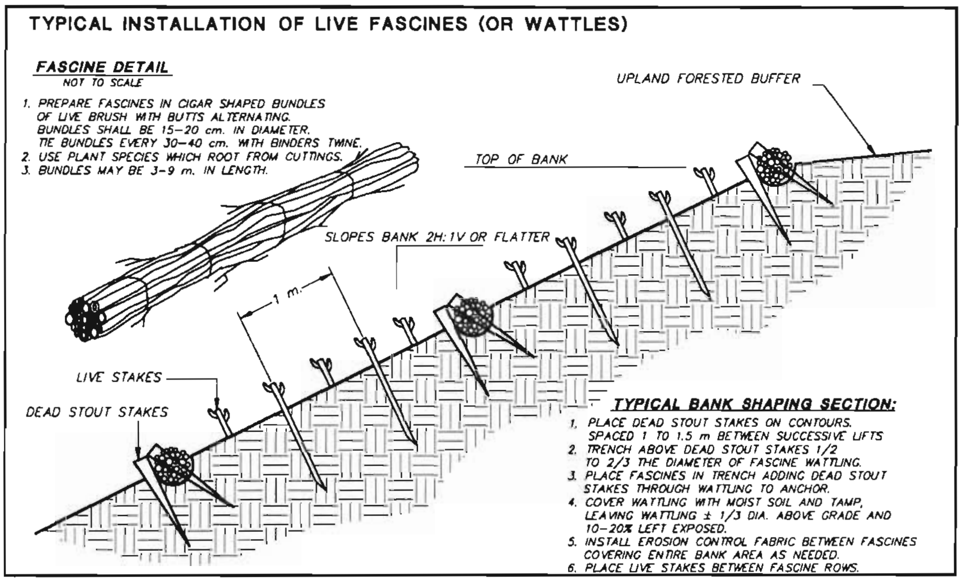

Figure 6-7. Typical installation of live fascines.

Figure 6-8. Live fascine being assembled.

Brush mattresses are a layer of live branches laid flat in the bank zone and secured with dead stout stakes and a network of smooth wire or jute rope drawn tight by setting the stakes. The mattresses consist of branches longer than 1.5 m placed at a density of 20 to 50 branches per meter. The butt ends of the branches are buried to facilitate rooting and a thin soil cover is placed over the entire mattress (Fig. 6-9). Labour force should be directed to walk gently on backfill soil to work it into voids. The banks should be graded to a 3H or 4H:1V slope, and are generally used to cover banks greater than 2 m in height. They may be used in areas that receive direct fluvial attack and in areas of high water velocity if rock toe keys or fascines are included. The finished, tightened and backfilled mattress should be at least 30 cm thick, and the securing stakes should be driven a minimum of 1 m into the bank (Figs. 6-10 and 6-11).

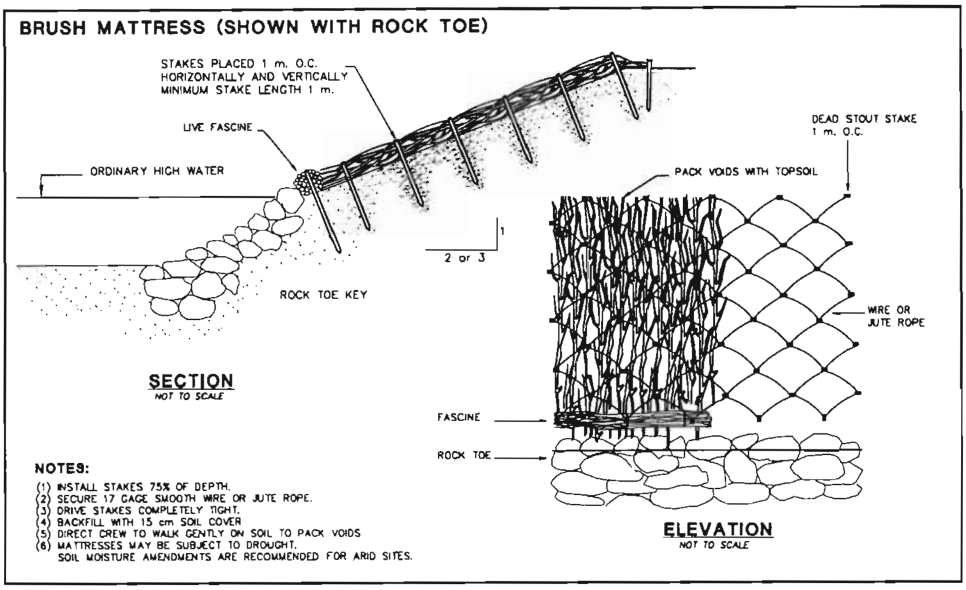

Figure 6-9. Brush mattress with rock toe.

Figure 6-10. Brush mattress with live fascine during construction.

Brush layers are live cuttings or rooted stock placed in successive horizontal rows dug into the bank zone parallel to the stream. Unlike wattles, the branches are left loose, placed perpendicular to the stream and buried between successive layers of fill (Figs. 6-12 and 6-13). This technique is less labor intensive than wattling or brush mattresses, but erosion protection is minimal until the herbaceous cover develops. It is recommended for use in low energy environments that have non-cohesive, well-drained banks and do not receive direct fluvial attack. Wattling may be preferred over brush layers if equipment access for trench excavation is difficult. Toe protection requirements must be evaluated.

Figure 6-11. Brush mattress during construction; note rock toe.

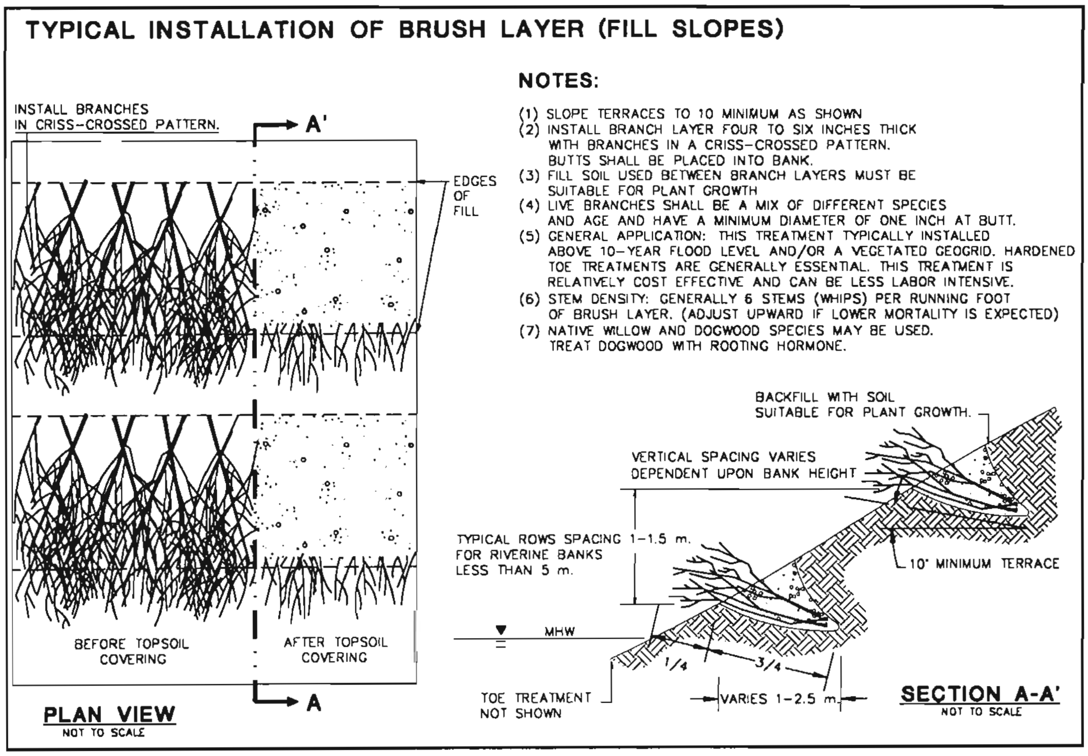

Figure 6-12. Typical installation of a brush layer.

Figure 6-13. Brush layer during construction.

Integrated Methods

The use of integrated methods of bank protection has increased in recent years as attempts to balance habitat issues with budgetary constraints and site conditions have become necessary. Integrated methods have also become popular for use in areas where bank regrading is limited due to close proximity of built structures (e.g., roads or buildings) or sensitive habitat (e.g., backchannels). For unconsolidated banks, rock methods require regrading to 1.8H:1V and vegetative methods often require regrading to 4H:1V or flatter. However, some integrated methods may be constructed with near-vertical banks, and prime fish habitat may be provided if undercut banks are established by underwater cribbing.

Joint plantings are live cuttings installed within a riprap matrix either during or after riprap placement. Installation during riprap placement dramatically reduces labour time and increases survival of plantings. This treatment improves bank protection by forming a root mat and increasing deposition of sediment and debris. This technique requires little maintenance and improves the aesthetics of rock revetments, but can have high mortality rates if the stakes are not driven into the underlying soil layer (Fig. 6-14).

Vegetated geogrids (Figs. 6-15 and 6-16) are similar to brush layers except that the fill soil in the alternating layers is wrapped in geotextile material. Geotextiles used for slope stabilization may consist of natural biodegradable materials such as jute, reed, or flax, or synthetic fibers such as cellulose. Choice of geotextile should depend on climatic conditions, plant characteristics, soil type, slope angle and hydraulic factors. Vegetated geogrids provide immediate erosion protection and are useful where steep banks cannot be sloped back, but the installation costs are high and they require careful design. They may be used in more energetic environments than brush layers, but they should not generally be used in streams displaying dynamic stability or regular planform changes (Fig. 6-17).

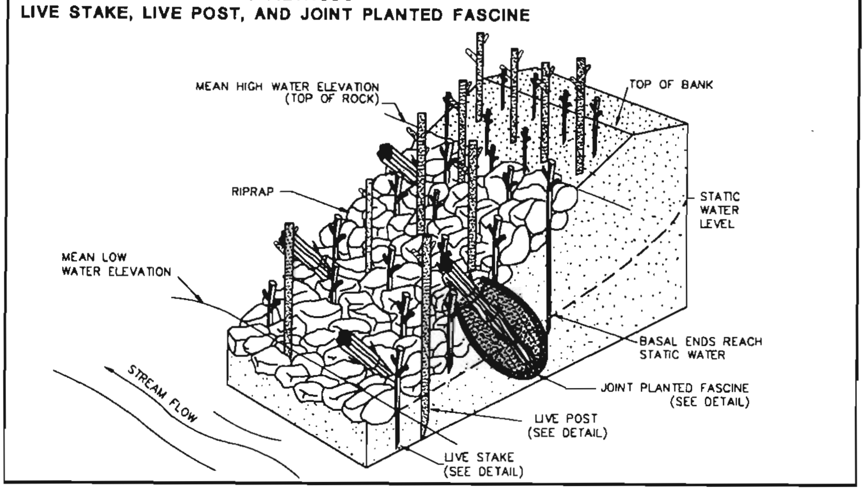

Figure 6-14. Typical joint planting methods.

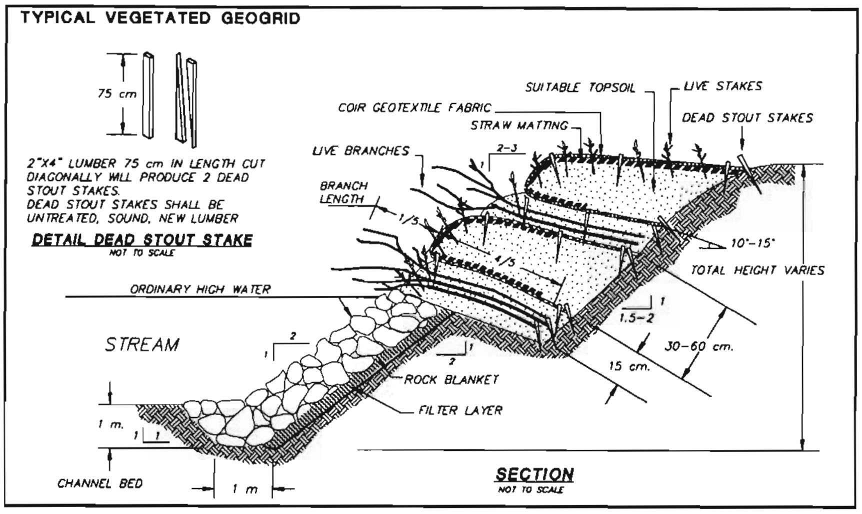

Figure 6-15. Typical vegetated geogrid.

Live cribwalls are frameworks of logs or untreated timber, rock and live cuttings. They may be installed on slopes as steep as 1H:10V. However, steep batters will require analysis for anchoring against rotation (Figs. 6-16 and 6-18). As with geotextiles, live cribwalls provide immediate erosion protection and supply overhanging vegetation and space for fish habitat. Cribwalls typically require work in the toe zone, and they often include a rock toe key, so they should be built during low flow conditions. The live cuttings used are similar to those described for brush layers. Johnson and Stypula (1993) include design recommendations. They may be used in regions of direct fluvial attack, but should not be utilized if the risk of channel avulsion is high. Construction of live cribwalls may require considerable disturbance to riparian areas.

Figure 6-16. Vegetated geogrid during construction; note live cribwall in lower left corner.

Figure 6-17. Vegetated geogrid after three years.

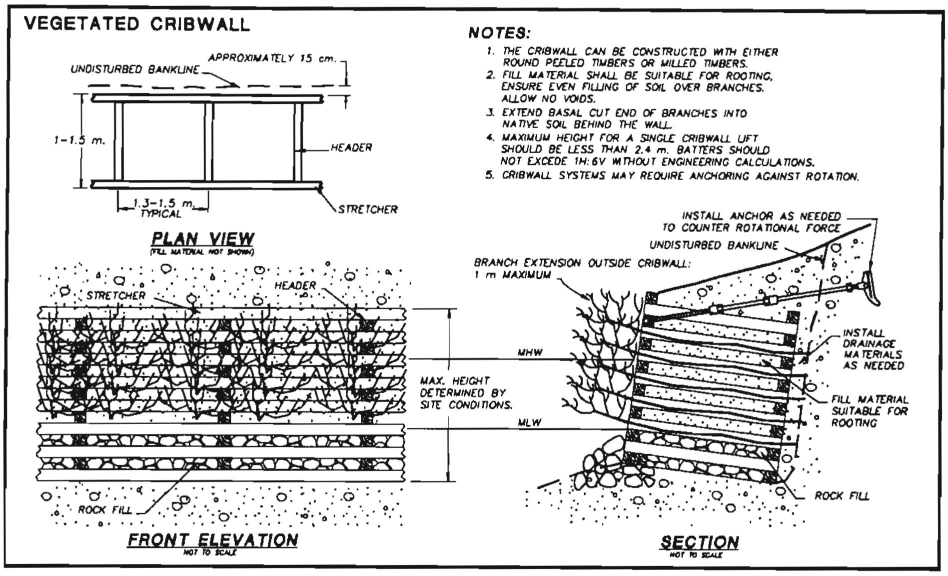

Figure 6-18. Typical vegetated cribwall.

Tree revetments act as a permeable structure to protect banks from fluvial scour and toe erosion. Two types of revetment designs are presented. The first is recommended for low velocity settings with non-cohesive banks, which are prone to toe erosion. The second application is for moderate energy sites.

Lower energy sites: Whole coniferous trees are anchored to stream banks; the butt end or rootwad is typically pointing upstream, but downstream-oriented structures have also proven successful (Figs. 6-19 and 6-20). Project success relies upon anchoring the tree tightly with galvanized cable at both ends with minimal damage to the banks.

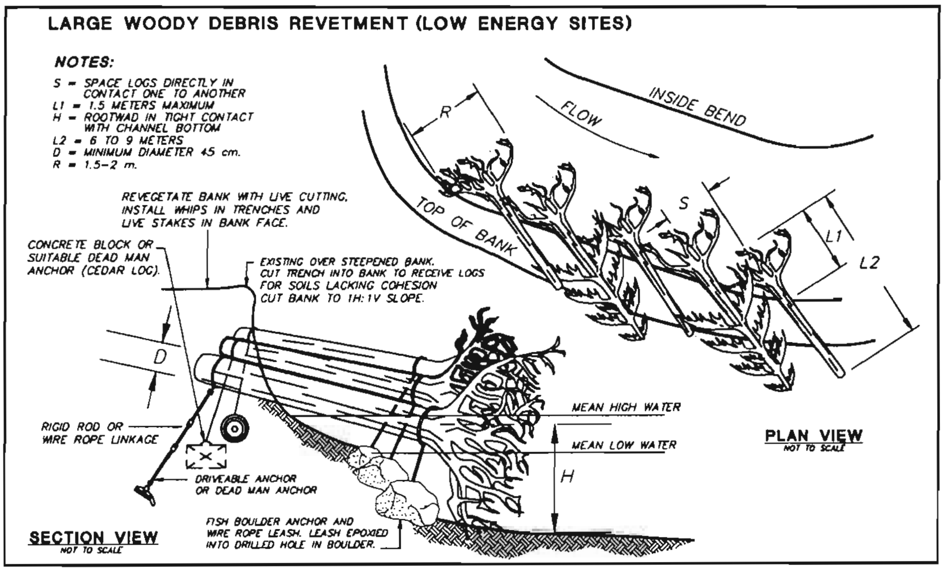

Figure 6-19. Typical low energy tree revetment.

Figure 6-20. Tree revetment installed at a low energy site.

Moderate energy sites: Moderate energy sites can be treated with an integrated tree-rock-live cutting structure built in an interlocking matrix. If installed in cohesive material, trenches may be cut to receive each debris unit. Sites lacking cohesive material should be prepared by first cutting a bench broad enough to receive the largest trunk to be used (generally less than 9 m). Revetment assembly is performed most easily by starting at the downstream limit and progressing in an upstream direction. Ends of treated banks must be well protected. Footer logs are excavated as deeply as possible relative to the thalweg. Maximum depth of placement will be determined by substrate and flow conditions at the time of installation. Rootwads are then installed with the root fan overhanging the footer log. Header logs and rocks are then added; backfill soil should be heavily planted with live cutting whips, stakes and posts (Fig. 6-21).

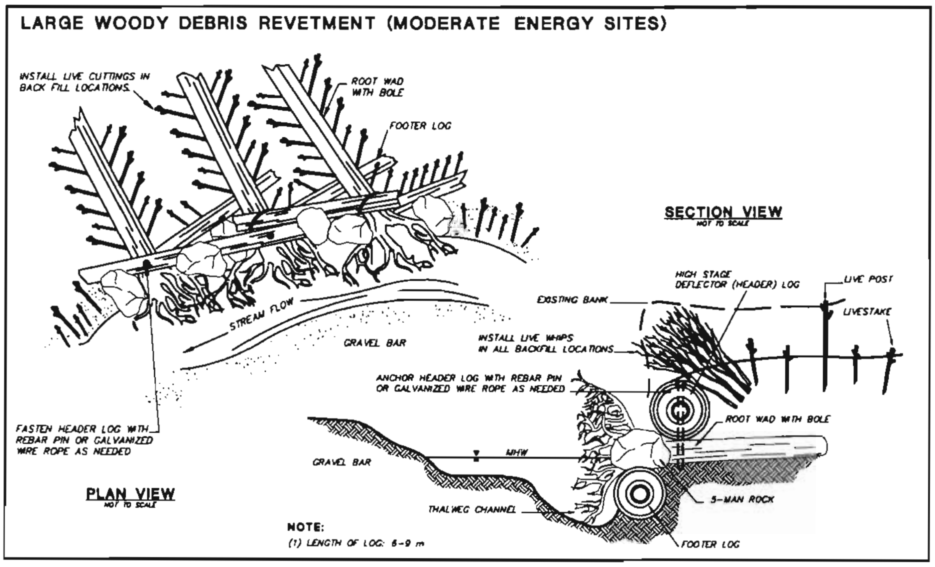

Figure 6-21. Typical moderate energy tree revetment.

Moderate energy tree revetments should be combined with deflectors or tie-backs to decrease the risk of outflanking or damage from floating ice. Tree revetments have been successful on B.C. Interior creeks with gradients less than 2% and bankfull widths less than 30 m. Local energy dissipation may be achieved by installing riffles downstream of the tree revetment to decrease the water surface slope. If the water depth at the tree revetment exceeds 1 m or if the gradient exceeds 2%, a rock toe key should also be used. Reduction of current speeds will induce sedimentation and accelerate vegetation establishment (Fig. 6-22). The lifespan of tree revetments is related to damage, deterioration, and the degree of wetting and drying, but should not be expected to exceed 7 to 10 years, unless mostly submerged. If available, dense coniferous species such as western red cedar, hemlock or Douglas fir should be utilized.

Figure 6-22. Tree revetment during installation at a moderate energy site.

Large woody debris may be utilized as a component of integrated bank protection to enhance habitat by providing cover, drop-in nutrients and hydraulic diversity. The morphologic variability provided by woody debris often serves to improve fish habitat by creating hydraulic diversity, resting and rearing areas, such as undercut banks and pools. Functional large woody debris generally measures at least 6-9 m in length and 60 cm in diameter (Fig. 6-23). It has the ability to significantly affect local flow velocities, sediment transport, and erosion of bed and banks within a stream reach. Placement must be carefully planned to address the specific engineering objectives and habitat requirements.

The most critical design consideration is the permanence of the wood relative to the challenge of anchoring each element in place. Key factors include the type of woody debris, the size and shape, location and orientation within the reach, exposure to currents and resistance to movement. The longevity of any wood will be enhanced if it remains fully saturated. For maximum longevity, resistant coniferous species such as Douglas-fir or western red cedar are recommended. For bank protection, woody debris may create a hydraulic effect similar to deflectors; placement at an upstream angle will deflect flow towards the center of the stream. This technique is most effective when used in series of several wood pieces, and in combination with rock toes and vegetative methods in the bank zone (Fig. 6-24). Many techniques for anchoring woody debris have been attempted, including partial burial, tie-back anchors, and cabling to large rocks or other structures. The method employed should be based on the overall design, but care must be taken to minimize any possible movement of the woody debris. The stability of woody debris is maximized if its length approximates the bankfull width, more than 70% of its length is anchored to the bank and its orientation to the flow is less than 30 degrees. These suggestions should be balanced with the benefits to aquatic habitat. More details on utilization of large woody debris are included in Chapters 8 and 9.

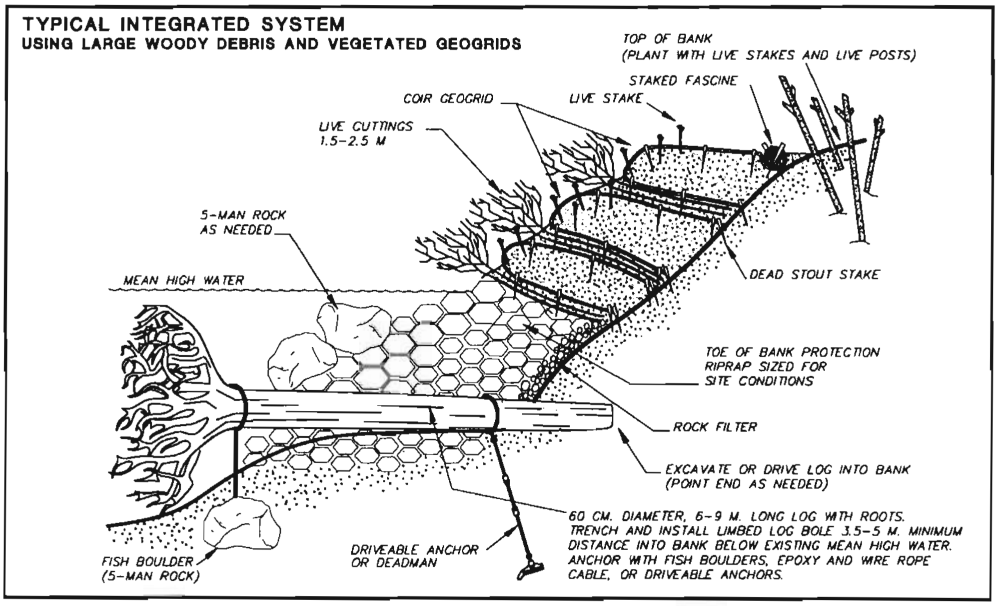

Figure 6-23. Integrated woody debris and vegetated geogrid system.

Figure 6-24. Large woody debris revetment.

COST ESTIMATES

A broad range of cost estimates are possible for each protective technique because the cost of planning and supervision, materials, machinery and labor will vary as a function of project size and location. Table 6-2 describes the costs of the rehabilitative techniques in relative terms: high (H), medium (M) or low (L).

The goal of maintenance programs for bank protection should be not only to maintain specific design concerns, but to continue improving the ecological quality and habitat diversity. Extremely detailed maintenance plans have proven to be impractical and costly. The most effective technique has been to provide specific prescriptions for short periods of time and to ensure regular training of the individuals responsible for maintenance.

Table 6-2. Relative costs for bank rehabilitation projects.

BANK STABILIZATION METHOD	CAPITAL COSTS	MAINTENANCE COSTS
Rock toe keys	M - H	L
Deflectors	M - H	L - M
Riprap	H	L
Herbaceous cover	L	L - M
Live cuttings	L	L - M
Rooted stock	M	M
Live stakes	L	L
Brush mattresses	M - H	L - M
Live fascines or wattles	L - M	L - M
Brush layers	M	L - M
Joint planting and joint-planted fascines	L	L
Vegetated geogrids	M - H	M
Cribwalls	H	L
Tree revetments	L - M	M

Chapter 7

Rehabilitating Off-channel Habitat

D. Brent Lister[1], Rheal J. Finnigan[2]

INTRODUCTION

Development and rehabilitation of off-channel areas is receiving increased attention as a practical means of restoring salmonid fish habitat. This approach is particularly attractive for high-energy coastal streams where flow extremes and channel instability often make it impractical to attempt rehabilitation of the main channel. Off-channel habitat rehabilitation can also be a worthwhile option in the interior, where winter conditions may be severe in the main channel. However, only certain species and life stages of salmonids utilize off-channel areas. The benefits of rehabilitating off-channel habitat will therefore depend on the presence of an appropriate physical environment and the fish species and life stages adapted to that environment.

The Nature of Off-channel Habitat

Off-channel habitats, including overflow, groundwater, and wall-base channels (Fig. 7-1), are created by long-term processes of alluvial deposition, channel migration, and changes in stream bed elevation (Kellerhals and Church 1989). While overflow channels will carry flow only during flood events, groundwater channels can occur in a range of floodplain situations that to varying degrees are removed from the active channel. Wall-base channels, whether groundwater or surface fed, occupy higher portions of the floodplain or a terrace outside the influence of active channel processes (Peterson and Reid 1984). Each of these situations generally develops in a meander channel that has been abandoned by the main stream as it migrates across the valley. Groundwater and wall-base environments can be expected to provide relatively stable flows, a moderated temperature regime (Fig. 7-2) and, in some cases, a complex of channel and pond habitats. Another common feature of these habitats is their modification by beaver (*Castor canadensis*) activity, described in detail in Chapter 15 of this publication.

Salmonid Use of Off-channel Habitats

Among the salmon species, chum and coho are most commonly associated with off-channel habitats. These species are apparently attracted to sites fed largely by groundwater. Late-run chum stocks, throughout their range, have been noted to spawn in groundwater-fed channels or seepage areas (Salo 1991). Coho spawn in groundwater channels to some extent (Sheng et al. 1990), but most coho spawning occurs in relatively small surface-fed streams (Sandercock 1991). Coho juveniles, on the other hand, make widespread use of off-channel habitats, often gaining access to small stream and pond environments that are either inaccessible to adult coho or unsuitable for spawning (Peterson 1982a; Brown and Hartman 1988). In coastal streams, juvenile coho move into off-channel areas as post-emergent fry during spring and early summer, or during fall, in advance of the larger mainstem freshet events (Fig. 7-3). While coastal coho juveniles appear to use off-channel habitat mainly for overwintering, studies suggest that interior coho characteristically move to off-channel ponds after fry emergence in spring, and may remain

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there for the entire 1 or 2 years of freshwater rearing (Bustard 1986; Swales and Levings 1989). A fall movement of coho juveniles from mainstem to off-channel sites for overwintering has also been observed in the interior population at Coldwater River (Beniston et al. 1988). Juvenile coho are also known to migrate considerable distances downstream from summer rearing habitat to off-channel sites for overwintering. Coho marked in headwater rearing areas have been recaptured at overwintering sites up to 33 km downstream in the Clearwater River, Washington (Peterson 1982a) and 52 km downstream in the Chilliwack River, British Columbia (Fedorenko and Cook 1982).

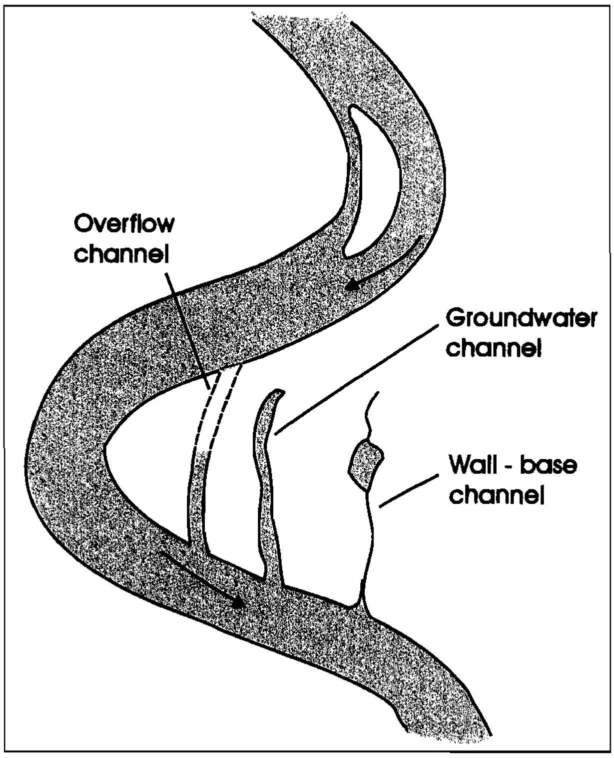

Figure 7-1. Types of off-channel habitat (adapted from Peterson and Reid 1984).

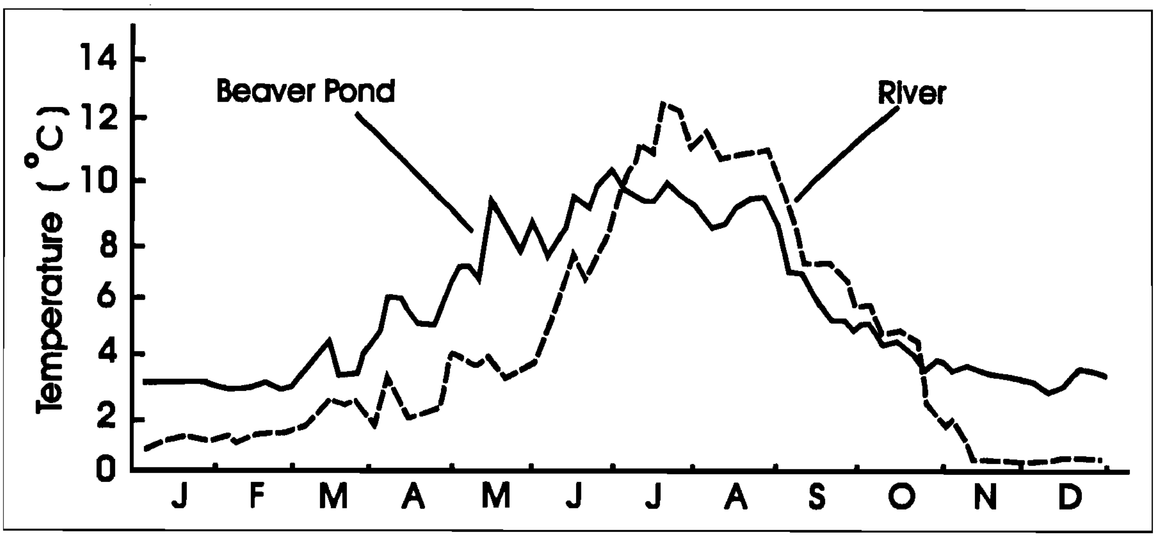

Figure 7-2. Water temperature regime of an off-channel beaver pond and river mainstem, Coldwater River, B.C. (Swales and Levings 1989).

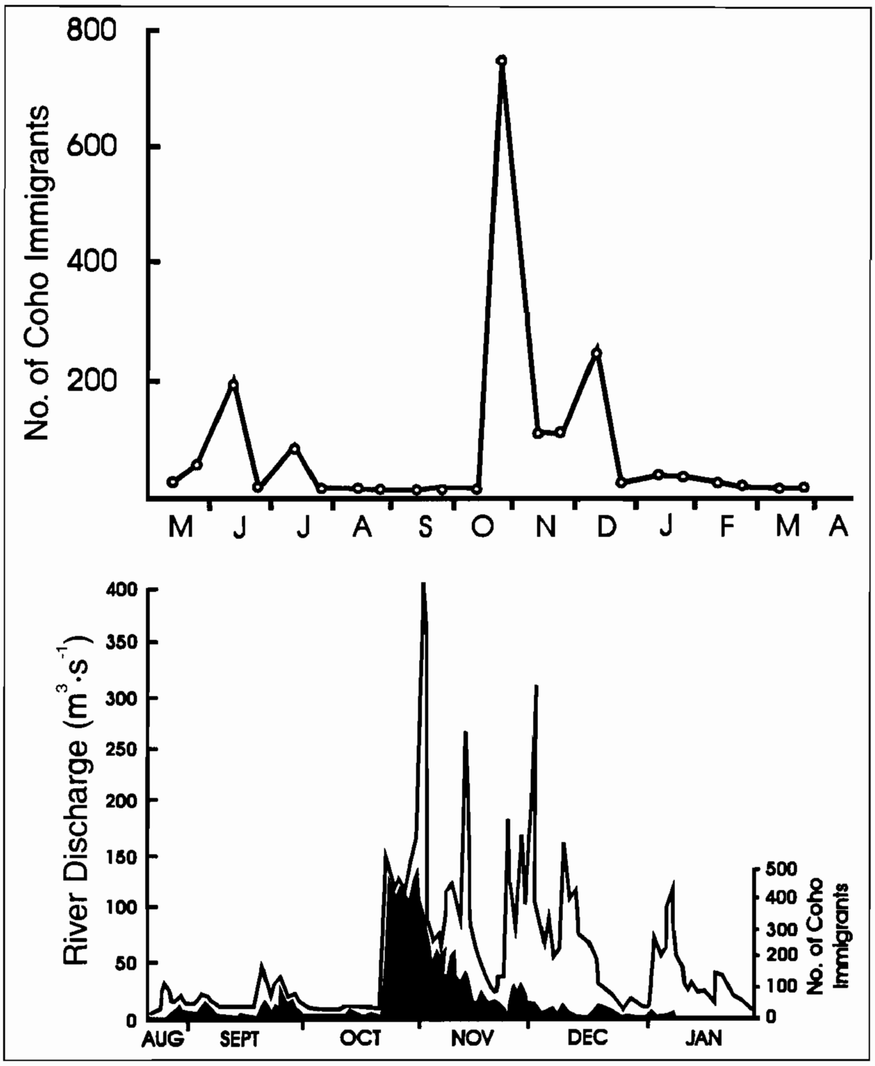

Figure 7-3. Seasonal pattern of juvenile coho salmon recruitment to off-channel ponds (Peterson and Reid 1984) and relationship of coho recruitment to daily discharge (Peterson 1982a) Clearwater River, Washington.

Other salmon species have not been observed to utilize off-channel habitat to a significant extent in British Columbia. Pink salmon are not reported to utilize off-channel areas (Heard 1991). Chinook salmon do not spawn in off-channel habitat, but interior stocks make some use of off-channel ponds and side channels, often associated with tributaries, for juvenile rearing and overwintering (Anon. 1987; Swales and Levings 1989). Sockeye salmon have been reported to spawn in off-channel spring areas in Kamchatka (Burgner 1991) and Alaska (Mathisen 1962), and on groundwater-fed lake beaches (Burgner 1991). Though off-channel habitat use by sockeye is apparently not common in British Columbia, groundwater channels developed at Adams River and Kitsumkalum Lake in the interior have been used extensively by sockeye for spawning and, in the former case, for juvenile rearing over summer (M. Foy and M. Sheng, Department of Fisheries and Oceans, Vancouver, pers. comm.). As the capacity of nursery lakes to rear juveniles frequently limits sockeye production (Burgner 1991), off-channel habitat rehabilitation for sockeye will be restricted to situations where spawning habitat is considered the limiting factor.

Of the trout species, coastal cutthroat (*O. clarki clarki*) are most likely to be found in off-channel environments. Adult and juvenile coastal cutthroat can be expected to cohabit many off-channel sites with juvenile coho (Cederholm and Scarlett 1982; Hartman and Brown 1987). Seasonal movements between main-channel and off-channel sites enable cutthroat to utilize small tributaries for spawning, juvenile rearing or overwintering. In these situations, cutthroat may be partially segregated from coho juveniles by their preference for more permanently wetted environments with higher flow (Hartman and Brown 1987). Interior stocks of west slope cutthroat trout (*O. clarki lewisi*) have generally not been documented in off-channel habitat, but in the Elk River and its Fording River tributary in southeastern British Columbia, yearling and older cutthroat do overwinter in groundwater-fed off-channel ponds (G. Oliver, Interior Reforestation, Cranbrook; D.B. Lister & Associates 1980, pers. comm.).

Steelhead trout do not commonly spawn in off-channel streams, and juvenile steelhead apparently use such habitats to a much smaller extent than coastal cutthroat. Steelhead are not abundant in off-channel ponds (Cederholm and Scarlett 1982; Swales and Levings 1989). In coastal streams steelhead underyearlings and parr prefer small surface-fed tributaries to groundwater environments for rearing and overwintering (Cederholm and Scarlett 1982). Some coastal groundwater channels do, however, overwinter significant numbers of parr and pre-smolt steelhead (King and Young 1986) and a groundwater channel at Deadman River, in the British Columbia interior, attracted significant numbers of underyearling steelhead for rearing and overwintering (Sheng et al. 1990). Adequate velocity and habitat diversity were likely requisites for juvenile steelhead use of these sites. Though off-channel habitat use by resident rainbow trout has not been reported, underyearling rainbow are known to rear in seepage-fed ponds and side channels when these habitats are available (B. Chan, Ministry of Environment, Lands and Parks, Kamloops, pers. comm.).

The stream-dwelling species of char, Dolly Varden and bull trout, have not been commonly observed in off-channel habitats. Studies of coastal streams in southern British Columbia and Washington indicate little use of off-channel areas by Dolly Varden. This species may, however, be more abundant in off-channel habitats of northern streams. In the Skeena River system, juvenile Dolly Varden utilize off-channel ponds in the presence of juvenile coho and stickleback (*Gasterosteus aculeatus*) (David Bustard and Associates 1993), and have been observed to overwinter in a groundwater channel at Kitwanga River (M. Foy, Department of Fisheries and Oceans, Vancouver, pers. comm.). Dolly Varden are also relatively abundant in southeast Alaska streams, where they make considerable use of beaver ponds (Bryant 1984). Though bull trout are suspected to spawn to some extent in groundwater-fed areas, studies to date have not revealed the use of off-channel habitat by this species (Baxter and McPhail 1996).

Use of off-channel habitat by Arctic grayling has not been well documented. Grayling appear likely to utilize off-channel habitats, as they have been noted to frequent marginal low velocity areas, side channels and backwaters as underyearlings, and to distribute into a variety of habitats, including spring-fed areas, for feeding and overwintering in the juvenile to adult stages (Northcote 1993).

Evolution of Off-channel Habitat Rehabilitation

Early development of off-channel habitat for anadromous salmonids on the Pacific coast of North America involved construction of surface-fed side channels, primarily for spawning sockeye, pink and chum salmon, during the 1950's and 1960's. The first artificial spawning channel was constructed in 1953 at Jones Creek on the lower Fraser River (Hourston and MacKinnon 1956). Following that project, 14 artificial spawning channels were built in British

Columbia, and another 7 channels went into operation in the northwest United States. Certain spawning channels produced significant numbers of adult salmon to the commercial fishery (Fraser et al. 1983; West and Mason 1987), but the relatively high capital and maintenance costs, particularly sediment problems in non-lake-fed situations, tended to make spawning channels generally less attractive than other salmonid enhancement options.

In the mid-1970's, the Department of Fisheries and Oceans (DFO) began to examine the potential for increasing chum salmon production in British Columbia by restoring groundwater-fed spawning areas (Marshall 1986). Groundwater spawning channels were relatively inexpensive to build and essentially free of the maintenance problems associated with many surface-fed spawning channels. Also at this time, research on seasonal habitat and movements of juvenile coho was revealing the importance of off-channel streams and ponds for rearing and overwintering (Bustard and Narver 1975; Peterson 1982a). Development of off-channel habitat for chum salmon, and to a lesser extent for coho, continued in British Columbia, Washington and Alaska during the 1980's (Bachen 1984; Bonnell 1991; Cowan 1991). Evaluation of the groundwater chum spawning channels indicated that these sites also provided spawning and juvenile nursery habitat for coho (Sheng et al. 1990). The quarry rock (riprap) used to protect the banks of these channels from erosion by chum spawners inadvertently provided excellent cover for coho juveniles, which also benefited from stable flows and temperatures as well as an abundance of food consisting of aquatic insects supplemented in winter by chum salmon carcasses, alevins and emergent fry. Recent research suggests that salmon carcasses are also a significant source of nutrients to the food chain supporting stream-rearing species such as coho, cutthroat and steelhead trout (Bilby et al. 1996). In the 1990's, off-channel habitat projects have therefore tended to emphasize a multi-species approach that includes, for example, creation of spawning areas for species such as chum salmon with little or no stream-rearing requirement, as well as spawning and rearing habitat for coho, cutthroat or steelhead, which have more complex freshwater habitat needs.

ASSESSING THE NEED AND THE OPTIONS

Effective off-channel habitat rehabilitation is best achieved from a thorough assessment of conditions in the watershed of interest. An overview fish habitat assessment, including review of existing information on fish resources and watershed conditions, will normally be required. It should examine evidence for declines in fish stocks and the linkage between fish population changes and habitat changes. If existing information is not adequate to assess the need for a project, it may be necessary to obtain detailed site-specific habitat information through field assessment. Guidelines for planning watershed restoration work, and fish habitat rehabilitation in particular, are presented in Watershed Restoration (WR) Technical Circular No. 1 (Johnston and Moore 1995). Procedures for overview and detailed field assessments are described in WR Technical Circular No. 8 (Johnston and Slaney 1996).

If initial assessment confirms the need for fish habitat rehabilitation measures, project planners should decide on the appropriate strategy and whether or not it will involve main channel or off-channel habitat. Off-channel habitat rehabilitation will be favoured on relatively large streams, and in situations where the main channel is too unstable for in-channel habitat rehabilitation measures. Selection of the off-channel option also depends, of course, on the presence of salmonid species that will take advantage of habitat created outside the main channel. A process for selecting between main channel and off-channel habitat options is presented by a flow chart in Chapter 8 of this publication.

PROJECT PLANNING AND SELECTION

The process for planning, selecting and investigating suitable off-channel habitat projects is described in the following sections and summarized in Figure 7-4.

Target Species and Water Sources

It is important to confirm at the outset the fish species and life stages involved, and the type of water source, e.g., surface runoff, lake or groundwater, that will be employed. One should understand how salmonid populations utilize the drainage for spawning, juvenile rearing, and overwintering, as well as the role played by main channel, tributary and off-channel habitats. Do any stocks spawn in lake-fed or groundwater-fed situations that offer more benign winter conditions (moderate temperature regime, stable flows, and sediment-free water) than surface runoff streams? The answers to these questions will lead to decisions on the species, water source and habitats, which will be the focus of the project.

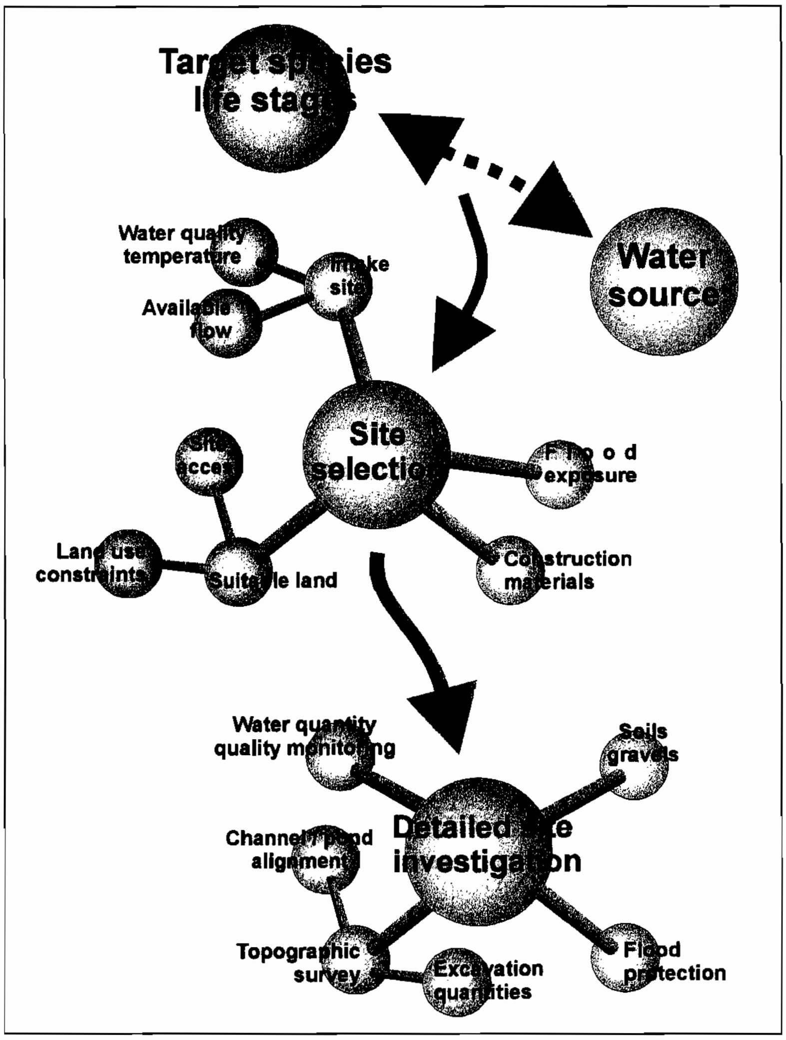

Figure 7-4. Principal elements of project planning, selection and investigation.

Identifying Prospective Sites

The nature of the primary water source will guide site identification. If the project is to utilize surface water, it will need to be located on a bench or in the upper floodplain. Abandoned or cutoff river channels offer natural depressions, which can sometimes be used to minimize excavation quantities. A surface water source must be reliable. It should provide a year-round flow that does not freeze in winter, and it should be relatively free of fine sands and silt, bedload (sand and gravel), and wood debris. In colder climates, lakes are an attractive water source because their moderating effect on winter temperature tends to ensure ice-free operation. To avoid sediment bedload, intakes should be located on the outside of a stream bend. Relatively stable sections of stream, such as a lake outlet reach, are the most favourable situations.

Groundwater quantities required for off-channel habitat development are most likely to be available on a relatively large stream, over 300 km^2 in watershed area, with a wide valley and extensive alluvial floodplain. Relic meander channels and areas of standing groundwater are commonly candidates for detailed investigation. Identification of prospective sites will be aided by inspection of topographic maps and recent, larger-scale aerial photographs. The latter are especially useful for identifying abandoned river channels, which are revealed by the presence of bands of deciduous vegetation, often less mature than surrounding vegetation because of more recent exposure to flood flows (Fig. 7-5). A helicopter survey can be of considerable assistance. Under winter conditions, groundwater sources can often be identified from the air by the absence of snow and ice cover due to elevated ground temperature. Promising sites should also be inspected on the ground to confirm their suitability for development.

Exposure to Flooding

It is important to minimize intrusion of off-channel habitat rehabilitation projects onto the active river floodplain. Adoption of such a philosophy will avoid impact on currently functioning stream habitat.

Most projects will be located in and around abandoned flood channels that may become active during high flow events. This raises the question: should projects be designed to withstand extreme floods or should they be located and designed to accommodate overtopping by floods in order to minimize their impact on the river regime? Experience suggests that it is better to design for overtopping by a moderate flood event with, for example, a 1 in 30-year recurrence interval. Off-channel projects located and designed with this *safe-fail* philosophy should require only minor maintenance and repairs after an extreme flood. This approach tends to reduce floodplain impact and flood protection costs.

One consideration in assessing exposure to flooding is the benefit of providing modest site protection with a berm of granular material excavated in the course of developing a channel or pond. The excavated material is normally used to create a low berm between a side channel and the main river channel (see Project Design Concepts section).

It is not uncommon for a major road, railway, or flood protection dyke to cut off an active flood channel or a channel that has been abandoned by the main river. Restoration of such habitat, using the flood protection attributes of the existing facility, is a good strategy (see Fig. 7-19). It will be a sound approach wherever the road or dyke is an integral part of the infrastructure and will therefore be adequately maintained.

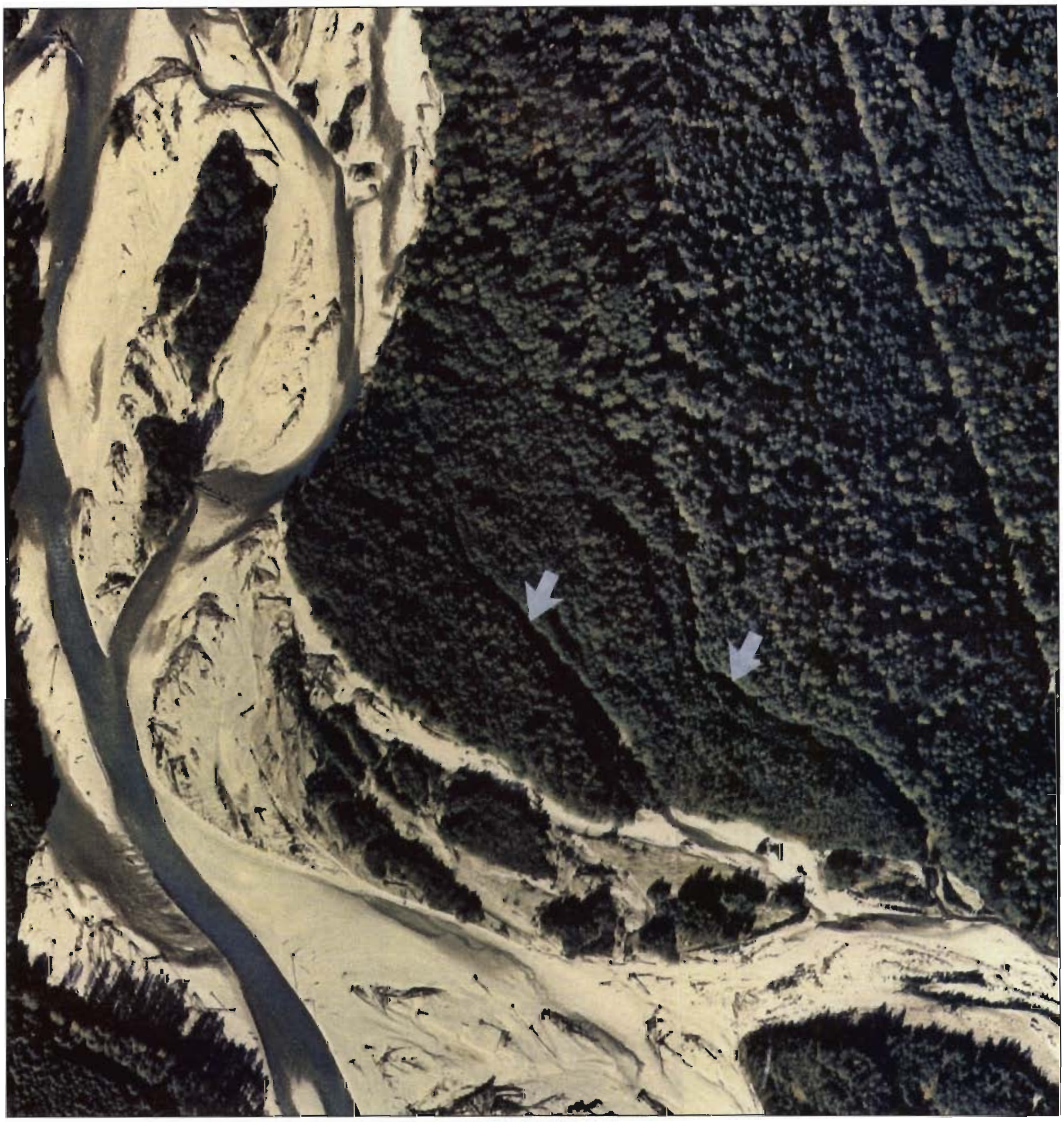

Figure 7-5. Abandoned channels on the upper Pitt River floodplain.

As flooding risk varies greatly from site to site, that risk should be assessed by review of aerial photographs and stream discharge data, by consultation with a fluvial geomorphologist, and by contacting individuals who have experience in the project area.

Site Access

Road access will be needed for most off-channel projects. The access must be adequate for heavy construction equipment and periodic maintenance or monitoring activities. Location of an access road should minimize impact on the floodplain, using the flood protection berm where possible. Cost and feasibility of creating new access or upgrading existing road access are important to project feasibility.

Land Tenure

Land tenure and possible restrictions on land use must also be considered. As stream habitat rehabilitation projects will generally involve Crown forest land, it will likely be expedient to contact the appropriate regional or district office of the Ministry of Forests. The B.C. Lands Branch can also provide information on status, responsible management agency, and land use restrictions pertaining to a given parcel. Through its six regional offices, the Lands Branch operates the computerized Crown Land Registry for the province. In some instances, access to Crown land may have to be across private land. Information on private land ownership can be obtained from one of six regional land title offices. To initiate a title search requires specific identifying information, i.e., legal description or parcel identifier number, which must be obtained from the appropriate municipal or district office, or the B.C. Assessment Authority. Information on land use restrictions pertaining to private land may be gained from the local district or municipal office.

Construction Equipment and Materials

Availability of suitable construction equipment, particularly excavators, and off-site construction materials are also factors to consider. For stream channel projects, rock bank protection material, either angular quarry rock (riprap) or natural boulders, is normally employed for lining banks to prevent erosion. Other common requirements are suitable gravel for an access road or large wood debris for instream cover.

Operational Considerations

Some off-channel projects, particularly those with surface intakes, must be regularly inspected and maintained to ensure reliability of the water supply. The primary task will be to remove accumulated debris from facilities such as trash racks, water control structures, culverts and fish enumeration fences and traps. Periodic maintenance work, involving heavy machinery, will also be required. Availability of organizations and personnel to perform these operational functions, such as stewardship groups or a local contractor, must therefore be taken into account.

Detailed Site Investigation

Sites that hold promise for off-channel habitat development should receive additional investigation to determine (1) the nature and suitability of alluvial materials, (2) the quantity and quality of surface or groundwater sources, (3) excavation quantities, (4) amount and type of material, if any, to be moved to or away from the site, (5) the best stream channel alignment and/or pond limits, and (6) flood protection requirements. A site topographic survey will be required to provide the physical information and enable the channel or pond layout to be optimized. This topographic survey, including establishment of benchmarks for reference, should provide ground elevations relative to adjacent stream elevations and high water marks. In addition to the survey, a number of test holes should be excavated to determine the nature and layering of substrate materials in the area to be excavated. Another practical way of testing depth of overburden above the gravel layer, an important consideration for a groundwater channel, is to probe the ground with a 6-12 mm diameter steel rod.

For a groundwater channel, standpipes should be installed in the test hole pits to enable monitoring of water table level as well as groundwater temperature and dissolved oxygen. Excessive levels of chemical constituents such as iron and hydrogen sulfide should also be identified by analysis of groundwater samples. It is desirable to monitor groundwater levels and quality at about monthly intervals over an extended period, ideally covering one annual cycle.

The topographic survey should identify standpipe locations and should enable the investigator to compare elevations of the water table and the adjacent stream.

Regulatory Agency Approval

It will be essential to obtain project approval from appropriate government agencies such as the Ministry of Environment, Lands and Parks and the Department of Fisheries and Oceans (Johnston and Moore 1995). For this purpose, the project proponent will have to prepare at least a conceptual plan, describe the project's purpose, define its water requirements, and describe how the project would affect existing fish and wildlife habitat values. The regulatory agency submission should occur as soon as the proponent has adequate information and has decided that the project is likely to be technically and economically viable. The regulatory agency approval process is described in detail in Chapter 1 of this publication.

PROJECT DESIGN CONCEPTS

Site investigations provide the basis for an initial project layout and conceptual design, as well as information needed to confirm feasibility. From this preliminary stage, the design should proceed to development of detailed design drawings. Design drawings for an off-channel habitat project should include a site plan showing ground elevation contours at 0.5 m intervals and locations of significant trees to be avoided. The drawing should also include cross-sections that indicate elevations and the extent of excavation at appropriate intervals along the project site. Plotting of channel or pond cross-sections relative to the existing ground surface will enable the estimation of excavation quantities and development of a plan for disposal of excavated material, which is commonly used for the flood protection dyke and the access road. For spawning and rearing channels, it is also desirable to plot a centerline profile showing the drop in bed elevation over the channel, and the bed elevation in the adjacent river channel. Also needed are drawings of associated facilities such as channel intakes, culverts (see Chapter 5) and beaver control features (see Chapter 15). Regulatory agency staff typically require drawings such as a plan view, cross-sections and profile to facilitate project approval.

The following sections describe three principal concepts for off-channel habitat development: (1) the groundwater-fed spawning and rearing/overwintering channel; (2) the surface-fed spawning and rearing/overwintering channel; and (3) the rearing and overwintering pond. A single project may incorporate only one or all of these concepts, depending on available water supplies, terrain conditions, and the target fish species. It is desirable, however, to provide some habitat diversity within each project to accommodate the requirements of several species and life stages. A multi-species approach is appropriate in light of the fact that all species in a given watershed are likely to have been affected by habitat impairment, and improvements made for one species may benefit another.

Groundwater-fed Channels

Suitable groundwater channel sites have a gravel substrate, relatively free of silts and fine sands, with the water table near the ground surface. Such sites typically occur on streamside benches with an overall gradient of 0.2 - 0.5% parallel to the main stream (Bonnell 1991). Lower gradients tend to be associated with sandy materials and higher gradients with cobble-boulder material in the alluvium. Water table elevation should be quite stable from season to season. The groundwater should have a minimum dissolved oxygen concentration of 5 $mg \cdot L^{-1}$ (Sowden and Power 1985), and temperature and other water quality parameters should be within acceptable ranges for the species and life stages of interest (Sigma Resource Consultants 1979; Piper et al.

1982). Bjornn and Reiser (1991) provide a useful review of the literature on water temperature and dissolved oxygen requirements of salmonids.

Excavation of a groundwater channel causes drawdown of the water table in the vicinity of the channel (Fig. 7-6). To ensure year-round flow, groundwater channels constructed by DFO in British Columbia have generally been excavated to 0.9 - 1.2 m below the lowest level of the water table in summer, based on water table monitoring prior to construction (Sheng et al. 1990). The bed of a groundwater channel, which usually parallels the adjacent river, is typically about 1.5 m below the bed of the river channel. Excavation requirements can be minimized by routing the new channel along an abandoned meander channel to the extent possible. Depths of excavation for groundwater channels are typically 1-2 m, but may be up to 3 m at the upper end.

In cross-section, groundwater channels are trapezoidal with bank slopes of 1.5 horizontal to 1 vertical (Fig. 7-6). Bottom width and gradient are selected to achieve a water depth of 25-50 cm (Bonnell 1991). Channel gradient is generally flat or very low, but it may range up to 0.5% in some cases (Bonnell 1991; Cowan 1991). Bottom widths of excavated groundwater channels are commonly 5-6 m. Where salmon spawning is expected, channel sides are armoured with a 50 cm thick blanket of 20-50 cm diameter riprap or boulders (Fig. 7-7). Experience has shown that rock armouring is essential to prevent serious bank erosion by salmon spawners. If the rock is installed in a rough or non-uniform fashion at a thickness of at least two layers, the interstices in the rock also provide good summer and winter cover for juvenile salmonids (Sheng et al. 1990). Wood debris is generally added to the channel to provide high quality cover for salmonid juveniles and for mature adults during spawning (see Chapter 8). Alcove-type ponds, connected to the channel, are also being used to augment juvenile rearing and overwintering capability of groundwater channels. Off-channel pond habitats are described later in this section.

The present custom is to use the native in-situ material for the substrate of groundwater channels. Comparison of chum salmon survival in channels with substrates of either native gravel, or artificially graded gravel, with smaller size fractions (<10 mm diameter) removed, has indicated that graded gravel offers no advantages in terms of egg-to-fry survival or density of fry production (Bonnell 1991). Large voids in the artificially graded gravel are thought to trap fine organics, which could result in increased biological oxygen demand (Bonnell 1991). It has been shown experimentally that coarse sand in the native gravel/sand matrix tends to filter out finer sands and silts in the upper layers of the stream bed (Beschta and Jackson 1979). Coarse sands probably also reduce the penetration of fine organic material into the spawning bed.

Excavated groundwater channels usually produce small discharge volumes (0.08-0.20 $m^3 \cdot sec^{-1}$) and low water velocities of 5-15 $cm \cdot s^{-1}$ (Sheng et al. 1990; Cowan 1991). The minimum desirable water depth for salmon spawning (25 cm) is maintained by the use of rock weirs installed at intervals dictated by channel slope.

Protecting a groundwater channel from flood damage involves (1) adequate setback from the active river channel, and (2) construction of a protective dyke. The upstream end of the channel should be set back at least 30 m from the active channel to maintain an adequate buffer of protective vegetation. A band of undisturbed vegetation should also be left between the channel and main river along the length of the channel. The flood protection dyke, constructed by sidecasting the excavated alluvial material, is usually located between the groundwater channel and the main channel (Fig. 7-6). These granular dykes cannot be expected to withstand the erosive forces of extreme flows, but they can provide a measure of flood protection at moderately high flows. Both the channel and dyke need to be located so as to minimize encroachment on the floodplain.

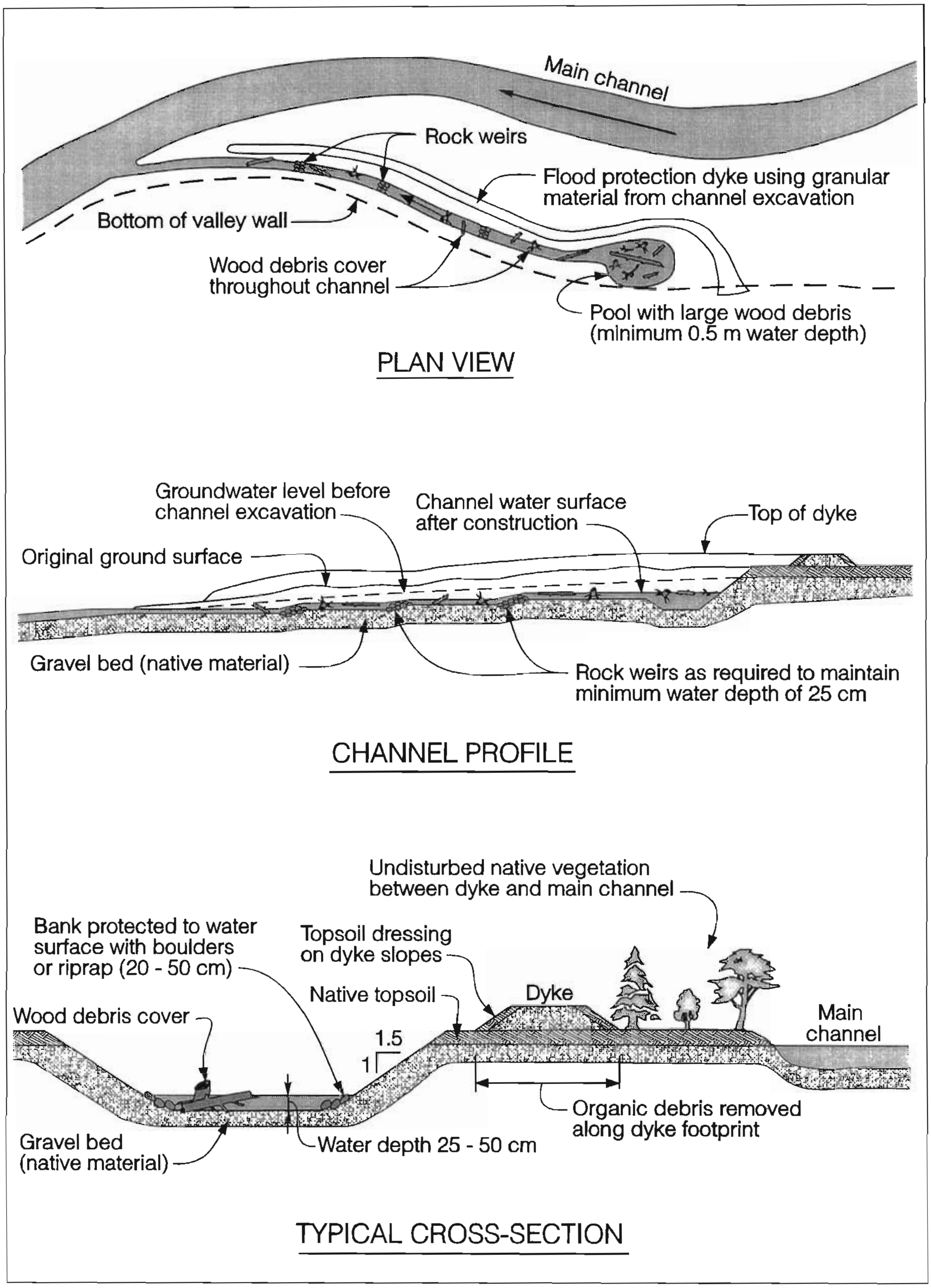

Figure 7-6. Concept of a groundwater-fed spawning and rearing channel.

Consideration should also be given to creating a small bench at least 1.5 m wide between the channel and the dyke to provide a path for channel inspection, and to catch sediment that may be eroded immediately after construction.

Figure 7-7. A groundwater channel just after construction, Usher's Channel, Chilliwack River.

Surface-fed Channels

Side channels fed by stream surface water are being employed to an increasing extent for rehabilitation of off-channel spawning and rearing habitat. This trend is occurring because suitable sites for groundwater channels are being exhausted in some areas, and certain salmonid species, e.g., chinook and pink salmon and steelhead trout, are adapted to surface temperature regimes and relatively high water velocities. The advantages of a surface water source lie in the availability of large water volumes and flexibility in project siting. The disadvantage of a surface water source is the possibility of significant sediment introduction and the need to expend considerable effort on maintaining substrate quality. A surface-fed channel also has the cost of a river intake, which is not a requirement for a groundwater channel.

Because sediment is such a critical concern, surface-fed channels should not be located on systems, such as glacial streams, with high suspended sediment loads. Other siting prerequisites are a bench of land with adequate flood protection, and a suitable water intake site. The bench on which the channel is located should have a reasonably high overall slope of at least 0.5% parallel to the main stream. Relatively high channel gradient is required to provide an adequate range of water velocities and habitat types in the channel.

Intake Location and Design

Intake structures for projects that utilize surface water require special consideration. A minor shift in the main channel during a flood event could have serious implications for the continued operation of a surface intake structure. Hence, permanent intakes should be located on stable reaches, which are unlikely to be affected by flood flows. In some locations it may be necessary to armour the bank in the immediate vicinity of the intake to ensure bank stability under extreme flows. In addition, fill material around the intake structure must be adequately armoured with heavy riprap or boulders to withstand high local velocities.

The intake for a surface-fed channel should be located on the outside of a bend in the main stream, along the downstream half of the bend (Fig. 7-8). Secondary or lateral circulation in that area tends to be toward the outside bank on the stream surface, and away from the outside bank along the stream bottom. Such an intake location will minimize amounts of sands and gravels entering the channel because sediment bedload tends to accumulate on the inside bend. To avoid debris accumulation, it is also important to locate the intake where there is a positive downstream flow along the bank. Localized backeddies should be avoided.

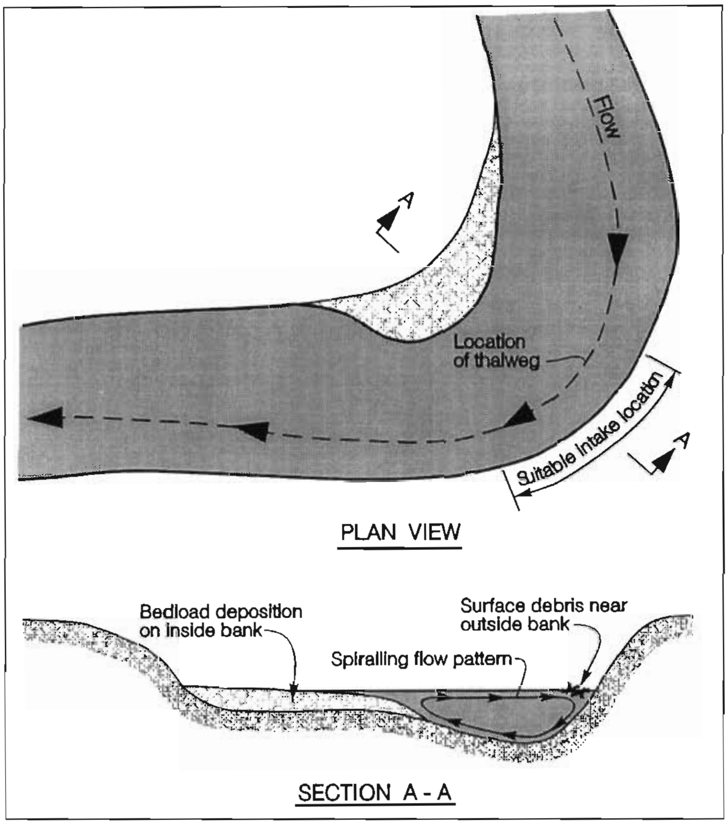

Figure 7-8. Suitable channel intake location on outside of river bend. Cross-section shows secondary circulation pattern.

The appropriate type of intake will depend on site conditions. Where the bank is stable on the outside bend, a log curtain wall can be employed to deflect floating log debris (Figs. 7-9 and 7-10). The flow control valve, with a trash rack for smaller debris, is set back from the stream bank. A settling pond, between the curtain wall and the trash rack, is an essential feature. The pond can be expected to settle out fine to coarse sand fractions, but silts and clays are likely to pass through to the channel. The settling pond should be as large as site conditions permit. A smaller pond will have to be cleaned out more frequently. It is also important to provide road access for heavy machinery required to clean the pond.

Figure 7-9. Log curtain wall under construction, Shovelnose Creek, Squamish River.

Figure 7-10. Log curtain wall above intake, Anderson Creek Pond, Chilliwack River.

There are several intake designs that can be employed to control flow volume at the head of the channel. The simple wood frame structure shown in Figure 7-11 will be adequate if upstream fish passage, past the regulating valve, is not needed. If fish passage is required, then a larger slide-gate control structure should be employed (Fig. 7-12). The latter structure will be most suited to channels with relatively large flow volumes that might attract considerable numbers of migrating salmon destined for spawning areas upstream of the channel.

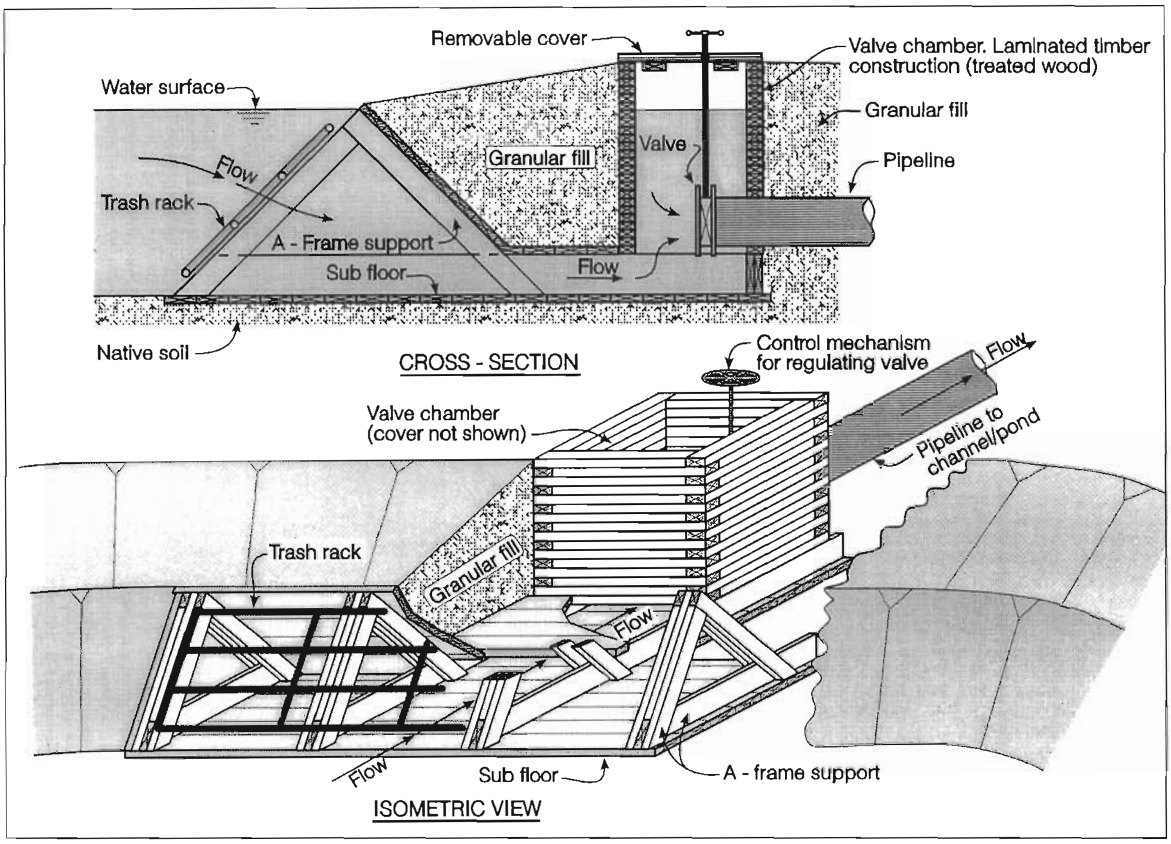

Figure 7-11. Wood frame intake structure, Or Creek project, Coquitlam River, B.C.

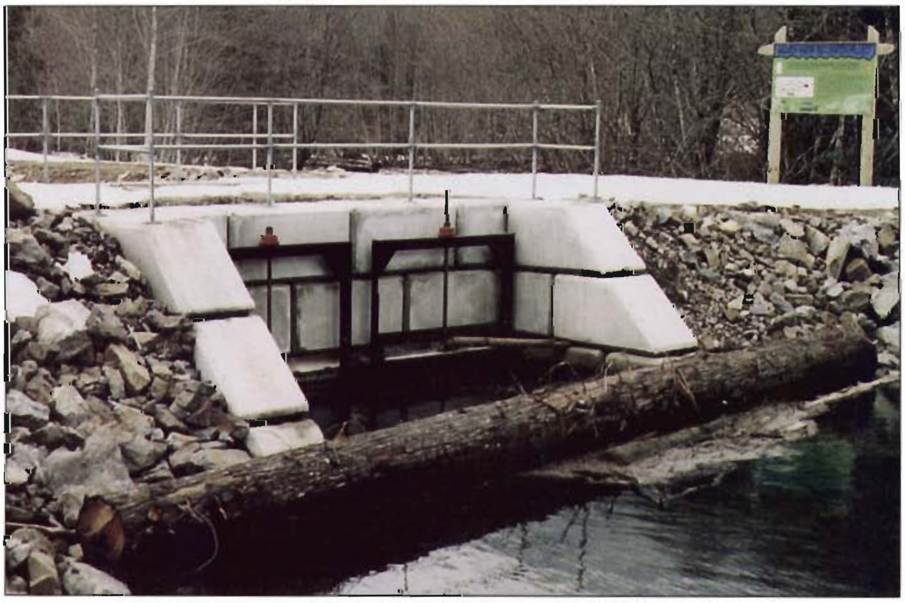

Figure 7-12. Concrete intake with box culverts and manually operated slide gates, Centennial Channel, Chilliwack River.

Where sand and gravel bedload is a concern, it may be appropriate to locate the intake off the stream bottom. A manifold-type intake is suited to this purpose, and has the added advantage of requiring little stream bank disturbance. It consists of a horizontal, heavy wall steel pipe with an intake slot and trash bars facing upstream or downstream, parallel to the direction of flow (Fig. 7-13). This type of intake must be located on a stable reach and at a location with a positive downstream flow to carry floating debris past the intake. Backeddies should be avoided. To minimize wood debris and bedload problems, water depth at low flow needs to be at least 60 cm plus the pipe diameter.

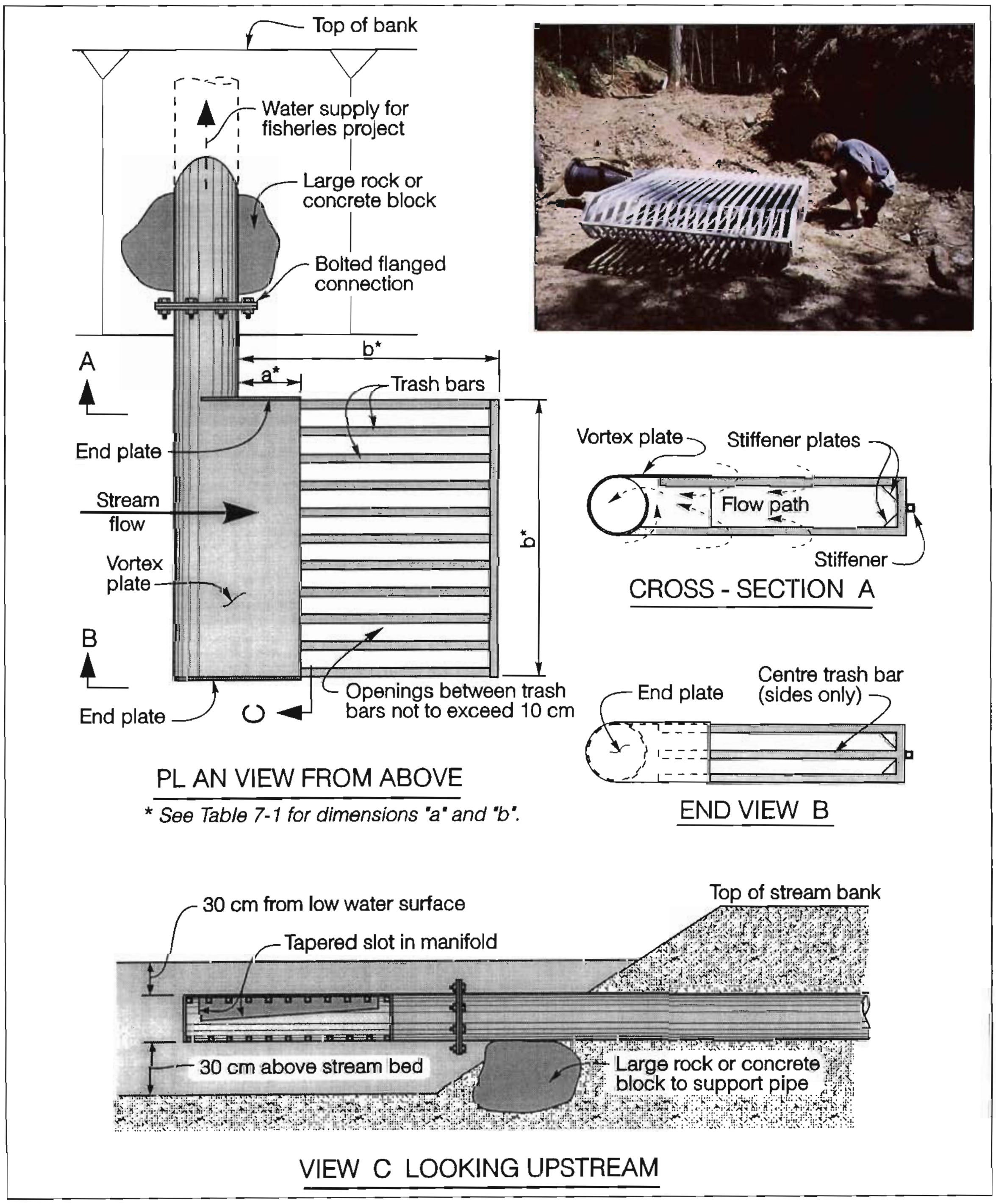

Figure 7-13. Concept of a manifold-type intake, bolted to steel pipe buried in stream bank.

Water is drawn into a manifold intake through a tapered slot in the pipe, with the wide end of the slot at the offshore end (Fig. 7-13). Cross-sectional area of the tapered slot should approximate the pipe cross-section. The narrow end of the slot should exceed 5 cm in width; the wide end dimension is dictated by the required open area. Design parameters for a manifold intake are given in Table 7-1.

Table 7-1. Design parameters for selected flow capacities of a manifold-type intake.

Design Pipe Flow ($m^3 \cdot s^{-1}$)	Pipe Diameter (cm)	Width of Vortex Plate[a] (cm)	Trash Rack Dimension[b] (cm)
0.05	20	30	90
0.12	30	40	120
0.20	40	45	150
0.35	50	50	180
0.55	60	60	275

[a] Vortex plate width as indicated by dimension "a" in Figure 7-13.
[b] Trash rack dimension on one side, as indicated by dimension "b" in Figure 7-13. Trash rack length and width should be equal.

Channel Design

A surface-fed channel should provide a range of habitat conditions to accommodate spawning, rearing and overwintering, as well as the habitat needs of individual species. Rearing habitat requirements, for example, can differ among species (Hartman 1965; Bisson et al. 1988), among life stages of a species (Everest and Chapman 1972), and among seasons (Bustard and Narver 1975; Nickelson et al. 1992a). The channel should have pools interspersed between run or riffle sections (Fig. 7-14). In a meandering stream with a natural flow regime, pools occur at intervals of roughly 5-7 channel widths (Leopold and Langbein 1966). In a controlled flow channel, however, pool spacing and size are not similarly constrained. The proportion of a surface-fed channel devoted to pool habitat, relative to riffles and runs, can therefore be governed largely by the habitat requirements of the fish species and life stages involved. Research on salmonid behavior suggests that a larger number of smaller habitat units will promote greater fish utilization per unit area than fewer but larger units. The head of a pool, for example, is known to be a focal point for rearing salmonids because of its proximity to the supply of insect drift food from the upstream riffle (Mundie 1974), and cover provided by the higher velocities and surface turbulence at that location (Lewis 1969). Salmonids establish social hierarchies with larger, dominant individuals usually located at the head of the pool, and smaller, sub-dominant individuals distributed over downstream areas of the pool where the dissipation of velocity results in less favourable feeding stations and cover (Mason and Chapman 1965; Griffith 1972; Fausch 1984). The velocity entering pools, and the size and frequency of pools, are therefore important considerations in channel design.

Velocities in pools, and water depth and velocity in the run and riffle sections, can be manipulated by varying channel slope and width. Addition of boulder clusters can enhance cover and habitat complexity in runs (see Chapter 10), and can increase channel roughness to create suitable velocities for spawning in steep riffles (Fig. 7-15). Water depth, velocity and space requirements of various salmonid species and life stages are reviewed in Bjornn and Reiser (1991) and Keeley and Slaney (1996).

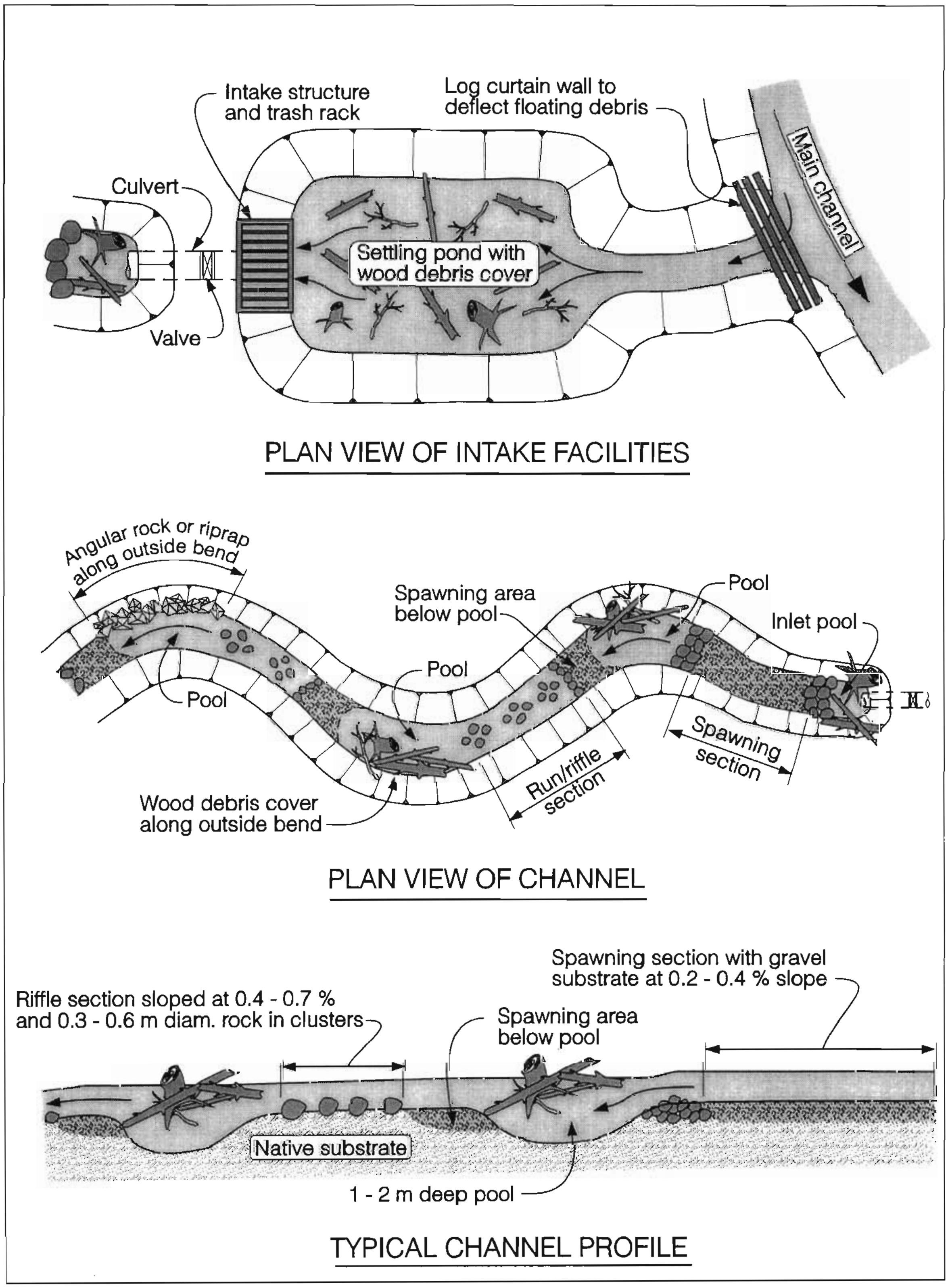

Figure 7-14. Concept of a surface-fed channel for spawning and rearing.

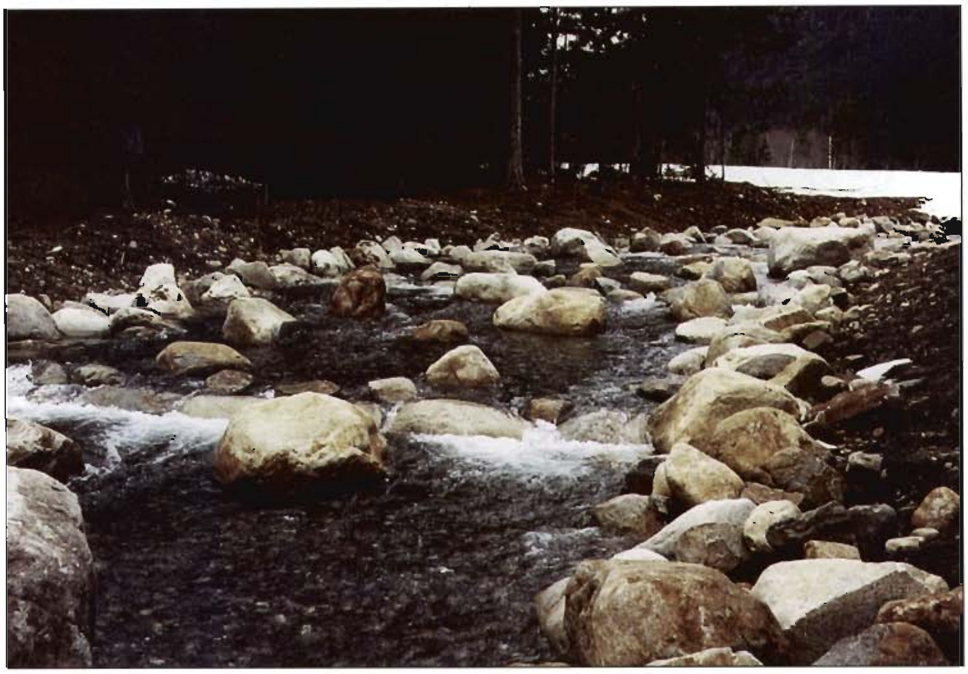

Figure 7-15. Riffle section of channel with boulders added for habitat complexity, Centennial Channel, Chilliwack River.

The cross-section of run and riffle sections in a surface-fed channel should be similar in concept to a groundwater channel (Fig. 7-6). To prevent bank erosion by spawners, and provide stability until riparian vegetation establishes, channel banks should be constructed with a slope no steeper than 1.5:1 and lined with boulders or riprap (20-50 cm diameter) to a level above the design water surface. The channel alignment may be adjusted to take advantage of large trees or stumps to provide cover features such as undercut banks (Fig. 7-16). The bank along the outside bend of a pool can be protected from erosion by placement of large boulders, riprap, or cabled wood debris. While both rock and wood debris provide cover and habitat complexity for juvenile salmonids, wood debris is generally preferred for that purpose. Where both materials are available, the best solution may be to armour the outside bank with riprap for hydraulic protection, and employ wood debris along the bank to improve habitat complexity and fish escape cover (Fig. 7-17). If riprap is used for bank armouring in pools, its attractiveness to juvenile salmonids will be enhanced if rock size is large (> 50 cm mean diameter), the bank is steep and irregular, and velocities along the bank are relatively high (Lister et al. 1995).

As discussed for groundwater channels, native gravels should be used for the channel bed wherever possible. If gravel has to be imported for the project, its size composition should be comparable to natural spawning beds, and it should include fines down to 1-2 mm diameter. Guidelines on spawning gravel sizes for various salmonids are summarized in literature reviews (Bjornn and Reiser 1991; Keeley and Slaney 1996). Designers should also check the hydraulic stability of selected gravel and rock sizes with the tractive force equation given in Chapter 12.

Design width of a surface-fed channel should be in keeping with the available water supply, and should take into account the site's physical constraints and fish production objectives. Channel design width and slope can be varied, along with the planned operating discharge, to produce desired water depths and velocities, and to provide variation between channel sections. Once habitat requirements are defined, an experienced fluvial geomorphologist or hydraulic engineer should be consulted to determine appropriate channel discharge, slope and width.

Designers should avoid the temptation to maximize channel length to gain the largest possible channel area within the project site. Such a strategy may result in a marginally acceptable channel slope, and increase the risk of sediment accumulation. It is therefore prudent to provide for adequate, or possibly excessive (1-2%), channel slope. Excess slope can always be accommodated by adding weirs or by increasing channel roughness with boulders in steep riffle sections (Fig. 7-15).

Figure 7-16. Undercut stump habitat in pool, Grant's Tomb Channel, Coquitlam River.

Figure 7-17. Pool with riprap bank armour and wood debris cover, Centennial Channel, Chilliwack River.

Rearing and Overwintering Ponds

Off-channel pond environments play a significant role in juvenile salmonid rearing and overwintering, particularly for coho salmon (Peterson and Reid 1984; Swales and Levings 1989). Many natural ponds result from beaver dams (Bryant 1984). Creation of pond environments for juvenile salmonids may be the main focus of an off-channel habitat project, or it may be an adjunct to groundwater or surface-fed channel development (Fig. 7-18).

Figure 7-18. Alcove-type pond connected to Centennial Channel, Chilliwack River.

For pond sites that are independent of spawning channels, it is advantageous to incorporate some stream spawning habitat into the project, to provide greater assurance of juvenile recruitment and to accommodate stream-dwelling fish species. If suitable spawning habitat cannot be provided, the outlet channel must be designed to facilitate upstream juvenile passage from the main stream. Because juvenile salmonids have relatively high swimming capabilities, up to 10 or more body lengths per second (Webb 1975), they are able to surmount short, high-velocity stream sections. Though a steep outlet channel may be required in some cases, the channel slope should probably not exceed 5%. Outlet channels over 2% slope should be stepped down to the main stream over a series of low drops, not more than 10 cm high and separated by pools or runs that dissipate the hydraulic energy and provide resting areas for the fish. Rough and irregular channel margins, with alternating sections of high velocity and back eddy, are also essential features for juvenile passage. Conditions at the entrance to the main river will be difficult to control and should not be a concern. Juvenile salmonids appear capable of locating and entering off-channel sites under a variety of physical conditions.

Rearing and overwintering ponds can be created by either: (1) flooding an existing site or increasing water depth over the site, possibly an existing wetland or abandoned river channel, through construction of a dam or dyke; or (2) excavating to achieve adequate water depths within or adjacent to an existing watercourse. Some projects combine these approaches. Off-channel pond projects can vary greatly in size, depending on physical attributes of the selected site. Though pond areas of projects in British Columbia have generally been less than 0.5 ha, ponds of up to 1.5 ha have been constructed. It is worth noting that larger ponds will generally not support as many fish per unit area as smaller ponds (Keeley and Slaney 1996). Examples of off-channel rearing and overwintering pond projects are discussed in the following paragraphs.

The Anderson Creek project on the Chilliwack River is an example of creative use of site characteristics to restore salmonid spawning and rearing habitat (Fig. 7-19). Since construction of the Chilliwack Lake Road, upstream passage of fish into upper Anderson Creek had been blocked at the road culvert, and an old meander channel of the Chilliwack River had been cut off from the main river. The restoration effort involved diverting a portion of the Anderson Creek flow just upstream of the road culvert, and installing a new road culvert 300 m east of Anderson Creek to flood the old meander channel and to provide fish passage under Chilliwack Lake Road. The project has created a 1.5 ha pond (Fig. 7-20), 200 m of inlet and outlet spawning and rearing channels, and has re-established fish access to upper Anderson Creek. A 2 m deep channel was excavated along the dyke on the north side of the pond to increase water depth for juvenile salmonid overwintering, and to make it difficult for beavers to construct a dam at the pond outlet. A beaver-proof intake box (see Chapter 15) prevents blockage of the outlet culvert while allowing adult and juvenile salmonids to move upstream into the pond. The outlet culvert was oversized to provide low velocities for upstream passage of juveniles. The inlet and outlet streams are now being used for spawning by coho and chum salmon, and the pond supports juvenile coho and steelhead rearing and overwintering.

Studies of juvenile coho utilization of off-channel ponds for overwintering have indicated that while shallows, less than 0.75 m deep, may be beneficial to coho in terms of benthic insect food production, the presence of deeper areas (to 3.5 m) tends to maximize survival for smolt emigration (Peterson 1982b; Cederholm et al. 1988). Off-channel ponds that have both shallow areas or shoals for food production and deep areas for overwinter security (Fig. 7-21) are most likely to produce good numbers of large, viable smolts.

Alcove-type pools or ponds, which are essentially a backwater environment connected to the main stream channel, are also being created to provide off-channel rearing and overwintering habitat, primarily for juvenile coho. This type of habitat, similar in concept to Cook Creek pond in Figure 7-21, fosters limited water exchange, low velocity, and development of pond-like conditions. Alcoves are usually quite accessible to salmonid juveniles and coho utilization of alcoves is high compared to other habitats in winter (Nickelson et al. 1992b). Alcoves have therefore been included in several off-channel habitat developments in British Columbia. As a note of caution however, the point of connection between the alcove and the main stream can be blocked as a result of shifts in the bed of the main channel under high flows (Nickelson et al. 1992b). The alcove concept therefore appears best suited to hydraulically stable environments, such as a groundwater channel or a surface-fed side channel with controlled flow.

Addition of wood debris cover to streams can improve salmonid rearing and overwintering capability (see Chapter 8). There is limited evidence, however, of similar benefits to salmonid production in ponds. Comparison of juvenile coho populations in a series of artificial off-channel ponds at Coldwater River, with and without wood debris added, revealed an average of 2.5 times higher densities in ponds with debris cover (Beniston et al. 1988). The advantage of added wood debris appeared to be greatest in winter and smallest in summer.

Experience with performance of constructed off-channel pond environments is not extensive. Research to date would suggest incorporation of the following design principles:

- limit the area of individual ponds to 0.1 - 0.3 ha;
- provide diverse water depths for fish growth and overwinter security;
- limit water exchange rates to foster development of a pond environment, but recognize the need to maintain suitable water temperatures and dissolved oxygen levels;
- incorporate, where feasible, some spawning habitat upstream of the pond, to reduce reliance on upstream movement of juveniles for recruitment; and
- add wood debris cover, to improve rearing and overwintering capability.

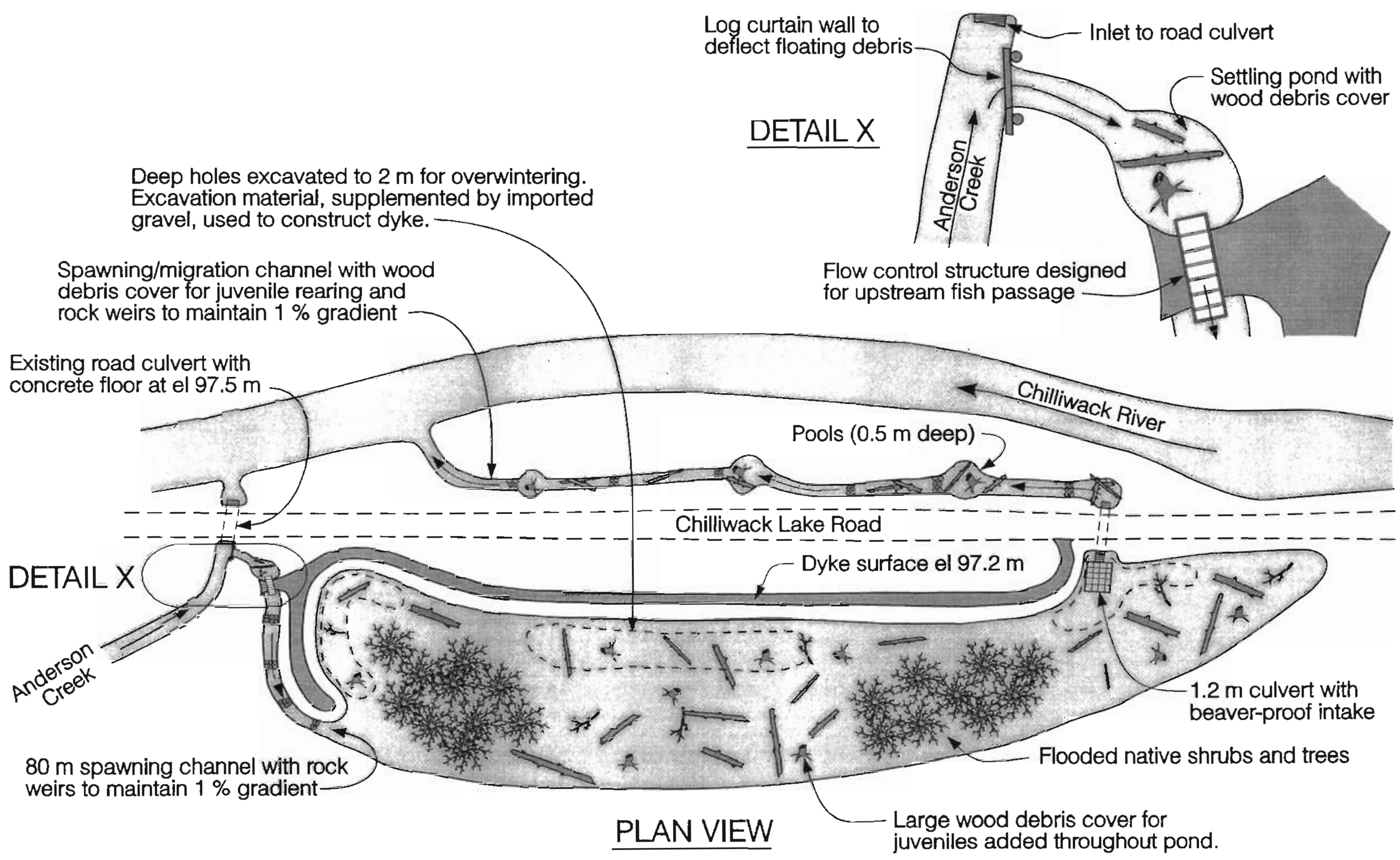

Figure 7-19. Rearing and overwintering pond with inlet and outlet stream habitat, Anderson Creek, Chilliwack River.

Figure 7-20. Rearing and overwintering pond at Anderson Creek, Chilliwack River.

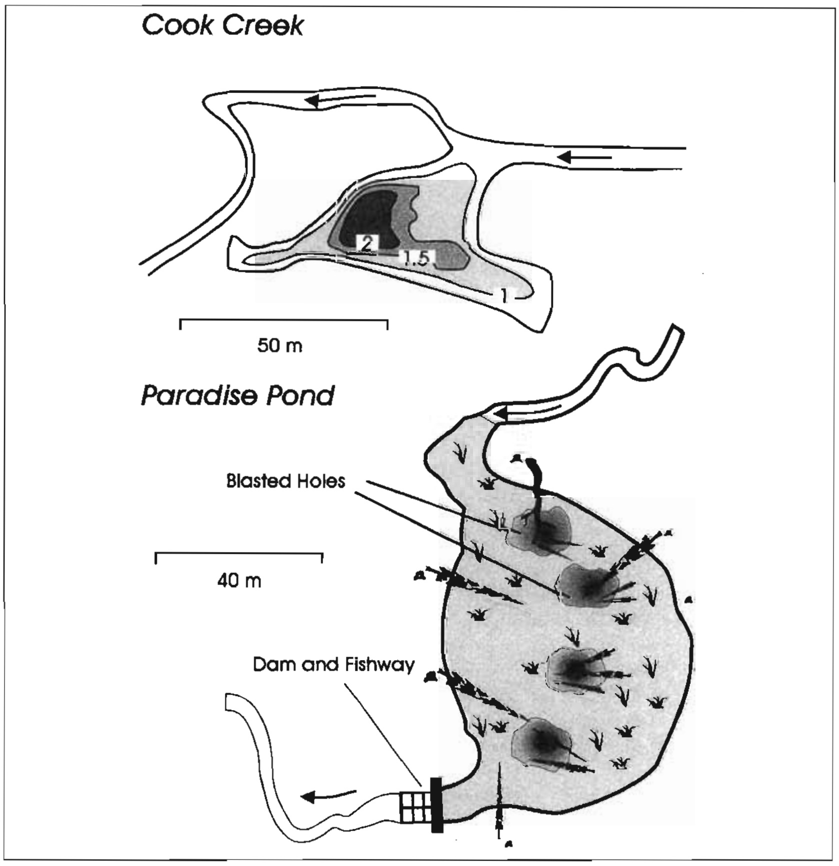

Figure 7-21. Alcove pond at Cook Creek, North Thompson River (Lister and Dunford 1989) and beaded channel at Paradise Pond, Clearwater River, Washington (Cederholm et al. 1988).

Project Costs

Costs of off-channel habitat projects vary with scale and type of habitat, as well as the particular site conditions (Table 7-2). Rearing and overwintering ponds of various sizes can be created at modest cost ($2.50 - 4.00 per m^2) in relation to excavated groundwater-fed channels with armoured banks ($14.00 - 18.00 per m^2).

CONSTRUCTION PROCEDURES

Construction of off-channel habitat, as with any fish habitat project, is largely about dealing with water. This influences construction timing and procedures, and it also poses challenges in controlling sediment to avoid impact on downstream fish habitat.

To prepare for construction the limits of clearing and excavation as well as the channel centerline, should be flagged. Flagging may reveal the potential loss of exceptional trees that could be avoided by a modest shift in project alignment or by confining the excavation limits. Clearing of vegetation should also be undertaken in a manner that avoids unnecessary disturbance and loss of trees. Conifers that are suitable for providing habitat complexity in the finished project should be stockpiled (Fig. 7-22).

Figure 7-22. Excavation of a surface-fed channel showing stock piles of conifer trees and boulders, Centennial Channel, Chilliwack River.

Excavation and handling of topsoils should be undertaken during the dry summer season. A groundwater channel should ideally be excavated in late summer when the water table is low. Instream work windows, established by regulatory agencies to avoid fish habitat impacts, are also an important constraint on the construction schedule. Projects should be completed early enough to provide time for germination and growth of grasses to stabilize soils before the fall rains. Seeding of grasses needs to be conducted before temperatures decline in fall.

Table 7-2. Construction costs of selected off-channel habitat projects in British Columbia. Estimated costs include construction labour, equipment rental, and materials. Costs of design and construction supervision are not included.

Project Name and Location	Construction Year	Project Description[a]	Site Dimensions	Estimated Costs ($)	
				Total Cost	Cost·m^{-2}
Adams River Side Channel	1990	Groundwater spawning/rearing channel, with riprap banks and native gravel, for sockeye and coho.	980 m x 5 m	88,000	18.00
Usher's Channel Chilliwack River	1991	Groundwater spawning/rearing channel, with riprap banks and native gravel, for chum and coho.	625 m x 6 m	54,000	14.30
Shop Creek Channels Squamish River	1994-95	Three small groundwater channels with deep pools and wood debris cover for coho overwintering. No bank armour.	2,300 m^2 (580 m x 3-4 m)	11,000	4.80
28.5 Mile Creek Squamish River	1996	Two ponds, groundwater channel for coho spawning/rearing. Woody cover added.	Ponds 3,500 m^2 Channel 6,000 m^2	84,000	8.80
Or Creek Coquitlam River	1994-95	Surface intake with spawning/rearing channel sections between 4 rearing ponds, for coho, cutthroat and steelhead. Boulders and wood debris cover added.	1.42 ha of ponds 1650 m^2 of channel (540 m x 3 m average)	130,000	8.20
Fletcher Challenge Channel Englishman River	1992-93	Manifold-type surface intake and channel to increase flow to relic side channel with beaver ponds. Spawning/rearing habitat for several species.	290 m of improved channel, 1000 m relic channel, ponds (18,000 m^2)	88,000	5.00
Golden Ponds Alouette River	1994	New pond (2700 m^2); fish access improved to existing beaver pond (5600 m^2); and spawning/rearing channel.	0.83 ha of ponds	22,000	2.60
Fee Creek Ponds Birkenhead River	1991-92	Five rearing ponds created by excavation and earth dams. Includes groundwater channels to enhance flow, timber control structures and fishway.	1.66 ha of ponds; 780 m^2 groundwater channels (290 m x 2.7 m)	45,000	2.60
Anderson Creek Pond Chilliwack River	1995	Old meander channel flooded and deepened; wood debris added. Includes intake, spawning/rearing channels and culvert.	1.5 ha pond; 200 m x 4 m channels	66,000	4.10

[a] Equipment included one or more of the following: tracked excavator; small bulldozer/loader; dump truck; and gravel screen.

In the case of groundwater channels, and some pond habitat projects, site excavation will penetrate the water table and cause seepage into the excavated area. An earthen plug can be left at the downstream end to isolate the site from the adjacent stream. Keeping initial excavation above the water table, and lowering the bed of the channel or pond in stages, can also assist in dealing with seepage. A staged excavation strategy could involve removal of overburden, then excavation to the water table, and lastly, commencement of ditching at the lower end of the channel to pull down the water table. Water that can't be retained on the site should be pumped or diverted to a constructed sediment settling basin or natural depression for treatment. Clean water flowing into the construction area should be diverted or pumped around the site to assist construction and minimize water volumes to be treated for sediment control. It is advisable to develop a sediment mitigation plan and to obtain agreement from habitat protection staff of the regulatory agencies in advance of construction.

Excavated overburden and gravels will normally be sidecast to form a flood protection dyke on the main river side of the project. Where practical, topsoil should be stockpiled so that it can be later used on disturbed areas such as channel and dyke slopes, to improve the growth medium for revegetation. Rootwads and large boulders that have to be removed should also be stored on-site for subsequent placement as instream cover or bank protection. Trees and shrubs, which can be salvaged alive with intact roots, should be covered with soil and stored for site revegetation.

Following site excavation, channel side slopes should be armoured and rock weirs installed. Vegetative techniques for slope stabilization may also be appropriate (see Chapter 6). Wood debris and/or large rocks should be added to enhance habitat complexity.

A surface intake on a stream should be constructed during the low water period and within the approved instream construction window. If necessary, the intake can be isolated from the stream by retaining an earth plug or by sand bags, to avoid downstream sedimentation and facilitate the construction.

The final stage involves stabilization of banks and other disturbed areas to control surface erosion during the fall-winter period. Available top soil should be spread over disturbed soils, and slopes should be lightly scarified to improve conditions for establishing grasses and shrubs. The site should be seeded with an appropriate mix of grasses and clover. A light dressing of hay or straw may then be spread over the seeded areas to provide some erosion protection until grasses germinate and begin to grow.

OPERATION AND MAINTENANCE

Operation and maintenance requirements of off-channel habitat projects vary considerably depending on the type and complexity of the project. Projects that utilize a groundwater source normally require little operational effort and also have modest maintenance needs. Surface-fed channels or ponds, on the other hand, will often require an active operation and maintenance program. In this respect, it is prudent to engage a local entity, such as a fish and game club or salmonid restoration society, to carry out the routine operation and maintenance.

For a groundwater project, the operational concern is generally related to fish access, which may be restricted by a beaver dam or inadequate flows, particularly in the early fall. The gravel substrate and rock armour of a groundwater channel will accumulate fine organic material, and may experience some encroachment by vegetation or rooted aquatic plants. These problems are generally addressed by scarifying the gravel and turning over the rock armour. Reconstruction of rock weirs, regrading of spawning gravel, and addition of bank armouring may also be required from time to time. Groundwater-fed channel and pond projects should be inspected periodically during the spawning migration period to ensure fish access and at least annually to monitor channel substrate quality and other features.

A surface-fed channel or pond will generally require greater operational attention than a groundwater project, because of relatively high flow volume and potential for intake blockage. The intake and flow control gate will need to be regularly inspected and kept free of debris. During high flow periods, inspections may be required weekly or more frequently, while at other times the inspection frequency can likely be reduced. Once the best discharge for fish spawning is established, the flow control gate or valve should be left at the required setting throughout the spawning period. It may be desirable, however, to reduce channel discharge during the incubation period in order to minimize introduction of suspended sediment to the channel.

Surface-fed channels need to be inspected annually to assess the maintenance requirements. Features to be examined include intake condition, sediment deposition in the settling pond, condition of weirs and bank armour, and possible accumulation of fine silts and organics in the gravel substrate. Maintenance could involve sediment excavation from the settling pond, weir repair or removal, bank armour repairs, and gravel cleaning by either scarification or, in an extreme case, by removal and replacement with new or screened material. The latter activity should be only an occasional requirement.

Though a pond environment is unlikely to require maintenance, the stream connecting it to the main stream should be inspected periodically for potential obstructions to fish passage, particularly beaver dams. It is also prudent to periodically monitor water quality, especially dissolved oxygen, to identify any trend toward deteriorating water quality.

Chapter 8

Rehabilitating Stream Channels and Fish Habitat Using Large Woody Debris

C. Jeff Cederholm[1], Larry G. Dominguez[1], Tom W. Bumstead[2]

INTRODUCTION

Recent reviews of the status of Pacific Northwest salmon stocks indicate that many have either already gone extinct or are in a threatened status (Nehlsen et al. 1991; Slaney et al. 1996; Van Alen 1996). The causes of these declines in the western U.S. have been summarized by Nehlsen et al. (1991) in four general categories: a) overharvest of weaker stocks; b) problems caused by hatcheries; c) hydropower facilities; and d) habitat loss. Nehlsen et al. (1991) concluded that there is a need for a paradigm shift that "... advances habitat restoration and ecosystem function rather than hatchery production ... for many of these stocks to survive and prosper into the next century." The need for taking an ecosystem perspective when planning restoration of anadromous salmon runs is now widely recognized. Attempts to restore habitats and ecosystem function are already occurring throughout the Pacific Northwest; many of these efforts include placement of large woody debris (LWD) in streams.

LWD is generally described as wood material (>10 cm dia. and >2 m long) that mainly enters stream channels from stream bank undercutting, windthrow, and slope failures. In the Pacific Northwest, instream coniferous LWD abundance has been greatly diminished in the past due to logging to the stream banks and stream clearance practices, creating the potential for streams to reach minimum coniferous LWD abundance within 100 years after these original impacts. In other words, until about the middle of the next century, many impacted streams may experience their lowest LWD abundance. One of the challenges for watershed and fish restoration work is to provide an interim period of artificially-constructed instream LWD habitat, while planning for the self-restoration of river basins by expediting recovery of forest and riverine ecosystems. Although interim restoration work is vital to sustaining many weakened fish stocks, it is misleading to believe that it is the complete answer to recovering salmon habitats to predisturbance productivity.

There are several salmon habitat and watershed rehabilitation manuals (Anon 1980; House et al. 1988) and a tremendous amount of related literature. Many of these articles caution the user to be aware of the dynamic variability of streams and establish the importance of recognizing unique site-specific characteristics during restoration. Theoretically, each piece of wood that is introduced into stream channels will respond differently due to the variables associated with that particular system. Every attempt at artificially loading LWD into a stream should be approached with caution and with a goal of learning. A "failed" project (one that does not accomplish what was "engineered" on paper) can be a valuable addition to the restoration ecology literature. Also, a "failed" project may even be an unrecognized success, positively contributing to a different part of the stream ecosystem that the researcher, or restoration worker, has overlooked (e.g., stabilizing a stream feature).

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Despite significant amounts of research and improved understanding of LWD and its associated processes, we are in the early stages of understanding the role of LWD from an ecosystem perspective. As a template for understanding the basic physical and biological processes at work in watersheds, we recommend awareness of the river continuum concept put forth by Vannote et al. (1980) and modified by Triska et al. (1982). Many abuses of our landscapes have occurred because of incomplete understanding of stream ecology, and have left scientists with few opportunities to confidently describe LWD processes in an undisturbed environment. It is recognized that the recommendations we provide may be modified as understanding of the forest ecosystem increases.

THE PHILOSOPHY OF LARGE WOODY DEBRIS REHABILITATION

Habitat rehabilitation must never be viewed as a substitute for habitat protection. Communication between fishery managers and land managers is an essential element of habitat protection. We should begin the process of habitat rehabilitation by protecting those watersheds and riparian ecosystems that still remain in relatively good condition. Maintaining natural forest hydrology, building fewer and better roads, and providing riparian buffers of sufficient width to protect the aquatic corridor will go a long way towards ensuring sufficient LWD loadings into the future. For a complete discussion of salmonid habitat protection in forest settings, we refer the reader to Forest Ecosystem Management: An ecological, economic and social assessment (Femat 1993).

Many Pacific Northwest watersheds are in a state of early recovery from habitat degradation caused by past land use practices, and without assistance, it could take centuries to recover lost LWD-associated processes. Stream channel rehabilitation begins at the mountaintop. Most degraded watersheds can point back towards altered hydrology due to vegetation removal as the cause of degradation. Consequently, the stream channel manifests the changes in the hydrologic cycle processes that occur on mountaintops, on the ridges, in the upland forest, and in the riparian corridor. With many of our lands under intensive management for natural resource extraction, the riparian forest remains the last line of defense for preserving stream health. Van Cleef (1885) emphasized the necessity of protecting the structure of stream banks and riparian areas over 100 years ago. Today, the message is as fresh as when it was written. During the period of watershed recovery, there may be some helpful upslope, riparian and in-channel rehabilitative work using LWD that can speed the recovery of stream channel processes and benefit fish resources. Our recommendations will include LWD placement to not only rehabilitate fish habitat, but also to restore the connectivity of the stream to the riparian ecosystem and floodplain. In some cases this includes placement of LWD in non-fish bearing waters or even out of sight, under the streambed, to add stability to the channel. Such practices would begin to rehabilitate the habitat-forming processes ensuring long-term benefits for the salmonid environment.

THE ECOLOGICAL ROLE OF LARGE WOODY DEBRIS IN STREAMS

Importance For Channel Function

Small to Intermediate Streams

LWD provides important physical functions in a wide variety of channel configurations. In small first and second order channels, abundant LWD is individually established or bound together in continuous networks of mostly conifer pieces. In these channels, LWD traps sediment, causes local bed and bank scour, and creates a stepped-channel profile. It has been found that over half the total sediment stored in first to third order streams is retained by organic matter. These relatively small channels tend to be straight rather than meandering as they are tightly constrained by adjacent slopes. Because of high gradient (>5%), and frequent waterfalls, these streams usually have sparse fish populations.

In small (<10 m bankfull width (BFW)) to intermediate size (10-20 m BFW) streams, LWD contributes to channel stabilization, energy dissipation, and sediment storage. Small channels are highly dependent on in-channel woody debris structure for stability. LWD provides important physical and biological functions in the wide variety of habitats used by all species of Pacific salmon. LWD contributes to escape cover from predators and high velocities for adult and juvenile salmonids. Also, LWD creates storage sites of biological activity, trapping spawned out salmon carcasses and other organic matter, which contributes to riparian and aquatic productivity (Cederholm et al. 1985, 1989; Bilby et al. 1996).

Single or multiple pieces of conifer trees may hold drift jams together in steep headwater tributaries. Complex arrangements or simply individual pieces of LWD may be found scattered along the channel, from the very headwaters all the way downstream. Deciduous wood decomposes quickly, but it also regrows rapidly, while conifer trees may take centuries to reach full size and decompose very slowly. Important accumulations of LWD are also buried out of sight below the gravel surface, providing important structure and nutrient supply to the surface or subsurface "hyporheic" zone. Scour from floods or channel reconfigurations often expose a legacy of this old buried LWD and this newly exposed material often functions for many more years. In some stream channels, LWD contributes to major habitat forming processes such as bar stability, side-channel development, island formation, and channel feature formation.

Intermediate stream orders (3rd-5th) have less continuous accumulations of LWD, but may have "drift jams" that can block the flow and occasionally redirect the stream course, resulting in evacuated floodplain channel features that can become important overwintering habitat for juvenile salmonids. The main channels of these streams have gradients of less than 5% and tend to show signs of meandering. It is common to see full-sized trees laying within and across these streams and huge chunks of wood protruding out of the gravel. Large wedges of spawnable sized gravels are held back by logs, and plunge pools and dam pools are a common association. Typically, many species of resident and anadromous salmonids inhabit these streams, as well as a diversity of non-salmonid fishes. These streams have some of the highest salmonid productivity.

Large Streams

The highest order channels (>5th order) are characterized by infrequent, but occasionally massive accumulations of LWD. Gradients tend to average less than 0.5%. The LWD tends to be of large diameter and often complete trees with rootwads and branches can be seen holding together accumulations of smaller logs and other wood debris. Much of this debris has floated down from upstream areas during flood events or has entered the channel from bank undercutting of relatively young stands of trees growing on gravel bars. Large LWD accumulations in the lower floodplain of coastal rivers can direct the flow into meander loops and result in formation of riverine ponds and other off-channel habitat features. These habitats are used heavily by immigrant juvenile coho and cutthroat seeking to escape the main river discharge and turbidity. There is also evidence that main river channels in large interior rivers may serve in a reverse way compared to coastal rivers, acting as refuge for emigrant juvenile steelhead and chinook leaving tributaries during winter freeze-up periods. Large rivers function both as fish migration corridors to access spawning and rearing habitats and as rearing habitats for a whole variety of salmonid and non-salmonid fishes.

Evidence of Salmonid Use of Natural and Artificially-placed LWD

The benefits of LWD for juvenile salmonids rearing in streams change seasonally. Summer-rearing coho, steelhead, and cutthroat juveniles are known to evacuate their summer habitats and seek refuge in deep pools with woody debris as winter temperatures decline and stream discharge increases (Bustard and Narver 1975). Grette (1985) found that the rearing densities of juvenile coho in Olympic Peninsula streams were closely associated with LWD in winter. Murphy et al. (1986) found no correlation between summer coho densities and debris in S.E. Alaska streams, but a close association during the winter. On the Keogh River in B.C., coho densities were not closely correlated with large woody debris in the summer, except in shallow pools or "flats" which comprised 24% of the area of the stream (P. Slaney, pers. comm.).

In Oregon it was found that large expanses of gravel and fines were deposited upstream of full spanning logs placed in the Nestucca River (House et al. 1991). Many of these sites were readily used by chinook and steelhead the first winter after restoration. In Washington, "spawning pads" made of logs and planks have been used to hold spawnable sized gravels in Willapa Bay and Grays Harbor tributaries, and these sites were used primarily by spawning chum and coho salmon (Cowan, pers. comm.). Full crossing logs installed in Porter Creek, an experimental stream along the Washington coast, trapped spawnable sized gravels that previously transported through the system. The retained gravels were used by spawning coho and steelhead the first years after installation (Cederholm et al., in prep.).

In Oregon, pools formed from constructed full-width log structures resulted in a 3-fold increase in juvenile coho numbers in summer (House and Boehne 1986). Nickelson et al. (1992a,b) found that adding bundles of small trees to dammed pools resulted in significant increases in coho density during winter. At Big Beef Creek in Puget Sound, Quinn and Peterson (1996) indicated a positive correlation between end of summer LWD volume and coho overwinter survival. Research in Oregon on instream restoration shows that addition of conifer logs to debris-poor streams can increase salmonid smolt production several fold (Fig. 8-1A; Murphy 1995), and in Washington careful placement and anchoring of LWD in Porter Creek increased coho smolt yield 2 to 8-fold under various treatments (Cederholm et al., in prep; Fig. 8-1B).

In the Clearwater River, on the Olympic Peninsula coast, experimental addition of small debris bundles to main river pools was effective in attracting substantial numbers of summer rearing juvenile coho and trout, and many of these same fish later immigrated into wintering ponds (Peters et al. 1992). The addition of debris and creation of depth in off-channel overwintering ponds called "wall base channels" (Peterson and Reid 1984) along the Clearwater River of Washington produced a 5-fold increase in winter survival of juvenile coho (Cederholm et al. 1988).

In the last few decades, hundreds, perhaps thousands, of low-cost habitat restoration and improvement projects have occurred throughout the Pacific Northwest through watershed programs and volunteer efforts. The effectiveness of these approaches, however, is not well-documented. A variety of large-scale LWD restoration work that has been evaluated in the Pacific Northwest points out that salmon habitat restoration work using LWD can be costly (Table 8-1).

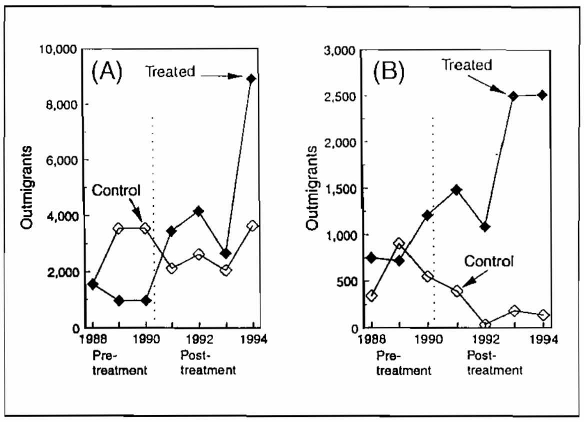

Figure 8-1A. Increases in number of outmigrant coho salmon smolts after experimental addition of large woody debris to debris-poor streams in the Alsea River basin (A) and Nestucca River basin (B) in western Oregon. Treatment occurred in summer 1990 (Murphy 1995).

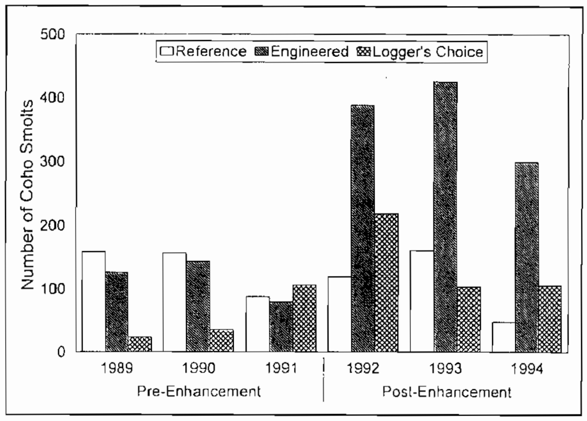

Figure 8-1B. Coho smolt yield increases three years before and three years after large woody debris enhancement in Porter Creek, a tributary of the Chehalis River, coastal Washington (Cederholm et al., in prep).

Long-term Effects on LWD Ecology from Stream Clearance and Logging

Prior to large-scale forest clearcutting, large quantities of naturally-downed LWD dominated stream channels, and provided important stream bank and riparian forest structure. The riparian linkage provided by LWD played an essential part in preserving the stream ecosystem. Clearcut logging to the stream edge was common practice throughout Oregon and Washington until the early 1980's and in British Columbia until the late 1980's. These activities seriously impacted salmonid habitat. Perhaps its greatest long-term impact was the reduction of instream LWD. The loss of streamside, large diameter conifers translates into the loss of the benefits that wood contributes. Cross-stream yarding and widely accepted practices of salvage logging within the stream further depleted LWD (Hicks et al. 1991).

The practice of stream clearance and channelization has also significantly contributed to a general lack of LWD in many streams (Cederholm 1972). These practices occurred earlier in the century to make rivers more navigable; more recently, they were employed to make streams accessible to migrating salmon, and to reduce the threat of flooding.

Reductions of LWD material have been noted soon after streamside clearcut logging (Bilby and Ward 1991). Lammel (1972) reported that a 50% reduction in volume of coarse debris (LWD) occurred immediately after logging in stream channels that were unprotected by buffer strips in western Oregon. Toews and Moore (1982) note that significant but less dramatic reductions occurred following log yarding in Carnation Creek, British Columbia. Bryant (1980) found a reduction in the number of log jams about 20 to 25 years after logging in Maybeso Creek, southeastern Alaska.

Ralph et al. (1994) analyzed stream channel morphology and LWD abundance in 101 western Washington streams, and concluded that intensive streamside logging leads to simplification and homogenization of stream habitat. Lestelle (1978) and Bilby (1984) observed large changes in channel structure in western Washington after removal of LWD. Sullivan et al.

(1987) reported that pool area is significantly reduced after stream clearance, declining from 70% to 20% of the pool area. Generally, there is an initial release of large quantities of sediment immediately following woody debris removal. Thus, within a stream reach these adjustments may result in a smoothing of channel gradient and filling of the deepest pools.

Analyses of long-term effects caused by logging on LWD availability to streams indicate that there is a long-term decline of old growth LWD, and that it can take a century or more for the forest to regrow to the point where it again becomes an important source of LWD. Second growth LWD is often made up of greater proportions of small diameter deciduous and conifer trees than the old-growth forest. These materials have far less value as LWD because they degrade more easily than the large old-growth conifers.

The Ecological Role of Beaver

Beaver are a very important part of the LWD story in watersheds. In many cases, salmon evolved in ecosystems significantly regulated by beaver populations. Impoundments created by beavers serve many physical, chemical, and biological functions and need to be considered in most watershed restoration projects. Among many natural functions, beaver ponds influence channel stability by regulating the flow of water and by retaining sediment. Beavers modify the riparian zone's tree species composition, contribute valuable rearing habitat for many freshwater fish species, and assist in the stream's nutrient cycling processes by retaining organics for regulated dispersal. Beavers also ingest wood and contribute to stream fertilization. Managing beaver activity for ecosystem advantages can be a vital part of restoring watersheds (see Chapter 15).

Large Wood in Upslope Landscape Rehabilitation

In the same way that streams exhibit stepped profiles to provide sediment-storage elements in a stream, so does LWD function to hold storage elements on hillslopes. Most watershed restoration efforts should begin in upslope areas where unnatural activities have been the cause of their instability. Carrying out instream work, without first addressing unstable slopes, has very short-term benefits and rarely contributes to the cause of restoring watershed processes. A past recommendation had been placement of LWD below roads to catch and store sediments. Hillslope LWD faces the same crisis as instream LWD in that future sources are being eliminated due to harvest and management activities.

Although the focus of this paper is on in-channel LWD we feel that upslope areas are the first place to look when addressing the needs of a watershed (Figs. 8-2A and 8-2B).

Riparian Zone Rehabilitation

An important realization is that while we wait for the forests to regrow and upslope areas to stabilize, highly degraded stream channels may take hundreds of years to recover without active management intervention in riparian ecosystems. It is wise to deal with riparian restoration issues as soon as possible, because it may take decades to centuries for these forests to recover[3] (Fig. 8-2A; flowchart). For example, although cedar plantings can be established with deer-browsing protection, alder-dominated riparian areas are generally susceptible to poor conifer regeneration due to low light and poor seedbed conditions, and general lack of a conifer seed source.

[3] There may be exceptions to activity in riparian access — sometimes a "tote road" or trails need to be constructed to undertake fish habitat rehabilitation. Tote road areas and road spurs are areas that can be replanted after disturbances.

Table 8-1. Cost of LWD Restoration in several Pacific Northwest streams. Existing site conditions, access, scope of project, and expertise involved all contribute to the make-up of project costs.

NAME /LOCATION	YEAR	SCOPE	REHABILITATION PRESCRIPTION	EQUIPMENT	DIST. (km)	COST/KM	COMMENTS @ time of project (C$)
Upper Keogh River, BC (Ward and Slaney 1993)	1977	Experimental Management	Various boulder and LWD attachments.	N/A	1 km	$30,000 ($1995)	Limited LWD, emphasis on boulder clusters.
Fish Ck., OR (D. Heller, pers. comm.)	1988	Experimental	Attached LWD.	N/A	14 km	$50,000	N/A
Paradise Pond (Cederholm et al. 1988)	1988	Hab. Enhancement Experimental	Flooded wetland with LWD placement.	Explosives, hand tools, import LWD.	0.25 km	$56,000	Limited planning, no engineering.
Swamp Creek Beaded Channel (Cederholm and Scarlett 1991)	1991	Hab. Enhancement Experimental	Series of interconnected pools with LWD placement.	Explosives.	0.2 km	$23,000	Limited planning, no engineering, readily available LWD.
Porter Ck., WA (Cederholm et al., in prep)	In prep.	Experimental	Free-fall, cabled LWD throughout a stream reach.	Tree-felling equipment, work crews.	0.5 km	$18,000	Limited planning, "loggers choice" reach.
Porter Ck., WA (Cederholm et al., in prep.)	In prep.	Experimental	Attached LWD using cable and epoxy resins throughout a stream reach.	Heavy equipment, extensive log anchoring.	0.5 km	$224,000	Extensive planning and engineering with hydraulic and topographic analysis.
Shop Ck., BC (P. Slaney, pers. comm.)	1994	Management Experimental	Log "V" weirs, boulder clusters, LWD, groundwater side-channels and pond.	Hand work crews and tracked excavators.	1.0 km	$60,000	Additional 0.5 km rehab. outside of ck. Excludes 20% in-kind money. Readily available LWD.
Hoh River, WA, Lewis Ranch (WDNR)	1994	Management	LWD placement in groundwater-fed spawning/rearing channel.	Hand crews and tracked excavators.	0.5 km	$375,000	Extensive hydraulic and construction engineering.
Skagit R., WA Park Slough and Extension (Cowan et al. 1995)	1994	Management Hab. Enhancement	LWD placement in groundwater-fed spawning/ rearing channel.	Heavy equipment, tracked excavators.	1.1 km	$230,000	Extensive engineering and planning.
Coquitlam R., Oxbow Project (P. Slaney, pers. comm.)	1994	Rehabilitation	Side-channel/pond development.	N/A	1.5 km	$80,000	1 km., included a relic side channel.
East and Lobster Cks., OR (T. Nickelson, pers.comm.)	Unpub.	Experimental Hab. Enhancement	LWD and "alcoves".	N/A	3.4 km	$29,000	Siltation problems during recent major flooding

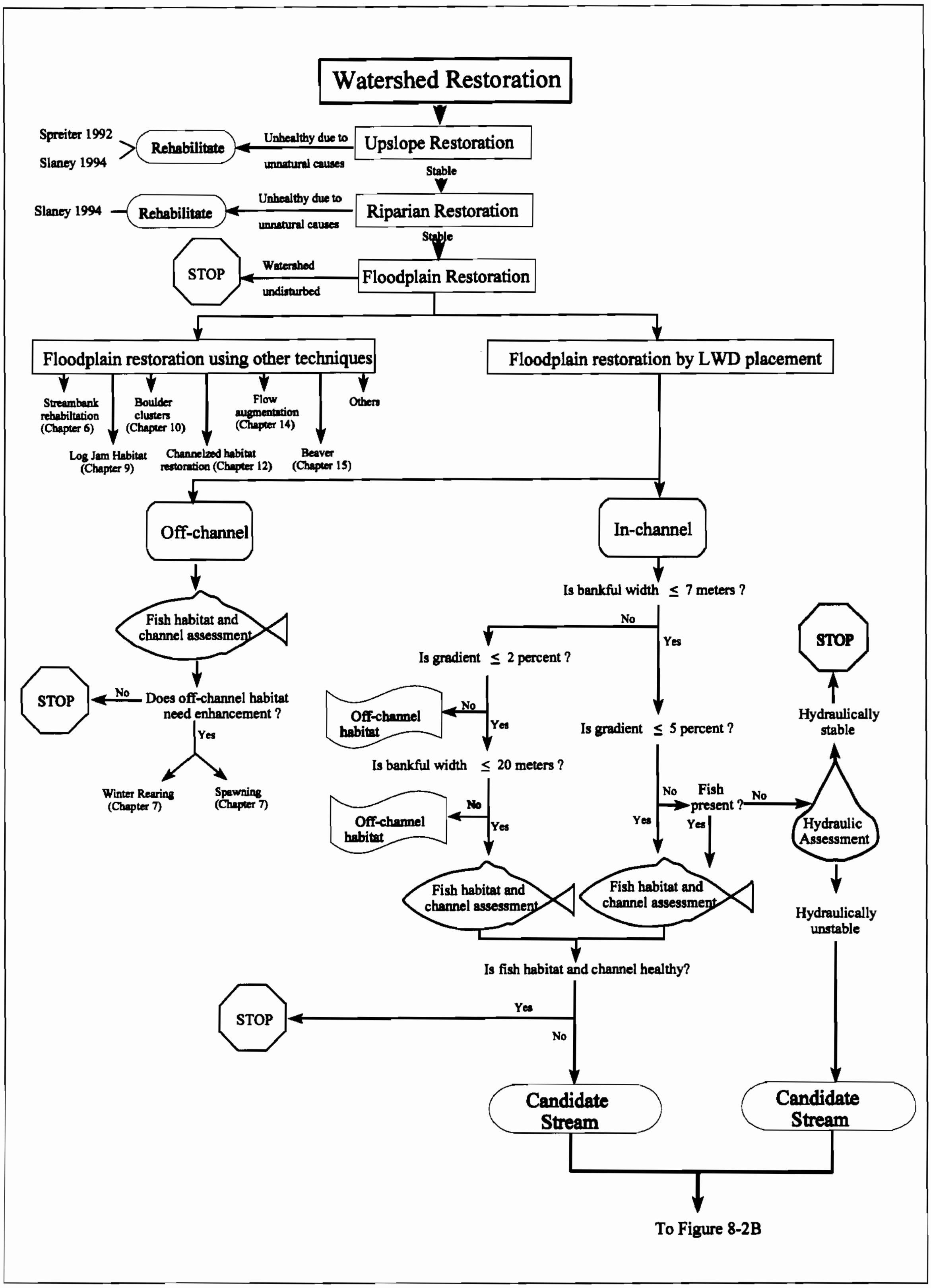

Figure 8-2A. Flow chart for determining candidate streams for rehabilitation.

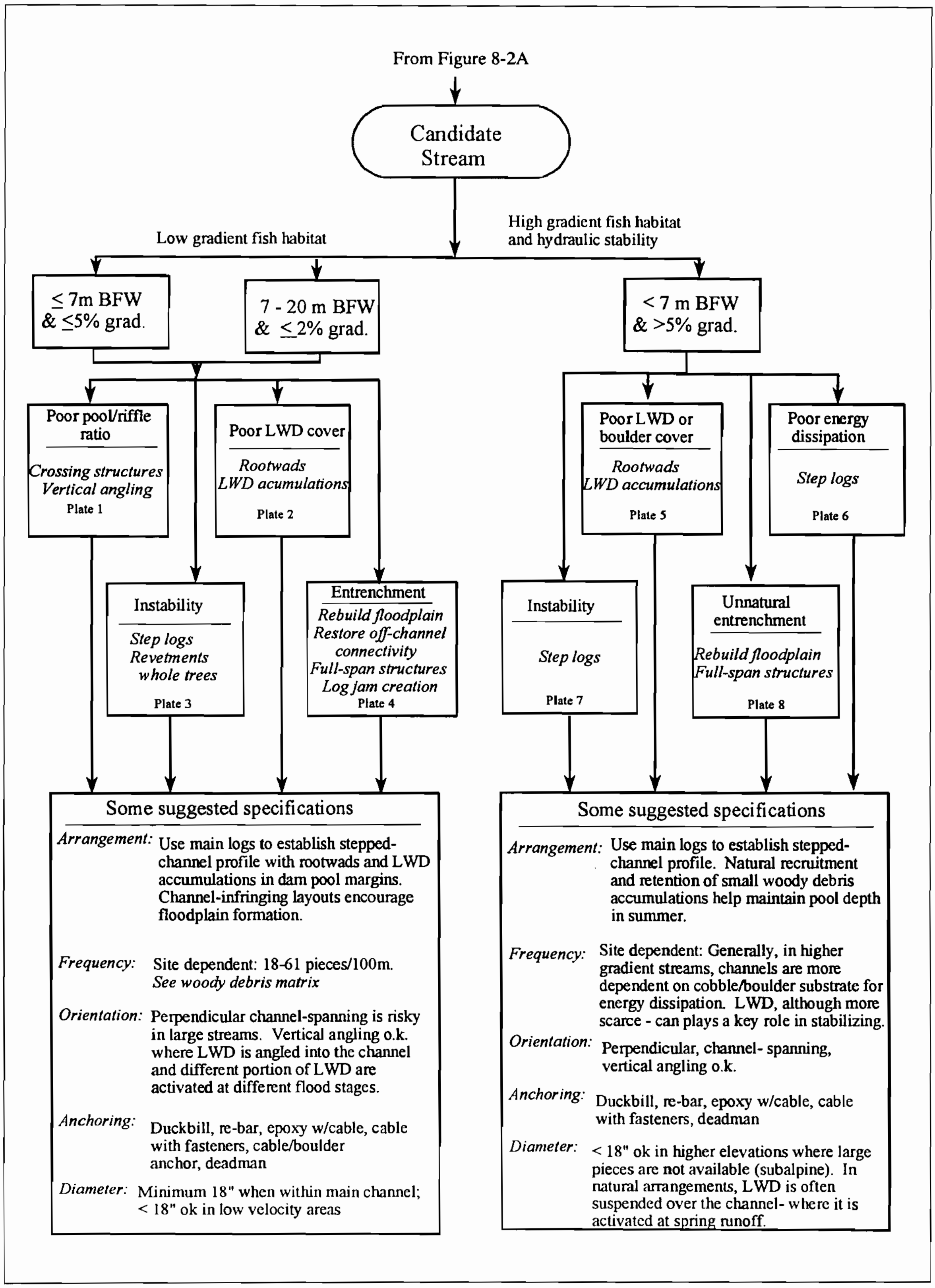

Figure 8-2B. Flow chart for determining candidate streams for rehabilitation (continued) with emphasis on potential applications.

Silvicultural treatments have potential long-term benefits in restoring habitat functions of riparian areas. Underplanting and thinning of deciduous trees to re-establish native conifers along streams that have been logged in the past is being tested in many areas of the Pacific Northwest. Silvicultural thinnings of overly dense stands of conifer to increase diameter growth have been successful in upland forests, and could be readily applied to riparian corridors to increase future LWD trees.

Regulated girdling of deciduous trees, in combination with conifer planting and instream LWD placement, is undergoing experimentation in some previously logged Oregon coastal watersheds (Solazzi, pers. comm.). The increased susceptibility to windthrow expedites input of deciduous LWD into the streams which provide short-term LWD functions. Instream LWD rehabilitation projects provide interim salmonid habitat while the riparian areas restore conifer dominance.

Riparian degradations associated with livestock impacts can be remediated by livestock exclusion. In remote, forested rangelands where fencing of hundreds of miles of riparian corridors is not feasible, range managers are experimenting with placement of local, downed woody material in heavily impacted areas to discourage multiple watering/crossing sites in streams, thus restoring bank vegetation.

Stream Channel Rehabilitation

Generally, the most recent research and suggested method of restoring and perhaps enhancing salmonid fish populations in streams is to improve the overwintering habitat in tributary stream channels. Increasing the "fish holding ability" of tributary stream channels helps to attain full use of overwintering habitat area high up in drainages and thus overcomes the negative factors that have contributed to fish declines in downstream large river channels (i.e., poor water quality, increased predation, loss of quality rearing habitat, feeding competition between wild populations and hatchery-origin populations).

Work to re-establish LWD within stream channels for the benefit of salmonids is still in its infancy. Some past efforts at instream placement of LWD structures have been criticized as ineffective. Frissell and Nawa (1992) found some widespread damage to LWD structures in 15 Oregon and Washington streams with recent watershed disturbance, high sediment loads, and unstable channels. Cross-stream (channel-spanning) structures were the most vulnerable. A questionnaire that evaluated enhancement projects, prepared for the British Columbia Ministry of Environment, Lands and Parks, found, on average, only a 50 to 55% success rate with the balance split between marginal successes and failures (Hartman and Miles 1995)[4]. Some well-planned projects in Oregon, however, have been successful at rehabilitating in-channel salmonid habitat. House et al. (1991) and Crispin et al. (1993), in coastal Oregon, report a high degree of success with over 1,000 instream habitat structures evaluated 1-8 years after placement. A preliminary report on the instream structural durability of about 3,000 structures on U.S. Federal lands indicated that 75% were functional and 16% were lost after the extreme February 1996 floods (Heller et al. 1996). In Washington, only seven of over 250 pieces of LWD carefully placed and anchored in Porter Creek showed instability (Cederholm et al., in prep.), and this was after several significant flood events during a 6-year period.

[4] Many of these projects were conducted as research or pilot projects.

Many types of instream structures have been used for stream rehabilitation in the Pacific Northwest (Crispin 1988, Fig. 8-3A; Koski 1992, Fig. 8-3B), and Cederholm et al., in prep. (Fig. 8-3C). Most in-channel structures have been installed in streams of fourth to fifth order with normal peak flows about 6 to 60 $m^3 \cdot sec^{-1}$ and channel gradients of 1 to 3%. This doesn't mean that nothing should be done in the other stream orders; however, objectives may have to be changed. For example, work in hydrologically dynamic rivers may best be carried out along the periphery of the stream or in more stable off-channel habitats located on floodplain terraces above the influence of the active river floodplain (Peterson and Reid 1984, Fig. 8-4).

Flow diagrams are useful to guide decisions on when to work with LWD rehabilitation within the active channel and when to work off-channel (i.e., wall-base channels) using other techniques (Figs. 8-2A and 8-2B). We generally recommend improvements in off-channel sites when dealing with large rivers with no natural regulation (i.e., lake-headed systems). The active channels (within the high water marks) of large rivers and streams have proven to be a risky site for locating traditional LWD habitat enhancement structures. In addition to traditional LWD projects, there are several other ways to approach offsetting habitat impacts in large, unstable stream channels, including stream bank rehabilitation (see Chapter 6), off-channel habitat rehabilitation (see Chapter 7), placement of boulder clusters (see Chapter 10), flow augmentation (see Chapter 14), encouragement of beaver activity (see Chapter 15), and large-scale log-jam habitat formation (see Chapter 9).

Some off-channels habitats may already be producing salmonids up to their potential, or may have other fish and wildlife values that are better left undisturbed. Further direction through the flow charts (Figs. 8-2A and 8-2B) would include a fish habitat and channel assessment, to help determine which particular wall-base channel rehabilitation strategy is appropriate (rearing, spawning, both). We recommend:

> **off-channel** LWD work in **fish habitat rehabilitation** when the site has either of the following characteristics: a) the channel is greater than 7 m bankfull width[5] and has a gradient greater than 2%; b) the channel has a bankfull width greater than 20 m.

When working in active channels, bankfull width and gradient will be key decision thresholds in project selection (Figs. 8-2A and 8-2B). We recommend:

> **active channel** LWD work in **fish habitat rehabilitation** when the site has either of the following characteristics: a) the channel is less than 7 m bankfull width and the gradient is less than 5%; b) the channel is 7 to 20 m bankfull width and the gradient is less than 2%.

> **active channel** LWD work in **headwater channels** that are less than 7 m bankfull width and greater than 5% gradient for the purpose of providing channel hydraulic stability.

There may be exceptions to these criteria when dealing with larger, naturally-regulated, lake-headed streams present on coastal and interior systems. Generally, the channels downstream of lakes, within hydrologically mature watersheds, have hydraulically stable channels. Once the candidate stream has been selected, consult Fig. 8-2B in order to match candidate stream channel characteristics with appropriate enhancement strategies.

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[5] Bankfull width is practically defined as the distance between two points on the right and left bank of a stream channel where perennial vegetation exists (Mean Annual Flood). The transect formed by the two points is perpendicular to the stream channel.

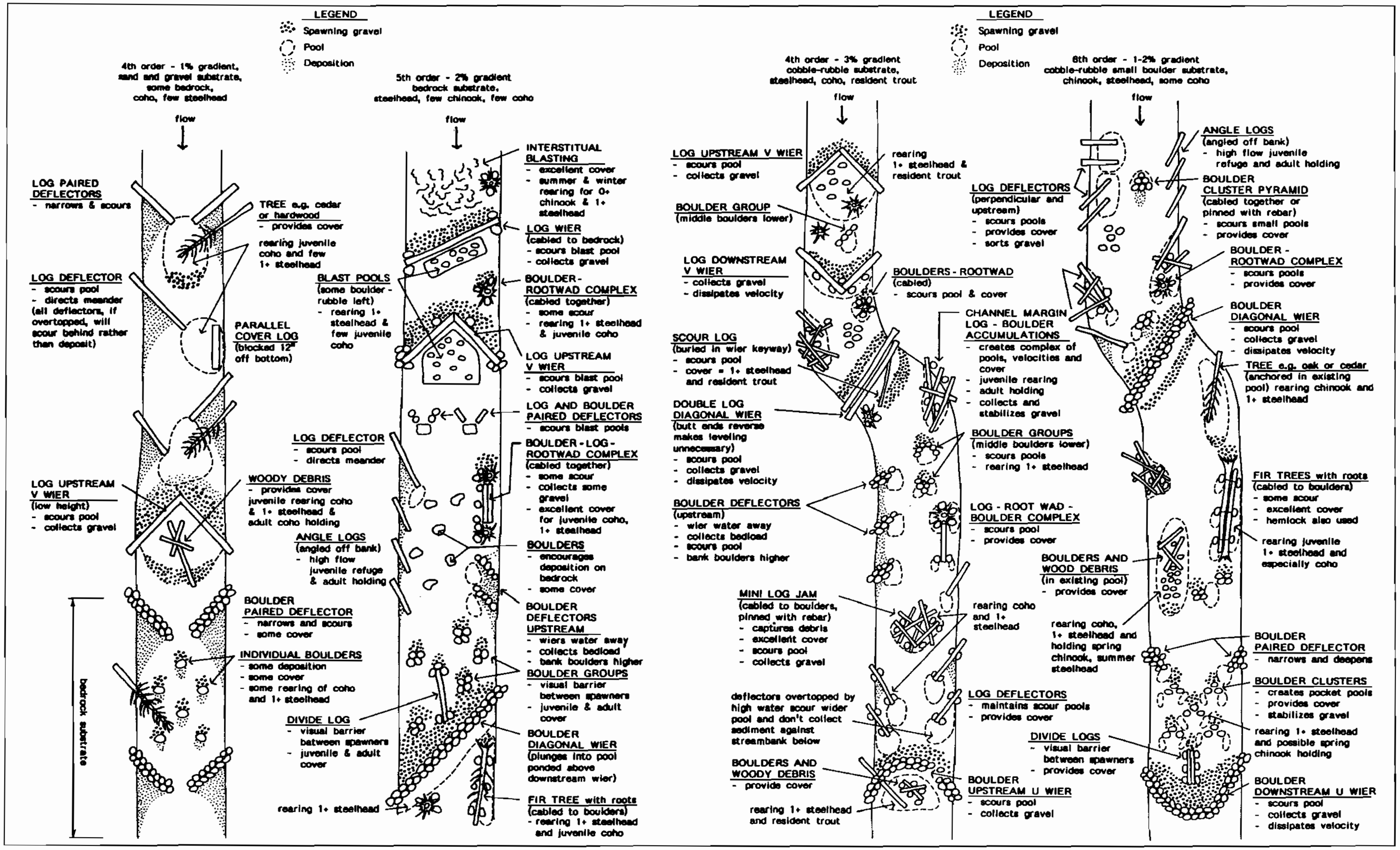


Figure 8-3A. Typical structures used in representative small- and medium-sized (4th and 6th order) streams, low gradient/sediment laden streams, and in bedrock streams (Crispin 1988).

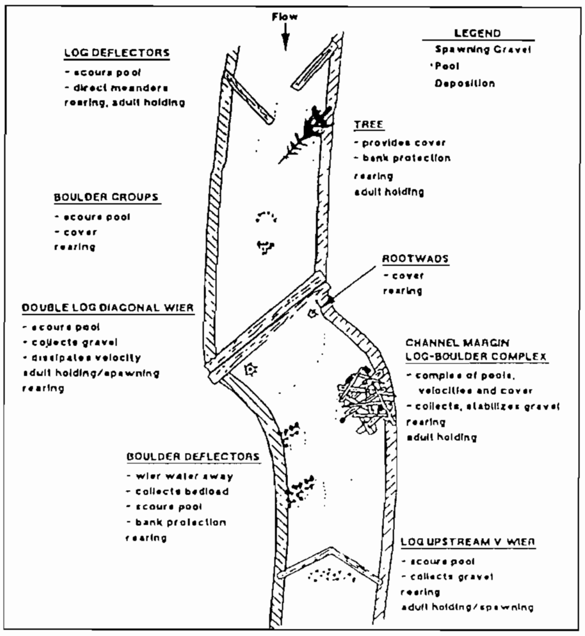


Figure 8-3B. Log structures recommended for stream habitat restoration (Koski 1992).

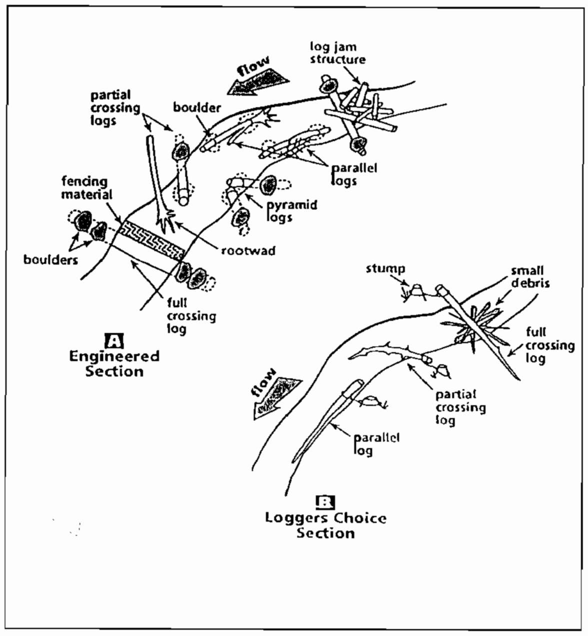


Figure 8-3C. Log structures to experimentally increase juvenile salmonid overwintering habitat at Porter Creek (Cederholm et al., in prep.).

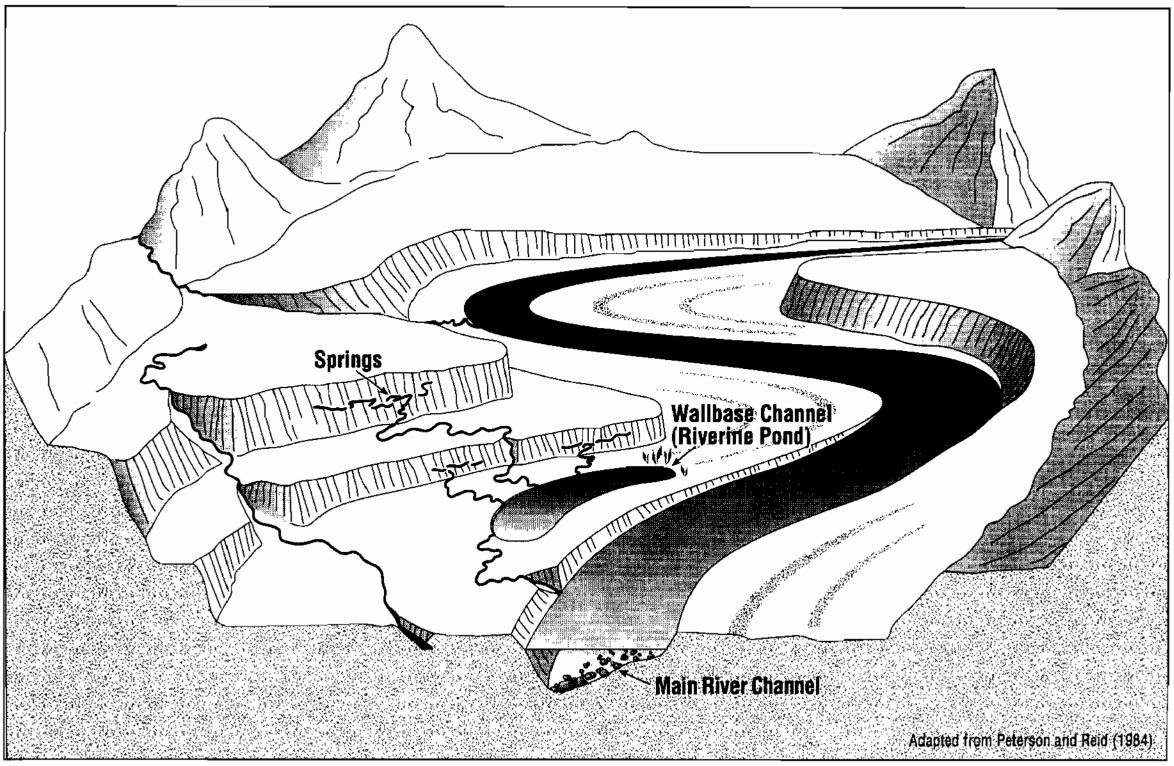


Figure 8-4. Schematic of a typical floodplain showing river meanders and where common types of off-channel habitat are located.

PLANNING LWD ENHANCEMENT PROJECTS

Watershed and Goal Assessment

The goal of effective fish habitat rehabilitation is to produce greater overall improvements in fish productivity, not just to redistribute existing fish numbers within the watershed with isolated projects.

Since funding sources for many watershed programs may have short-term sociologic and geographic objectives, or be directed at landownership criteria or suppressed fish stocks, there are few rehabilitation efforts that have occurred in a long-term, systematic matter. In these cases, "targeted" funding can be detrimental to the long-term success of complete watershed rehabilitation programs.

Figures 8-2A and 8-2B (flow charts) were developed to categorize stream sizes and physical and biological characteristics to identify instream LWD placement candidate streams. Upslope and riparian areas are the priority areas of assessment and restoration, generally in advance of effective, instream restoration. The authors have visited several fish habitat rehabilitation sites throughout Oregon, Western Washington, and British Columbia. A general conclusion is that the majority of the work that has occurred in the past has taken place in streams that are too large and unstable, which may be the main reasons instream rehabilitation projects do not reach their expected benefits.

Hartman and Miles (1995) conducted a widespread questionnaire survey of many types of fish habitat improvement projects in British Columbia and made preliminary recommendations on the development of guidelines for future work. **They strongly point out the need to integrate both the physical and biological considerations when doing stream channel rehabilitation work.** They stress the need to incorporate interdisciplinary teams during the design and construction phase of projects to help insure their success in accomplishing the intended benefits to salmon habitat. With few exceptions, the identified factors which affected biological success were physical in nature. They point out several factors that contributed to successful or outstanding projects:

- appropriate physical locations;
- small stream size and gentle gradient;
- small post-construction floods;
- regulated water supply;
- successful emulation of natural structures;
- experienced design and construction team;
- proper installation;
- the ability of the structure to collect large volumes of debris and withstand freshets;
- provision of adequate cover;
- managed by people that have an ongoing interest in the project;
- regular monitoring and maintenance.

Large Woody Debris Assessment

LWD assessment is undertaken as part of a fish habitat assessment. This section reviews LWD-related literature to help develop criteria of expected LWD abundance in streams.

Several characteristics have been used to describe LWD material in streams, including: piece length, numbers, width, volume, age, species, decay class, orientation to stream flow, habitat-forming capability, and mapping of spatial distribution in the active channel. In an extensive review of LWD abundance literature, Peterson et al. (1992) found that the number of pieces of LWD in streams flowing through unmanaged forests varies between 180 and 610 pieces per kilometer in small streams (< 5 m wide), and 30 to 460 pieces per kilometer in large streams (greater than 23 m wide). In research within medium-sized (5-8 m wide) western Olympic Peninsula old growth streams, Grette (1985) documented between 400 and 800 pieces of LWD per kilometer of stream, and between 100 and 510 pieces of old growth LWD per kilometer still remaining in streams logged up to 62 years prior to his study. Cederholm et al. (in prep.), in their study of Porter Creek, found an average of 60 pieces of old-growth LWD per kilometer still remaining in a stream that was logged and cleaned over the previous 50 years. At Shop Creek, a similar stream in B.C., approximately 40 pieces per kilometer were evident prior to LWD restoration (P. Slaney, pers. comm.).

Bilby and Ward (1991) found that the number of LWD pieces significantly varied with channel width, larger streams having fewer pieces than smaller streams. New LWD categories such as "key pieces" and "functional pieces" have been suggested by habitat surveyors to emphasize LWD function more than quantity. These categories of wood are described as pieces that are independently stable in the stream, and perform habitat forming functions or retain other pieces of LWD. Peterson et al. (1992) emphasizes that logging may not change the number of pieces, but rather the relative size of LWD pieces, and this may be a way of detecting cumulative effects of clearcut logging. The natural arrangements of LWD in stream channels can be quite complex. In a typical debris jam or accumulation, there may be a few "key" pieces that are responsible for the initial formation of the LWD complex. It is the quantity of these "key" pieces (usually larger diameter and/or length than the average) that can give indications of a stream's stability or potential stability. Washington State's watershed analysis process (WDNR 1993) recognizes key LWD pieces as contributors to watershed stability during floods.

Because simple computation of LWD volume per stream length or area may not adequately index spatial irregularities, Robison and Beschta (1990a, b) recommend that LWD pieces be differentiated by zones of influence. Ungrouped LWD may not benefit fish habitat, per se, in the form of pools or sediment storage, but may have a greater overall effect on channel morphology because resistance to flow is spread over a longer distance. Peterson et al. (1992) and the Washington Department of Natural Resources' revision to Watershed Analysis (WDNR 1993) suggest that LWD surveys should not only be limited to fish bearing waters, and that the type and amount of information collected during LWD surveys should be expanded. The Ministry of Environment, Lands and Park's Watershed Restoration Program Technical Circular No. 8 (Fish Habitat Assessment Procedures) includes an overview of LWD assessment methods.

One of the most comprehensive, management-oriented, mass LWD survey methods available is the LWD module included in the TFW Ambient Monitoring Manual (Schuett-Hames et al. 1994). This procedure, which describes LWD abundance (pieces and volume), distribution, type, size, and potential contribution to channel stability and habitat formation (key piece), is an important element in LWD restoration project planning and design. This information on existing conditions can be used to determine additional LWD needs for the proposed reach. Some of these procedures have been adapted for use in British Columbia as the Fish Habitat Assessment Procedures (FHAP; Johnston and Slaney 1996) where LWD frequency has been scaled to channel width (BFW) and rated as poor (<1 piece/BFW), fair (1-2 pieces/BFW), and good (>2 pieces/BFW).

Channel Assessment

The LWD project must consider more than the biological components. Analysis and evaluation of the physical components of the project must be completed by an engineer with experience in hydrology, natural channel flow, construction methodologies and construction supervision. This blend of expertise provides the kind of input that is necessary for successful project completion. Reliance on only one perspective or allowing one perspective to dominate can result in project designs and installed projects that do not achieve the desired results.

The Channel Conditions and Prescriptions Assessment (CCPA) (Hogan et al. 1997), the Channel Assessment Procedure (CAP) Guidebook and Field Guidebook, produced under the authority of the Forest Practices Code of British Columbia Act (Anon. 1996a, b), are designed to identify past occurrences of channel changes in a consistent, repeatable process across various landscapes. With information acquired from CCPA and the Fish Habitat Assessment Procedures (FHAP), candidate watersheds can be identified for rehabilitation needs and possibilities. Information on channel stability, available habitat, limiting factors, etc., can then be synthesized to determine what applications of LWD rehabilitation can occur.

Channel assessment procedures may vary in complexity according to professional preferences, experience of project crews, and the need for post-structural monitoring. For example, components of a channel evaluation conducted by an engineer at a successful project in a 10-meter wide Washington State coastal stream (Porter Creek, WA), are summarized:

> During the site surveys, a benchmark for elevation was established on or near a prominent physical feature within the project area. A surveyor's transit was used to complete a site elevation and position survey. Physical features such as edge of channel, existing topography, toe and top of banks, gravel bar islands, secondary channels, floodplains, existing LWD habitat features, habitat type boundaries, and water surface elevations were located by determining the horizontal angle and distance to each feature from the instrument.
>
> Upon completion of the site survey, the horizontal angle, vertical angle, and slope distance data recorded for each point were used to generate a site map of the project area. This map and the elevation data were then used in the design of the LWD habitat structures. During the site survey, locations of existing physical features were determined with an accuracy of ± 15 cm horizontally and ± 3 cm vertically. This level of accuracy was utilized for the engineering evaluation and design of the project.

Hydrologic and Hydraulic Geometry Assessment

Successful LWD habitat designs require an understanding of regional and local hydrologic characteristics. Within the project area, the stream channel and habitat features must be designed to 1) withstand floods; 2) create the desired low flow channel, and 3) provide the preferred habitat components for appropriate life stages of the target fish species.

Streamflows in the potential project reach must be evaluated to determine the range of conditions the proposed LWD structures will be exposed to during each season. Characteristic flows to be identified include the 7-day average low flow, average annual flow, and average flood flow. These flows define the anticipated summer conditions, the magnitude of the stream, and the typical high flow conditions, respectively.

Determining design flows for a LWD habitat enhancement project will require the use of streamflow records for the stream or a regional hydrologic model to determine flood, average and low flows. Flows to be estimated using the streamflow records or the regional model (such as extrapolation from gauged streams nearby) should include average annual flow, 7-day average low flow, average flood flow and average daily flood flows with a 20- and 50-year recurrence interval. Average monthly flows to be estimated should include monthly minimum, monthly mean, and monthly maximum.

Hydraulic geometry is the relationship of channel width, average depth and average velocity to discharge. Once the streamflows within the proposed project area have been identified, then the width, depth, and velocity at each flow can be estimated to define the physical conditions within the stream at each flow. These relationships are used to identify the estimated flow characteristics in light of the hydrologic analysis and to evaluate the impact of the proposed LWD placement on the low flow and flood flow characteristics of the channel. This information is then compared with the existing channel features determined during the project area survey to identify any major discrepancies in the channel shape. Chapters 9 and 12 provide necessary information in determining appropriate size of materials (boulders and logs) to be used for a channel rehabilitation project.

Large woody debris installed in the channel will create localized changes in the streamflow pattern. If these changes in streamflow pattern are severe, the water surface profile may change significantly and cause bank erosion and/or new channel formation during high flows. With such added variability in LWD placement, we generally recommend that designs be targeted to withstand a 50-year flood event (see Chapter 1).

Fish Habitat Assessment

Physical Habitat Requirements of Salmonids

Developing effective LWD habitat rehabilitation designs that maintain stream channel characteristics and create fish habitat features requires knowledge of the target fish species and their habitat utilization periods within the project area. Each of the target species may utilize the project area in a different manner. Fish species of primary concern vary regionally; for example, coho and cutthroat are ubiquitous along the coastal areas, while resident trout, arctic grayling, and especially bull trout may be of greatest concern inland. Knowing the species of fish you are dealing with is important — as is knowing the age class of a species like steelhead and cutthroat, which have multiple ages, each with a different critical habitat need. The seasonal movement behavior of juvenile fish will also differ regionally, for example, immigration into wall-base channel tributaries in the fall and spring along the coast compared to spring immigrations to tributaries in interior rivers.

Identification of the physical habitat requirements for the target species within the project area is necessary to develop an effective habitat rehabilitation plan. For each of the target species identified, periods of utilization for each age class must be defined. This information is used to identify the habitat features required by the target species within the potential project reach.

Methods of Fish Habitat Assessment

An inventory of the existing physical habitat must be completed to quantify the types and distribution of habitat features within the project area. This inventory is needed to identify the existing features that provide good habitat in some locations and/or limit the production of the target species in other locations. Habitat types can be defined as the relationship between the stream reach and the "microhabitats" of the stream biota. Differentiation of habitat types is due to their variability in morphologic and hydraulic properties. Each habitat type exhibits a unique set of physical characteristics, which have been related to the composition of the associated biological community. Once these features have been identified, comparisons with the physical habitat requirements of the target species can be completed.

Parameters in these evaluation procedures typically include bank height, bank slope, bank stability, vegetation type, water depth, water velocity, substrate size, substrate embeddedness, overhead canopy cover, instream cover type and undercut banks. After the data has been collected, it is entered, edited and summarized using database software.

The Fish Habitat Assessment Procedures (Johnston and Slaney 1996) provides a systematic approach towards evaluating fish habitat in which key questions are asked to pinpoint habitat limitations by which quantitative data are utilized to rate habitat features as either poor, fair, or good.

Limiting Factor Assessment

Reeves et al. (1991) put forth the idea that a fundamental concept of habitat management is that fish production is limited by discrete factors, or "bottlenecks". They point out that when planning habitat rehabilitation projects, care must be taken to identify aspects of habitat that limit production, and attention should be focused on improving those elements. The timing of life history events is also an important consideration. For example, increasing the quantity or quality of some aspect of habitat that limits the abundance of emerging fry will generally be of little use if a critical shortage of cover or some other resource occurs at a later stage in life. Increasing initial fry abundance may benefit chum, pink, and sockeye (or "spawning limited species"), but probably not steelhead, cutthroat or coho salmon because of rearing limitations. These authors put forth a concept of the bottleneck effect as a guide to choice of life history stage to focus on, in order to achieve the greatest success in improving ultimate smolt yield.

The overall objective of a rehabilitation plan using LWD is to create a mixture of macro and micro habitat features that provide the preferred habitat components of the target species or group of species. Preparation of the plan needs to begin with the **identification of the preferred habitat features**, i.e., depth, velocity, and cover, for each age class of the target species. Using this information, the macro habitat types and micro habitat characteristics that create these features can then be defined. Comparison of the existing site features with the preferred features identified for the target species defines the habitat components that are missing from the project area. By knowing what habitat components are missing from the stream, a habitat rehabilitation plan can be developed to create the missing or lost habitat components.

Choosing Rehabilitation Applications

Debris torrents, frequent flooding and other major disturbances can damage or completely remove habitat improvements. In determining where to implement habitat efforts, input from agencies, local interest groups and industry interests is an important consideration. The results of the Fish Habitat and Channel Assessment should indicate the strategies of LWD placement. The authors' intent is to present conceptual applications of LWD placement rather than prescribe a particular LWD arrangement for a particular reach of stream. Most often, a degraded stream channel lacks sinuosity or impoundment capability. The combination of applications such as creating a dam and step pools, slack water rearing area, gravel retention structures, and lateral channel inundation is desirable for most stream reaches (Fig. 8-5).

DESIGNING REHABILITATION PROJECTS USING LARGE WOODY DEBRIS

Experienced Personnel

Recent LWD rehabilitation work at Porter Creek (Cederholm et al. in prep.) has shown that when both hydraulic and biological considerations are planned for, through integration of principles of hydraulic engineering and salmon ecology, there is a vastly improved chance of success. In the past, the placement of LWD was often carried out by biologists alone, who often didn't understand the hydraulic forces involved with placing logs in high-flow channels. Alternatively, an engineer may have designed a sound project that is stable, exhibits an appropriate number of meanders, and curtailed an erosion problem, but didn't match the habitat complexity needs to the fish species that were present. The consequence of much of this earlier work was that many structures failed to function physically as they were intended, or did not assist in increasing the productivity of a fish population. The Porter Creek study shows that interdisciplinary approaches can work well when the disciplines complement each other.

A thorough understanding of the existing physical and biological conditions within the project area must be developed to produce accurate design drawings for LWD rehabilitation projects. This understanding is needed to identify the existing features and/or habitat deficiencies that may be limiting production of the target fish species. Once these features and habitat deficiencies have been identified, design features necessary to create the desired habitat components can be developed.

Identification of the engineering and biological design specifications for LWD rehabilitation projects is imperative prior to preparing conceptual design drawings. These specifications provide a detailed list of specific requirements or guidelines that must be incorporated into the designs to maximize the engineering and biological benefits of the project.

Synthesis of a hydrologist's and biologist's expertise is necessary for an effective project. Project managers are responsible for informing work crews of correct procedures. With government agencies funding projects in cooperation with job-creation programs, many available workers possess applicable forest-worker skills such as heavy machinery operation, winching, and tree falling. If these workers have participated in restoration training classes, they may be capable of small project planning, material assemblage, and implementation.

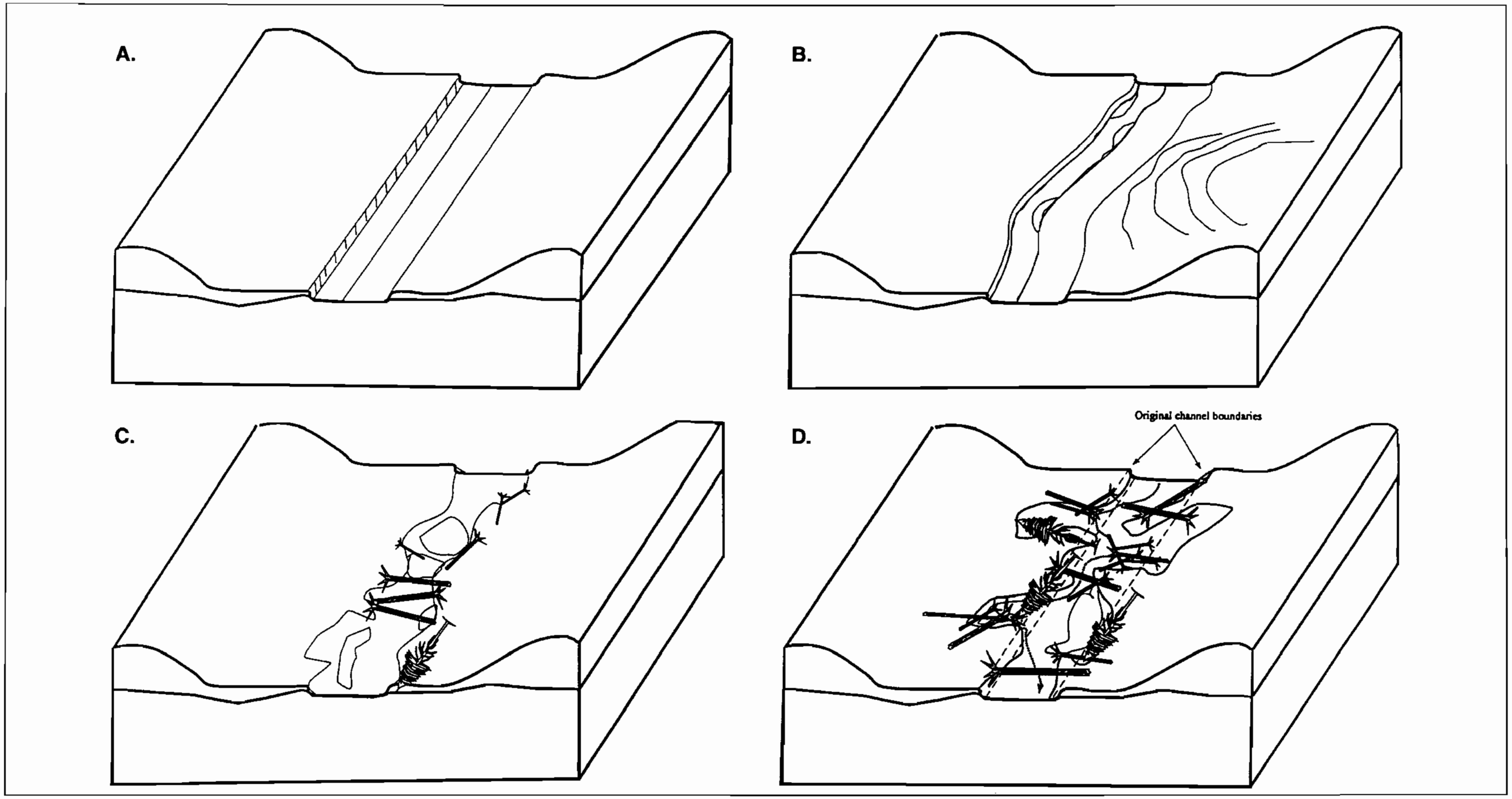


Figure 8-5. Working within a channel's natural evolutionary strategies to develop LWD placement techniques. Simple channels (A) may undergo a disturbance such as a landslide or LWD input (B) and develop some irregularity. LWD input creates some complexity (C), activates side channels and increases sinuosity. Further debris loading (D) activates the floodplain, creates greater pool surface area, refuge bays, and re-connects off-channel rearing habitat (note the original channel boundaries of simple channel in Figure 8-5D). LWD loading may have to occur over a period of several years.

Equipment

Many types of equipment and machinery used for logging and reforestation practices have some capabilities in stream rehabilitation. Chainsaws, axes, peaveys, polaskis, shovels, rakes, hoes, chainsaw-driven winches, and hand winches (come-alongs) are primary tools. Other equipment may include hammers, sledge hammers, drills, drill bits, power generators, wrenches, pliers, and wire cutters. Heavy equipment use will range according to terrain, ease of access, size of stream, size of material to be moved (logs, boulders), and excavation specifications. Most heavy equipment work should be performed from the banks. When necessary, stable areas such as bedrock or low bank areas can be identified for crossings. Confined channels, dense riparian forests, and high banks limit stream accessibility. In these cases, operating the machinery from within a relatively uniform streambed may be acceptable. For example, work within bedrock or boulder/cobble bedded channels with heavy equipment may be preferable to working on the stream bank or within the riparian corridor, because of the potential damage that could occur to the riparian vegetation and soils. This latter approach should be viewed as a last resort and investigations of expected fish and fish egg use during the construction period should occur.

Spider harvesters/log loaders and other types of low ground pressure equipment are the heavy equipment available for working in riparian areas that produce the least impact, although their work may be slower and LWD movement capability less. Some of the most cost-efficient equipment, however, may be some of the most damaging to the riparian ecosystem. Planners need to consider the advantages of a smaller, less damaging piece of equipment that requires more trips through a riparian area, but results in a final result that does less damage. For example, low ground pressure thumb-bucketed/tracked excavators are versatile in log placement and bank slot excavation and can be less damaging to the forest floor than rubber-tired excavators.

LWD placement can also occur by using helicopters. The following table lists common applications.

TYPE	LIFT	COST	DESCRIPTION
Chinook 234 Commercial, Canadian Air Crane	Up to seven tons.	C$ 9,460 to 10,810/hour	Largest available for interior forest work, mass delivery of LWD.
Bell-Huey, UH-1 series 204, 205	Up to 1,700 kg.	C$ 2,030 to 2,700/hour	Most common and readily available for forest work, precision debris placement.
Vertal, Hiller, and Hughes 500	Up to one ton.	C$ 675 to 2,030 /hour	Most versatile for forest work. Capable of rapid transit of LWD and boulders and precision debris placement.

A helicopter's lift capacity is dependent on fuel level, air temperature, and altitude of operation. Altitudes above 4,000 to 5,000 feet reduce lift capacity as do warmer air temperatures.

Specifications

The use of native wood materials is recommended for instream LWD placement. Even though there are some advantages of using imported, unnatural materials to construct artificial structures, their use is in direct contrast to the current goals of ecosystem restoration. In the Pacific Northwest, Western red cedar (*Thuja plicata*), Port Orford cedar (*Chamaecyparis lawsoniana*) and Douglas fir (*Pseudotsuga menziesii*) generally last the longest, especially in a continually saturated state. Western hemlock (*Tsuga heterophylla*), White fir (*Abies concolor*), Sitka spruce (*Picea sitchensis*), pine (*Pinus* spp.), and hardwoods are least durable. Cederholm et al. (in prep.) observed that, within 4-6 years, most alders used in a LWD experiment experienced various degrees of decomposition. Most deciduous trees lose all structural integrity within 5 years, in contrast to red cedar, which can be durable for 25 years in artificially-placed applications. However, hardwoods have some advantages to stream ecosystems such as rapid canopy shading in disturbed areas, increased litterfall and nutrient input, and consequent increased macrobenthic production.

How much wood does a stream need? Table 8-2 is designed to guide a project developer in determining how much LWD is enough for a given stream reach. Because there exists considerable variability in channel characteristics and LWD arrangements in streams, the process outlined in Table 8-2 uses LWD volume as a standard. This decision was based on somewhat consistent findings in the LWD literature concerning LWD volume/stream length and size and the fact that project supervisors will be using different LWD piece sizes. The steps are explained in Table 8-2 and can be followed accordingly. This method does not intend to portray the idea that we have a complete understanding of stream LWD needs; it is merely a starting point for general loading rates. Adjustments can be made for gradients, available channel margin habitat, off-channel habitat, montane rivers, and experimental loading rates. Generally, as stream size increases, the diameter of effective LWD increases.

IMPLEMENTING REHABILITATION PROJECTS USING LARGE WOODY DEBRIS

Materials

Use of entire trees with rootwads, sections of tree trunks, rootwads with short sections of trunk attached, or other pieces of woody debris that will remain stable in the stream during the anticipated flow regime can be used to create critical micro habitat features. It is important to visualize the water level and resulting shear and buoyancy forces involved during high flows in each stream reach, and install micro-habitat features in those parts of the channel that maintain the lowest velocities for fish refuge.

Placement Strategies

In developing LWD placement strategies it is important to consider both the physical and biological approaches in combination, to achieve channel modifications that will ultimately have long-term benefits for salmonids. Both considerations must be included, because one without the other is often a prescription for project failure. Initially, physical channel stabilization and energy dissipation functions should be addressed before fish habitat is provided. For example, full crossing logs can provide both energy dissipation and pool formation, and some logs may even need to be buried within the streambed to provide gravel stability. Once a stream gradient is lowered and the channel is stabilized, then it is time to place debris cover factors for fish. The most used cover types are stable rootwads, debris clusters, log jams, and full tree accumulations. These structures should be located in areas of lowest anticipated stream velocities (channel margins, back eddies, etc.) that exist during the high flow period of winter and spring. The best places for this purpose are usually in side channels and eddies, along shorelines, and in backwater pools.

In a review of several projects (Frissell and Nawa 1992) the highest frequency of structure failure occurred with full spanning structures, especially as stream size increased, as compared to bank-aligned structures.

Table 8-2. Process for determining appropriate LWD amounts for enhancement of a stream reach.

Although this question is difficult to answer due to the variability among watersheds, by using some data provided by Grette (1985), a target number of pieces based on the average volume of available pieces of wood can be recommended. Since a wide range of LWD sizes will be used throughout the various regions, this techniques will at least guarantee that streams are attaining consistent LWD volume loading. When LWD sources are off-site, measurements of these stockpiled wood pieces can occur to determine LWD piece needs for the project before bringing them on-site.

Grette (1985) found an average of ~80 m^3 LWD per 100 m stream reach in unlogged tributaries in the Pacific Northwest with < 2% gradient in <8 km^2 watersheds. The maximum volume of LWD observed was 100 m^3 per 100 m stream.

ESTIMATED WOOD VOLUMES (m^3) FOR A GIVEN LENGTH AND A DIAMETER

Length (m)	Diameter (m)																									
	0.25	**0.3**	**0.35**	**0.4**	**0.45**	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**	**0.75**	**0.8**	**0.85**	**0.9**	**0.95**	**1**	**1.05**	**1.1**	**1.15**	**1.2**	**1.25**	**1.3**	**1.35**	**1.4**	**1.45**	**1.5**
3	0.15	0.21	0.29	0.38	0.48	0.59	0.71	0.85	1	1.15	1.33	1.51	1.7	1.91	2.13	2.36	2.6	2.85	3.12	3.39	3.68	3.98	4.29	4.62	4.95	5.3
4	0.2	0.28	0.38	0.5	0.64	0.79	0.95	1.13	1.33	1.54	1.77	2.01	2.27	2.54	2.84	3.14	3.46	3.8	4.15	4.52	4.91	5.31	5.73	6.16	6.61	7.07
5	0.25	0.35	0.48	0.63	0.8	0.98	1.19	1.41	1.66	1.92	2.21	2.51	2.84	3.18	3.54	3.93	4.33	4.75	5.19	5.65	6.14	6.64	7.16	7.7	8.26	8.84
6	0.29	0.42	0.58	0.75	0.95	1.18	1.43	1.7	1.99	2.31	2.65	3.02	3.4	3.82	4.25	4.71	5.2	5.7	6.23	6.79	7.36	7.96	8.59	9.24	9.91	10.6
7	0.34	0.49	0.67	0.88	1.11	1.37	1.66	1.98	2.32	2.69	3.09	3.52	3.97	4.45	4.96	5.5	6.06	6.65	7.27	7.92	8.59	9.29	10.02	10.78	11.56	12.37
8	0.39	0.57	0.77	1.01	1.27	1.57	1.9	2.26	2.65	3.08	3.53	4.02	4.54	5.09	5.67	6.28	6.93	7.6	8.31	9.05	9.82	10.62	11.45	12.32	13.21	14.14
9	0.44	0.64	0.87	1.13	1.43	1.77	2.14	2.54	2.99	3.46	3.98	4.52	5.11	5.73	6.38	7.07	7.79	8.55	9.35	10.18	11.04	11.95	12.88	13.85	14.86	15.9
10	0.49	0.71	0.96	1.26	1.59	1.96	2.38	2.83	3.32	3.85	4.42	5.03	5.67	6.36	7.09	7.85	8.66	9.5	10.39	11.31	12.27	13.27	14.31	15.39	16.51	17.67
11	0.54	0.78	1.06	1.38	1.75	2.16	2.61	3.11	3.65	4.23	4.86	5.53	6.24	7	7.8	8.64	9.52	10.45	11.43	12.44	13.5	14.6	15.75	16.93	18.16	19.44
12	0.59	0.85	1.15	1.51	1.91	2.36	2.85	3.39	3.98	4.62	5.3	6.03	6.81	7.63	8.51	9.42	10.39	11.4	12.46	13.57	14.73	15.93	17.18	18.47	19.82	21.21
13	0.64	0.92	1.25	1.63	2.07	2.55	3.09	3.68	4.31	5	5.74	6.53	7.38	8.27	9.21	10.21	11.26	12.35	13.5	14.7	15.95	17.26	18.61	20.01	21.47	22.97
14	0.69	0.99	1.35	1.76	2.23	2.75	3.33	3.96	4.65	5.39	6.19	7.04	7.94	8.91	9.92	11	12.12	13.3	14.54	15.83	17.18	18.58	20.04	21.55	23.12	24.74
15	0.74	1.06	1.44	1.88	2.39	2.95	3.56	4.24	4.98	5.77	6.63	7.54	8.51	9.54	10.63	11.78	12.99	14.25	15.58	16.96	18.41	19.91	21.47	23.09	24.77	26.51
16	0.79	1.13	1.54	2.01	2.54	3.14	3.8	4.52	5.31	6.16	7.07	8.04	9.08	10.18	11.34	12.57	13.85	15.21	16.62	18.1	19.63	21.24	22.9	24.63	26.42	28.27
17	0.83	1.2	1.64	2.14	2.7	3.34	4.04	4.81	5.64	6.54	7.51	8.55	9.65	10.81	12.05	13.35	14.72	16.16	17.66	19.23	20.86	22.56	24.33	26.17	28.07	30.04
18	0.88	1.27	1.73	2.26	2.86	3.53	4.28	5.09	5.97	6.93	7.95	9.05	10.21	11.45	12.76	14.14	15.59	17.11	18.7	20.36	22.09	23.89	25.76	27.71	29.72	31.81
19	0.93	1.34	1.83	2.39	3.02	3.73	4.51	5.37	6.3	7.31	8.39	9.55	10.78	12.09	13.47	14.92	16.45	18.06	19.74	21.49	23.32	25.22	27.2	29.25	31.37	33.58
20	0.98	1.41	1.92	2.51	3.18	3.93	4.75	5.65	6.64	7.7	8.84	10.05	11.35	12.72	14.18	15.71	17.32	19.01	20.77	22.62	24.54	26.55	28.63	30.79	33.03	35.34
21	1.03	1.48	2.02	2.64	3.34	4.12	4.99	5.94	6.97	8.08	9.28	10.56	11.92	13.36	14.89	16.49	18.18	19.96	21.81	23.75	25.77	27.87	30.06	32.33	34.68	37.11
22	1.08	1.56	2.12	2.76	3.5	4.32	5.23	6.22	7.3	8.47	9.72	11.06	12.48	14	15.59	17.28	19.05	20.91	22.85	24.88	27	29.2	31.49	33.87	36.33	38.88
23	1.13	1.63	2.21	2.89	3.66	4.52	5.46	6.5	7.63	8.85	10.16	11.56	13.05	14.63	16.3	18.06	19.92	21.86	23.89	26.01	28.23	30.53	32.92	35.41	37.98	40.64
24	1.18	1.7	2.31	3.02	3.82	4.71	5.7	6.79	7.96	9.24	10.6	12.06	13.62	15.27	17.01	18.85	20.78	22.81	24.93	27.14	29.45	31.86	34.35	36.95	39.63	42.41
25	1.23	1.77	2.41	3.14	3.98	4.91	5.94	7.07	8.3	9.62	11.04	12.57	14.19	15.9	17.72	19.63	21.65	23.76	25.97	28.27	30.68	33.18	35.78	38.48	41.28	44.18

To determine an approximate number of LWD pieces for a rehabilitation project, use the table above and apply the following equation:

$$N = \frac{80m^3}{V_a} \times \frac{L}{100}$$

where
N = number of suggested LWD pieces
V_a = average volume/piece of available LWD (from table above)
L = length of proposed reach (meters)

For example: 1.59m^3 is the average LWD volume/piece available for use in rehabilitation (determined from table after averaging diameter and lengths of available LWD). 300 m is the reach length (< 2% gradient).

$$N = \frac{80m^3}{1.59m^3} \times \frac{300}{100} = 150 \text{ LWD pieces/ 300 m stream.}$$

Therefore, 150 LWD pieces are recommended for this particular 300 m reach when the average available LWD piece is 1.59 m^3 in volume. This information is consistent with findings in old-growth and old second-growth forests (Grette 1985) and with extensive literature review (Peterson et al. 1992) where LWD frequency ranged between 18-61 pieces/100 m in small unmanaged streams and 40-80 pieces/100 m in medium streams (5-10 meter BFW). Larger streams ranged between 3-46 pieces/ 100 m.

Fastening Systems

Several LWD anchoring systems have been developed (Fontaine and Merritt 1988; Flosi and Reynolds 1994; Koonce 1990) and individual projects throughout the Northwest have often developed variations of these fastening techniques. Figure 8-6 exhibits different variations of fastening techniques. Commonly used are: fastened to boulders using epoxy resin; rebar typically driven 2.8 meters into the substrate with the top 10-12 cm bent and driven into the log and dead man applications. Galvanized chain has also been used in British Columbia for floating log or raft structures.

Consistent with ecosystem principles, the authors encourage the experimental use and monitoring of unfastened or delayed fastening. The role of the intragravel wood matrix is not well understand but biologists and geologists assume it provides an important resistance factor in stream stability and gravel migration. By not fastening LWD, we recognize the importance of continual input and depletion phases in the LWD cycle. In unfastened applications, LWD is positioned in the stream or wedged between standing trees. The sheer mass of the LWD, confined channel characteristics, wedged position, low resistance orientation, or some combination of these, are capable of holding the LWD in place. Project developers can estimate LWD sizes that are more likely to remain within the system for several years and locate or recommend those particular LWD sizes for placement. In delayed fastening applications, key LWD pieces are anchored after one or two storm events, after the piece has been distributed and positioned by flood waters. This application can occur in plane bed, channelized, or in streams scoured to bedrock where there are limited channel irregularities or meanders in which LWD accumulations naturally occur. Fastening is essential in areas with low in-channel LWD and very poor future LWD recruitment. Care should always be taken to avoid direct damage to downstream public structures (i.e., bridges) and adjacent private property.

Generally, the use of unnatural materials is discouraged. Geotextile fabric, plastic sheeting, and chain-link fencing have short effective life-spans in streams with altered hydrology. Most channel-spanning structures will seal with sediment and organic material within the first year or two.

MONITORING AND EVALUATING PROJECTS

Documenting fish presence in areas of restored habitat is a common approach to evaluating habitat restoration projects. Increased fish presence in a previously little-used area may indicate that favorable habitat conditions are created as a result of a certain woody debris arrangement. However, this information must be interpreted cautiously, because it can be misleading in evaluating increases in fish productivity. Since many small-scale restoration projects occur on a site-by-site basis, it is very difficult to determine their actual contribution to overall stream productivity. The matter becomes even more complicated if multiple species are involved and if there are artificial influences (hatcheries, fry outplants, artificial flow conditions). The best way to evaluate the effects on anadromous salmonid fish abundance as a result of restoration projects is to quantify basinwide smolt output. Often winter habitat limits fish production (see Fish Habitat Assessment Procedures), and therefore, it can be important to gain knowledge on the smolt yield benefits (with a viable control) before concluding what improvements have been achieved. Because of the proven seasonal mobility of juvenile salmonids during the winter, it can be misleading to evaluate enhancement projects using summer standing crop estimates. When treatments begin to improve the survival of fish through the "bottleneck" period of winter, then restoration projects are probably making a significant difference. For evaluating resident fish response in interior regions, enumerations over extended reaches using mark-recapture and/or systematic underwater counts, are typically required.

PROJECT COSTS

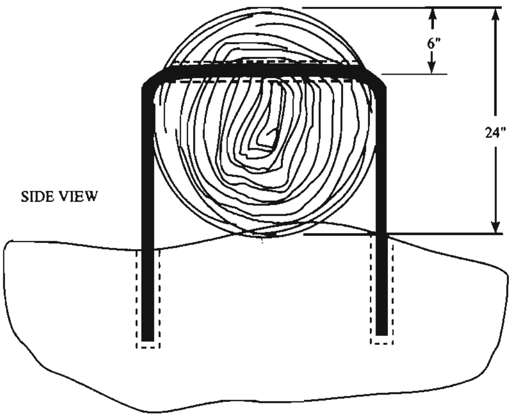
Over the past century, stream rehabilitation has occurred at all levels of project scales from strict volunteer work within a habitat unit to multi-decade, million-dollar/year watershed rehabilitation programs. Since funding is often temporary, the most promising work can occur on a stream or reach level. In this capacity, evaluation efforts are more likely to show effects as compared to scattered basin-wide efforts in which their cumulative positive effects may be masked by existing unstable conditions. Table 8-1 lists examples of restoration project costs of various stream reaches. The costs per kilometer of rehabilitated stream reaches can vary. Usually, higher costs are associated with rehabilitation projects that have undergone extensive planning and engineering and/or were conducted for experimental purposes.

CONCLUSIONS

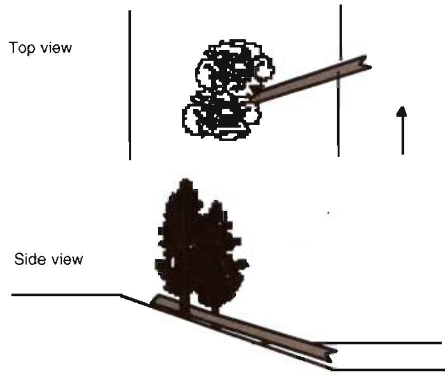
The literature related to rehabilitation and habitat improvement has provided some consistent recommendations that should be adhered to in principle and practice:

- There is no substitute for habitat protection.
- Rehabilitation efforts should focus on underlying processes, not on superficial improvements; active use of existing natural templates or "analogues" will assist in focusing on processes.
- Priority upslope and riparian rehabilitation work can occur simultaneously with instream work. However, in cases of extremely degraded upslope and riparian conditions, it is advisable to rehabilitate these areas before initiating instream work.
- In addressing instream rehabilitation, understanding the habitat requirements and the limiting factors of existing fish communities contributes to the development of a successful project.
- Understand the existing state of channel disturbance or recovery, and design projects that consider these conditions; avoid unstable geomorphic settings.
- Do not necessarily limit LWD placement strategies to existing manuals and designs, but attempt to simulate natural abundance and arrangements.
- Biologists and engineers should complement each other by considering the physical and biological components of LWD rehabilitation.
- When available, large diameter (>0.6 m or 24") LWD conifer pieces are preferred, to assure stability and long-term function.
- LWD volume requirements are a safe and consistent recommendation since there may be regional differences in LWD sizes.
- We recommend **off-channel** LWD work in fish habitat rehabilitation when the site has either
- of the following characteristics: a) the channel is greater than 7 m bankfull width and has a gradient greater than 2%; b) the channel has a bankfull width greater than 20 m.
- We recommend **active channel** LWD work in fish habitat enhancement when the site has either of the following characteristics: a) the channel is less than 7 m bankfull width and the gradient is less than 5%; b) the channel is 7 to 20 m bankfull width and the gradient <2%.
- We recommend LWD work in **headwater channels** that are less than 7 m bankfull width and greater than 5% gradient for the purpose of providing channel hydraulic stability.
- Monitoring, as a form of learning, is essential for the development of any watershed program concerned with maintaining or improving the existing level of aquatic productivity.

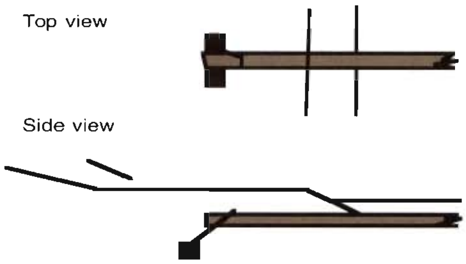
For medium to large streams: 5/8" cable (galvanized or stainless).
3/4" diamond-tipped drill (very tight fit)
Hilti c-10 epoxy cartridges
Drill 8-10" hole in boulder with Hilti gas-powered drill. Clean hole thoroughly of dust by rinsing. Insert epoxy followed by cable. In small streams, 1/2" cable with 5/8" hole is acceptable.



Standing tree wedge technique. Applicable when riparian area has large stable trees. Sweeper logs can be placed between two trees and cabled. Fasten end into streambed with rebar or cable onto existing boulders.

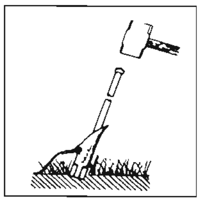


Use of wood or concrete deadman for soft or gravely soil. Excavate perpendicular trench 0.5 to 1.5 meters below elevation of log bottom. Fasten 5/8" cable, or wrap cable to deadman. Add large rock for weighing down if loamy soil. Thoroughly compact fill with heavy equipment.



The duckbill anchor. Effective in loamy and gravely substrate.

DRIVE ANCHOR TO DESIRED DEPTH: DUCKBILL anchors are driven into the soil using a hammer and drive steel. As the anchor is being driven, it is actually compacting the soil around the anchor head. Once the anchor is at the proper depth, the drive steel is removed.



LARGER DUCKBILL ANCHORS:
To set larger anchors, use the fulcrum (lever) principle, manual or hydraulic jack, winch or post puller.

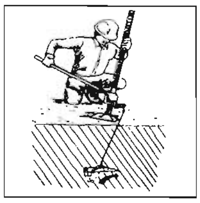


Figure 8-6. LWD attachment techniques for salmon habitat enhancement.

Figure 8-7. Porter Creek, WA. Full-spanning log, logs vertically angled, rootwad and shoreline LWD accumulations.

Figure 8-8. Porter Creek, WA. Full-spanning log, rootwad and energy dissipation.

Figure 8-9. Porter Creek, WA. Step logs and energy dissipation.

Figure 8-10. Porter Creek, WA. Debris catcher.

Figure 8-11. Porter Creek, WA. Debris cover.

Figure 8-12. Hoh River, WA. A small tributary with full-spanning log, logs functioning as energy dissipators.

Figure 8-13. Stequalaho Creek, WA. Sediment dam on a small tributary that has sluiced out.

Figure 8-14. An unnamed small high-gradient tributary where LWD provides energy dissipation.

Figure 8-15. Shop Creek, B.C. A large rootwad that had been left on the bank after logging was moved to a corner pool to provide prime juvenile rearing (coho, steelhead and char) and spawner holding habitat. The rootwad is secured by a chain at the upstream end, where it stays in position to maintain the deep pool.

Figure 8-16. A log deflector with floating bank cover installed in Shop Creek in the upper Squamish River watershed

Figure 8-17. Attached LWD at USFS project on the Mount Baker Snowqualmie National Forest. Logs are secured by boulders and rebar. (Myron Kozak photo)

Figure 8-18. Attached woody debris at a USFS project on the Mount Baker Snoqualmie National Forest. Logs are attached to bedrock (epoxy-cabled) and the stream bank. (Myron Kozak photo)

Chapter 9

Accelerating the Recovery of Log-jam Habitats: Large Woody Debris-boulder Complexes

Pat A. Slaney[1], Rheal J. Finnigan[2], Robert G. Millar[3]

INTRODUCTION

In mature to old-growth forests, streams are structured by abundant pieces of large wood that store sediments, create pools for fish rearing as well as hydraulic "tailouts" of gravels for spawning of salmonids. Log jams comprise about 10% of LWD in small streams, in contrast to medium-sized streams, where log jams constitute 40% of LWD (data on file, Hogan pers. comm.). Jams are vital fish habitat for summer and winter rearing, adult holding, and prime spawning at pool "tailouts".

Applications

Chapter 8 (Cederholm et al.) provides guidelines for restoring natural quantities and sizes of large wood in streams up to 20 m in width. This chapter focuses specifically on restoring and creating the more complex habitat structures commonly referred to in streams as "log jams", but employing conceptual designs of structures that only moderately impinge on the hydraulics of the channel. These include full-spanning elevated structures over residual shallow pools in very small streams, but primarily lateral log jams, streamside debris catchers, and stream reefs, applicable to stable moderately-sized streams. Lateral log jams (with logs attached on sloping banks in a triangular design) are the preferred and more conventional option for these complex habitat structures, and templates are most common in nature.

As with other techniques described in other chapters, log jams should not be applied exclusively. For example, boulder clusters as described in Chapter 10 are most applicable to riffles, and LWD placements, as described in Chapter 8 are most applicable to low gradient riffles and shallow pools as broad restorative treatments. Large composite structures are targeted on geomorphic settings where there is either historical evidence of log-jam structures (air photo or residual jams) or where a systematic survey and guidance of an individual with experience in such prescriptions indicate suitable residual pool sites. Application of these complex structures to break up steeper gradients (>2%) within extended riffles should be approached with caution because of excessive stream power (gradient x mean annual flow). Also, much of the microhabitat velocities at these steeper sites will exceed holding or rearing preferences of salmonids (Fig. 9-1), versus usable microhabitats in lower gradient hydraulic units such as residual shallow pools, runs, glides and "flats" (Keeley and Slaney 1996). Of course, any stream reach may receive prescriptions that are a combination of techniques including composite structures, as described in this chapter and in Chapter 8, Fig 8-3A. On a cautionary note, although a survey of 2,000 diverse structures installed in small to medium-sized streams of the

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Mt. Baker-Snoqualmie National Forest indicated that only 12% were lost after 50 to 75-year floods of 1990 (Doyle 1991), most of those losses were in medium-sized streams, as was also documented by Heller et al. (1996) for a 100-year flood in Oregon and southern Washington in 1996.

Figure 9-1. A natural lateral log jam above a dry flood channel of Mashiter Creek, B.C.; the steep gradient at the jam (~2.5%) minimizes the percentage of the scour pool or run that is of a usable velocity range for juvenile fish.

Although natural large wood is frequently a stabilizer of stream channels, its use in diverse geomorphic settings should be approached cautiously. Actively eroding geomorphic settings, destabilized by logging the floodplain to the stream banks, should be deferred in favour of off-channel habitat mitigation. Channel-spanning structures were frequently more vulnerable to flood damage in a study conducted on 15 Washington and Oregon streams (Frissel and Nawa 1992). In remote settings, dislodged structural elements are typically caught on LWD located downstream. However, use of these structures in less remote settings needs to be approached with a greater margin of safety because of stream crossings and adjoining private lands. Because large wood is a stabilizer of stream channels, Washington State's watershed analysis process recognizes "key" pieces of large LWD as contributors to watershed stability during floods (Washington Department of Natural Resources, Chapter 8). As emphasized by Beschta (1979), past removal of large wood from streams, often with an assumption of improving fish passage, has accelerated downcutting of previously stored sediments, causing an increase in suspended sediments that have downstream consequences to both water quality and salmon spawning habitats.

Applications of large LWD-boulder composites or jams, to restore or replace lost salmonid habitat as complex pools and runs, are four-fold as: (1) full-spanning log jams (small streams only), (2) lateral log-rootwad-boulder composites, (3) woody debris catchers, and (4) woody debris boulder reefs. Although most of these have been applied for habitat rehabilitation in stable smaller streams (Chapter 8) by design or by alterations after flood events, there have been only limited applications to stable larger streams, albeit at an increasing frequency (e.g., Oliver 1994; Slaney et al. 1994a; Brunfelt 1996).

LWD AND BOULDER COMPLEXES AS PRIME SALMONID HABITAT

Chapters 1 and 8 focus on the role large wood plays in storing sediments, trapping fish carcasses (as sources of nutrients and carbon), structuring channels, and providing fish habitat in streams, as well as the long-term LWD recruitment process to stream channels from the riparian zone and upstream sources. Applications of common techniques in restoring large wood in stream channels are aptly described as a short-term measure until other watershed components, especially riparian functions, are restored for the long term. Several studies document a close association of instream large wood, such as logs and rootwads, with juvenile salmonid abundance, particularly as overwintering refuges (also reviewed in Chapter 8). Natural or placed full-spanning logs are also effective in trapping and creating fish spawning areas. Three recent examples are reported of before-and-after controlled evaluations of the effects of placements of LWD on smolt yield from small coho salmon streams in coastal Oregon and Washington. Although a sample size of three streams is small, experimental results of 3 to 4-fold increases on average (range, 2 to 8-fold) in output of coho smolts relative to controls are convincing evidence that abundance of LWD drives coho salmon production in smaller streams (Chapter 8). As emphasized by Cederholm at al. in Chapter 8, large woody debris is most highly utilized as a winter refuge, but experimental additions of small debris bundles in pools also attracted substantial numbers of juvenile coho and trout in summer.

Large wood and boulder structures installed in northern and interior regions of the Pacific Northwest demonstrate similar responses in fish utilization as on the south coast. Shirvell (1990) found juvenile coho salmon and steelhead trout preferred habitat conditions created by rootwad additions to Kloiya Creek located in north coastal B.C.; 99% of coho fry and 83% of steelhead parr colonized "artificial" or natural rootwads during regulated normal, flood and drought streamflows. Similarly, Espinosa and Lee (1991) reported high densities of juvenile trout and chinook salmon within structures including rootwads, log weirs and boulder clusters in Lolo Creek, Idaho.

There is some experimental as well as descriptive evidence that LWD in jams or lateral accumulations at stream meanders, or in combination with boulders, provide prime salmonid rearing and holding habitat. Because large boulders entrap large wood causing further scour to a coarse armour layer, boulders are a feature of many jams, except at very low gradients. As stream size increases, log jams and large boulder features play a key role in the abundance and distribution of both juvenile and adults salmonids. For example, in the Big Qualicum River most (60%) steelhead trout parr were enumerated in log jams, over coarse rocky substrates (Pearlstone 1976). In the large upper Nechako River, a preliminary study indicated rearing chinook salmon were highly associated with masses of woody cover, including windfalls, debris jams and beaver lodges. Thereafter, two types of pilot shoreline debris structures, "debris bundles" and "debris catchers" were installed and evaluated as potential mitigation for losses of instream cover resulting from a proposed hydroelectric diversion. Salmonids were enumerated by underwater counts using the method outlined by Slaney and Martin (1987). After the installation of 21 bundles and 9 catchers over three years, chinook fingerlings readily colonized the structures over the 20 km reach; most were enumerated at these sites. During the peak rearing and migration month (June), the average number of juvenile chinook was greater in debris catchers, or 500 per debris catcher on average in 1991, and density was similar to that in natural instream woody cover such as fallen trees and beaver lodges (Slaney et al. 1994a). In contrast to the bundles, the debris catchers were much more durable; they have filled with woody debris and remained in place for the past seven years regardless of severe winter ice conditions and major overtopping flows (H. Goldberg, Arc Environmental Ltd., pers. comm.). Utilization of catchments of woody debris by rainbow trout parr and adults have also been significant, although most catchers were installed at design velocities and depths preferred by young chinook juveniles. High densities of trout have been observed in debris catchments created elsewhere, such as at the St. Mary River (8 cutthroat trout per structure; Oliver 1994) and the West Kettle River in the southern interior of B.C. (data on file).

Similarly, throughout the Keogh River on Northern Vancouver Island, the density and biomass of steelhead parr in summer was a function of boulders in riffles (67% of the variance) plus, to an added degree, woody cover (10-15%). In contrast, the density of juvenile coho salmon in summer was only highly correlated with instream woody cover in shallow pools (r = +0.7; data on file). Subsequent experimental placements of several sets of 5-7 boulders clusters with attachments of small LWD in the upper Keogh River resulted in densities and biomasses of rearing salmonids equal to that of prime natural runs and pools with boulders and LWD. Also, boulder deflectors with large wood attached to the revetments were well utilized, but revetments without LWD were poorly colonized. With some scouring of the substrate around the clusters with wood attachments, coho fingerling densities were 3 per boulder on average and one steelhead parr per boulder. The best composite site was inhabited by 17 trout parr and 50 coho fingerlings (Fig. 9-2). However, without scour of cobbles at a mid-river reach, sites were only highly utilized by trout parr (Ward and Slaney 1979).

Figure 9-2. A boulder cluster-log complex located in a low gradient riffle of the upper Keogh River, highly utilized in summer by age 1+ and 2+ steelhead parr and coho fingerlings. Such structures have been functional for 20 years, with only the loss of smaller woody attachments.

The importance of large boulders and woody debris combined with boulders in larger streams is also evident. The Rio Grande River in Colorado (fourth order; channel width, 55 m; peak flow 60 $m^3 \cdot s^{-1}$) was historically utilized for log drives that simplified the river. From 1978 to 1985, large boulder habitat structures were installed throughout a 4 km reach to rehabilitate trout habitat. Evaluations from 1981 to 1991 demonstrated that single boulders were not effective, but mid-channel boulder clusters and boulder wing-dams (loose sets of 12-15 boulders angled downstream), as well as natural boulder-woody complexes on the banks, were highly utilized by brown trout. Sixty-five and 69% of adult and juvenile trout, respectively, held positions near structures, avoiding areas with no structures (Shuler et al. 1994). Similarly, a study of habitat use by juvenile salmonids in the large South Thompson River and the Coldwater River in B.C. demonstrated that steelhead parr and juvenile chinook preferred large boulders placed at the toe of the slope in the two rivers, versus small riprap or cobble-boulder banks (Lister et al. 1995).

CONDITION ASSESSMENTS AND PRESCRIPTION TEMPLATES

An assessment of fish habitat (Johnston and Slaney 1996) is needed to determine whether there are low quantities of large wood as a result of historical logging to the stream bank and past gully failures, and therefore a need to restore the frequency of pools. As emphasized in Chapter 8, the quality of LWD is more important than the quantity and the larger "key" and "functional" pieces that form a LWD complex or jam may have been lost after logging to the stream banks. If possible, historical air photos should be examined to determine the nature of the channel, and compared to an old-growth reach of the same channel type, preferably within the same watershed. Next, a search for templates or analogues of composite debris structures such as log jams should be undertaken (Fig. 9-3 and 9-4), preferably in an unlogged reach. These observations can then be applied to assist in identifying residual pool templates (or "flats") in the logged reach in preparation for detailed prescriptions. Survey of the streambed profile and plan mapping as outlined in Chapter 12 is a sound practice in advance of prescriptions because it will assist in identifying flat sections where these composite structures will be most effective at pool formation. As outlined in Chapters 2 and 12 on natural fluvial characteristics, pools typically repeat at 5-7 channel widths, but with natural LWD inputs in old growth forests, pool spacing of 3-4 channel widths are common in coastal B.C., and spacings have been recorded as low as 2 channel widths in southeast Alaska streams with high LWD loadings (Montgomery et al. 1995). **In stable geomorphic settings a well-experienced habitat biologist can rapidly provide prescriptions using conceptual designs from this chapter, which are assigned (flagged with survey ribbon) to the appropriate residual shallow pools, glides as well as "flats", typically within bends to assure long-term durability (Fig. 9-5).** *In practice, most reaches will receive a range of prescriptions ranging from boulder clusters in riffles (Chapter 10), basic LWD prescriptions (Chapter 8) to composite-jam techniques in residual pools, glides and flats as described in this chapter.*

Figure 9-3. A natural template of a large woody debris and boulder complex at a bend of the upper Keogh River.

Figure 9-4. A natural analogue of a lateral log jam, enhancing a pool in a bend of the upper Keogh River.

Figure 9-5. A series of lateral jog jams installed in 1996 (pre-scour before winter floods) at bends in residual low gradient sites adjoining steeper (2%) sections of a reach of the upper Keogh River. Post-freshets, these boulder and bank anchored logs and rootwads formed lateral scour pools. (Encroachment of LWD complexes on the channel were limited because of stream bank confinement associated with past road fills.)

A more detailed assessment of the condition of the channel is advised where destabilization is indicated by various levels of sediment accumulations on bars, widening of the channel, and the loss or infilling of instream structures including large wood and boulders. A channel condition and prescriptions procedure is described in Hogan et al. (1997), which is adapted from the Channel Assessment Procedure (CAP) for the B.C. Forest Practices Code (Anon. 1996a, b). A stable reach can be considered a candidate for composite-jam structures, but unstable reaches with eroding banks should either be avoided or "seasoned" expertise in channel geomorphology and reconstruction should be enlisted. For example, at the West Fork of the Hood River, Oregon, channel structure within two reaches (1.6 km in total, including a stable and unstable reach) were restored (Brunfedt 1996). The destabilized reach required measures to restore the channel width and its fish habitat as close to the historic condition as possible by conducting pre-studies of hydrology and channel geometry, followed by measures to decrease the width to depth ratio, and increase LWD complexity. Excavated material from anchoring large wood into banks was used to accentuate existing bars and adjust channel geometry to a suitable unlogged analogue (Brunfedt 1996).

There is also a need to ensure that hillslopes are stabilized and risks of debris flows, leading to torrents in the mainstem, are minimized, as outlined in other chapters. Losses of many of the decade-old structures from Fish Creek, a fifth order stream in Oregon, during the 1996 100-year flood were caused by debris flows from logged steep gullies and hillslopes. Regardless of advance completion of hillslope stabilization, there still may be risks of sedimentation from channel widening if an alluvial floodplain has been logged to the stream banks. As old-growth root stability is lost, the channel becomes unstable with considerable erosion at meander bends (Kellerhals and Miles 1996). Clearly, these geomorphic settings are to be avoided because further "unravelling" is likely to occur. Although debris transported from such destabilized alluvial reaches may add to the complexity of composite structures installed along downstream reaches, it is more effective to focus most rehabilitative works on off-channel habitats, to ensure high survival of salmonid eggs and overwintering juveniles.

PRESCRIPTIONS FOR SPECIES LIFE HISTORIES AND MICROHABITATS

An understanding of life histories, microhabitats and macrohabitats at each life stage of target fish species is essential to effectively undertake habitat restoration. For example, numerous studies and surveys in B.C. and Idaho have confirmed that fry of resident rainbow trout, cutthroat trout, bull trout and Arctic grayling do not inhabit the mainstems of inland rivers as underyearlings (in contrast to steelhead). Rather, adults spawn in tributaries or side-channels, where their progeny rear from fry to parr stage, entering the river as age 1+ to 3+ parr. In most rivers studied in B.C. the amount of nursery rearing habitat limits the mainstem population of adults. Thus, subject to the results from habitat condition assessments, much restorative work, including log-jam structures, needs to be focused first on tributary rearing areas (or side-channels, especially for grayling), and second on mainstem habitat. Finally, for species that rear more than one summer, it is important to recognize that suitable or usable habitat in summer is rarely limiting at the fry stage, but rather at the parr stage. This is because it is well established that the amount of territorial space required is proportional to cube of fish length or directly proportional to body weight. Thus, the territory defended by a 2.5 cm (0.3 g) fry is 2% (0.015-0.02 m^2) of that defended by a 10 cm (10 g) parr (1.0 m^2). Because of size-related overwinter survival (for steelhead) a minimum of 20-30 fry per 100 m^2 of stream in summer are needed to attain a carrying capacity density of 4-6 age 1+ parr per 100 m^2, equating to 20% fry-to-parr overwinter survival in a coastal river (Ward and Slaney 1993a). Thus, availability of fry habitat as a primary limitation to a population could only occur in higher gradient streams that flow at bankfull width during summer, offering negligible low velocity areas at the margins.

Microhabitat features (velocity, depth, substrate, cover) preferred by target species must be provided by ensuring complexity within pools, such as overhanging ledges of large wood at banks. Velocities will frequently be reduced at sites by installation of structures. This factor needs to be accounted for in advance for species that prefer higher velocities, such as adult and parr stages of trout and char as well as chinook salmon. In contrast, juvenile coho prefer lower velocities close to stream banks. With some experience, it is possible to design macro- and microhabitats for multiple species in the same composite structure. Velocity is the key factor, because if woody cover is available, depth is less important. Rearing velocities increase with fish size; ranging from a few $cm{\cdot}s^{-1}$ at the fry stage to 20-40 $cm{\cdot}s^{-1}$ at the parr to adult stages. Bjornn and Reiser (1991) and Keeley and Slaney (1996) provide suitable ranges of target velocities, depths and substrates. As a "rule of thumb", selection of sites with about twice the design velocity is required to achieve preferred velocities post-construction, at target summer flows (Slaney et al. 1994a).

FULL-SPANNING LOG COMPLEX PLACEMENTS

Restoration of full-spanning log structures has been commonly employed for pool restoration or improvement techniques in small streams, and there have been several smaller, uniform variations on this theme, including diagonal log weirs, V-log structures and K-log or log-ramp drop structures, as described in Chapter 8 and Chapter 11 on mainstem techniques. Based on natural analogues, full spanning elevated "log complexes" have also been used in small streams. Risks of loss or failure of full-spanning structures are low in stable small streams with moderate gradients (<2%). Generally, no attachments are required, other than the weight of the mass of LWD materials and locking cross-spanning logs into trees on both stream banks (Fig. 9-6, and Fig. 8-11 in Chapter 8). In confined channels with coarse substrates, there is little risk of outflanking and bank scour, provided the structure is elevated slightly above where a pool would naturally form, or more specifically, where the hydraulic energy from the riffle is attempting to form a pool over the long term. Alternatively, log complexes should be anchored to the bases of trees and stumps. Although there are many natural templates in medium-sized streams (>10 m channel width), the results of placements are less predictable and restoration of full-spanning jams is not advised except on an experimental basis (although use at U.S. projects has increased in the past few years). Also, they are unlikely to be approved by regulatory agencies until more experience is gained from either small pilot structures, or larger-scale systematic research applications. There is a trend toward slightly higher frequency of structural failures of cross-spanning structures, especially in unstable settings as storm frequencies increase, compared to lateral LWD and boulder clusters (Frissel and Nawa 1992).

Figure 9-6. Full-spanning LWD elevated jam structures combined with boulder clusters in Shop Creek, a small 1.4 km tributary of the upper Squamish River, B.C. In 1996 7,500 coho smolts were produced, 75% originating from the mainstem and 25% from two excavated groundwater channels and a pond.

LATERAL LOG-JAM STRUCTURES

Lateral or stream bank log jams are a common natural structure in streams with mature or old-growth forests, particularly as bankfull channel width increases above 20 m because large wood is shifted to the side of channel at bends (e.g., Fig. 9-4). Such lateral log jams can range from a small (5-10%) to a substantial (50-100%) proportion of the channel width, but until more experience is gained, a cautious approach is to limit encroachment of the channel width to < 30-40%, and with a low cross-sectional profile (Figs. 9-7 and 9-8). In larger streams in summer, these prime habitat areas hold the highest diverse abundance of fishes (Slaney and Martin 1987; Slaney et al. 1994a) except where they are located in steep riffles (Fig. 9-1). Although not well documented, log-jam pools are also sanctuaries in winter. Unfortunately, after logging to the stream banks with a loss of supply of coniferous LWD, natural lateral log jams are gradually lost over time as mature trees decay and are washed downstream. Unless a pool is maintained by the energy of a steep riffle, infilling occurs and a shallow pool or "flat" or "glide" is the residual "footprint", a hydraulic unit that is devoid of instream cover in summer and especially in winter. In summer, fish densities in these marginal flat habitat units are 5-10% of deep pools with cover, or runs or riffles with abundant cover. Yet in streams logged to the banks the former comprise a substantial proportion of habitat and are well known by riverine biologists as the "biological deserts" of the small and large rivers of the Coast and Interior.

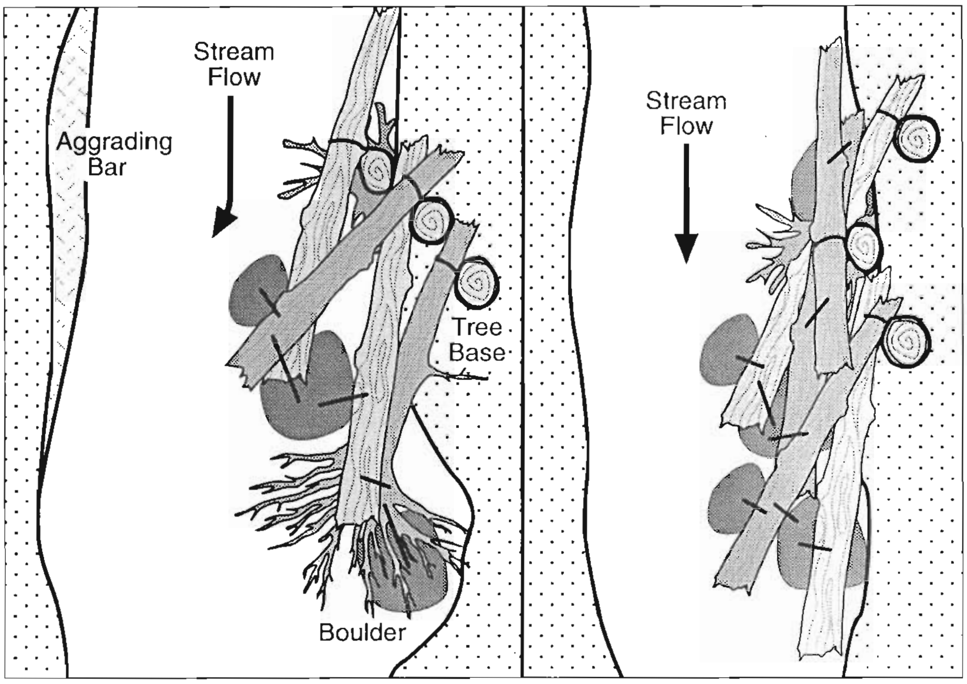

Figure 9-7. Conceptual drawings of lateral log jams, constructed of logs and rootwads secured to large boulders, aligned with the stream banks and attached to tree bases; the amount of the jam within the channel is reduced where the channel is confined by steeper stream banks (right).

Figure 9-8. A lateral log jam installed in the Keogh River aligned to a sharp bend, to armour an eroding bank, catch debris and scour a deep pool as prime habitat for juvenile and adult fish.

Conceptual Designs and Fastening-Ballast Systems

Restoration of lateral log jams can be accomplished by use of two designs: (1) lateral placements of several logs (3-4) and rootwads (1 or 2) at bends or curves in the channel (Fig. 9-8); (2) placements of a series of logs at right angles to the stream, in a triangular configuration angled down from the stream banks in the same setting (Figs. 9-9 and 9-10). These structures are placed at residual pool sites, i.e., pools or runs that at some time in the past contained natural LWD accumulations of a similar nature. Both need to be well anchored with boulder ballasts, attaching the boulders to the large logs and rootwads. In the lateral configuration the inner logs on the bank are attached to tree bases or stumps using galvanized cables, while in the triangular design, logs are attached on the banks to trees or stumps more removed from the channel. Because it is difficult to obtain whole trees with rootwads, rootwads usually have to be transported separately and attached to the matrix. Note that such lateral jams should be installed in low gradient sites (shallow pools, glides or flats) because at a minimum design target of a 50-year flood, the hydraulic forces on the LWD surfaces increases greatly with slope. Clearly, the mid-portion of the shallow pools or glides are more stable locations because of energy dissipation at the front of the pools; highest velocities are at the upstream portion. An equation for boulder sizing is provided in Chapter 12; boulders are much more at risk of dislodgement at higher gradients (> 2%) of confined channels with high stream banks.

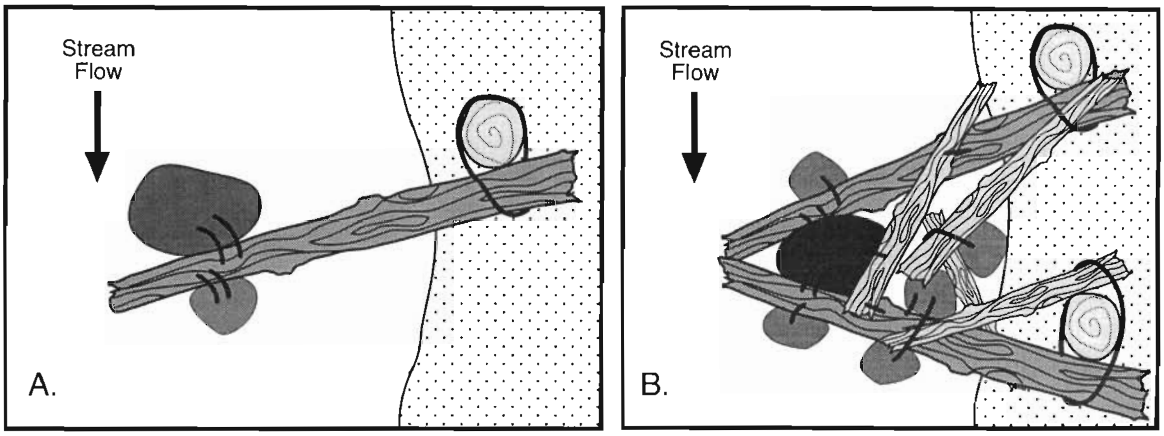

Figure 9-9. Conceptual design of lateral log jams. (A) Single-Log. Note that the ballast boulder is placed on the upstream side of the log, and that the log is attached to a tree or stump on the bank. (B) Triangular. The triangular structure forms the basis for the log jam. The logs are both attached to trees or stumps on the bank, and are cabled to a common anchor boulder in the stream. Additional LWD and rootwads can be attached to the basic triangular structure.

A fastening and boulder ballast system is required to provide assurance that some of the logs and rootwads are not dislodged. Two to three small boulders attached together are used in place of a single large boulder of the same weight, which benefits rearing salmonids in the LWD-boulder complex, and are easier to transport. Logs and rootwads are cabled to each other by drilling holes within the top quarter of the logs and then attached to boulders along the sides and within the center of the matrix using the epoxy technique as described in Fontaine and Merritt (1988). High strength galvanized cable (1.27 mm - 1.43 mm or 1/2" - 9/16") is commonly utilized, which is attached to the boulders with epoxy resin (Hilti system) designed for securing cable to rock (Fig. 9-11). Boulders are placed on both sides of the logs, with the larger boulder upstream. To meet bond attachment specifications, 20 cm holes must be: (1) drilled with a carbide-tipped bit no larger than 0.16 mm (1/16") greater than the cable diameter, (2) thoroughly cleaned with wire brushes (1.9 mm or 3/4" diam.) to remove all rock dust, and (3) repetitively rinsed with clean water in advance of injecting resin into the hole (Fig. 9-11). Although the epoxy dries within a few minutes above water and several minutes longer if used under water, it needs to set undisturbed for 15 minutes and an hour, respectively. If two holes are drilled in a rock, they should be at least 30 cm apart, and larger logs and rootwads require a double loop through the log to provide a margin of safety. If logs are connected together by cables, 2 cable clamps are used, alternating them from side to side at a minimum 10-15 cm from the cable ends. High-strength galvanized chain can also be used to tie logs together when log movement in high flows is expected; chain is a more durable linkage than cable for log booms. A "deadman" can also be utilized by excavating a deep trench on the bank, in which a log is placed with a "farmer's eye" and pulled tight with an excavator. Used cable salvaged from logging sites is not recommended for LWD attachments because of unpredictable strength, wear, and corrosion, as well as unknown quality.

Figure 9-10. A triangular lateral log jam anchored with large boulders in the channel and to tree bases on the bank. The log-rootwad-boulder composite structure was installed in a residual pool within a minor bend of the Keogh River, logged to the stream banks by past logging practices.

In the following section design charts and guidelines are presented for estimating boulder ballast requirements for lateral log jams.

Ballasting of Lateral Log-jam Complexes

There are two basic structural elements of lateral log-jam complexes: (1) single-log; and (2) triangular. The single-log lateral jam consists of a log projecting from the bank into the stream (Fig. 9-9A). The log is attached at one end to a tree or stump on the bank, while the opposite end in the stream is ballasted with one or more boulders to prevent movement during high flows. Clusters of single logs with rootwads can be grouped together to form a complex (Figs. 9-7, 9-8).

The basic structural form of the triangular log-jam consists of two logs that are attached to trees or stumps on the bank, and are both ballasted by a common anchor boulder in the stream (Figs. 9-9B, 9-10, 9-17). The triangular lateral log-jam is inherently more stable than the single log because the lateral bracing provides resistance to the drag forces exerted by the flow. Once the basic triangular structure has been constructed, additional LWD and rootwad complexing can be added.

The triangular log-jam is much preferred over the single log structures because of the structural stability and the relatively large amount of habitat produced.

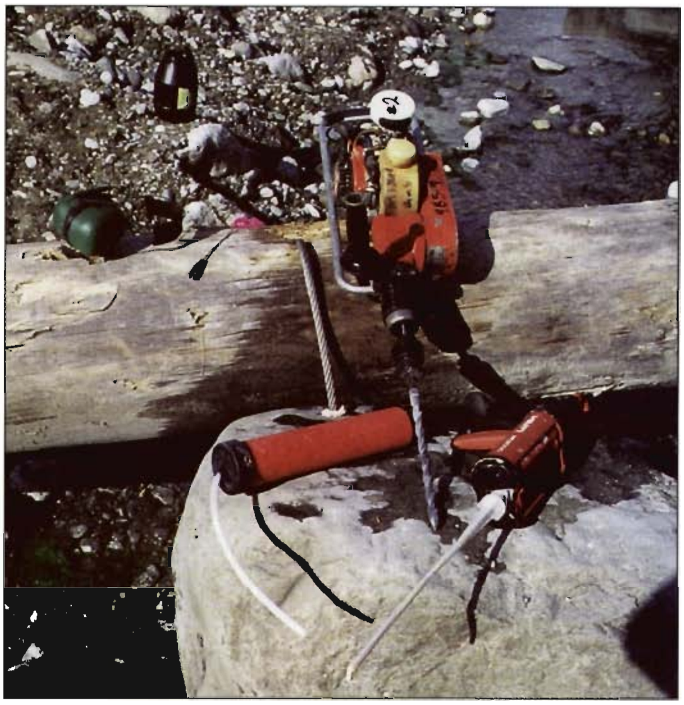

Figure 9-11. The Hilti system for anchoring logs to boulders, including a gas driven drill with ear protection, a flushing and brushing system for the 20 cm hole, and the dual epoxy resin dispenser.

Design charts have been prepared to assist in determining the ballast requirements for the two structural elements of lateral log-jams (Figs. 9-12A and 9-12B). The design charts have been developed from an analysis of the buoyancy, drag and lift forces exerted on the LWD and boulders, and include a factor of safety of 2.0 for the single log-jam structures, and 1.25 for the triangular log-jams. The lower factor of safety for the triangular log jams reflects the lateral stability of these structures. The theoretical basis for the design charts, together with some preliminary field verification is given in Millar (1997). The design charts are based on a simplified analysis of the fluid forces. Scaled hydraulic model testing of unusual designs may be warranted.

For the single-log lateral jam, the mass of the required ballast rock depends upon the diameter of the log, the velocity of the flow, and the effective length. The **effective length** refers to the length of log projecting into the stream. The portion of the log on the stream bank is not considered in the analysis. Ballast requirements for triangular lateral log-jams depend only upon the effective length and the diameter of the logs and rootwads used in the complex, and are not greatly affected by the flow velocity.

For the single-log log-jam, the design velocity, V, can be estimated using the Chezy equation:

$$V = 20\sqrt{HS}$$

where V = design velocity in $m \cdot s^{-1}$, H = height of the floodplain above the channel bed in m; and S = slope of the channel ($m \cdot m^{-1}$).

For a given design velocity, V, the ballast requirements for a single-log lateral jam can be determined from Fig. 9-12A. For a particular log diameter and design velocity, the mass of the ballast required **per meter of effective length** is read from the Y-axis. The total ballast required is obtained by multiplying the value obtained from Figure 9-12A, by the effective length of the log. For a composite structure such as that shown in Figure 9-7, the ballast requirement of each log must be determined individually.

For most streams of interest, the design velocity will generally lie within the range of 2 to 4 $m \cdot s^{-1}$. If the design velocity is less than 2 $m \cdot s^{-1}$, the design curve for V = 2 $m \cdot s^{-1}$ should be used. It is unlikely that the actual velocity in a stream would exceed 4 $m \cdot s^{-1}$. In the event that the Chezy equation does indicate that $V > 4$ $m \cdot s^{-1}$, caution should be exercised; however, the design curve for V = 4 $m \cdot s^{-1}$ can probably be used.

The ballast requirements for triangular lateral log jams can be estimated from Figure 9-12B. Figure 9-12B gives the ballast required **per meter of effective length** for each log in the complex. As in the case of the single log structure, the total ballast requirement for each log or rootwad in a triangular jam is obtained by multiplying the value obtained from Figure 9-12B by the effective length of the log in the stream. To estimate the ballast requirement for a rootwad, the dimensions of the rootwad need to be converted into an equivalent diameter and length of a log of equal mass.

Figure 9-12C has been included to assist in the sizing of the ballast rocks. One, two or more boulders that have a total mass greater than or equal to the calculated requirement can be used. Use of multiple boulders is generally preferred, as this can result in additional habitat. When constructing a single-log jam it is important that the largest boulder be placed on the upstream side (Fig. 9-9A) to prevent the structure from "flipping over" during high flows.

Two example calculations are presented in Appendix 9-1.

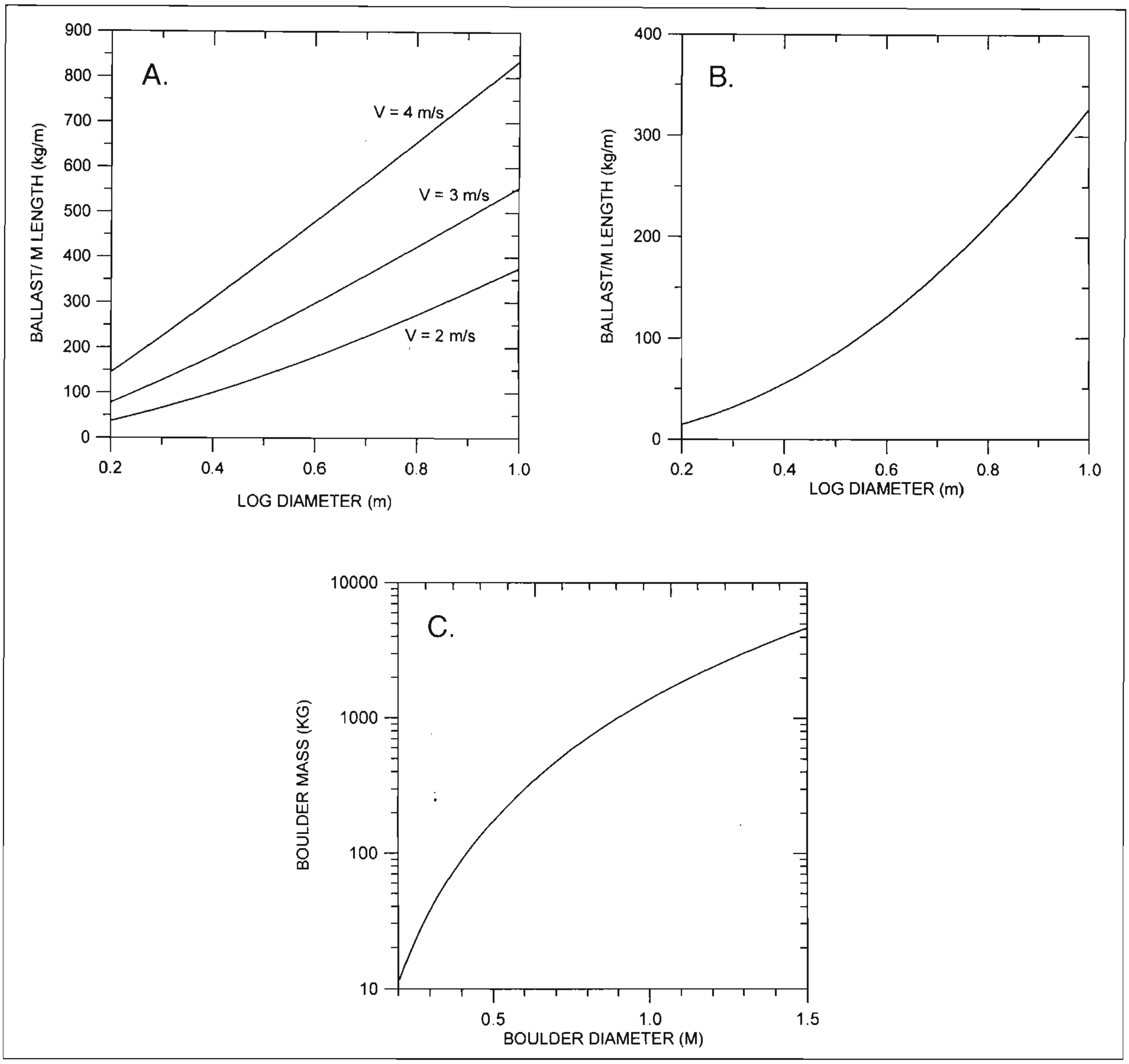

Figure 9-12. Design charts to determine ballast requirements per meter of effective length for constructed lateral log-jams. (A) Single-Log. (B) Triangular. (C) Relationship between boulder diameter and mass. Note the log scale on the Y-axis. To convert boulder mass to volume, divide the mass (in kg) by 2,650.

Although scouring of a pool or run under a lateral jam is the goal of this design, this process can be accelerated by moving coarser materials to the toe of the bank, where they form both a revetment and prime fish habitat. Similarly, depending on current patterns, some of boulders used as ballast can be staggered in 3-boulder clusters (each 0.5-1 m apart and clusters 3 m apart) near the bank, to promote use by trout species.

Machinery required is described in Chapter 8, including an excavator and trucks for material transport, or by helicopter at sites where there is no road access. Flexible spider-type excavators fitted with a winch and hydraulic thumb on the bucket are ideal for this work (Fig. 9-13). They have a lifting capacity of about 1,275 kg (2,800 lbs) extended and 4,455 kg (9,800 lbs) retracted, and can be manoeuvred on rear tires and front pads without leaving a "footprint" in medium-sized stream channels (10-20 m) or within the riparian zone. Similarly, more conventional excavators fitted with hydraulic thumbs, have a capacity of 3,270 kg (7,200 lbs) extended and 7,275 kg (16,000 lbs) retracted, and are more suitable in larger channels. Although such machines simplify and accelerate work, lateral jams can also be constructed by a crew of forest workers, using portable winches to move materials from the slopes or floodplain, and a helicopter to sling in boulders if they are unavailable at the work site (as described in Chapter 10). Also, the U.S. Forest Service has used skyline carriages successfully to transport logs, rootwads and boulders, both locally near the stream as well as from roads into streams. In gently sloping terrain, a narrow-gauge tote road can be constructed for access, provided it is environmentally sound, erosion proofed and pre-approved by regulatory agencies responsible for the FPC in riparian areas. Conversion to a trail for demonstration tours is an advantage of this approach.

Figure 9-13. Spider excavator installing a right-angled LWD-boulder lateral jam at a minor bend of the Keogh River to restore large woody structure for scour pool formation. Most of the boulders, logs and rootwads were transported by helicopter to this reach where there was no adjacent road access.

Variations on these designs can also be used at remote sites to armour eroding stream banks, but where the main focus is on restoring fish habitat, e.g., by increasing depth of pool scour lateral to tailouts, using a combination of large wood and large boulders (Fig. 9-14A, B). As another example, large log-rootwads weighted down with large (1 m diam.) boulders were utilized to armour an eroding bank of the Green River (Washington), thus stabilizing a highly eroding bend (Fig. 9-15). On the upper bank, more conventional geotextile was used, staked with deciduous cuttings, recontoured and trees planted, as described in Chapter 6. In northwest Washington, multiple large log structures secured to large boulders were used effectively by the U.S. Forest Service in a medium-sized stream, Deer Creek, to divert the stream away from highly eroding banks and also provide habitat. There, past logging had destabilized the slopes, and coupled with hillslope-gully stabilization, large populations of summer-run steelhead and coho salmon have recovered from near extinction over the past decade (Doyle et al. in press). Such designs should be approached on a site-specific pilot basis and, in more complex and unpredictable settings, scaled flume studies would be useful to define structural requirements to resist hydraulic forces generated by extreme (20 to 50-year) flood events.

Figure 9-14A. Before: a shallow pool of the upper Keogh River, lacking fish habitat features including pool depth and LWD.

Figure 9-14B. After: a deepened pool that was backwatered to increase its depth by increasing the height of the downstream riffle (see Chapter 12); a LWD-boulder complex was anchored into the tail of the pool, also armouring the eroding stream bank.

STREAMSIDE LARGE WOODY DEBRIS CATCHERS

Alternatives to restoring lateral log jams in medium to larger streams, are streamside or lateral debris catchers, for which templates or analogues are also common in nature, and typically comprising a small portion of the wetted channel in summer. Common LWD catchments in streams include (a) large boulders on the outside of bends near the thalweg and where the banks are armoured with rock or large wood; (b) catchments of a few large trees from windfalls or erosion, anchored to the banks by a rootwad mass; and (c) catchments at point bars to secondary or tertiary channels or side-channels, often spanning such accessory channels, thereby creating stable flows. These debris catchments can be duplicated with little transport and handling of materials because floating LWD is collected to create small streamside jams, although as stream power increases it is more difficult and has a greater risk of structural failure. Three types of streamside designs have been used: (1) boulder-debris catchers, (2) pile-debris catchers, and (3) floating V-logs. Each has design features that are the key to their structural integrity and effectiveness in trapping debris. Similar to lateral log jams, only lower gradient habitat units, including low gradient riffles, glides and shallow pools, should be considered because of stream power and excessive scour that can dislodge structural components. Similarly, on larger streams, a low profile is advisable to ensure that at the most extreme flows, a large hydraulic head is not generated and excess debris is bypassed. Although log jams are natural hazards in any navigable stream, man-induced structures must be located near shore so that there is ample space for navigation of boats and canoes at summer flow.

Figure 9-15. Use of large boulders and full length rootwad complexes to stabilize an eroding bend of the Green River, Washington; the upper bank was treated with geotextile, cuttings and staking, revegetation and riparian tree planting (Hamakami Biostabilization Project; photo by Johnson and Stypula).

Of note, studies of chinook salmon in the Nechako River demonstrated that large debris catchments (100 m^2) were not as effective as small ones (15-25 m^2). Salmonid densities decreased with the size of the matrix because large catchments were typically dominated by slack waters, which were highly colonized by non-target cyprinid species, including squawfish (Slaney et al. 1994a). An optimum size for maximizing colonization by juvenile and adult salmonids and minimizing non-target species, was about 25 m^2, provided velocity distributions were in the preferred range of salmonids.

Boulder Debris Catchers

Boulder debris catchers are common in nature in medium-sized streams, at the outside of bends where there are a few meters of space between a large boulder or bedrock block and an armoured stream bank. These can be constructed by securing two large logs from large rock(s) to boulders or bedrock on shore, using the fastening techniques (epoxy resin) described above (Fig. 9-11). To ensure trapping of wood in freshets, two logs can be placed at a 60° angle sloping up from the stream bottom in front, and cabled to the cross logs. Provided the bank is well armoured, debris will collect in the gap. An ideal template exists at the West Kettle River, a southern interior rainbow trout stream (Figs. 9-16 and 9-17). A similar concept is depicted in Fig. 9-18, which is intended to duplicate natural large wood structures that were observed to form debris catchers near the banks of the Quinsam River, a lake-headed stream on Vancouver Island.

Figure 9-16. A natural template for a boulder-LWD catcher at the West Kettle River in the southern interior of B.C. A large 1.5 m boulder and boulder-lined bank provided a natural catchment for both LWD and small wood, creating prime habitat for adult rainbow trout and mountain whitefish as well as refugia for redside shiners (*Richardsonius balteatus*). Most of the resident trout in this reach inhabited this boulder-woody debris complex.

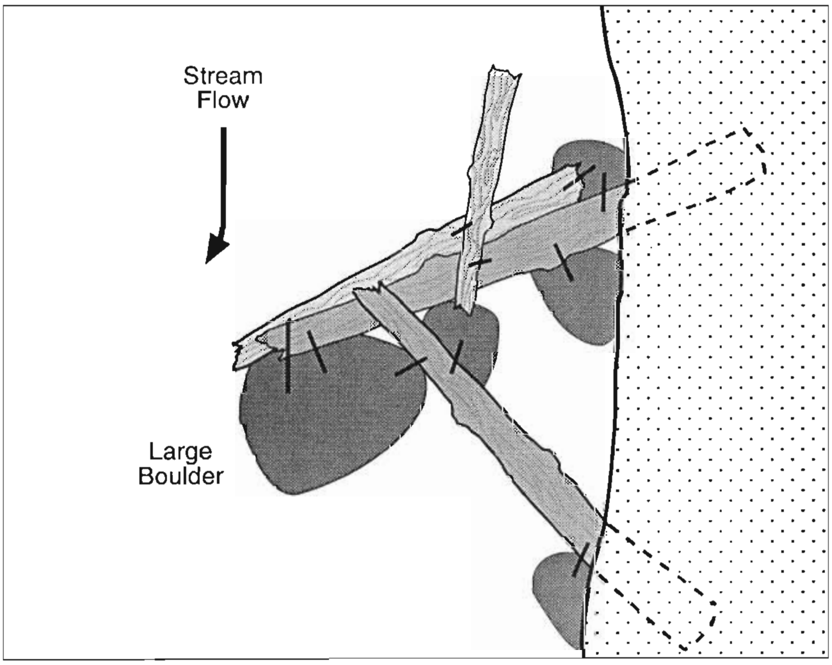

Figure 9-17. A conceptual drawing of a boulder-LWD catcher, similar to a natural analogue in the West Kettle River, including key logs for trapping drifting woody debris in floods. The front log facing upstream is set at about 45° from the stream bottom up to the cross logs to catch drifting wood.

In the upper Keogh River, a large boulder (3 m from the bank in a 12 m channel) was linked with logs to bedrock on shore (Fig. 9-19). An excavator may be used to place materials and pre-load woody debris. In addition, coarse bed material can be excavated to accelerate scour and used to armour nearby banks. Where large boulders (1 m^3) are unavailable at the site, they need to be transported, placed, and connected together as required. Forces and ballast sizes can be estimated, as in the foregoing section on lateral jams, but ideally these structures should be approached "opportunistically", where a natural site requires only securing of wood.

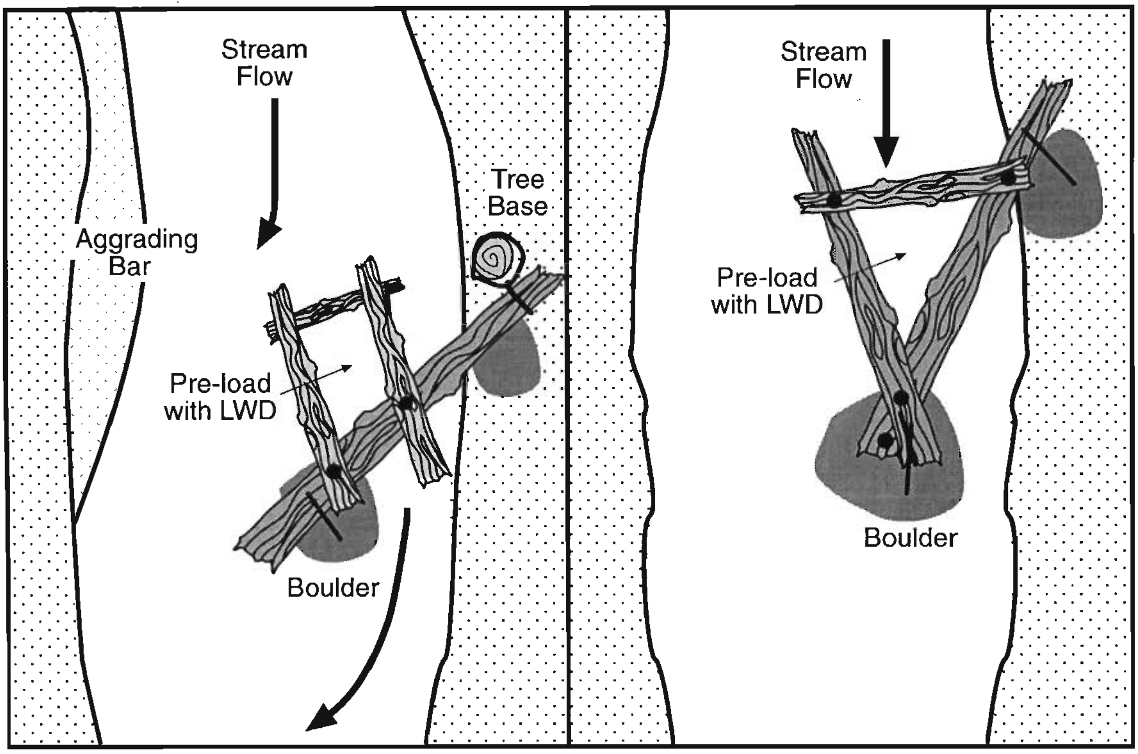

Figure 9-18. Examples of conceptual drawings of boulder-woody debris catchers, based on templates in lower gradient sections of the Quinsam River. Debris-trapping logs are a ramp spanning from the boulder attachments to the stream bottom.

Streamside Pile-debris Catchers

Stream debris catchers can be constructed using steel piles (used rails) driven into a gravel to cobble stream bottom. Piles are driven with a vibrating pile driver that attaches to most excavators. By welding a suitable collar to the driving surface, a pin and collar can be fastened to the pile for lifting and for driving into the substrate. The targeted depth of penetration into the substrate is dependent on the amount of scour predicted from templates elsewhere in the streams; 3-4 m provides a margin of safety. Three piles are driven in a V configuration 3 m apart, with two 3-m logs attached by loose rings of heavy-gauge rust resistant chains. If rails or pipe are used, they should be encased with "logs-slabs" with carved tops to improve aesthetics. Also, their extension above the low summer water surface (< 1 m) should be the same height at which debris is transported, but less than extreme flood heights; the hydraulic forces against the debris retains the woody matrix in place even though it is overtopped.

Figure 9-19. A debris catcher installed in the Keogh River in 1996 to create complex lateral pool habitat.

An attempt has also been made to design LWD catchers leaving only the logs exposed, by driving the piles level with the substrate, and attaching 10 m lengths of boom chain from the top of the piles to a floating V-log configuration (logs 3 m in length, 30-40 cm in diameter and chained at the V). However, these devices "porpoise" at moderate to high flows, which spills small debris and can wear the chain connections as well as the logs that contact the streambed. A chain basket in the V is required to snare debris, but the success is subject to random placement of a key log to stabilize the porpoising movement (Fig. 9-20A). Thus, pre-loading to establish a key log, is more effective by use of a backhoe, loader or excavator, where a large log can be connected from the V into tree bases or boulders on shore. If the banks are not comprised of coarse cobble to boulders, either bank-aligned logs or riprap could be used as a revetment to prevent scour of fine materials, and provide additional habitat. If the channel is wide with a low floodplain, this may be unnecessary because the trapped debris can form the revetment (Fig. 9-20B).

Figure 9-20A. Loading a floating pile debris catcher with a rootwad and large key log connected from the V of the catcher to the base of a tree on shore.

Figure 9-20B. A lateral log debris jam created in 1994 by a floating V-log debris catcher in the West Kettle River. The resulting 2 m deep and complex pool was inhabited in 1996 by 15-20 rainbow trout and about 40-50 mountain whitefish.

Single or double piles (as above or as a deadman), extending slightly above the stream substrate, can also be driven as anchors similar to the large boulders described in the section on boulder-debris catchers. In some locations these may be more efficient than attempting to locate, transport and handle very large boulders for anchors. Boom chain attachments to the cross logs are utilized to ensure durability. If there are no tree bases to attach to above the bank, epoxy resin is used to attach to boulders or bedrock.

Woody Debris-boulder Reefs

In the marine environment, many coastal nations are extensively involved in construction and placement of marine reefs, which are rapidly colonized by a rich plethora of biota including diverse fish populations. This concept has application to freshwater, and various reefs have been used for several years for enhancing habitat of warm-water fish species in ponds and lakes. In streams, there has been little use of reefs as a potential technique to augment salmonid rearing capacity, as well as providing escape refuges. The technique has application for fish habitat rehabilitation because the large old-growth trees, with massive 3 m rootwads that originally lined the stream, cannot readily be obtained for restoration purposes. Reefs are an attractive innovation because they can be used to simulate the benefits provided by large old-growth trees by using highly preferred habitat elements, boulders and LWD, for their construction (Fig. 9-21). Finally, experienced forest workers are usually skilled and well suited to construct and place reefs in shallow residual pools that lack habitat structure, and where energy from adjoining riffles will keep them from infilling with fine sediments. Reefs and similar structures, as outlined in the previous sections, are more applicable to medium-sized streams that are relatively stable as a result of either recovered hillslopes, or because they are lake or reservoir-headed. The low profile of a stream reef is well suited for durability through freshets, although sediment deposition may be a constraint in sites with limited hydraulic energy. A log-crib design, incorporating a complex matrix of cross-pole lattices to exclude predators of young salmonids, was pilot tested in Shovelnose Creek (Fig. 9-22). The design was observed to be highly utilized by juvenile chinook salmon and steelhead, and as a refuge by spawning chinook (Fig. 9-22). In large northern streams, Arctic grayling have been observed to avoid dense log jams, which are highly used by rainbow trout, bull trout, and mountain whitefish. However, grayling have an affinity for natural instream configurations of LWD analogous to a streamside reef. Further testing of reefs is required to develop mechanisms for installation at remote sites, optimize the hydraulic setting to minimize bedload deposition, and to confirm fish utilization by different species and age classes.

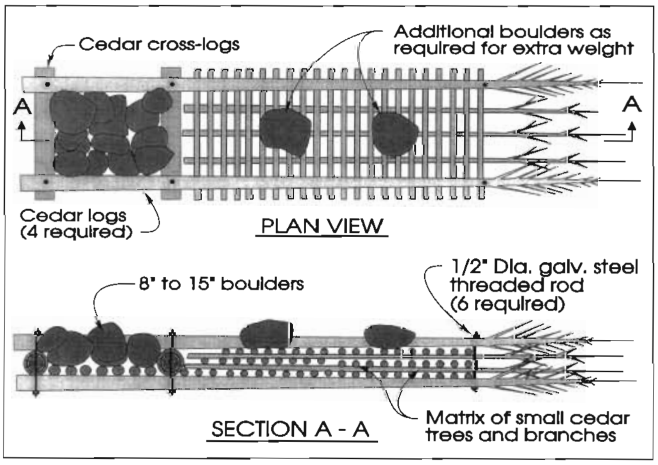

Figure 9-21. A conceptual drawing of a log-boulder reef (cables are also used to prevent the large logs from spreading). The reef is located in a residual shallow pool at the downstream end of a riffle to ensure flushing of sediments. Boulders and cobble are used to sink the structure and hold it in place.

Figure 9-22. A low profile reef installed in a coastal stream is inspected for fish utilization and depth of scour. Cables were wrapped around the main logs at the two points where notched cross logs were attached. A matrix of small poles and branches was used to support the cobbles and boulders required to sink and secure the reef.

PROJECT MONITORING AND EVALUATIONS

A historical criticism of habitat improvement projects is that the same fish are being moved from marginal habitats into preferred habitats, with little increase in net production. This same scepticism was levelled at marine reefs, but was rejected eventually as a "red herring" as evidence of fish production became overwhelming. Similarly in streams, use of controlled evaluations involving whole-stream smolt trapping (anadromous fish) and whole-reach population estimates (resident fish) are gradually eliminating uncertainties. Of more risk are those streams with alternative prime habitat elements, such as abundant large boulders in steep gradients that are inappropriately treated with large wood, boulder ramps and drop structures, a problem evident in some earlier habitat improvement projects. In such instances, benefits can be expected to be marginal. Accurate assessments of habitat limitations are required in advance of selecting appropriate designs and construction techniques. Underwater counts of fish, separated by size classes (Slaney and Martin 1987), before and after restoration of a reach and compared to an untreated control reach, is a minimum level for project effectiveness monitoring. In addition, more intensive evaluations by means of either extended before-and-after controlled experiments (as at Porter Cr; Cederholm et al., Chapter 8), or replicated streams design are needed at research sites to confirm benefits.

Appendix 9-1: Example Calculations Of Ballast Requirements For Lateral Log Jams.

Single-Log Lateral Log Jam

Determine the size and number of boulders required to ballast a log with a diameter of 0.5 m and a length of 10 m. The log is to project 6 m into a flow; thus, the effective length is 6 m.

Conduct a field survey to determine the height of the floodplain, H = 1.5 m; and the channel slope S = 0.01 m·m^{-1} (1%). Using these values, calculate the estimated velocity from the Chezy equation:

$$V = 20\sqrt{1.5 * 0.01}$$
$$= 2.45$$

or 2.5 m·s^{-1}.

Fig. 9-12A shows the ballast requirements per meter length are approximately 180 kg·m^{-1}. This value was obtained by interpolating between the design curves for V = 2 m·s^{-1} and V = 3 m·s^{-1}. A total ballast requirement of 6m · 180 kg·m^{-1} = 1,080 kg is therefore required to anchor the log. This requirement could be met with two boulders of 540 kg each. Fig. 9-12C can be used to estimate the size of the two boulders. Each would require an average diameter of about 0.75 m. Alternatively, the ballast requirement could also be met using a single boulder with a diameter of about 0.95 m, or using three boulders, each with a diameter of about 0.65 m.

Triangular Lateral Log Jam

A triangular lateral log-jam is to be constructed using two logs each with a diameter and length of 0.5 m and 10 m, respectively. The log jam is to project 6 m into a flow. Additional complexing is to be provided by attaching a rootwad, and a third log with a diameter and length of 0.6 m and 5 m, respectively. It has been estimated that the rootwad has a mass equivalent to a log with a diameter of 0.8 m, and a length of 3.0 m. Determine the ballast requirements.

Fig. 9-12B can be used to determine the ballast requirements. They are tabulated below for each element of the log jam.

Appendix Table 9-1. Ballast requirements for triangular lateral log jam.

Element	Diameter (m)	Effective Length (m)	Ballast/meter (kg·m^{-1})	Total Ballast (kg)
Log 1	0.5	6	80	480
Log 2	0.5	6	80	480
Rootwad	0.8	3	210	630
Log 3	0.6	5	120	600
Total				**2,190 kg**

The basic triangular structure would be constructed using Logs 1 and 2, and should be ballasted with one or more boulders with a total mass of not less than 960 kg. Each additional LWD or rootwad should be ballasted individually, and attached to the basic triangular structure. The total ballast requirement for the triangular lateral log jam is about 2,200 kg.

Chapter 10

Using Boulder Clusters to Rehabilitate Juvenile Salmonid Habitat

Bruce R. Ward[1]

INTRODUCTION

Boulders, substrate materials greater than 0.3 m diameter in streams, can provide suitable habitat conditions for salmonids. The casual observer of streams becomes quickly aware that areas with boulders are not only pleasant in sight and sound, but that they are also structurally complex. They typically contribute variety in stream substrate conditions, water depth and velocity, and, for fish using the stream, cover and rest areas. These beneficial conditions are diminished where interstitial spaces are filled in by a continuous delivery of fine sediments. Upslope rehabilitation techniques can reduce sediment delivery rates; carefully chosen stream sites can be rehabilitated with boulder clusters to further accelerate the overall watershed recovery process. This chapter provides guidelines for the placement of boulder clusters to rehabilitate fish habitat in streams.

Channel morphology, food abundance and salmonid reproductive biology are key variables that, together with fish behaviour (foraging and social interaction) and predation, determine the distribution of fish, their growth, survival, abundance, size composition, and adult recruitment. These features together determine the shape of the relation of the number of fish that reproduce in a stream system, or spawners, and the number of reproductively mature adults that contribute to the succeeding generation, or recruits. For salmonids that spend some part of their developmental history residing in stream environments, the abundance of available summer and winter habitat can be a limiting factor to their recruitment to the adult stage. Thus, in theory, factors that increase the availability of preferred habitat characteristics will increase the capability of the system to produce fish recruits, where such factors are limiting either productivity or stream carrying capacity, or both (Fig. 10-1, and see Ward and Slaney 1993a, b).

Density dependence in stream-resident fish is closely linked to the amount of preferred or usable habitat. For steelhead, the "bottleneck" to production occurs mainly between the fry and parr life stages, in relation to density and habitat availability (Bjornn 1978; Ward and Slaney 1993a). Similar conclusions have been derived from the study of Atlantic salmon, *Salmo salar* (e.g., Chadwick 1985), and the critical early stages of the life history of brown trout (Elliott 1989). Thus, techniques that improve the quantity and quality of rearing habitat at this life stage should result in increased returns of adults. Applied techniques that improve conditions favouring high survival and abundance through critical stages, thus increasing the carrying capacity, should benefit the resource, particularly under conditions of exploitation or stress from human or environmental factors (Saunders and Smith 1962; Hunt 1969; House and Boehme 1985).

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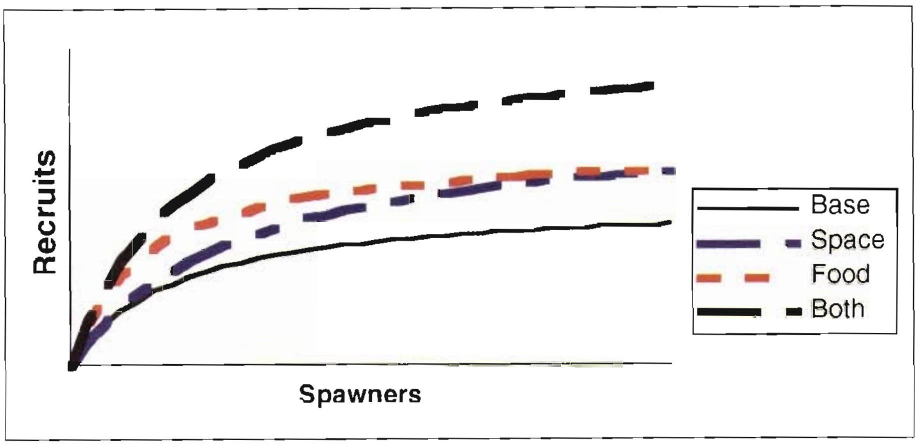

Figure 10-1. Those salmonids which are limited at some period of their life history by freshwater habitat availability (e.g., during juvenile stages in streams) may display asymptotic, or Beverton-Holt, recruitment relationships (base case). An increase (or decrease) in the availability of either food, space, or both, may change the carrying capacity of the environment, resulting in a positive or negative change in recruitment.

In a typical coastal stream profile (Fig. 10-2), three main channel morphologies have been defined by Hogan et al. (1997): step-pools, cascade pools, and riffle-pools, as described in Chapter 2. In undisturbed higher gradient sections in particular, large boulders are dominant features of these channel types (Fig. 10-2). A score of less than 10% boulder cover in riffles in the fish habitat assessment procedures diagnostics signifies a poor quality habitat condition for riffle-dwelling salmonids (Johnston and Slaney 1996). Channel morphology and boulder abundance are thus directly connected to salmonid carrying capacity, i.e., the capability of a watershed to produce salmonids is a function of the stream habitat, in which large boulders play a key functional role.

EVIDENCE FOR SALMONID USE OF BOULDER HABITAT

While attempts to relate salmonid abundance and yield to habitat capability have been many, few have been successful, as the reviews in Fausch et al. (1988) indicate. Nevertheless, for salmonids that rear for some time in freshwater (e.g., coho salmon and steelhead trout), abundance in the stream has been related to the number of large boulders present (Facchin and Slaney 1977) or added (Ward and Slaney 1993b, 1981, 1979). Bjornn and Reiser (1991) provide a review of habitat requirements of salmonids in freshwater, and emphasize that cover, although difficult to measure, may seriously limit fish yield in streams. A smolt yield model developed by Slaney (in Lirette et al. 1987) was based on a multiple regression approach to the analysis of steelhead densities and the physical characteristics of the habitats in which they were found, stratified by type (e.g., riffle, pool, run, etc.), in the Keogh River, B.C. The model uses boulder composition in riffle habitats as a dependent variable in estimating the abundance of steelhead parr (fish aged 1+ and older; Fig. 10-3):

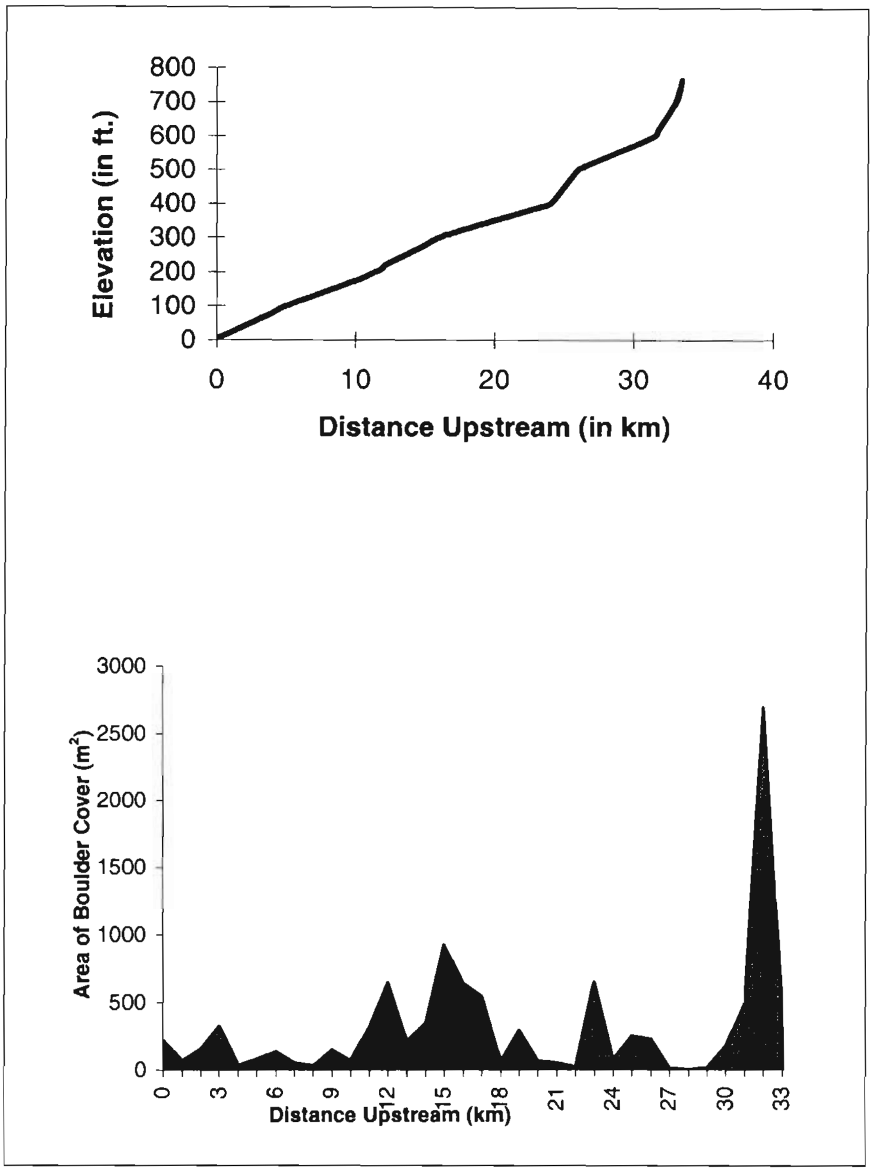

Figure 10-2. A stream profile of the Keogh River, a typical British Columbia coastal stream, and the distribution of areas of boulder habitat.

$$P_{ri} = \{2.9b + 3.1c - 4\} \cdot 10^{-3}$$

where

P_{ri} = abundance of steelhead parr in Keogh River riffles,

b = wetted area (%) of riffles comprised of protruding boulders > 30 cm diam., and

c = wetted area (%) of riffles comprised of overstream cover (i.e., debris, cutbank and/or vegetation within 1 m of the water surface).

Overstream cover adds slightly to this relation (boulders, r^2=0.67; boulders and overstream cover, r^2=0.82; Keeley and Slaney 1996). It is likely that similar relations with boulder habitat exist for other salmonids residing in streams (e.g., rainbow trout, cutthroat trout, Dolly Varden, bull trout, Arctic grayling). Schuler et al. (1994) provided evidence suggesting that brown trout in Colorado selected feeding sites primarily based on water velocity and cover, and that boulder structures provided more locations that were energetically favourable. Trout used the boulder structures (U shaped clusters and loose wings from shore) preferentially day and night.

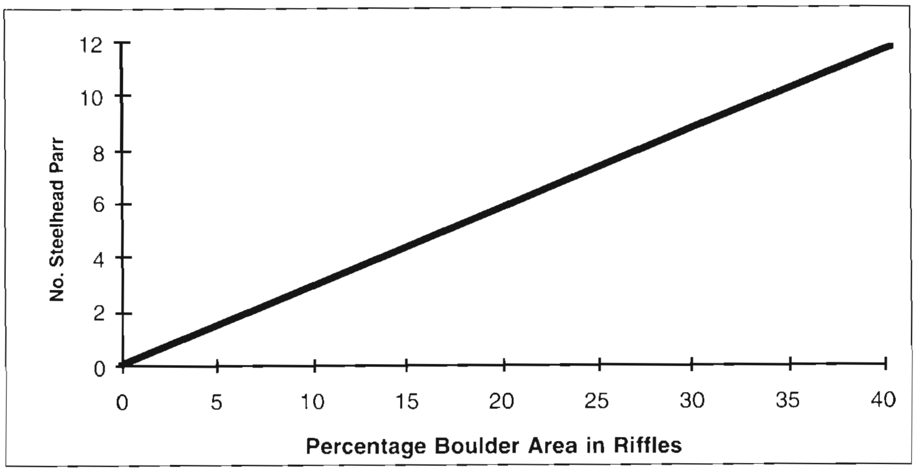

Figure 10-3. The number of steelhead parr in riffle habitat (100 m^2)of the Keogh River was a function of the amount (%) of riffle area with boulders > 30 cm, here expressed as though overstream cover was zero.

INFLUENCES OF PAST FOREST PRACTICES ON BOULDER HABITATS

Past forest practices of logging to stream banks in B.C. has reduced large woody debris (LWD) from the streamside riparian area and within stream channels (Fig. 10-4A, B). Boulder additions can serve as a surrogate for the complexity of stream habitat where LWD recruitment is unlikely for several more decades. Similarly, Bjornn et al. (1977) found significant reductions in the numbers of juvenile steelhead in stream channels where boulders were embedded in sediment. Aggraded channels and increased sediment delivery as a result of poor road construction and maintenance in the past have been shown to impact salmonid production (Slaney et al. 1977a, b). Where reductions in depth and velocity occur, the usable area for juvenile salmonids, in theory, is reduced (Hogan and Church 1989).

HABITAT REHABILITATION WITH BOULDERS: A REVIEW

Ward and Slaney (1993b) reviewed the history of stream habitat rehabilitation in B.C. and concluded that such techniques cannot proceed successfully without consideration of watershed processes affected by land use and an overall ecosystem approach. In other words, generic "cookbook" approaches must be avoided. An adaptive, experimental procedure with pilot testing and evaluation based on empirical evidence and site-specific application is required. Furthermore, future practitioners should familiarize themselves with the habitat characteristics and placement procedures at historical stream rehabilitation sites through inspections, mentorship and participation in WRP fish habitat assessment, prescription and rehabilitation courses offered at demonstration sites (e.g., Squamish and Keogh Rivers).

Efforts towards fish habitat restoration have been numerous on the west coast in recent years (Frissell and Nawa 1992). Earlier habitat rehabilitation experiments were attempted in the central and western U.S. Many of the recent projects in coastal streams (e.g., House and Boehme 1985) were similar to earlier research in B.C. (Ward and Slaney 1979; 1981) where boulder clusters were found to be both durable in moderate-sized streams and preferred by steelhead parr and coho fry.

Figure 10-4. A) Many coastal watersheds had been logged in the riparian area under forest practices of the past, affecting recruitment of large woody debris to the stream. Often, stream sections may become wider and shallower, with a reduction in the available rearing spaces for juvenile salmonids. B) In appropriate locations, where local gradient is suitable (e.g., tail end of riffle habitat) and bedload aggradation is expected to be low, such as this section of the Keogh River, B.C., in the upper reaches of the watershed downstream of Keogh Lake, large boulders may provide heterogeneous habitat with characteristics conducive to the survival and abundance of steelhead parr and coho fry.

Initial results in B.C. evaluations demonstrated that some designs of boulder structures may prove inadequate in coastal conditions where extreme winter freshets and significant bedload movement are prevalent (Ward and Slaney 1981), and longer-term assessment is required of those more cost-effective designs, especially boulder clusters. Some of the recent attempts at creation of artificial habitat in Washington and Oregon streams have not been durable (Frissell and Nawa 1992). This result was related to both structural design, particularly for the wooden devices, and stream flow dynamics. Boulder clusters were one of the more effective techniques. Successful stream restructuring in Oregon was reported by Armantrout (1991), with boulder structures proving most durable. Few researchers have returned to the sites of habitat creation to examine the durability and fish use of habitat improvement structures several years after installation, although the economic evaluation of this rehabilitation tool often involves the assumption that benefits associated with the structures, as measured one or two years after installation, are maintained for 10 to 20 years, as assumed by Ward and Slaney (1979).

Reeves and Roelofs (1982) summarized a number of applications in the U.S. Pacific Northwest and Alaska where large boulders had been placed to rehabilitate and improve stream habitat. Their summary included boulder additions in the John Day River, Beech Creek (Oregon), and Redcap Creek (California), which achieved the desired effect of increasing abundance of juvenile salmonids, and particularly steelhead parr. More recently, Espinosa and Lee (1991) reported high use by juvenile salmonids in boulder structures, rootwads, and log weir pools placed in Lolo Creek, Idaho (average spring freshet, 14 $m^3 \cdot sec^{-1}$). Steelhead parr were present in boulder sites in densities very similar to that found at the Keogh River, or about 10 parr $\cdot$ 100 m^{-2}; structures in Idaho also included chinook underyearlings at very high density (65.3 fish $\cdot$ 100 m^{-2} of treated habitat). Manuals of fish habitat improvement in the U.S. suggest that the technique of adding boulder clusters has become standard practice (e.g., Seehorn 1985; Flosi and Reynolds 1991). In Montana streams, total numbers of brook trout and cutthroat trout were found to be least in partially altered stream sections, intermediate in sections with rock jetties, and greatest where random boulders were placed.

Boulder clusters in the upper Keogh River were also installed using helicopters (Tsumura and Ward 1987; maximum flows were about 60 $m^3 \cdot sec^{-1}$), and proved highly durable. Boulders remained within the area of placement; after the initial year, no boulder movement in clusters was detected, and after 15 years most had not moved. Of the few boulders that shifted, they rolled once, or less than a distance of 2 m. However, material used in structures tested earlier (deflectors and rock weirs) was displaced if under 0.4 m diameter. Over time, the large material culled from "riprap" rock pits, which was used to build boulder clusters became more natural in appearance, as edges were rounded slightly by erosion and as moss accumulated. Some clusters were nearly dry during the summer low-flow period in drought years as the river channel or thalweg shifted, but this was minor, and could be corrected by more careful placement of clusters near the thalweg within riffle sections. Scour around the boulder clusters changed little 3 years after placement, where small pools or "pockets" were associated with each group of 3 to 5 boulders. These pockets were less common around clusters placed in the middle reach of the Keogh River where maximum flow approximated 100 $m^3 \cdot sec^{-1}$ but the substrate was comprised of larger cobble (>15 cm) material. Nevertheless, boulder clusters remained stable.

In the Salmon River, Vancouver Island, where boulders were placed in 1980 as a pilot test under severe conditions, flows and bedload movement were much higher (maximum flow in the treated area reached 800 $m^3 \cdot sec^{-1}$) than in the Keogh River, which strongly influenced durability of structures. In earlier reports Ward and Slaney (1981, 1993b) documented that 13% of boulders placed by helicopter remained functional, and larger boulders placed by machine were more durable, although 30% of those were ineffective (visible but surrounded by bedload) one year post-placement. After 10 years and a 1 in 50-year flood event, virtually all structures at this site were no longer in the main channel due to channel shifts. However, most clusters remained functional in one lower section where the river was associated with a wide adjacent floodplain and stream banks < 1 m in height. Clusters placed in smaller tributary streams (e.g., Springer Creek; Griffith 1982) continued to function in 1993, in contrast to the larger, more unstable mainstem. Griffith recommended use of rock > 0.6 m diam., with smaller material (<0.3 m) placed as a base, with clusters spanning the channel, as well as placement of boulder clusters in some deeper habitats, such as faster glides, where benefits in coho production and larger steelhead parr would be realized.

Utilization of boulder clusters by salmonids in the Keogh River was summarized in Ward and Slaney (1981, 1993b). On average, steelhead parr abundance in the upper and middle reach of the river was one parr per meter of stream (0.1 $parr \cdot m^{-2}$, 7.4 g·m or 0.9 $g \cdot m^{-2}$), or about **one steelhead parr per boulder** added. Coho fry density and biomass in the upper river were 2.2 fry per m (0.3 $fry \cdot m^{-2}$) and 0.3 $g \cdot m^{-2}$ or about **3 coho fry per boulder** in a cluster. While there was a 4-fold increase in the number of steelhead parr in the boulder-treated sites of the middle reach, coho numbers were not significantly different from pre-treatment levels in the middle reach probably because of a lack of scour in the cobble substrate. In the upper reach, where scour was common, coho numbers also increased about 4-fold in boulder clusters one year post-placement, and 3-fold two years post-placement (mean change in no. $\cdot m^{-1}$: +2.2 in 1978, +1.4 in 1979) compared to pre-placement levels at the treated sites and no change in untreated control sites. These values apply to nutrient-poor conditions; during years of nutrient addition experiments (Slaney and Ward 1993b), the highest juvenile salmonid densities observed at the Keogh River were in boulder clusters (e.g., fertilized sites in the upper reach in 1984 were 3 times higher in steelhead parr density than untreated controls, P.A. Slaney, data on file).

After 12 years, utilization of the boulder clusters by steelhead parr in the upper Keogh River had remained high. The positive relation between boulders at each site and parr use reported earlier (Ward and Slaney 1979) was reassessed and there was increased variability about the linear relation, but nevertheless still statistically significant results (Ward and Slaney 1993b). As the sites aged and evolved, one might expect more variable results; certain sites were preferred in some years but not others, depending on flow conditions, associated LWD accumulations or losses, or shifts in thalweg position.

While there is little empirical evidence that adding large boulders to streams increases the steelhead or coho smolt yield, Ward and Slaney (1993b) estimated about 3 steelhead smolts per site, or per cluster of 5 to 7 boulders, based on increases in steelhead parr utilization, and instream survivals (Ward and Slaney 1993a). Post-placement investigations at the Keogh River since 1977 included repeat sampling in the stream section rehabilitated with boulders, and further confirmed continuous steelhead and coho utilization of boulder clusters for over a decade. Maintenance costs have been zero, and monitoring costs low for up to 20 years. This site has been more extensively treated with LWD and further boulder placements in 1996 to 1997, including readjustments and improvements at several old sites, and pool-riffle reconstructions (Chapter 12) as part of the ongoing Keogh River watershed restoration project.

GUIDELINES TO PLACEMENT OF BOULDER CLUSTERS

Boulder clusters in groups of 5 to 7 boulders are durable and well-inhabited by fish when placed at the bottom half of riffle habitats (Fig. 10-5). At the higher velocity location in riffle habitats, which typically lack instream cover, large riprap boulders are more stable and less likely to fill in with bedload, and although some degradation (scoured 'pockets') behind the structure is preferred, large scour holes are less likely to evolve. The nature of aggradation and degradation around stream boulders in the lower sections of riffles is related to the hydraulic action of the site during bankfull discharge (Fig. 10-6). During peak flow events, the boulder cluster acts to stabilize the riffle crest and transfer the scouring forces to the pool downstream. The microhabitat effects around the individual boulders, where fines and gravels may be somewhat displaced, provides for excellent cover and foraging characteristics for juvenile fish during low flows. Boulder clusters placed at or near the riffle crest will cause aggradation and diversion. For the same reasons, unstable aggrading channels or braided channels must be avoided.

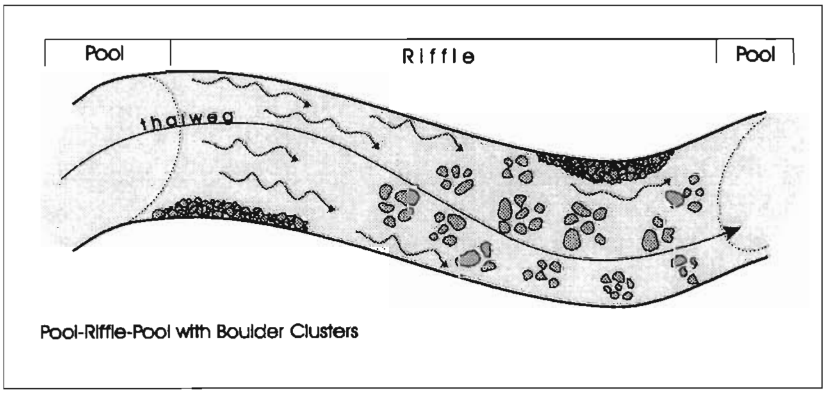

Figure 10-5. Overhead view of a stream riffle with boulder clusters installed.

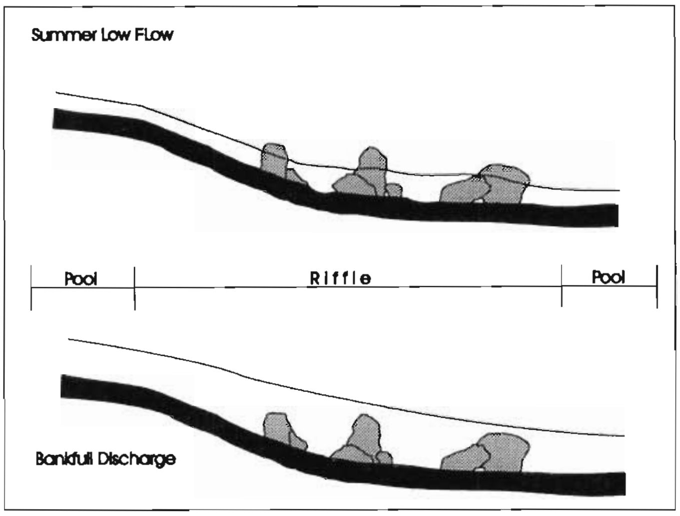

Figure 10-6. A cross-sectional view of riffle habitat in streams with boulder clusters added, during summer low flow and during bankfull discharge, to indicate the hydraulic forces which shape the rehabilitated area.

In Chapter 12, Newbury et al. (1997) discuss boulders at the riffle crest that function to maintain the riffle structure. Note that this is a different role for boulders than what is suggested here. Newbury et al. (1997) utilize boulders as construction material in combination with smaller material in a specified design to build stable riffle and pool habitat where a riffle:pool sequence has been disrupted or is lacking. They also suggest that large boulders should be placed on the downstream face of the riffle to build the riffle base and discourage excessive erosion in that area. Their approximation for boulder stability during bankfull discharge, with a safety factor, is based on tractive force (*T*). Since $T \approx$ incipient diameter (cm) (Newbury and Gaboury 1994), riprap boulders with minimum diameters of approximately 1 m or larger are preferred for clusters. For example, where the bank height is 2 m and the gradient 2%, minimum boulder size would be: $1500 \cdot 0.02 \cdot 2 = 60$ cm. Boulders of this size (0.6 to 1 m diam.) taken from rock pits in the Keogh River watershed weighed ~ 800 kg, based on estimates obtained by helicopter lift capacity during placement (Ward and Slaney 1981). Boulder size in the stream area can also provide an indication of the size of material that is unlikely to move.

Spacing within boulder clusters should be 0.5 to 1 m, increasing with stream size, and clusters staggered with about a 3 m separation, as an operational guide (Fig. 10-5). This configuration generates foraging and resting areas for fish and is hydraulically stable where bedload movement is minimal (i.e., channel change as a result of debris slides is unlikely). This spacing also provides for passage of floating LWD at peak flows, although some trapping of material around boulders is common and beneficial. The low profile of boulder clusters that are spaced carefully limits the potential for the development of unplanned or unwanted debris jams at that location. After nearly two decades of observing boulder clusters in the Keogh River, no debris jams were generated within the treated sites, but occasionally, LWD was caught, with no negative impact that could be detected in terms of durability of the structure. Note that clusters are inhabited by greater numbers of fish per boulder than single boulders distributed in a riffle (Schuler et al. 1994).

Boulder clusters should span the channel and be placed in an arrangement that guides the flow in its natural bend. Riffles are points of cross-over in streams, so the flow will be directed towards one side or the other. The structure should compliment the natural stream curvature, so that a cluster of 5 to 7 boulders directs flow into the next downstream cluster, and boulders within clusters work together to direct flow and provide fish cover (Fig. 10-6).

Stream invertebrates, the key food source for juvenile salmonids, reside in high densities in stream riffles. The insect drift from the riffle provides the major food item for these fish. Salmonids maximize their net energy gain by residing in low-velocity refuges with higher velocity flow nearby and food supply (Fausch 1984). Such conditions, particularly preferred by juvenile steelhead (Fausch 1993), are generated by the placement of boulder clusters in the middle to lower section of riffles.

The addition of boulder clusters can be attained in several other applications where humans work around streams. Lister et al. (1995) provided a summary of fish utilization of large riprap placed at the stream edge for bank stabilization in highway and railroad construction. Boulders are often a component of bridge abutments, and offer another opportunity to create fish habitat. Large boulders have also been used as anchorage for LWD (Fig. 10-7 and Chapter 9). It may often be advantageous to add additional boulders leading into the LWD complex during the installation phase, further improving the availability of habitat for salmonids as well as perhaps assisting the maintenance of the pool and riffle site.

Figure 10-7. At sites where large woody debris (LWD) had historically been present on the Keogh River, bank-side debris jams were constructed by importing LWD and boulders; key logs were anchored with large (>0.8 m diam.) boulders using wire rope cables and epoxy, and the whole structure was interconnected and secured to riparian trees. These structures have been stable following winter freshets, often capturing additional LWD. They have created highly usable habitat for juvenile salmonids during summer and winter, as well as cover for spawning adults.

Habitat in B.C. streams can be amended, where it has been impacted from forest practices of the past, provided the stream reach has not been destabilized. The addition of boulder clusters using large riprap from rock pits or old roads can generate habitat complexity that has the desired components of depth, velocity and cover crucial to the variety of habitat requirements of salmonids in their various life stages in fresh water. Done carefully, the work can benefit fish in streams for many years.

Boulder clusters can add lost complexity in streams impacted by past forest practices. Although it may not be feasible to restore LWD to historical levels due to a possible short supply, large boulders offer a rehabilitation alternative in stable channel sections where accumulations of fines and bedload movement are both low. As a tool for B.C.'s Watershed Restoration Program, boulder clusters can work in well-planned situations, where the practitioners step up the application based on initial field trials and knowledge gained from other experience, such as that at the Keogh River.

Chapter 11

Rehabilitating Mainstem Holding and Rearing Habitat

Jim H. Allan[1], Sheldon Lowe[2]

INTRODUCTION

Rearing and holding habitat in the mainstems of medium-sized streams is often associated with deep water habitat types such as runs and pools that are present during periods of critical low flow. Deep pools and runs are formed by local scour. They may be permanent if associated with a bedrock control but can also be transient when formed along the outside of a bend or adjacent to large woody debris. The loss of these habitat types is not common and is usually a consequence of excessive sediment loads and deposition. In destabilized watersheds, excessive bedload from debris torrents and valley wall failures, in combination with higher than normal peak flows, may result in the filling of deep runs and pools further downstream in the mainstem, particularly where gradients start to decrease and stream power is less. Other factors such as channelization and reduction in large woody debris recruitment may also reduce the availability of deep pools and runs.

Rehabilitation usually takes the form of encouraging bed scour, thereby creating deep water. This is achieved by local acceleration of velocity using some form of structure to form a hydraulic control. The fluvial geometry involved is described in Chapter 12.

Excessive bedload deposition can be avoided by rehabilitating destabilized watersheds to reduce bedload to normal. Watershed restoration, or at minimum "storm proofing" destabilized watersheds, is often a prerequisite to deep water habitat restoration in medium-sized streams.

ASSESSING THE NEED FOR HOLDING/REARING HABITAT RESTORATION

The results of MELP and WRP stream habitat assessments and diagnostic procedures will indicate the need to create mainstem rearing and holding habitat. A lack of deep pools and runs from the assessment normally suggests that creation of some deep water habitat would be beneficial. However, fish species that require and use deep water habitat must also be present. Some streams have hydrological characteristics that preclude the formation of deep water habitat even if they are undisturbed. When assessing stream inventory and diagnostic results, care should be taken to assure that a shortage is caused by a correctable land use. If mainstem holding and rearing habitat is created, the target species of fish must be present to make use of the habitat.

METHODS

Deep water habitat can be created by simply excavating holes in the streambed, but they tend to fill in over time, and often very rapidly. Because deep water habitat occurs naturally as a result of streambed scour at hydraulic controls where water velocity is increased, it is necessary

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to attempt to duplicate the natural process to restore and maintain deep water habitat. Instream structures that promote and maintain scour can be created in a variety of shapes and sizes, but all are designed to be as permanent as design and costs will allow. The best are "hard" structures that are constructed of competent, durable, natural materials that blend with the stream environment. Structural integrity should not be compromised to satisfy visual appearance.

Streambed scour can be encouraged by increasing water velocity downwards, as at a waterfall, or by constricting the channel width, forcing more water through a narrower gap, or both. Weirs (also referred to as dams, plunges or sills) cause water to plunge downward and can also be designed to constrict the channel. Deflectors narrow the channel, increasing velocity and downstream scour.

Low profile weirs or pairs of opposing deflectors constructed of large rock or logs are the preferred structures for promoting and maintaining scour to create deep water runs and pools. Although other materials such as gabion baskets, precast concrete or other artificial materials have been used, they generally lack durability or are unsightly. All structures must be designed and constructed to be overtopped at average summer flows in order to avoid reducing channel capacity for flood flows and minimize backflooding effects upstream of the structure. All structures must be well keyed into the stream banks and the adjacent banks armoured.

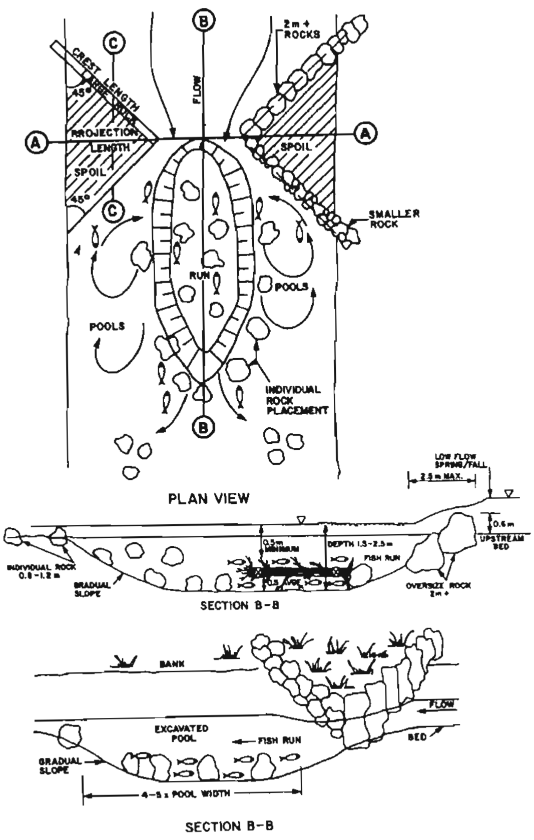
The input of an experienced hydraulic specialist is advised at the prescription or site design phase to assess durability in flood events, especially in medium-sized streams. Water and fisheries agencies will typically require plans and drawings of proposed undertakings to facilitate approvals and permits for instream works. Success is highly dependent on the quality of construction supervision and the experience of supervisors and equipment operators.

Opposing Deflectors

Creation of deep runs or pools using deflectors is best achieved using pairs of opposed deflectors (also referred to as groynes) (Figs. 11-1, 11-2, 11-3). The same effect can also be achieved by using a deflector and armouring the opposite bank to prevent erosion (Anon. 1980), but results have been mixed (Ward and Slaney 1979; see Chapter 3). The advantage of paired opposing deflectors is that the main force of the current can be centred in the channel, reducing erosion risk to adjacent banks. Paired deflectors constructed of large rock have been used successfully in streams up to medium/large-sized rivers 60 m in width, subject to other site criteria such as slope and channel stability.

Log deflectors (Fig. 11-4) can and have been used effectively, but are limited to use on small streams (generally < 5 m average channel width) with low gradients (< 0.2%). Detailed construction notes for log deflectors are given by Lowe (1996).

Normally the pool or run downstream of the deflectors is excavated to a design depth (1.5 to 2 m) and scour to create the deep water. Depending on stream flow events, natural scour could take several years to create the desired habitat. Boulder cover is normally placed within the run or pool (Fig. 11-1, Fig. 11-3 and Chapter 10).



CONSTRUCTION NOTES

1 - ***All rocks*** *(Class I, II, III, 2 M+) must slope* ***DOWN*** *to the middle of the stream to the point of the deflector.*

2 - *The upstream face* ***must contain the LARGEST rocks*** *so that the pressure of the flow may be resisted. Smaller rocks may be placed on the downstream face. Each rock is to be placed in the* ***shadow*** *of the previous rock from the point to the bank. All rock* ***must fit tightly together*** *and jammed together by machinery.*

3 - ***Place*** *the upstream rock face in a trench, then place the downstream rock face in a similar trench, taking care that the rocks slope upwards to the side of the stream such that the point of the deflector is about 0.3 m above the water level and the root is at least 1 to 1.5 m above current water level.*

4 - *Excavate the downstream run, placing much of the spoil material within the confines of the two rock faces. The top surface of the spoil* ***must be below*** *the level of the adjacent rock faces.* ***All remaining spoil*** *must be deposited 10 m outside the stream banks and preferably 1.5 m above the water level.*

5 - *In* ***very large rivers****, a double row of rocks will be required for both the upstream and downstream faces of the deflectors.*

6 - *The open area in the middle of the stream must be about 1/4 of the stream width or less, so that a section of rapid flow conditions exists to funnel the water into the downstream run. On occasion the opening must be constricted even more to provide higher flow velocities when necessary.*

7 - *The instream point of the deflectors shall be 0.6 m above the stream bed. The root of the deflectors shall be 1.0 to 1.5 m above current water levels and firmly imbedded in the stream bank.*

8 - *All elevations relate to low stream flow in the spring or fall.*

9 - *All individually placed rocks in and around the pool are to be 0.8 - 1.2 m in size or less, depending of the size of the river or stream.*

Figure 11-1. Opposing wing deflectors.

Figure 11-2. Opposing deflectors in the lower Coquitlam River, B.C. These structures have survived several flood events in a low gradient, sand/gravel bed section of the river. Note stable, well-vegetated banks.

Figure 11-3. Opposing deflectors in the Castle River, Alberta (1992 photo). Survived a >1:200-year flood (1995) with minor effects. Some material used to cover the interior of the deflectors was lost. The run was 10 m longer after the flood due to new scour.

Weirs

Upstream V weirs built with large rock (Fig. 11-5, 11-6, 11-7) have proven to be stable and effective and can be used in most streams up to medium/large rivers (to 60 m width) provided gradients are less than 0.3% with laterally stable channels. They tend to concentrate the current and subsequent scour in the middle of the channel, creating a long, narrow run or pool and avoiding potential impacts to adjacent stream banks. The upstream V has the strength inherent in an arch design. Weirs that extend straight across the channel at right angles to the flow create short pools that extend across the channel. Straight weirs are less stable than upstream weirs. Downstream V weirs are less stable than upstream V weirs, unless the V slopes into mid-channel. They tend to spread scour over a wider area, which may result in adjacent bank erosion. These latter weirs are not as effective at creating deep-water habitat (Klingeman 1984), but can be used to trap gravels to create spawning habitat (Anderson et al. 1984).

Log V weirs with the narrowest point facing upstream (Fig. 11-4, also Anonymous 1980, Lowe 1996) are preferred over straight or downstream configurations. Detailed construction notes for log weirs are given by Lowe (1996). Straight log weirs angled downstream (Anon. 1980) can be effective but are sensitive to local site conditions. Log weirs should only be used in small, low gradient (< 0.2%) streams less than 5 m in average channel width.

The run or pool downstream of the weir is excavated to design dimensions, rather than waiting for natural scour to create the deep water.

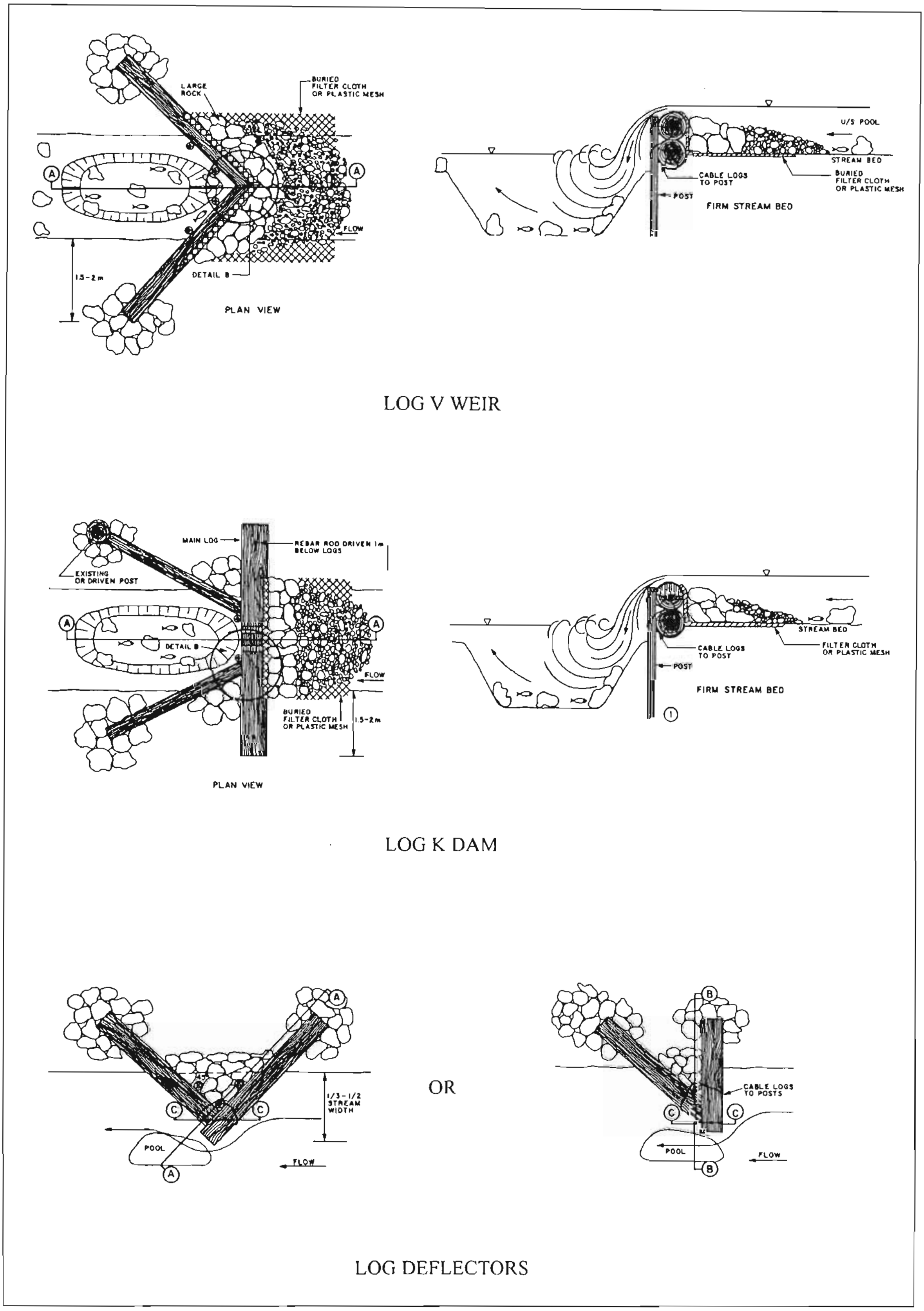
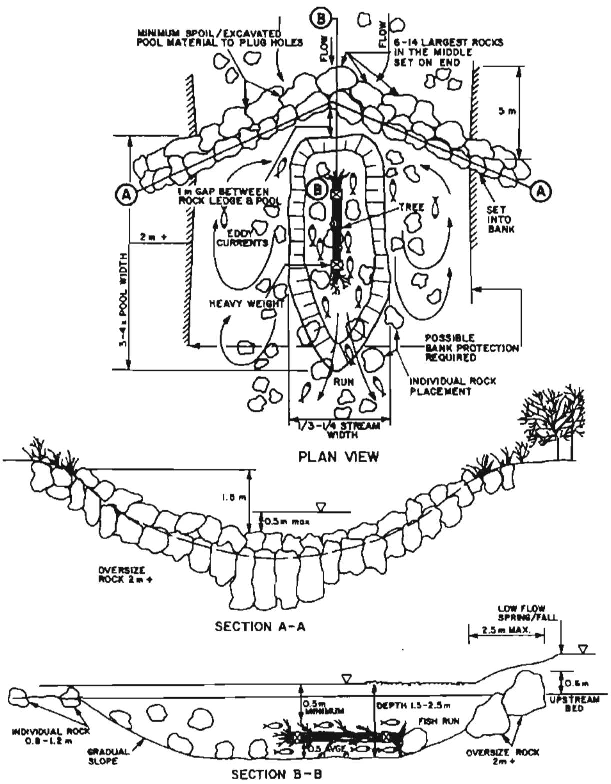


Figure 11-4. Log structures.



CONSTRUCTION NOTES

1 - ***All weir crest rocks MUST SLOPE DOWN*** *from the banks* ***TO THE UPSTREAM POINT*** *of the weir to confine the main flow to the middle 1/3 of the stream.*

2 - *All rock* ***MUST*** *extend* ***upstream*** *from the bank where they are buried deeply to the middle point of the weir.*

3 - *The largest (8-16) rocks (2 M+)* ***must*** *be placed at the point of the weir* ***in a double row*** *and set in place with the longest side pointing down (as shown) in a trench already excavated for this purpose. All rock is to be jammed together by machinery to provide tight as possible fit. Additional stabilizing rock and spoil are to be placed around these rocks, then the remainder of the weir crest may be built. The weir crest width should be 2.0 m.*

4 - *The upstream notch on the weir must be within the middle third of the river, but may be placed at any point within to move the current from side to side. Bank armouring may be necessary in such cases where potential bank erosion exists.*

5 - *The top of the rocks in the notch of the weir shall not be more than 0.6 m above the stream bed, unless an upstream pool is required. The bank tie-in location shall be 1.5 m above the stream elevation. The rocks shall taper gradually from the notch to the tie-in point on the bank.*

6 - *Only a minor amount of spoil material may be used to fill in the voids in the weir crest to prevent water from flowing through the weir. The spoil is* ***only*** *to ensure relative water tightness. All remaining spoil material must be placed 10 m beyond the stream banks, preferably 1.5 m above current water level.*

7 - *Excavated material from the pool to be placed as follows: 10% around the weir crest to plug holes between the rocks; 90% to be spoiled 10 m minimum outside and above current channel banks.*

8 - *All elevation differences shall relate to the low stream flow conditions in the fall, or at time of inspection, whichever is less.*

9 - *All individual placed rocks to be approximately 0.8 - 1.2 m in size.*

10 - *Pool depth to be 1.5 - 2.5 m maximum.*

Figure 11-5. V-weir - double crest.

DESIGN CRITERIA AND SPECIFICATIONS

Site Selection

The simplest and most effective criteria for selecting suitable sites for mainstem holding and rearing habitat creation using instream structures are stream gradient or slope (usually expressed as percent), channel morphology and stream power (slope · discharge · constant). Several years of monitoring instream structures in southern Alberta and elsewhere after major flood events indicate these are the critical factors that must be addressed.

Larger streams with average slopes exceeding 0.4% usually have excessively high stream power or energy during floods that results in structural failure, burial of structures by excess bed load or channel shifts that render structures ineffective. The use of instream structures in the mainstem of streams or stream sections with gradients in excess of 0.4% is not recommended. There may be sections within a high gradient stream or stream reach that have gradients less than 0.35%. If the lower gradient section is 10 or more average channel widths in length, instream structures can be used. The structure should be located approximately 3 channel widths downstream of the upstream boundary of the low gradient section. Log structures are less durable in high energy streams and should only be used in streams or stream sections with slopes less than 0.2% and average channel width less than 5 m.

Figure 11-6. Rock V-weir in the Oldman River, Alberta. Note excavated pool/run and cover rocks downstream of the weir. The left upstream arm of the weir extends across the gravel bar to tie in to the bank.

Figure 11-7. Rock V-weir in the Castle River, Alberta. Scour immediately downstream of the point of the weir caused the point rocks to slip downstream during a >1:200-year flood.

The channel at the site should consist of a relatively straight, single main channel with cobble/gravel substrates and vegetated banks consisting of cobbles and gravels. Channels with evidence of lateral instability, such as braiding or excessive bar deposits, should be avoided. Bedrock banks and beds prevent proper keying in of structures and should also be avoided. Bed and banks composed of fines (silt, sand, small gravel) are easily eroded, seriously compromising structural stability. However, structures can be built and will survive in very low gradient streams (< 0.12% slope) having banks and beds of fine substrate materials if the banks are well vegetated and stable (Fig. 11-6). It is critical that structure design account for the very high erodability of the fine bed material. Structures in series should be separated by at least 10 channel widths and ideally should be separated by a riffle to serve as a source of insect drift to the pool or run. Also, caution must be exercised to avoid creating extended shallow backwatering upstream of opposing wing deflectors and especially weirs because these are poor habitats for salmonid juveniles and adults.

Materials

Specifications for rock are given in Table 11-1. The 1:50-year flood velocity determines the rock size for tie-ins and bank armour. Select the next highest class of rock for the portion of the structure within the channel. The construction notes on Figures 11-1 and 11-5 provide some guidance for rock size selection and placement for the structures. Rock should be competent and angular rather than rounded. Rounded rock should be avoided as it fits poorly and tends to roll easily.

Table 11-1. Specifications for rock for instream structures. Velocities are the average for the 1:50-year flood. Average rock weight in brackets.

Nominal Diameter	CLASS 1 < 2.3 m·sec^{-1}	CLASS 2 < 3 m·sec^{-1}	CLASS 3 < 3.8 m·sec^{-1}	CLASS 4 < 4.7 m·sec^{-1}	CLASS 5 < 5.6 m·sec^{-1}
Dmax	0.45 m (130 kg)	0.80 m (700 kg)	1.2 m (2400 kg)	1.8 m (8000 kg)	2.7 m (27000 kg)
D80	0.35 m (70 kg)	0.60 m (300 kg)	0.90 m (1000 kg)	1.5 m (4700 kg)	2.2 m (15000 kg)
D50	0.30 m (40 kg)	0.50 m (200 kg)	0.80 m (700 kg)	1.2 m (2400 kg)	1.8 m (8000 kg)
D20	0.20 m (10 kg)	0.30 m (40 Kg)	0.50 m (200 kg)	0.80 m (700 kg)	1.2 m (2400 kg)

Specifications for logs are given in Lowe (1996). Generally, sound, straight-limbed logs from coniferous species are preferred. Log structures may be subject to ice damage and rot due to wet/dry cycles.

Machinery And Equipment

Tracked excavators (backhoes) equipped with a bucket and grapple or thumb are best for construction of rock structures. Smaller backhoes, such as the Hitachi EX 100 and 200 series or JD 490 to 690 series or equivalent, are preferred over larger machines, which are more expensive, less maneuverable and leave a larger "footprint". Water depth at the work site may occasionally require a larger machine. Wheeled hoes or walking hoes may be used where terrain permits or dictates. Rubber-tired loaders should be used to transport materials from stockpile sites to construction sites. Log structures can often be built by hand, but construction is more efficient with the aid of a small tracked or wheeled loader/hoe combination.

Costs

Costs vary depending on site accessability, materials availability and distance to sources. Borrowing large rock from natural sources such as slides and scree slopes may require a permit, but is generally less expensive than purchasing rock from a quarry. Machinery and labour costs tend to be less variable. Table 11-2 gives a range in estimated costs for various components of weir and deflector structures. The cost for a rock V weir or paired wing deflector structure in a medium-sized river (average channel width 20 to 30 m) is about $15,000 to $30,000 and yields about 300 to 800 m^2 of holding/rearing habitat. The cost for similar structures in smaller streams (10 to 20 m average channel width) ranges from about $4,000 to $15,000 and yields correspondingly less habitat.

Table 11-2. Range of estimated costs for materials and equipment.

Rock	Logs	Backhoes	Loaders
$10.00 to > $60.00 per tonne delivered	$10.00 to $100.00 each delivered	$70.00 to $140.00 per hour	$60.00 to $120.00 per hour

MONITORING AND MEASURES OF SUCCESS

Structural integrity and function should be inspected on a regular basis, but can also be triggered by a major discharge event. For example, structures could be monitored after a 1 in 5-year flood event. Performance, structural integrity and maintenance requirements should be assessed. Fish responses to structures can be monitored using methods given by Koning (1994). Maximum fish use usually occurs during extreme low-flow periods, but can be highly variable depending on season and behavior of species and life cycle phases within the fish community. Table 11-3 gives some results from rock V weir and opposing deflector runs in the moderately productive Castle and Crowsnest Rivers in southern Alberta.

Table 11-3. Mean and range (in brackets) of numbers of rainbow trout and bull trout per 100 linear meters in V weir and paired deflector runs in the Crowsnest and Castle Rivers, Alberta. Data from R.L.&L. 1993, 1994.

River	Structure/Habitat Type	Rainbow Trout		Bull Trout	
		Juvenile	Adult	Juvenile	Adult
Crowsnest	V weir runs	36.4 (17.1 to 68.1)	30.9 (8.7 to 62.9)	not present	not present
Castle	V weir runs	11.3 (6.9 to 16.7)	2.6 (0 to 7.8)	13.7 (5.2 to 16.7)	6.3 (2.3 to 13.9)
	Opposing deflector[a] runs	5.2 (1.7 to 11.8)	1.03 (1.7 to 2.4)	2.1 (1.7 to 2.4)	1.03 (0 to 2.4)

[a]The density of fish utilizing runs and pools created by deflectors can be improved substantially by incorporation of LWD, buried or anchored from a wing or revetment (Ward and Slaney 1979).

Chapter 12

Restoring Habitats in Channelized or Uniform Streams Using Riffle and Pool Sequences

Robert Newbury[1], Marc Gaboury[2], Dave Bates[3]

INTRODUCTION

Forestry-related road construction and industrial site development on floodplains, alluvial fans and deltas are often facilitated by relocating local stream channel reaches and channelizing (uniformly excavating) existing streams (Hogan 1986; Newbury and Gaboury 1993). A typical example is at Oulette Creek in Howe Sound in south coastal B.C., where relocation and channelization of this salmon and sea-run trout stream was undertaken several decades ago to establish a sawmill on the alluvial fan floodplain (Fig. 12-1). Flood flows in channelized reaches may rebuild naturally diverse hydraulic conditions but in most cases, the lack of suitable bed materials and long periods of recovery can eliminate fish rearing and spawning habitats for decades.

Natural stream habitats, which include the surrounding riparian zones as well as instream environments, are varied and diverse. Corresponding organisms have evolved to exploit both the spatial and temporal variations found within the stream. For example, Bisson et al. (1981) summarized the relationship between the presence of age-specific species and habitat utilization in summer from streams sampled in western Washington (Table 12-1). Coho fry and trout parr had an affinity for pools, and trout fry (steelhead and cutthroat) and steelhead parr had a preference for glides and riffles.

Table 12-1. Summary of average habitat utilization coefficients for selected salmonid species and year classes. A coefficient of -1 indicates total avoidance; 0 indicates equal use in all habitats; and increasing positive values indicate increasing preference (after Bisson et al. 1981).

Habitat Unit	Coho 0+	Sthd 0+	Sthd 1+	Cutt 0+	Cutt 1+	Cutt 2+
Pools	1.46	-0.19	0.58	-0.28	0.16	0.33
Riffles	-0.90	0.60	0.29	-0.40	-0.06	-0.64
Glides	-0.91	0.34	0.86	1.42	-0.77	-0.92

Sthd = steelhead trout; Cutt = cutthroat trout

[1] Newbury Hydraulics, Box 1173, Gibsons, BC V0N 1V0

[2] Ministry of Environment, Lands and Parks, Watershed Restoration Program, 2080-A Labieux Rd., Nanaimo, BC V9T 6J9

[3] FSCI Biological Consultants, RR 1, Box 60, Halfmoon Bay, BC V0N 1Y0

Figure 12-1. Oulette Creek 1978, Howe Sound, B.C. In 1978, the lower reach was diverted and channelized to create a sawmill and log sort yard on the alluvial fan. Single log and rock drop structures were constructed in the channel that subsequently failed.

In typical channelized stream reaches, complexity has been compromised, thus reducing or eliminating the stream's ability to support and maintain healthy fish populations. Major impacts occur from: the loss of spawning or rearing substrates; removal of stored detritus and large woody debris; loss of vegetation as cover and nutrient-energy sources; disruption of the run-riffle-pool sequence; loss of stream length; increased gradient and velocity; and dewatering of adjacent areas. Consequently, spawning, rearing, and overwintering habitats of salmonids are impacted. In particular, species that spend their entire life or a significant portion of their juvenile life (anadromous species) in streams, including steelhead/rainbow trout, coho salmon, chinook salmon, cutthroat trout, Dolly Varden char, and Arctic grayling, are most affected by channelization.

Properly designed rock riffles or rapids may be constructed in naturally uniform and channelized streams to re-establish some of the lost habitat. These structures are used to enhance pools, recruit gravel, re-aerate flows, and assist fish passage (Newbury et al. 1996). Other projects have enhanced walleye spawning habitat and fry passage in uniformly excavated drainage channels, created year-round adult rainbow and brook trout habitats in naturally uniform bedrock and boulder-dominated streams, and increased salmon spawning and overwintering habitats in steep coastal streams (Newbury and Gaboury 1993).

There are four fundamental questions to answer before rebuilding a stream reach and creating a pool and riffle profile:

1. is the existing stream condition a result of man's interference or due to natural stream processes,
2. what is the natural geometry of the channel that can be sustained during flood events,
3. will the creation of pools and riffles improve desired habitats, and
4. how can the riffles and pools be designed to mimic the form and stability that natural riffles would have in the reach?

The questions may be answered by analyzing the drainage basin, surveying the reach to be enhanced, evaluating the habitat requirements, and designing pools and riffles to have the same stability that a natural reach would have. An overview of the evaluation, design, and construction process for creating pool and riffle reaches is presented in the following three stages: Hydrology and Stream Analysis, Design and Construction, and Habitat Monitoring and Assessment.

A detailed description of a ten-step stream habitat analysis and design process with illustrative projects is presented in "Stream Analysis and Fish Habitat Design: A Field Manual" (Newbury and Gaboury 1994). Reference stream survey methods normally undertaken by teams of hydrologists and biologists are also described in detail in "Stream Channel Reference Sites: An Illustrated Guide to Field Technique" (Harrelson et al. 1994).

STAGE I: HYDROLOGY AND STREAM ANALYSIS

Drainage Basin Map Analysis

The area of the drainage basin tributary to the project reach can be determined from a suitably scaled and contoured topographic map (preferably 1:50,000 or smaller). A first approximation of the average slope of the channel in the project reach may be determined from contour intervals along the long profile in the reach. This value can then be checked in the field.

Channel Geometry: Width, Depth, and Discharge

The basin area may be used to predict the average channel geometry and bankfull/channel maintenance flood flows using regional curves that reflect local climatic and hydrological conditions. Summary graphs for the relationships between drainage area and the bankfull channel width, depth and discharge are shown in Figs. 12-2 and 12-3 (after Leopold et al. 1964). If flow records are available for the project or nearby streams, a second bankfull stream discharge estimate may be made from an annual flood frequency curve. In many streams, an annual instantaneous flood peak with a return period of approximately 1.5 years, or the 67% cumulative frequency event, corresponds to the bankfull or channel maintenance flood discharge. The relationship between the bankfull discharge and the channel width for a broad range of streams and rivers is shown in Fig. 12-4 (after Kellerhals and Church 1989). All of the bankfull dimension estimates should be checked by field surveys.

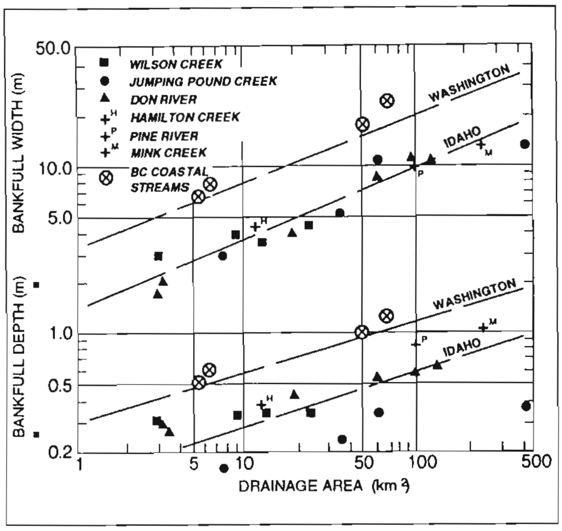


Figure 12-2. In regions with similar hydrologic regimes, the average bankfull width and depth are related to the drainage basin area in fluvial channels. The points shown were derived from channel reference surveys in western Canada.

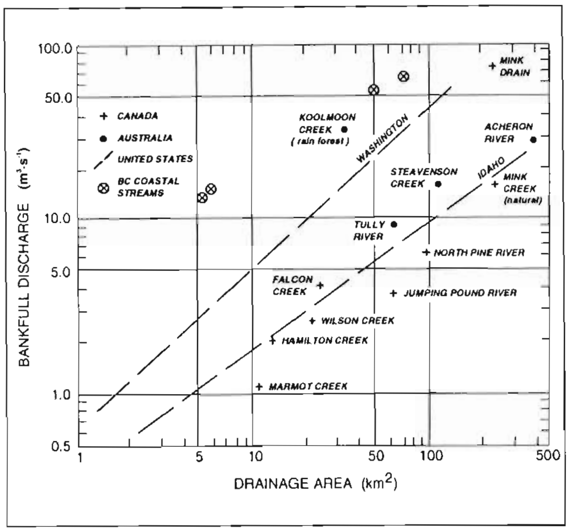


Figure 12-3. The bankfull channel discharge vs. drainage basin area relationship may be estimated from channel reference surveys using the survey data and a slope-velocity relationship such as Manning's equation (Chow 1959).

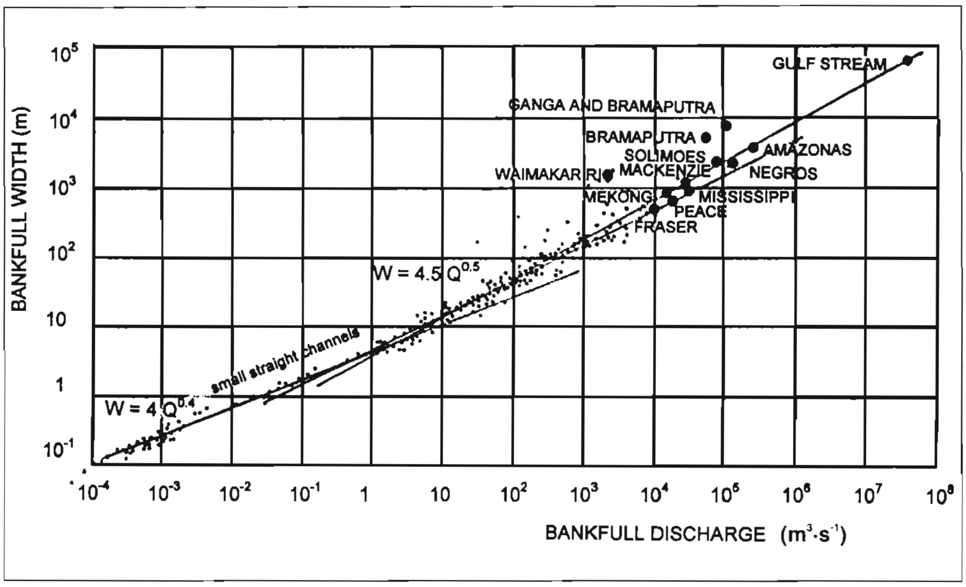


Figure 12-4. The relationship between bankfull width and discharge has been compiled for all ranges of river size by Kellerhals and Church (1989). For streams with bankfull discharges between 1 and 1,000 $m^3 \cdot sec^{-1}$, the relationship was estimated to be width = 4.5 · bankfull discharge$^{0.5}$.

The **bankfull width** of the channel is used as the base unit for other plan and profile dimensions of the river (Fig. 12-5). The bankfull width is defined as the distance between the edges of the floodplains if they are present. In many channels that are entrenched, the equivalent width is obtained by measuring between the upper limits of the regularly scoured channel banks where rooted perennial vegetation begins.

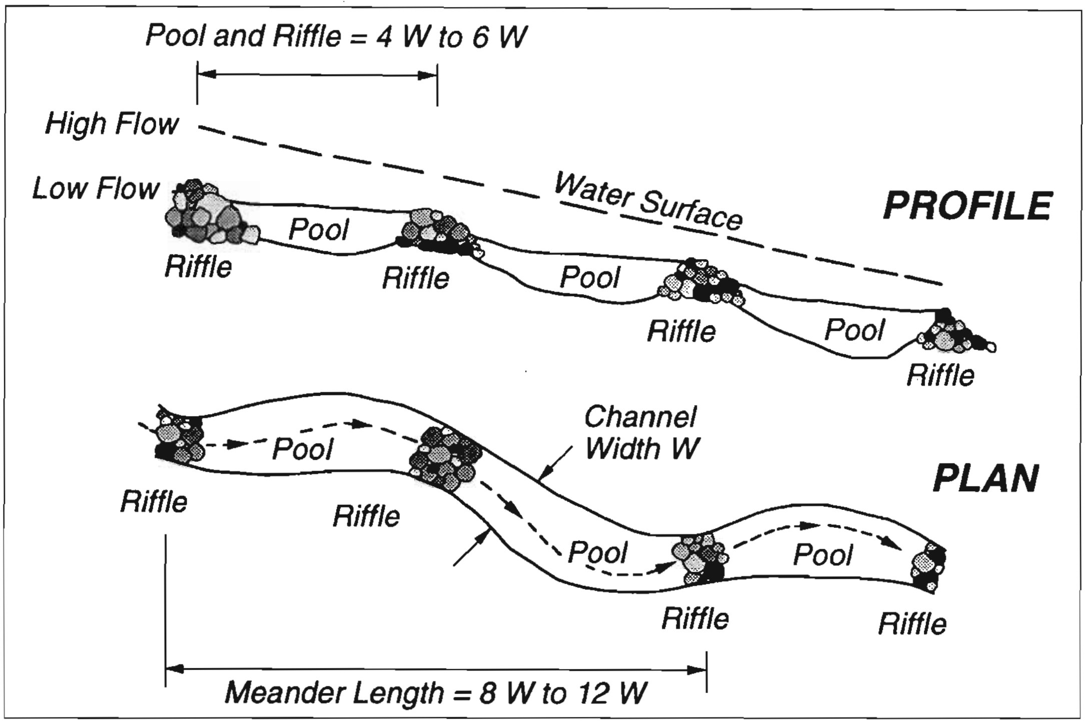


Figure 12-5. Pool and riffle profiles are formed in erodible channels with an average spacing of 6 times the bankfull width. In steeper streams, and where logs and tree roots are abundant, the spacing decreases.

On average the bankfull flood flow tends to wander from one side of the valley to the other and back every 12 times the channel width. If the bed and bank materials can be eroded by the flood flows, the stream often develops a meandering pattern with a corresponding average wave length of 12 times the bankfull width. Surveys of river meanders have shown that the average radius of curvature of the top of the meander bend is 2.3 times the bankfull width (Fig. 12-6). At this curvature, the energy lost as the flow changes direction is uniformly distributed around the curve.

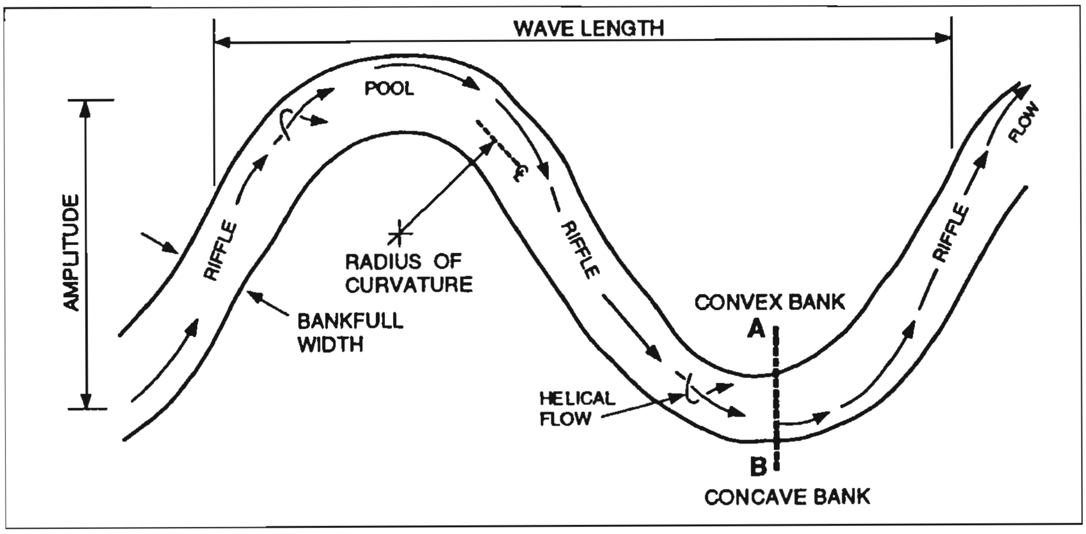


Figure 12-6. The average wave length of meanders is 12 times the bankfull width. The average radius of curvature is 2.3 times the bankfull width (Leopold et al. 1964).

The flood flow also forms a vertical wave, creating a pool in each bend and a riffle or shallow bar as the flow changes direction from one side of the valley to the other. Consequently, the average pool and riffle spacing is 6 times the bankfull width. After the flood peak has passed, the pattern established by the larger flow is emphasized by near-horizontal pools between the steeper riffle sections. In streams with gradients greater than 5% or where there are large log and boulder obstructions, the pool and riffle spacing may be reduced, forming a step-like channel with riffle drops every 2 or 4 times the channel width (Hogan 1986).

These observations of natural channel patterns provide the background for mapping and interpreting the forms and processes occurring in the project reach. They are also useful guidelines for designing pool and riffle restoration works. As Henderson (1966) advised, *"the river engineer should look when planning to simulate natural meanders in river training works"*.

Stream Surveys

Stream reach surveys are required to establish the natural channel dimensions for a given drainage area in a hydrological region. On average, sample reach lengths should be selected that are at least 12 times the bankfull width of the stream to contain a full set of pool, riffle, and meander characteristics. The bankfull channel widths and depths can be plotted on Figs. 12-2, 12-3, and 12-4 to obtain an estimate of the channel geometry, drainage area, and bankfull flow relationships as they develop along the river with increasing discharge.

In the project reach, in addition to measuring the channel dimensions, a surveyed profile of the reach is required to design riffle and pool restoration structures. An elevation benchmark and reference stations should be left in the reach to locate the restoration works. The channel geometry of the project reach may vary from the regional values if the stream is disturbed by channelization, but the design dimensions for the restoration project should be based on the channel geometry that is supported by the bankfull/channel maintenance flow. Survey procedures used to determine channel geometry and habitat conditions in a stream reach are summarized in Newbury and Gaboury (1994, refer to Chapter 2 and Appendix E for sample reach survey forms).

Salmonids have specific habitat preferences and the recognition and documentation of these components of the aquatic habitat complex provide a benchmark used in the restoration of suitable habitats. Habitat units can be noted on the reach plan, and their characteristics and extent measured in the sample reach. Features identified on the sketch should include: instream, emergent, and overhanging vegetation; large woody debris; undercut banks; size and distribution of substrate, including emergent boulders; side channels; off-channel ponds and the type and extent of stream bank vegetation. The pattern of flow through the reach, including the location of hydraulic jumps and horizontal eddies, and the depths and velocities of local riffles, chutes, runs and pools should also be noted, as these are important hydraulic features utilized by fish in different life stages.

STAGE II: DESIGN AND CONSTRUCTION

Concept

Data and observations gathered in Stage I can now be applied to designing and constructing pool and riffle sequences as a habitat restoration project. Constructed riffles should mimic natural rapids in form, materials, and function as closely as possible. Stability of the riffles is not absolute, but can be adjusted to the bankfull flow stage assuming that higher floods will utilize floodplains. In channels where floodplains are removed or constricted, higher than bankfull flows can often be accommodated by more robust designs. However, in some cases the higher flows may cause a partial failure of the riffle structures. With proper planning, this can be a safe-fail event, where the riffle becomes a run. In these cases, riffle materials should be stockpiled nearby for post-flood repairs.

Location

At low flow, the pool and riffle design distributes the fall in the reach in a series of steps. To establish a first approximation for the location of riffles, a template marked off in units of six bankfull widths, the average riffle spacing for all rivers, can be placed on a large scale plot of the reach profile as shown in Fig. 12-7. In many cases, the stream is attempting to re-establish the natural profile, and existing small drops or riffles found at that spacing will suggest where the template is to be located in the reach. Noting the proposed riffle sites relative to the cross-section locations allows them to be plotted on the reach plan. The spacing and locations can then be adjusted so that they take advantage of existing pools, cross-over points in the flow between meander bends or other habitat features. These locations should be checked in the field and on aerial photographs of the reach. In steeper sloping reaches (5% or more) or where large woody debris is present, the riffle spacing may be decreased (Hogan 1986). For example, in the Twin Creek restoration design (Fig. 12-8), the riffle spacing was decreased to 4 times the bankfull width of the channel in the steeper 6.5% slope upstream reach.

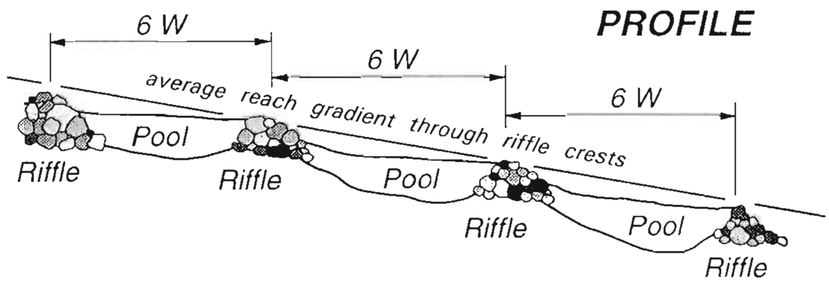


Figure 12-7. A design template based on average and observed pool and riffle spacing may be placed on the project reach profile to determine potential locations for constructing riffles. The riffle crest elevations are adjusted to follow the average reach gradient. The maximum height of the riffles above the streambed is set to allow the bankfull discharge to be conducted at critical velocity over the riffle crest within the channel.

Elevation and Flood Capacity

The height of riffle crests will depend on the local profile elevation, the slope of the stream and the desired depth of the low-flow pools. As a first approximation, the riffle crest gradient template with a line equal to the average reach slope may be placed on the profile and adjusted to obtain the desired pool depths as shown in Fig. 12-7. The trial gradient may be adjusted to coincide with upstream and downstream conditions in the reach, or it may be varied at each end for a smooth transition to the adjacent reaches.

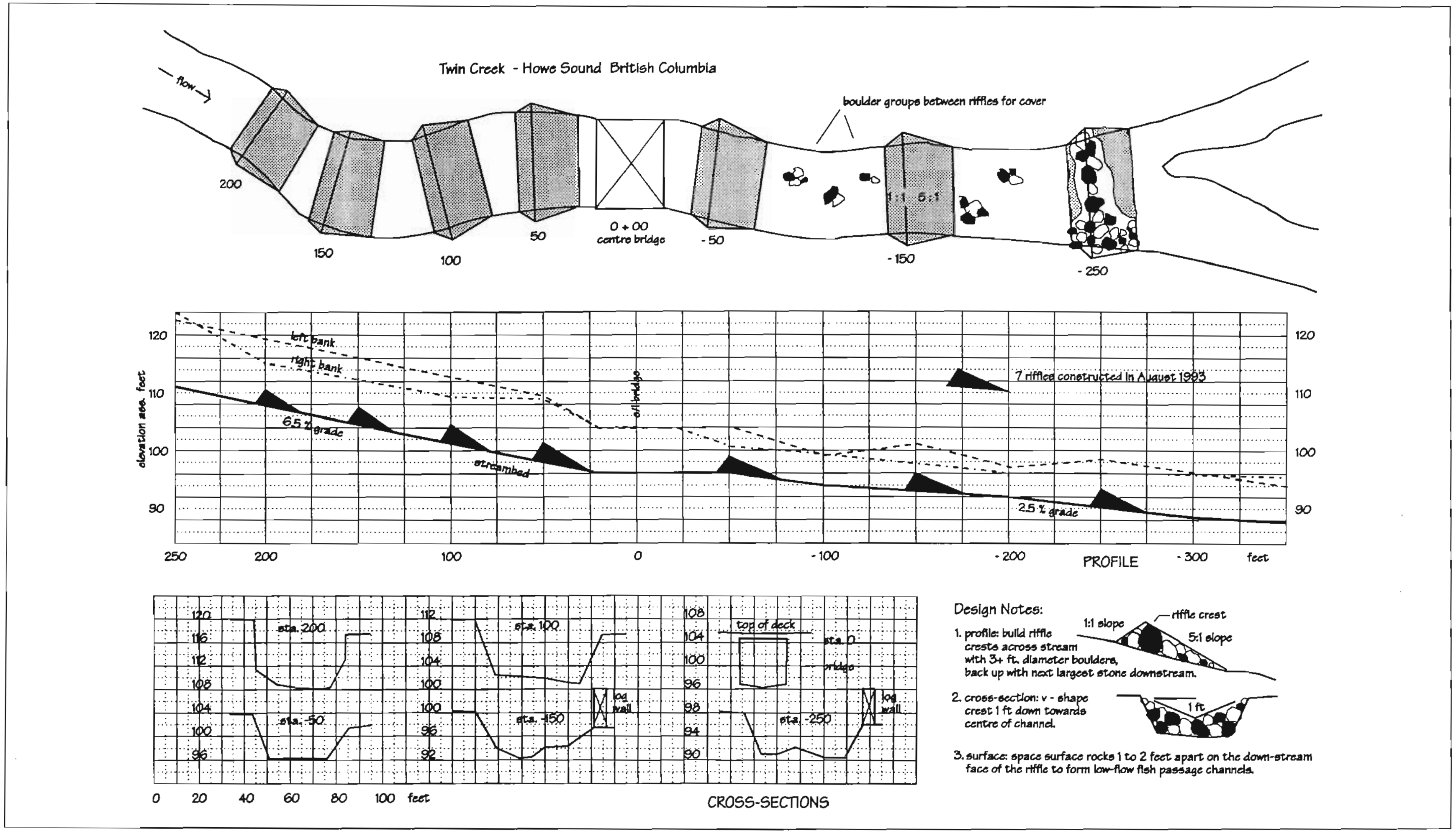


Figure 12-8. Twin Creek Restoration Project 1993, Howe Sound, B.C. Seven rock riffles were constructed on the lower channelized reach adjacent to a log sort yard. The upper riffles in the 6.5% gradient reach were spaced at 4 times the bankfull width. In the lower 2.5% gradient reach, the riffle spacing was increased to 6 times the bankfull width. In the first year, gravel and cobble bars were deposited in the upstream pools as the streambed stabilized.

The elevation of the riffle crests is then checked relative to the floodplain elevations to determine if there is sufficient local channel capacity to maintain the bankfull flows within the floodplain. The bankfull flow may be estimated from the reference channel surveys, regional flood frequency curves, or the drainage area relationship for the region. The discharge capacity at the riffle site can be estimated by assuming that the flow is critical at the riffle crest for in-channel, non-backwater conditions (see Chow 1959, and Newbury and Gaboury 1994, Chapter 3 for a discussion of locally varied flow conditions in streams). Typical bankfull flow conditions in a constructed pool and riffle reach in Oulette Creek are shown in Fig. 12-9. If more channel capacity is required, the proposed riffle crest gradient may be lowered relative to the floodplain, the local floodplain elevations may be adjusted with fill, or the riffle sites may be relocated to sites with higher banks. After several iterations of the spacing and elevation templates, sites are usually found that will allow the regular bankfull flows to be maintained at the natural level in the main channel. The channel banks at the riffle sites must be riprapped to conduct the locally accelerated flows over the riffle crests without scouring.

Figure 12-9. Oulette Creek Restoration Project 1994, Howe Sound, B.C. Downstream view overlooking constructed riffles at the bankfull flood discharge. The low-flow pool and riffle steps are submerged as the average gradient of the water surface and stream bed become parallel. Critical velocities are occurring locally on the riffle crest.

When flood flows are larger than the bankfull discharge, the channel and floodplain capacity can be assessed using standard open channel flow resistance formulas. Resistance values for the central channel should be chosen that are similar to those observed in pool and riffle rivers of similar dimensions (Chow 1959; Newbury and Gaboury 1994, Chapter 3). Complex channels with backwater conditions may require engineering flood routing studies to predict local water stages.

Configuration

Surveys of natural rapids and riffles, including collecting typical photographs, should be undertaken and used to develop natural riffle templates. The rapids shown in Fig. 12-10 illustrate the diverse surface and flow conditions that occur in a rough and steep natural channel. A riffle constructed on Langdale Creek (Howe Sound, B.C.) that mimics the natural conditions is shown in Fig. 12-11.

Figure 12-10. In a natural rapids, hydraulics jumps, pools, and chutes in various combinations dissipate energy and provide opportunities for fish to find navigable passages up the steep face. This diversity can be reproduced in man-made riffles with careful placement of large rocks on the downstream face.

Most natural riffles have a downstream slope of less than 6 degrees or 10% (10:1 slope). This allows the water to enter the pool at a shallow angle between the riffle face and the channel bottom as shown in the schematic construction template (Fig. 12-12). Surveys of spawning rapids used by walleye were found to have downstream slopes of 20:1 (Newbury and Gaboury 1994). Riffles surveyed in several B.C. coastal streams generally had downstream slopes of 10:1 with some as steep as 6:1 in bouldery channels.

The riffle crest and downstream surface is V-shaped, to direct the flow towards the center of the downstream channel. This reduces bank scour at the riffle site and assists in maintaining a central pool depth downstream. At higher flows, important back-eddies are formed above and below the riffles providing refuge for both adult and juvenile fish and promoting coarse gravel accumulation on the sides of the channel above and below the riffle. Additional complexity for salmonid rearing habitat can be provided by adding peripheral boulders and large woody debris to the back-eddies.

Figure 12-11. Langdale Creek Restoration Project 1995, Howe Sound, B.C. Diverse hydraulic conditions have been created by strategically placing large boulders on the downstream face of this constructed riffle. Note the well riprapped banks in the riffle zone adjacent to the reconstructed Sunshine Coast highway.

1. PLAN: build riffle crest across the stream with large diameter boulders; back up with next largest stone downstream.
2. PROFILE: construct downstream face of riffle at a shallow re-entry slope that mimics local natural riffles (5:1 to 20:1).
3. SECTION: V-shape the crest and face downwards to the centre of the riffle (0.3 to 0.6 m).
4. SURFACE: place large rocks randomly on the downstream face 20 to 30cm apart to dissipate energy and create low flow fish passage channels.
5. BANKS: rip-rap both banks with embedded boulders and cobbles to the floodplain level.

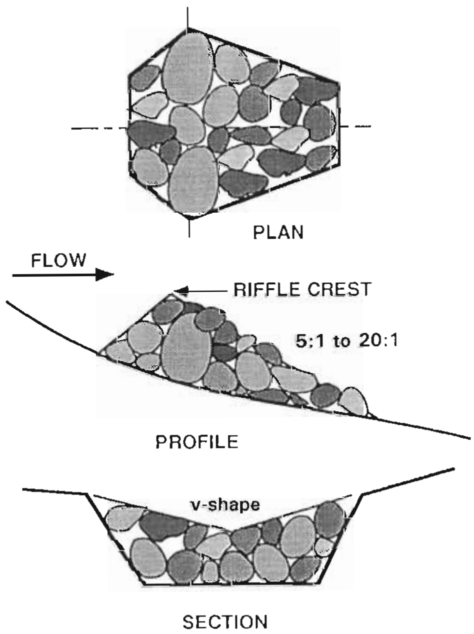


Figure 12-12. This schematic pool and riffle construction drawing may be augmented for machine operators with notes on the placement of construction survey stakes and photographs of natural and well constructed riffles (video, Newbury Hydraulics 1996).

Materials

The riffles are built with a range of rock sizes. The largest rocks are selected to be stable at the bankfull flood stage but may tumble as smaller boulders are initially adjusted around them. The larger rocks placed on the surface of the riffle create chutes and small drops that assist fish passage at low flows (Fig. 12-13). These rocks are the most vulnerable to movement and represent the upper range of rock size required for the riffle. An approximation of the maximum size required may be obtained by analyzing the tractive force on the face of the riffle and applying guidelines for selecting riprap materials (Newbury and Gaboury 1994). The tractive force T ($kg{\cdot}m^{-2}$) may be estimated as T = 1000 · Flow Depth (D in meters) · Slope of the Downstream Face of the Riffle (S) or:

$$T = 1000\ D\ S \qquad \text{(Chow 1959).}$$

Figure 12-13. Riffle-pool reconstruction at the upper Keogh River in 1996. The riffle crest was increased in height to add 30 cm depth to the pool upstream and to maintain a deep pool at the base of the riffle. As a key component, LWD was anchored (epoxy technique) upstream and downstream of the riffle to maintain sufficient cover for both rearing juveniles and adult spawners.

For bankfull design conditions, the maximum depth of flow will be established by the height of the floodplains above the riffle crest. In entrenched channels, this may be greater than the regularly scoured depth associated with the mean annual flood peak. Studies of stable channels summarized by Lane (1955) indicate that the relationship between the tractive force and bed material diameter at incipient motion for pebble-size and larger materials is T ($kg{\cdot}m^{-2}$) = diameter ϕ (cm). A safety factor of 1.5 is recommended (U.S. Federal Highway Administration 1988). In this case, the estimated diameter of the stable rock size ϕ_s (cm) may be summarized in the relationship:

$$\phi_s\ (cm) = 1500\ D\ S$$

The volume of rock required at each riffle site is approximately equal to the riffle height · the riffle length · the bankfull channel width. This volume allows for extra rock to riprap the banks adjacent to the riffle site and to roughen the downstream slope of the riffle face. The rock sizes should cover the entire range observed in natural template riffles, with an adequate number of the larger rocks to build the riffle crest and armour the downstream slope. Any remaining rock may be stockpiled nearby for adjustments to the riffle and banks following the first few flood events, or used as boulder clusters at the base of the riffle at the entrance to the pool.

Construction

The construction process is summarized in the notes accompanying Fig. 12-12 (also described in video form, Newbury Hydraulics 1996). This figure should be reproduced and supplemented with photographs of riffles and rapids as a guide for machine operators. To build a riffle with natural characteristics, large rock must be sorted and used with skill to create a stable crest and to form a properly roughened surface on the downstream face.

Construction surveys at each riffle site must be referenced to the temporary benchmark established during the project reach profile survey. Construction stakes should be placed on either side of the channel at the upstream toe, crest, and downstream toe of the riffle. The crest elevation at the banks and in the center of the channel can be marked on the location stakes. These elevations will have to be checked as the construction proceeds. This can be done with a hand or surveyor's level and a reference elevation. In smaller streams, measurements may be made by the operator from a horizontal string line between points previously established on adjacent floodplains or banks.

Natural riffle and pool habitat projects are designed to be adjusted by flood flows that will scour pools and deposit gravel bars. The adjustments often take place in the first 4 or 5 bankfull or greater flood events. After these events, the riffle configuration should be resurveyed and assessed to see if additional rock is required to infill gaps or to improve the configuration of the flow on the riffle face. For example, several experimental riffles with different foundation conditions and rock sizes were built on Chapman Creek, B.C. in 1992 and 1993 (Fig. 12-14). In the first year, the downstream faces of riffles one, two, four and five were sorted but not altered in elevation by bankfull flood flows of approximately 70 $m^3 \cdot sec^{-1}$. The central portion of the third riffle slid along the hardpan bed at that site and moved downstream to create a run. This could have been avoided by keying the riffle crest into the bed, but only at a high cost of drilling and blasting. The sixth upstream riffle crest was not altered by flood flows and has caused a large coarse gravel bar to accumulate upstream that is actively used for spawning. However, the downstream face of the riffle has been partially eroded as there was not a sufficient supply of large boulders to build the riffle base below the crest. Although the rocky bed of Chapman Creek could withstand the steeply falling water from the riffle crest, in more erodible streams a deep scour hole would develop that would eventually cause the large crest boulders to tumble downstream and be buried. In order to prevent this scour, boulders from adjacent reaches are added to the riffle face (Fig. 12-14).

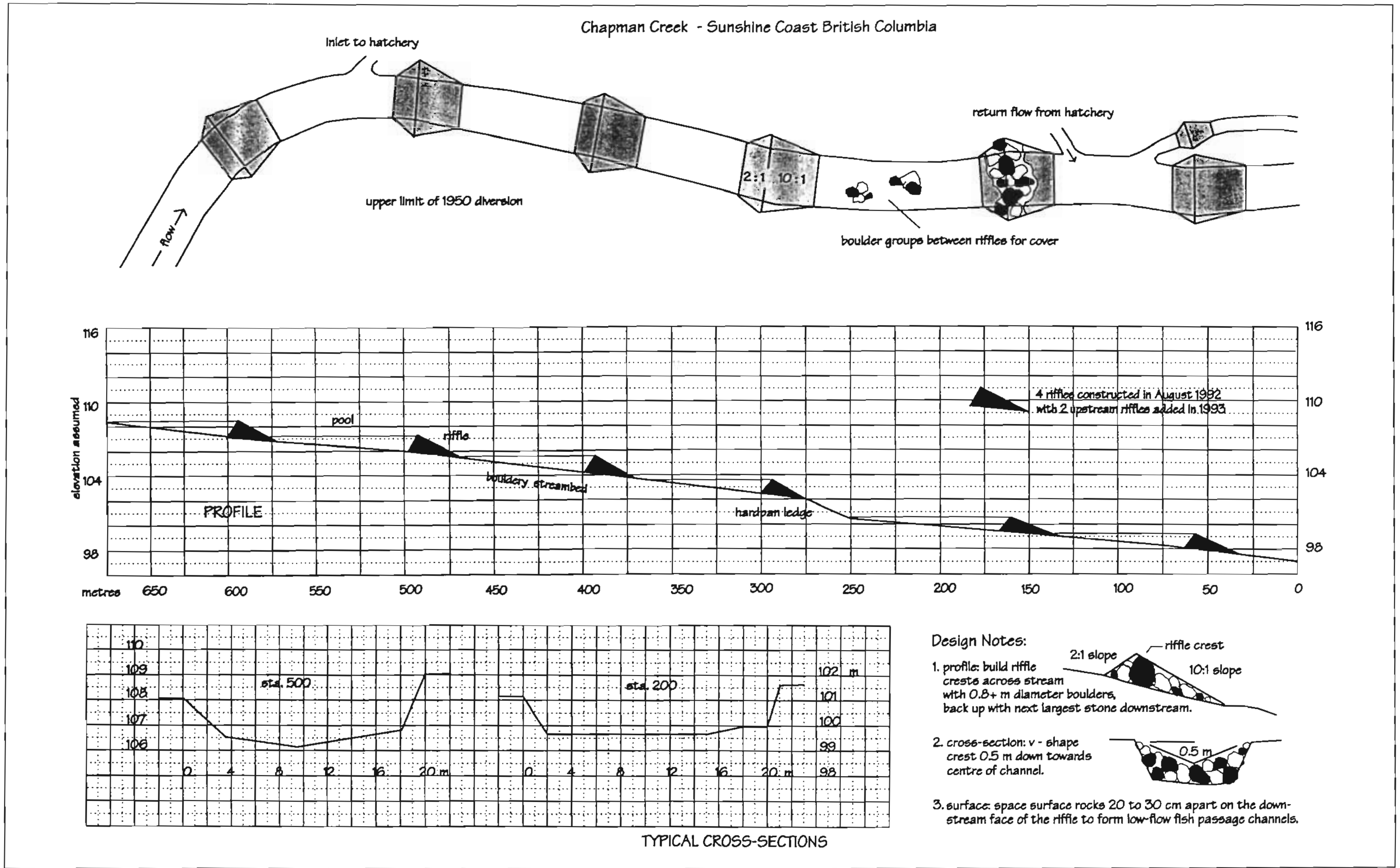


Figure 12-14. Chapman Creek Restoration Project 1992, Strait of Georgia, B.C. Condensed plan and profile drawings for the restoration project undertaken in 1992 and 1993.

STAGE III: HABITAT MONITORING OF PROJECTS

Habitat rehabilitation projects should begin with an assessment and inventory of the biotic community prior to instream work. The selected sampling design should include measurable key variables that will indicate a physical or biological response to pool and riffle rehabilitation, and allow for data comparisons in future monitoring studies (Keeley and Walters 1994; Newbury and Gaboury 1994).

The general steps in a routine monitoring project include:

Pre-project
1. initial survey including quantitative and qualitative evaluation of the existing habitat,
2. evaluation of the biotic community,

Post-project
3. re-evaluation of the aquatic habitat and biotic community following the period of initial adjustment and recruitment,
4. re-evaluation of aquatic habitat following significant flood events.

Monitoring and evaluation procedures for the Watershed Restoration Program are discussed elsewhere but two examples are provided below to demonstrate the results of restoring pool and riffle sequences in two widely different stream types with gradients of 0.3% and 3.0%.

Mink Creek Restoration (sand and gravel bed, 0.3% gradient)

An extensive program of channelization to improve agricultural drainage and reduce spring flooding occurred throughout the Dauphin Lake watershed (Manitoba) beginning in the early 1900's. From 1950 to 1984, a typical cycle of downcutting, bank slumping and channel widening occurred in the channelized reaches of Mink Creek (drainage area 250 km^2). The channel was originally excavated in 1950 with a width-to-depth ratio of 7:1. By 1984, erosion had re-established a more natural width-to-depth ratio of 12.5:1 (Newbury and Gaboury 1993). The extensive erosion had also lowered the bed by 1 m and created a 1 km^2 delta of bed and bank materials at the river's mouth. Channelizing and regrading eliminated many of the pools and riffles used by walleye as spawning and incubation habitats (Fig. 12-15). The characteristic slope of the natural spawning sites (Fig. 12-16A) served as a template for the man-made riffles shown schematically in Fig. 12-16B. The riffles were spaced 100 m apart along the channelized reach (Fig. 12-16C) and constructed (Fig. 12-17) as described in Newbury and Gaboury (1994). The spacing of riffles was 6.5 times the natural bankfull width of the creek. Each riffle was built with 100 m^3 of donated fieldstone and required approximately $1,000 (1985) of machine time to construct.

Large floods (up to 41 $m^3 \cdot s^{-1}$, a 1 in 40-year event) were recorded in Mink Creek in the first five years after the riffles were constructed. A comparison of the 1986 and 1991 profiles indicated that the pools and riffles remained stable (Fig. 12-18) with minimal change in the riffle crest elevations. Pool depths immediately upstream of the riffle structures have decreased since construction as a result of infilling. New pools were maintained at a residual depth of 0.5-0.7 m immediately downstream from the riffles. By 1991, the bankfull widths and depths of the pools had returned to an average ratio of 19:1, re-establishing the historic channel cross-section (R. Janusz, unpubl. data). Increasing the cross-section of the flow in the pools decreased eroding velocities and allowed the stream banks to revegetate and stabilize. Erosion of the streambed and banks upstream of the rehabilitated reach has continued unabated.

Figure 12-15. Mink Creek Walleye Spawning Restoration Project 1985, Central Manitoba. The channelized and unstable reach prior to the addition of rock riffles. The drainage area tributary to the reach is 250 km^2.

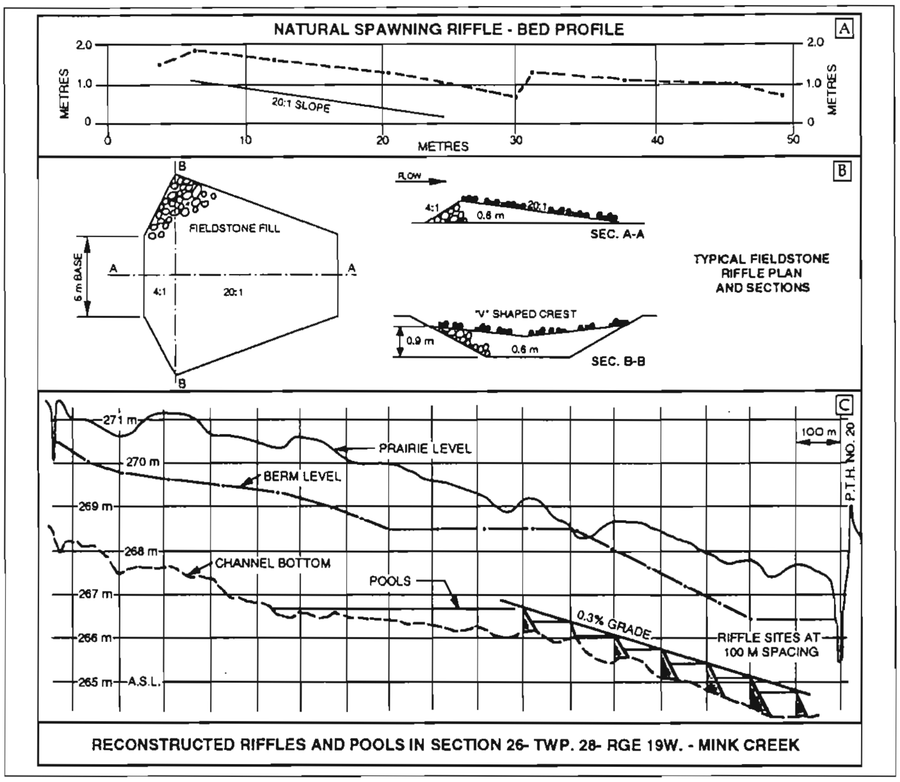


Figure 12-16. Mink Creek Walleye Spawning Restoration Project, Central Manitoba. A natural spawning riffle was surveyed to provide the design template (A). Seven 1 m high riffles (B) were added to the easily eroded bed of the channelized stream (C).

Figure 12-17. Mink Creek Walleye Spawning Restoration Project 1988, Central Manitoba. The channelized reach three years after rock riffles were added. After several bankfull and greater flood events formed downstream pools, the channel has stabilized. The riffles and pools are utilized by spawning walleye.

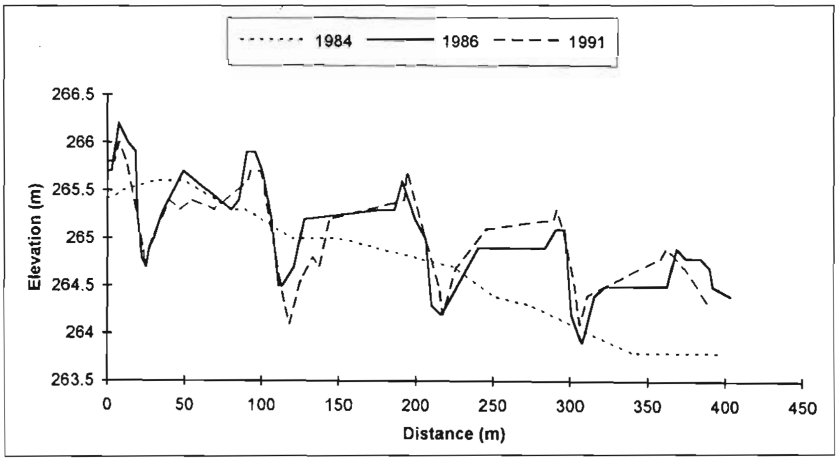


Figure 12-18. Mink Creek Walleye Spawning Restoration Project, Central Manitoba. Detailed profiles of the pool and riffle reach show that the pools that were scoured initially below the man-made riffles have maintained their depth and stability through several years of high-runoff events. The approximate profile of the pre-project channelized streambed is shown as a dotted line.

To evaluate the biological response to the rehabilitation works, walleye reproductive success was monitored by sampling eggs and larvae for six years between 1986 and 1991 (Newbury and Gaboury 1994). From the comparison between the rehabilitated section and isolated, shallow riffle-pool reaches in the channelized section, it was evident that the walleye utilized both habitat reach types for spawning and incubation. Also, the number of larvae produced appeared to be similar from both reaches. Viability of the eggs was similar with live eggs comprising 73 and 68%, respectively, of the samples from all years. These evaluations showed that re-establishing pool and riffle sequences provided both channel stability and fish habitat. As a viable rehabilitative tool, restoring pool and riffle reaches was adopted as a prerequisite to riparian restoration activities that are now being undertaken on all channelized Dauphin Lake tributaries.

Oulette Creek Restoration (cobble and boulder bed, 3% gradient)

The lower 0.5 km reach of Oulette Creek (drainage area 5.6 km^2) was diverted to the western and northern edge of its alluvial fan in west Howe Sound, B.C. in 1978 (Fig. 12-1) to create space for a sawmill and dry-land log sort with an offshore booming ground. The profile of the diversion channel was broken into 100 ft steps with alternating single log and single row boulder drop structures (Fig. 12-19). Channel downcutting was rapid (0.7 m in 2 years) in the unprotected bed below the drop structures where the energy of the flow was concentrated (Fig. 12-19). In 1994, the Oulette Creek diversion was reconstructed by adding 12 riffles to the channel, one at each of the old drop structure sites (Fig. 12-20). Initially, the reconstructed steps in the channel profile formed 1 m deep pools above the riffles. The energy in the drop was dissipated over a 10:1 boulder riffle leading into the next pool downstream. The spacing of the pools and riffles is 30.5 m, approximately 4.5 times the natural stream width of 7 m measured above the diversion (Fig. 12-21). Rock was hauled to the stream bank beside each riffle site from a nearby quarry prior to construction in the channel. The boulder sizes ranged from 0.5 m to 1 m in diameter. All of the riffles were built in 25 hours with a track-mounted Hitachi 220C backhoe working directly on the streambed. Funding (approximately $10,000, 1994) and equipment were provided by Terminal Forest Products, Langdale, B.C. The total volume of rock used for all 12 riffles was approximately 250 m^3 at a unit cost for hauling and placing of $\$35 \cdot m^{-3}$. The cost per riffle including design and surveys was approximately $1,000 (1994).

Figure 12-19. Oulette Creek 1982, Howe Sound, B.C. In the first three years following channelization, the single log drop structures added to the uniform channel were undercut and the single-line boulder drop structures were buried in deep scour holes formed immediately below the structure crests. There were no shallow downstream riffle slopes to convey the flows away from the toe of the structures.

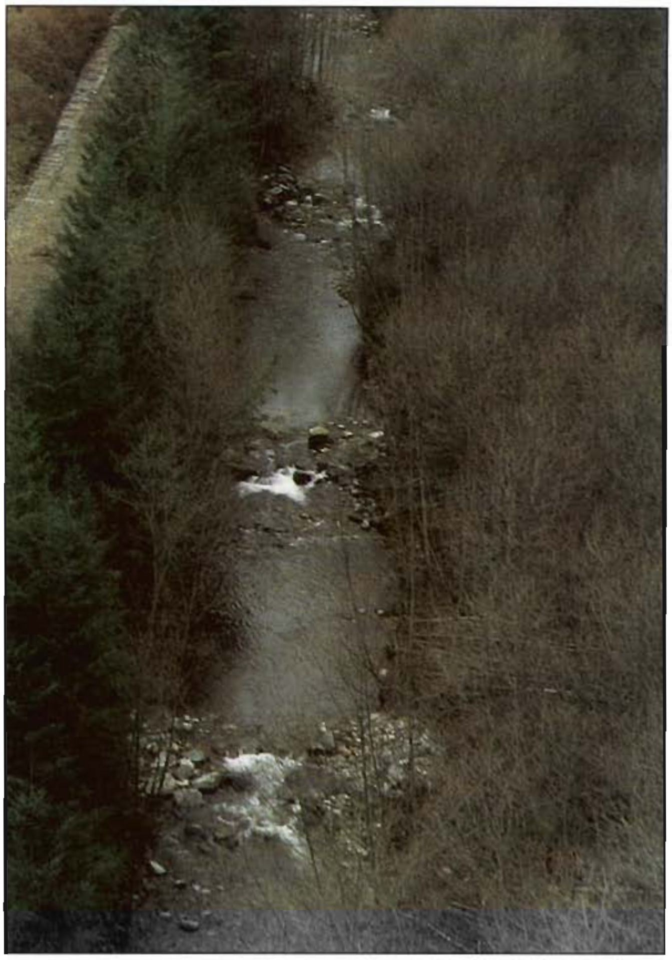


Figure 12-20. Oulette Creek 1994, Howe Sound, B.C. Rock riffles have been added to the former drop structure sites. In the ensuing 16 years, the riparian zone has revegetated with firs (planted), alders, maples and a shrub understory.

In 1994/95 pools up to 1.5 m deep were formed below the constructed riffles by midwinter bankfull flood flows of 17 $m^3 \cdot s^{-1}$. In the summer of 1995, minor adjustments were made to the surface rocks in several riffles, logs and boulder clusters were added to pools, and two floodplain ponds were excavated to augment overwinter rearing habitat. Gravel infilling immediately above the riffles and on the margins of the pools started at the upstream end of the restored reach and spread downstream to all of the pools by 1996.

Fish population data were collected from representative sample sites for each habitat unit before and after restoration (Bates et al. 1996 in prep.) by electrofishing enclosed sample areas using the multiple pass and total removal method. The channelized reach was dominated by riffles and shallow glides which accounted for 83% and 90% of the available habitat in 1993 and 1994 (pre-restoration) (Fig. 12-22). Restoration shifted the pool-riffle ratio immediately with pools increasing to 70% of the existing habitat (Fig. 12-23). In the ensuing year after several bankfull flood events, the habitat consisted of 51% pools and 49% riffles (Fig. 12-24).

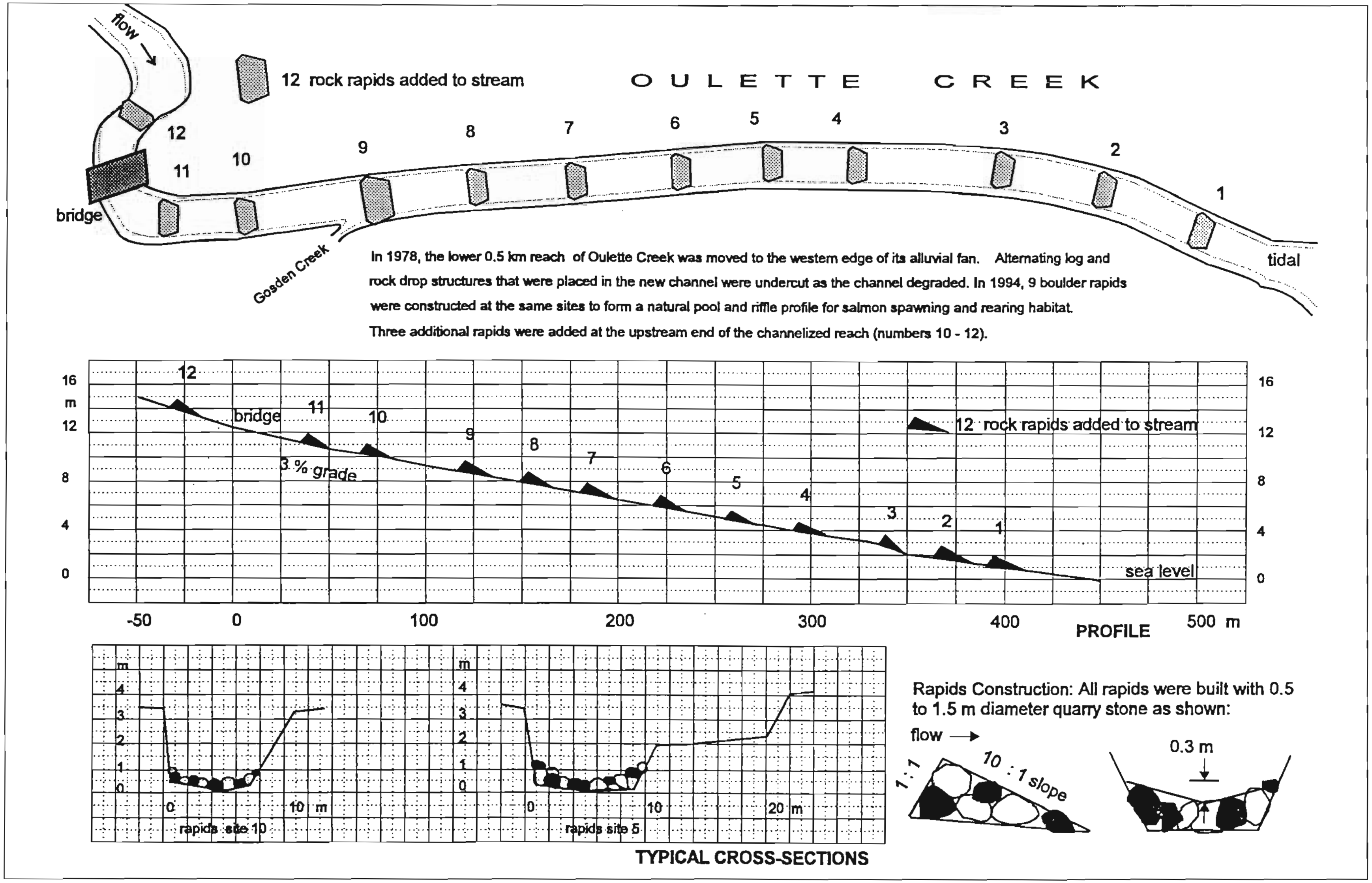


Figure 12-21. Oulette Creek 1994, Howe Sound B.C. Condensed plan and profile drawings for the restoration project undertaken in 1994.

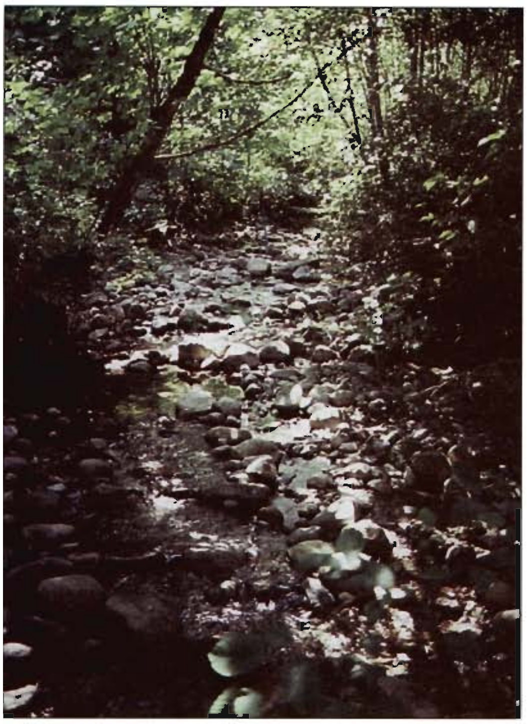


Figure 12-22. Oulette Creek 1993, Howe Sound, B.C. The channelized reach degraded approximately 1 m between 1978 and 1994, developing a uniformly sloping bed of large cobbles with limited hydraulic and habitat diversity.

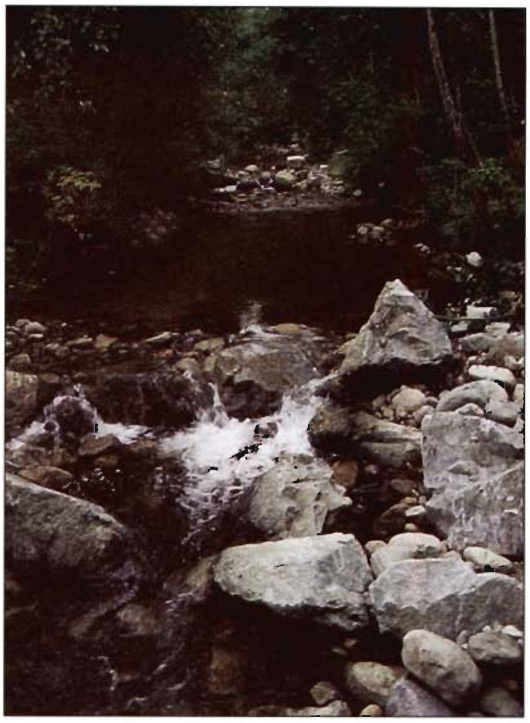


Figure 12-23. Oulette Creek Restoration Project 1994, Howe Sound, B.C. The channelized reach following the addition of rock riffles. Shallow gravel bars deposited in the pools are utilized for spawning. Juvenile fish have occupied the deeper sections. The habitat is now equally distributed between riffles and pools.

The total area of available habitat in 1995 increased by 10% from the 1994 (pre-restoration) value. Specific habitat change was greater, with productive pool habitat increasing by 450% from 1994 (pre-restoration) to 1995. Carrying capacity of the restored stream also appears to have increased. Calculated biomass per unit area ($g \cdot m^{-2}$) for all salmonid species increased after restoration suggesting immediate recruitment by fish to the new habitat from upstream reaches and a shift in species and/or age class structure. This increase resulted in a larger total biomass supported in the restored section. The most notable increase (540%) occurred in age 1+ steelhead and cutthroat trout (Fig. 12-25). Density results show a decrease in the post-restoration stream for all species followed by an increase one year later. Although densities of fry decreased, actual fish numbers increased as the species and age class composition shifted.

These results are consistent with those reported elsewhere in coastal B.C. where the incidence of pools and boulder cover were restored (Ward and Slaney 1979, 1993b), although maximum responses would be expected in the abundance of juveniles surviving through the winter freshet.

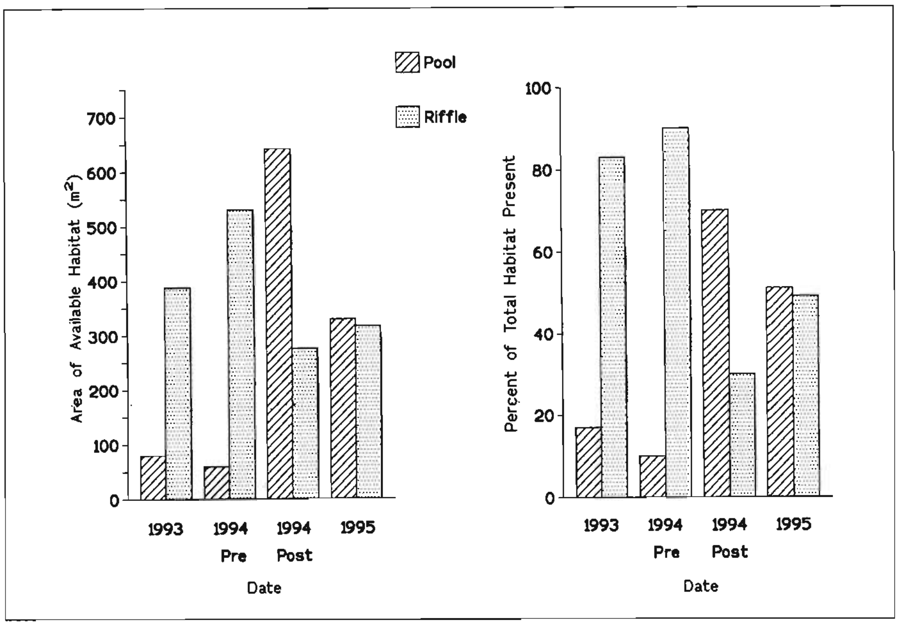


Figure 12-24. Available habitat (pool and riffle) in the restored section of Oulette Creek expressed as area available (m^2) and percent of the total available habitat.

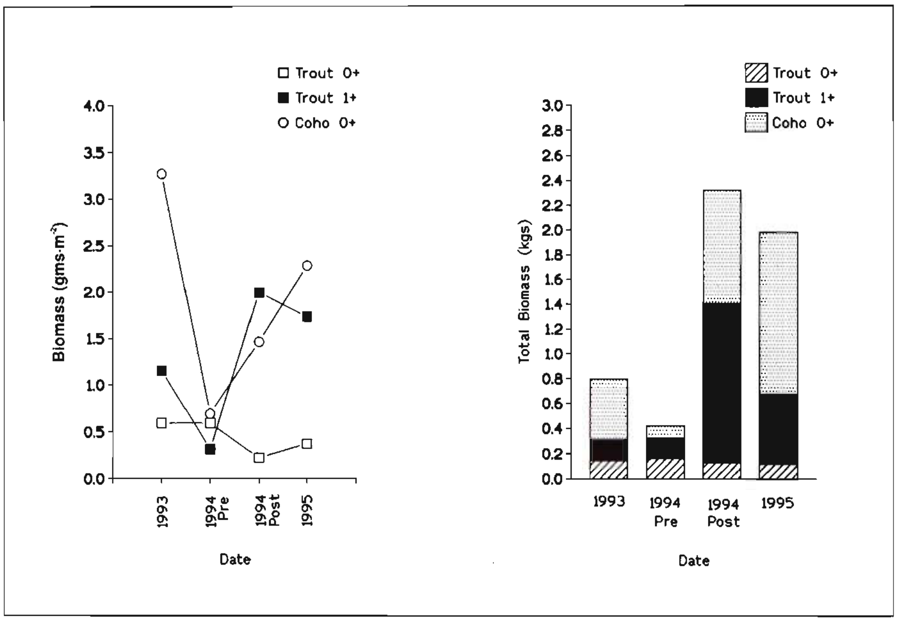


Figure 12-25. Salmonid biomass estimates in the restored section of Oulette Creek expressed per unit area (m^2) and total biomass of rearing salmonids pre- and post-restoration.

Chapter 13

Accelerating Recovery of Stream, River and Pond Productivity by Low-level Nutrient Replacement

Ken I. Ashley[1], Pat A. Slaney[2]

BACKGROUND

The addition of nutrients to freshwater ecosystems has received a considerable amount of research attention in the Pacific Northwest. Research was initially focused on eutrophication concerns (e.g., Lake Washington, WA), then on sockeye enhancement in large lakes (e.g., Great Central Lake, B.C.) and most recently on the process of "oligotrophication" in lakes and streams because of management agency interest in the role of marine-derived nutrients in maintaining the productivity of anadromous salmon stocks in oligotrophic watersheds. Concerns that salmonid stocks in general are on a downward trend due to combined fishing pressure and past forest harvesting practices, as well as impacts of industrial developments such as hydroelectric reservoirs as nutrient "sinks", has contributed to the strong regional interest in the efficacy of stream and lake fertilization as an ecosystem restoration technique. Although research on limiting nutrients has been conducted in Alaska since the 1950's, and B.C. since the early 1970's, the Watershed Restoration Program has accelerated research and development of innovative fertilization-related technologies including patented slow release fertilizer formulations and state-of-the-art liquid fertilizer application systems to replace nutrients. Results of research studies on fertilized streams confirm a strong growth response in fish populations. More recent research on the role of salmon carcasses as ecologically important sources of marine-derived carbon and nutrients for aquatic and terrestrial biodiversity (Schuldt and Hershey 1995; Willson and Halupka 1995; Bilby et al. 1996) places some urgency in rebuilding spawner escapement to historical levels in the long term (Larkin and Slaney 1996), and in the short term to replace carcass-derived nutrient influxes until stocks recover. This chapter reviews the ecological linkages between anadromous salmon and the productivity of freshwater fish habitat in the Pacific Northwest and outlines the applied aspects of stream, river and pond fertilization as currently practiced in British Columbia.

SCIENTIFIC RATIONALE

Indices of nutrients, including dissolved solids, have often been reported as positively correlated with salmonid standing crop (McFadden and Cooper 1962; Egglishaw 1968). However, inorganic fertilization of oligotrophic streams as a means to increase the invertebrate food supply in order to increase growth and abundance of salmonids has received only limited attention as a potential habitat restoration or mitigation technique (Hall and Baker 1982). This historical neglect likely arises from confusion about the role of allochthonous and autochthonous energy flow in forested stream ecosystems (France 1995), and regardless of evidence that primary production supports food webs in larger streams (Minshall 1978). Also, perhaps a

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tarnished history of cultural eutrophication of waters, especially lakes in eastern North America and western Europe delayed research on nutrient limitation of the productivity of stream ecosystems in spite of an early study that indicated inorganic fertilization could increase salmonid production by stimulating aquatic insect growth (Huntsman 1948). Pond fertilization, for the purposes of restoring salmonid stocks, has rarely been conducted in the Pacific Northwest. However, in the southeastern United States, fertilization of farm ponds has long been regarded as standard practice for increasing the aquacultural yield of fish due to close historical linkages with the agricultural community (Boyd 1982).

Food abundance functions through territory size as a major factor affecting the growth and abundance of salmonids, and thus the carrying capacity of streams (Slaney and Northcote 1974). In ponds, once other limiting factors have been satisfied, fish yield is strongly influenced by the availability of inorganic phosphorus and nitrogen (Boyd 1982). Stream fertilization also influences juvenile salmonid abundance through size-related effects on overwinter and marine survival. Small increments in juvenile and smolt size result in significant increases in overwintering (Scrivener and Brown 1993) and ocean survival (Ward et al. 1989) respectively (Figs. 13-1A and 13-1B). Hence, resident and anadromous salmonid abundance can be strongly influenced by stream productivity. Controlled seasonal applications of limiting nutrients, which can be readily reversed, should be beneficial to restoring the productivity of fish habitat of oligotrophic rivers, streams and ponds, which have been negatively impacted by past forest harvesting practices in combination with intensive fish harvesting.

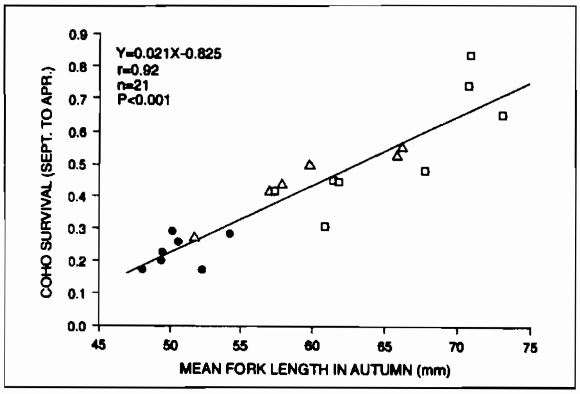

Figure 13-1A. The size of 0+ coho salmon for 1970 to 1990 and its relationship with their overwinter survival in Carnation Creek, B.C. Dots, triangles, and squares represent pre-logging, logging and post-logging years respectively (Scrivener and Brown 1993).

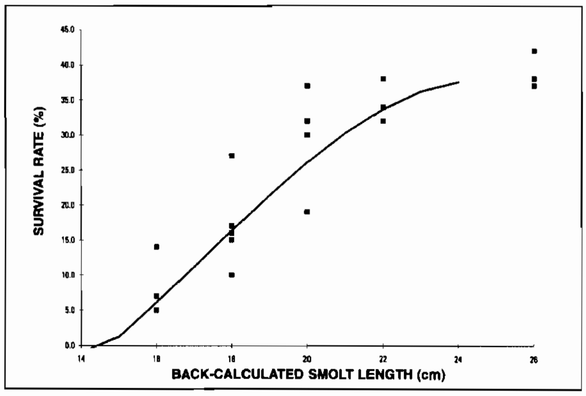

Figure 13-1B. Relationship between the marine survival of steelhead smolts and their mean length upon emigration from the Keogh River, B.C. (Ward et al. 1989).

Role of Nutrients in Salmonid Food Chains

In the North Pacific, aquatic scientists have long theorized on the importance of sockeye salmon carcasses in maintaining the productivity of oligotrophic nursery lakes. In the 1950's, pioneering whole-lake fertilization experiments were conducted in Alaska to test the hypothesis that commercial overharvesting of returning salmon could decrease the productivity of nursery lakes due to interception of the phosphorus supply. This hypothesis was re-examined in the 1960's with the experimental fertilization of Great Central Lake, which evolved into the current fertilization program of sockeye salmon nursery lakes in B.C. (Stockner and MacIsaac 1996) and

Alaska. More recently, fertilization has been used to offset the effects of "oligotrophication" in lakes and reservoirs following impoundment (Milbrink and Holmgren 1988) and/or introduction of *Mysis relicta* and has resulted in significant increases in plankton and fish abundance (Ashley et al. 1997). In recent years, convincing evidence obtained from stable isotope (^{15}N and ^{13}C) analysis of phytoplankton, zooplankton and sockeye (juveniles, adults and spawners) has confirmed the hypotheses of the previous four decades and quantified the importance of marine-derived nitrogen and carbon, and by inference, phosphorus, in lacustrine food webs (Kline et al. 1993).

Given the regional and historical perspective on the importance of nutrients derived from salmon carcasses in lacustrine food webs, researchers in Alaska and British Columbia experimented with adding inorganic nutrients to oligotrophic streams in an attempt to increase periphyton production at the base of the food chain (Stockner and Shortreed 1978; Peterson et al. 1985; Perrin et al. 1987), and thereby insect growth and abundance (Peterson et al. 1985; Johnston et al. 1990; Mundie et al. 1991), and ultimately the growth of steelhead trout, coho salmon (Slaney et al. 1986; Johnston et al. 1990), and Arctic grayling (Deegan and Peterson 1992). Stream fertilization has been shown to induce migrations of lacustrine fish into embayments to take advantage of the increased production of aquatic organisms (Milbrink and Holmgren 1988). Stable isotope (^{15}N and ^{13}C) analysis of stream periphyton, insects and juvenile salmonids has also been used recently to quantify the importance and pathways of marine-derived nitrogen and carbon, and logically phosphorus, in riverine food webs. Bilby et al. (1996) found that returning salmon spawners contributed up to 40% of the nitrogen and carbon content of juvenile salmonids in small streams, in addition to significant contributions to the N content of riparian vegetation and N and C content of epilithic organic matter and aquatic macroinvertebrates. Similarly, Schuldt and Hershey (1995) also provided evidence that carcasses from a small run of chinook salmon could influence nutrient concentrations and periphyton accrual in stream ecosystems.

Productivity and Nutrient Status of Coastal and Interior Waters

The productivity of British Columbia's rivers, streams and ponds is primarily a function of the watershed's underlying bedrock geology, as modified by the topography and precipitation regime, and varies considerably as B.C. has the greatest physiographic diversity of any Canadian province. Pioneering regional surveys by Northcote and Larkin (1966) demonstrated the linkage between underlying geology, total dissolved solids content of lakes and standing crops of plankton and fish, and identified a minimum of twelve limnological regions in B.C. (Fig. 13-2). As a general rule, productivity and nutrients tend to be lower in coastal waters as the underlying geology is mainly erosion-resistant granitic rocks. The interior plains, except for the northeast, are comprised mainly of unmetamorphosed sedimentary and volcanic rocks, hence interior rivers and streams usually have higher productivity and nutrient concentrations, although there are many examples of nutrient deficient streams in the interior.

For example, many coastal streams (e.g., Adam River, Big Silver Creek, Keogh River) usually have soluble reactive phosphate (i.e., SRP) concentrations $< 1\ \mu g \cdot L^{-1}$ (i.e., parts per billion) and adequate dissolved inorganic nitrogen (i.e., DIN $>20\ \mu g \cdot L^{-1}$), while some interior streams (e.g., Blackwater River) have $27\ \mu g \cdot L^{-1}$ P and $< 5\ \mu g \cdot L^{-1}$ nitrate. Rivers which connect two or more physiographic regions, may exhibit blended nutrient regimes as a ratio of their respective watershed areas and water yields. Thus, it is possible to have a productive system on the coast (e.g., Dean River) as the majority of the nutrients are derived from an interior watershed. Similarly, lake-headed systems can significantly modify downstream nutrient regimes owing to the uptake and retention of nutrients by the lake, although this is compensated somewhat in the immediate outlet zone due to washout of lake seston. For example, the Nechako River, which flows across the interior is both N- and P-limited, due to its large coastal watershed and headwater lake/reservoir, while the Blackwater River is N-limited due to the presence of headwater lakes and high natural concentrations of phosphorus.

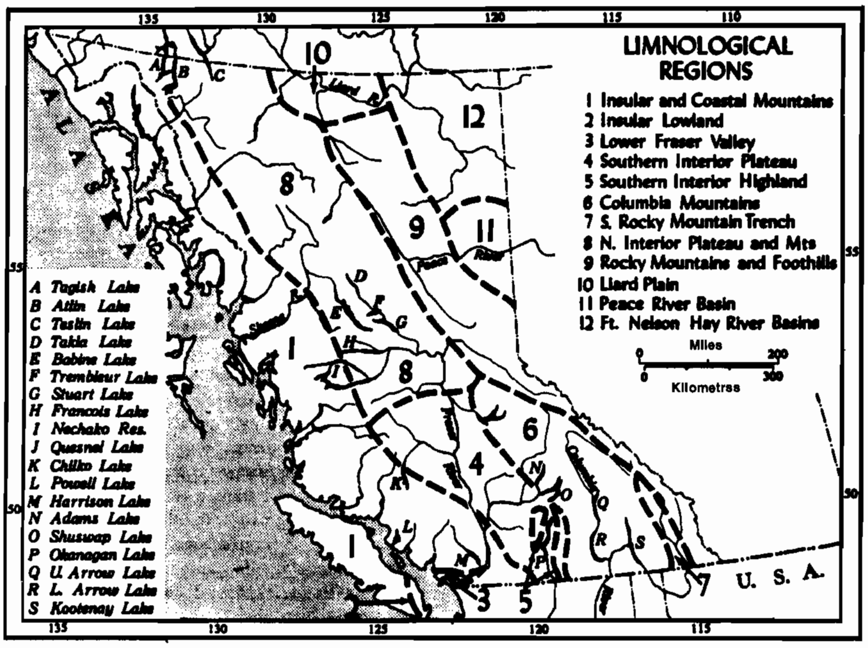

Figure 13-2. Limnological regions of B.C. and lakes with surface area > 100 km^2 (Northcote and Larkin 1966).

The underlying nutrient regime of a system can also be significantly modified by the biogenic importation of marine-derived nutrients by anadromous salmon, and this process likely played a role in the evolution of salmonids. Since oceans are typically more productive than freshwater environments in temperate and polar latitudes, and migratory behaviour can be correlated to latitudinal gradients in resource availability, anadromy likely evolved to capitalize on this productivity differential. The selective advantage gained by migrating to a more productive oceanic environment could be expressed in the freshwater environment via increased body size, fecundity, upstream migratory capability, nest guarding and ultimately the return of marine-derived nutrients to the natal system where current and future generations could benefit from the resultant increase in freshwater productivity through direct consumption and remineralization of the carcasses.

Nutrient Cycling and Spiralling

In streams, the unidirectional flow of water downhill displaces nutrients considerable distances downstream as nutrients cycle or "spiral" through the biota (Mulholland 1996). Experiments involving radioactive $^{32}PO_4$ applications to streams have confirmed that spiralling does occur, and that the distance travelled is dominated by the water component (i.e., water velocity). Spiralling distance may be reduced by increasing the uptake of nutrients from the water. For example, filter feeding invertebrates, through capture of seston may impede downstream transport of organic matter and effectively reduce spiralling distance (Minshall et al. 1985). In addition, some nutrient cycling does take place within the boundary zones created by benthic algae that does not involve downstream displacement, and hence is an alternative pathway to nutrient spiralling (Mulholland 1996). Evidence from river fertilization experiments indicates that increased periphyton (and presumably heterotrophic microbial) biomass can extract sufficient nutrients from the water to shift P-limited systems to N and P co-limitation, hence spiralling length has likely been reduced by increasing the biomass and effective nutrient uptake capacity of the biological community (Slaney et al. 1994a). A practical aspect of spiralling theory involves determining the most efficient placement of nutrient dispensers on a river. Fertilization experiments conducted on the Nechako River observed elevated periphyton accumulations 50 km downstream of the nutrient addition site; hence nutrients can be transported significant distances in larger rivers (Slaney et al. 1994a).

IMPACTS OF ENVIRONMENTAL DISTURBANCES ON NUTRIENTS AND SALMONIDS

Before the arrival of European settlers in British Columbia, salmonid stocks were likely at the natural carrying capacity of their respective environments, and fluctuations in climate would have likely been the principle variable influencing their distribution and abundance. Recent studies have concluded that climatically driven variations in ocean productivity can exert a significant effect on the marine survival of salmonids inhabiting the North Pacific (Beamish and Bouillon 1993). The first large-scale human impacts on salmonid stocks began with the onset of industrialized fishing and logging in the mid-19th century. B.C. commercial salmon catches routinely exceeded 20,000 tonnes by 1896 and catch is thought to have peaked during the Fraser River 1899-1902 sockeye cycles, despite a lack of modern electronics and fishing gear. These two industries, acting in concert, began to influence the historical distribution and abundance of salmonids by intensive fishing and habitat disruption, thus initiating a subtle and little-understood negative feedback loop on freshwater productivity, now over a century in progress, that is likely increasing in significance as the abundance of most wild stocks, as indicated by escapement records, continues to decline (Larkin and Slaney 1996). Most recently, an independent scientific review of anadromous salmon and trout in B.C. and the Yukon indicated 624 stocks were at high risk, 78 were at moderate risk, 230 were of special concern, and 142 stocks had been extirpated in this century (Slaney et al. 1996). In addition, 43% (4,172) of the stocks were unable to be classified due to an absence of reliable data. Habitat degradation associated with logging, hydropower and urbanization were responsible for most of the 142 documented stock extinctions (Slaney et al. 1996).

The impacts of forest harvesting activities on stream ecology and salmonid life histories are extremely complex (Hartman et al. 1996), and the resulting impacts on terrestrial and aquatic organisms dependent on salmonids are equally complex and still being unravelled with potentially far-reaching implications. For example, only in the past decade has the presence of large woody debris (LWD) been recognized for its importance in establishing stream channel morphology and habitat complexity. As described in Chapter 8 by Cederholm et al., LWD is now recognized as being important in retaining carcasses of spawned salmonids; thus ensuring their presence for terrestrial scavengers, aquatic vertebrates and invertebrates, and eventual decomposition and recycling of nutrients within the stream and riparian ecosystem (Bilby et al. 1996). Cederholm et al. (1989) compared the retention of coho carcasses in small logged and pristine old-growth forest streams in the Olympic Peninsula (Washington) and observed that carcasses rarely moved further than 600 m downstream and that large and small organic debris were the most important determinant of instream retention. Cederholm et al. (1989) concluded that the capacity of streams and rivers to retain salmon carcasses has been greatly reduced by a variety of human activities, including splash dams, channelization, debris removal and deforestation.

Thus, in the time span of only 100 years, wild salmonid stocks in British Columbia have gone from a relatively pristine state to one of numerous extinctions and moderate-to-high risk status for hundreds of stocks, as well as declining trends in escapements in most regions of south coastal B.C. Only enhanced or productive stocks are exceptions, and these are in the minority (Larkin and Slaney 1996). Although a variety of well-documented human impacts are responsible, a poorly understood interactive effect of large-scale forest harvesting in concert with intensive fishing has likely played a key role via a subtle negative feedback loop of decreased habitat suitability and reduced salmon escapement, thus causing further reductions in the influx of marine nutrients and incremental reductions in freshwater productivity. In unenhanced streams, wild stocks already in decline are likely to decrease further in this negative feedback loop because of lessened biological productivity and the size-dependent survival of stream rearing salmonid species (Larkin and Slaney 1996). The cause of the depressed sockeye escapements to Karluk Lake, Alaska (5.6 million annual escapement in the 1890's to 0.5 million for the past 35 years) may be largely explained by reduced nutrient influx and subsequent reductions in lake productivity. Lake fertilization in combination with modified harvest strategies has been suggested as the best option for resolving this century-old puzzle (Koenings and Burkett 1987). A detailed time-series, mass balance analysis of marine nutrients suggests the phosphorus content of Karluk Lake could have been reduced over several decades due to overfishing and reduced marine nutrient influx. This "oligotrophication" threat, although more subtle than the well-known negative environmental and fisheries impacts caused by excessive nutrient loading (i.e., cultural eutrophication), is equally threatening to freshwater fish stocks and should be taken seriously (Stockner and MacIsaac 1996).

PRINCIPLES OF FERTILIZATION: NUTRIENT REPLACEMENT

The sound premise behind river, stream and pond fertilization is to provide an interim supply of nutrients until the ecosystem recovers to its historical, more productive state. Therefore, a successful fertilization project is one in which external nutrient additions can eventually be reduced or discontinued as natural nutrient inputs from riparian vegetation and anadromous salmonids gradually recover. From a watershed perspective, ecosystem recovery requires restoration of several interrelated components: (1) stabilization of upslope erosion and/or reduction in sediment inputs from hillslopes, gullies and roads; (2) stabilization of river channels; (3) restoration of large woody debris and other structural elements in the channel in the short term; (4) regrowth of a riparian mix of deciduous and conifers with generation of mature conifers to supply new large woody debris (1-2 centuries) into the stream/river channel; and (5) rebuilding of wild stock escapements (Slaney and Martin 1997). The degree to which nutrient additions can be reduced is also dependent on some key external factors, namely variations in ocean productivity and sustainable management of the commercial fishery to allow sufficient escapement of spawners. Therefore, fertilization should be viewed as an interim measure that is most effective if all components of ecosystem recovery and key external factors (e.g., overfishing) are achieved in a coordinated fashion.

In situations where the degradation of the upslope areas or main river channel is too severe and unlikely to recover for several decades, an appropriate rehabilitation strategy is to emphasize salmonid production from off-channel habitats (Slaney and Martin 1997). Under this scenario, fertilization can be used to improve the resource benefits of recently constructed off-channel restoration projects (see Chapter 7). For example, reopened side channels, new side channels, overwintering ponds, and side channel-overwintering pond complexes can often benefit from low-level fertilization as these ecosystems have not been the recipients of any marine-derived nutrients for many years (in the case of relict side channels) or never had any anadromous nutrient loading (as in the case of newly constructed channels and ponds). In situations where riverine habitat is permanently lost, as in the case with reservoir impoundments, fertilization may be used as a mitigation technique to increase the productivity of the remaining habitat. Under these circumstances, fertilization may be viewed as mitigative, but could continue on a permanent basis for as long as the original habitat is inundated by the reservoir impoundment.

COST EFFECTIVENESS OF STREAM AND RIVER FERTILIZATION

As previously discussed, retention of salmon carcasses in the long term is unlikely to be achieved without restoration of large woody debris in streams. Similarly, fertilization, although likely one of the more cost-effective watershed restoration techniques currently available, must be integrated with off-channel or instream structure techniques to ensure sufficient salmonid habitat is available to improve overwinter survival. Many restorative and engineering techniques cost several tens of thousands of dollars per km (Slaney and Martin 1997). Although these measures can function for a few decades, annual addition of nutrients to the upper Salmon River (Vancouver Island), where large boulder habitat has been maintained, was effective over a large distance and at lower cost (i.e., 10-25%) relative to other potential habitat restoration techniques. Thirty kilometers of river were fertilized in 1992 for about $2,000 in fertilizer, and $2,500 in 1993. The cost of the fertilizer was $67-83 per km, including transport and labour, and on a routine scale, could be carried out annually for about $160-180 per km (the latter with urea-ammonium nitrate addition at the uppermost station for one month as in 1993; Slaney et al. 1994b). The effective distances on fish size, based on locations of a third (1990) and fourth (1992) tank, were km 10 to km 27 in 1990 and km 15 to at least km 27 in 1992, for effective distances of 17 and 12 km, or 15 km on average (Fig. 13-3). The response in 1992 dissipated rapidly thereafter, with average salmonid weights at km 38 and km 50 similar to the upstream control sites. Thus, recycling or spiralling of nutrients downstream from km 38 to km 50 was not indicated by fish size, which corresponds with low chlorophyll *a* and low insect biomass at km 38 (Fig. 13-4).

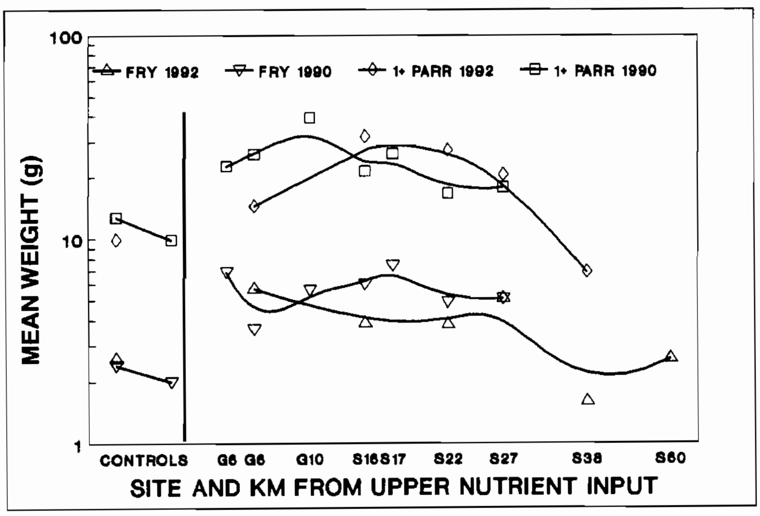

Figure 13-3. Trends in mean weights of rainbow (juveniles and adults) and steelhead trout (juveniles) within control, fertilized and downstream sampling sites in Grilse Creek and the Salmon River during 1990 and 1992. Spatial controls were located in the Upper Salmon River, G designates Grilse Creek and S the mainstem of the Salmon River, with distances in km from the upper fertilizer tank at Grilse Creek (from Slaney et al. 1994b).

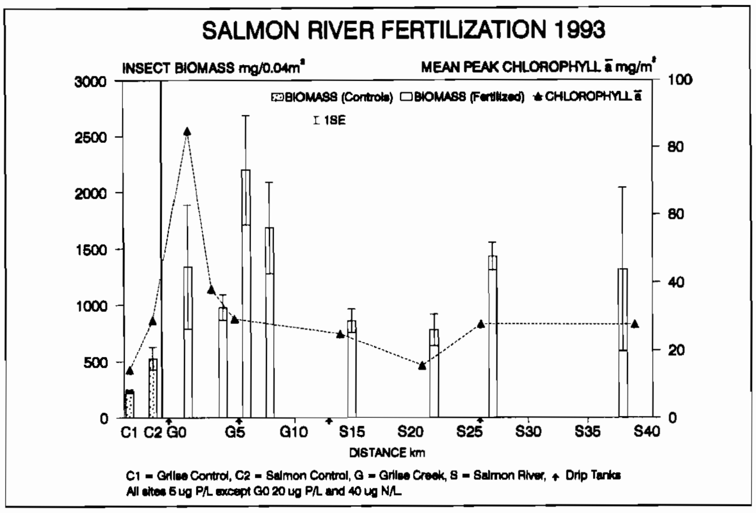

Figure 13-4. Mean peak chlorophyll *a* and mean benthic insect biomass in gravel colonization baskets placed in two control sections (Upper Grilse Creek and Upper Salmon River) and eight fertilized sections of Grilse Creek (4 sites) and within the Salmon River (4 sites) in 1993. (Vertical bars are 1 standard error; n = 6 per site) (from Slaney et al. 1994b).

Larger streams with greater mean summer flows require proportionately more fertilizer per linear distance to achieve the desired target nutrient loading. For example, on-site fertilizer costs for Big Silver Creek (mean summer flow of 23.7 $m^3 \cdot s^{-1}$; Harrison Lake) cost \$4,500 in 1995 (\$3,250 for ammonium polyphosphate and \$1,250 for delivery; Toth et al. 1996) for an effective distance of 13 km and base fertilizer cost of \$346 per km. Fertilization of the remote Mesilinka River (Williston Reservoir), with a mean summer flow of up to 100 $m^3 \cdot s^{-1}$, cost about \$20,000 per year (\$9,000 for ammonium polyphosphate, \$6,000 for urea-ammonium nitrate and \$5,000 for delivery). The effective treatment distance was approximately 35 km, hence base fertilizer costs were approximately \$571 per km.

Unfortunately, there are relatively few case studies where fish responses to stream fertilization have been adequately documented. Fertilization of 30 km of the Keogh River resulted in an average 62% increase in steelhead smolts, and about a 50% increase in adult steelhead or an additional 15 adults per km (Slaney and Ward 1993) plus about a 21% increase in coho smolts from the mainstem, although most coho reared mainly in untreated tributaries and lakes in the Keogh watershed. Thus, the cost of a wild steelhead is predicted to be \$11-12 per adult for a stream with a flow of 3-4 $m^3 \cdot s^{-1}$ similar to the Salmon or Keogh Rivers, or \$18-20 per adult at a higher flow of 10 $m^3 \cdot s^{-1}$. In comparison, the cost of producing a hatchery steelhead smolt is \$1.50 to \$2.00, and with an average survival of 4%, the cost of a hatchery steelhead ranges from \$38 to \$50 per adult. However, with the 50% lower survivals now being observed, the costs would double. Confirmation of the cost effectiveness of fertilization requires a longer-term commitment than the brief 3 to 4-year treatment at the Keogh River, but provided suitable habitat is present, nutrient addition in infertile streams is likely capable of producing adult wild steelhead at less than half the cost of hatchery fish, without the potential negative effects of the hatchery environment. In addition, fertilization has a number of benefits to non-target animals (e.g., eagles and a variety of carnivores/scavengers) as salmonid escapements increase. These benefits do not factor into the cost-effectiveness calculations but they are important for ecosystem restoration. For example, Cederholm et al. (1989) found that at least 22 different species of mammals and birds depended on salmon carcasses as a food source in Olympic Peninsula streams. This observation underscores the importance of this high quality food source during winter months when alternative food sources may be scarce. Willson and Halupka (1995) emphasize that anadromous salmon function as a "keystone species" for wildlife in the Pacific Northwest and form an ecologically important link between aquatic and terrestrial ecosystems. More recent case studies should provide more definitive evaluations of fertilization benefits.

STREAM AND POND FERTILIZATION STRATEGIES

The fundamental premise behind stream and river fertilization is to provide an interim supply of nutrients until the ecosystem recovers to its historical state. A successful stream or river fertilization project is one in which external nutrient additions can eventually be reduced or discontinued as natural nutrient inputs from riparian vegetation and anadromous salmonids gradually recover. It is important that an assessment of nutrients and biomass of the various trophic levels of the system in question be conducted early in the Level 1 phase. Some stream systems are not nutrient limited and nutrients should not be applied where they are not ecologically warranted. The appropriate provincial agency (i.e., Ministry of Environment, Lands and Parks) must be notified prior to adding nutrients to streams (refer to Chapter 1 for regulatory approvals). In addition, special attention should be directed towards not exceeding Ministry of Environment standards for algal biomass, as 50 $mg{\cdot}m^{-2}$ chlorophyll *a* is the maximum concentration permitted under aesthetic considerations and 100 $mg{\cdot}m^{-2}$ chlorophyll *a* is the maximum for aquatic life in streams (Nordin 1985).

Assessment of Nutrients and Periphyton Biomass Status

The first step in stream and river fertilization is to determine the nutrient status of the system in question. There are at least four nutrient assessment techniques in order of descending complexity: (1) nutrient bioassays to determine nutrient limitation (i.e., floating or streamside channels in which nutrients are applied at known rates); (2) natural or artificial substrates to determine periphyton and invertebrate biomass relative to a known nutrient-limited standard; (3) "**low-level**" water chemistry analysis for soluble reactive phosphorus (SRP) and dissolved inorganic nitrogen (i.e., DIN: NO_3-N + NO_2-N + NH_3-N) during the summer growing season; and (4) the "boot test" in which the general "slippery feel" of natural rocks is qualitatively assessed with a non-skidproof rubber boot during spring to summer. This latter technique is very basic. However, when conducted by an experienced stream ecologist it can be surprisingly informative. Techniques 2 and 3 will form the basis of most nutrient assessments for WRP purposes owing to their relatively low-cost and quantitative nature, while technique 4 will likely be used routinely by experienced individuals during preliminary reconnaissance surveys.

Stream Fertilization With Slow Release Fertilizer

Slow release inorganic fertilizer will likely be the preferred nutrient delivery strategy for most streams and smaller rivers (< 10 $m^3{\cdot}s^{-1}$ mean summer flows) due to the simplicity of once annual applications, no maintenance requirements and low profile vandal-proof design. The key variables are (1) concentration of applied nutrients; (2) nutrient formulation; (3) seasonal timing of nutrient addition; (4) frequency of nutrient addition; (5) location of application sites; and (6) N:P ratio of the fertilizer blend. However, due to the nature of slow release fertilizer, variables (2), (4) and (6) are fixed for any particular blend.

Concentration of Applied Nutrients: Sufficient slow release fertilizer briquettes of the slow (0.5%·d^{-1}) or faster releasing (0.6-1.5%·d^{-1}) formulation (17.5-17.7% initial P content by weight; Mouldey and Ashley 1996) should be added to the system to increase the instantaneous stream SRP concentration to approximately 3-5 μg·L^{-1} assuming that the treatment is going to last for approximately 120 days (0.5%·d^{-1} formulation) or 60 days (0.6-1.5%·d^{-1} formulation). This would be sufficient to treat several kilometers. The calculations required to determine the weight of briquettes are as follows (or see Table 13-1):

(1) P (kg) = flow (m^3·s^{-1}) x 1,000 (L·m^{-3}) x 86,400 (s·d^{-1}) x no. of days x desired conc. (μg·L^{-1}) x 1E-9 (kg·$μg^{-1}$);

(2) Total P_2O_5 (kg) = total P (kg) x 40/17.5 (where 40 = % P_2O_5 of slow release and 17.5 = %P);

(3) Total weight of fertilizer (kg) = total P_2O_5 (kg) x 100/40 x 3 (where 100/40 is P_2O_5 ratio of fertilizer and 3 is an expansion factor **that is subject to revision**).

Nutrient Formulation: The slow release fertilizer product currently in use is magnesium ammonium phosphate ($MgNH_4PO_4·H_2O$) with a formulation of 7-40-0 (N-P_2O_5-K_2O; % by

Table 13-1. Slow release fertilizer requirements (kgs) according to various flows by target soluble reactive phosphate concentrations. Note: assumes 120-day release period).

Target Concentration Mean summer flow (m^3·s^{-1})	3 μg·L^{-1} (2 μg·L^{-1} ambient SRP)	4 μg·L^{-1} (1 μg·L^{-1} ambient SRP)	5 μg·L^{-1} (<1 μg·L^{-1} ambient SRP)
1	533	711	889
2	1066	1422	1777
3	1600	2133	2666
4	2133	2844	3555
5	2666	3555	4443
6	3199	4266	5332
7	3732	4977	6221
8	4266	5688	7109
9	4799	6399	7998
10	5332	7109	8887

weight). Independent analysis indicates this formulation is initially 6.7% N (by weight) and 17.5-17.7% P (by weight), changing to 5.08% N and 14.49% P after placement in water for several weeks (Mouldey and Ashley 1996). Phosphorus in the 7-40-0 is in the form of 100% as orthophosphate, whereas nitrogen is 100% as ammonia nitrogen. This product consists of a metal ammonium phosphate fertilizer combined with a patented binder of Daratak™ XB-3631, which is essentially unpolymerized saran (Pers. comm., B. Rehberg, Vice- President R&D, IMC Vigoro Inc., Winter Haven, Florida) and pressed into briquettes using a patented production process. The product is safe to transport and handle and is available directly from IMC Vigoro. Negotiations are currently underway to establish a local supplier in Abbotsford, B.C. The product is relatively expensive at the moment, i.e., approximately $2,000 U.S. per tonne (t), in small hand-made research batches; however, the price should decrease with larger orders and conversion to automated production processes. Slow release fertilizer blends that contain additional nitrogen or micronutrients can be manufactured if sufficient demand is identified (B. Rehberg, Vice- President R&D, IMC Vigoro Inc., Winter Haven, Florida, pers. comm.).

Seasonal Timing and Frequency of Nutrient Addition: Slow release briquettes are typically applied during the mid-spring (May) to early summer growing season, following the descending limb of the hydrograph for the targeted river or stream (Mouldey and Ashley 1996). The goal is to apply the nutrients early enough in the year to increase periphyton (Fig. 13-5) and the growth and survival of early instars of aquatic insects for salmonids, but not so early that the product is flushed downstream or buried by bedload during freshet events. Briquettes are applied once per year assuming that the treatment is going to last for approximately 120 days ($0.5\%\cdot d^{-1}$ formulation) or 60 days ($0.6\text{-}1.5\%\cdot d^{-1}$ formulation) (Fig. 13-6).

Location of Application Sites: The exact number and spacing of application sites has not been completely resolved as additional research on nutrient spiralling is still required. However, given the preliminary results observed to date, access and the location of riffle areas will likely determine the location and number of application sites. The fertilizer is simply spread in a single layer in riffle zones that are far enough upstream of large pools to minimize the probability of freshet events burying the briquettes in pools (Fig. 13-7). The briquettes are currently applied by hand; however, research is underway to develop a suitable spreader bucket for helicopter application. The current effective distance is approximately 3-5 km based on preliminary results from the Salmon River, B.C., but may be less in smaller streams (Mouldey and Ashley 1996). The fertilizer can be applied at a single site at the upper end of a riffle section, or smaller amounts can be distributed among several riffle sites. A single application site has been used in most treatments. However, in the Salmon River, two sites 4-6 km apart have recently been used and additional sites will be added as slow release briquettes replace the remaining liquid fertilizer drip stations.

Figure 13-5. Periphyton accumulation on rocks above and below slow release fertilizer treatment site on Clear Creek, B.C.

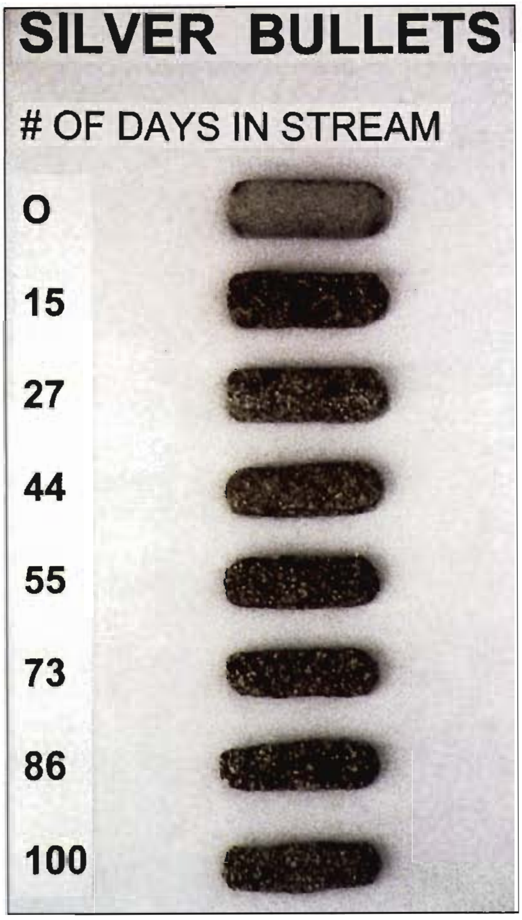

Figure 13-6. Appearance of slow release fertilizer briquettes from Day 0 to Day 100 in a stream.

Nitrogen to Phosphorus Ratios: The current formulation (i.e., 7-40-0) is initially 6.7% N and 17.5-17.7% P by weight (Mouldey and Ashley 1996), hence the N:P ratio (by weight) is 0.38:1. This formulation was selected to obtain the highest proportion of P possible in a slow release product. While the N component is quite low, most oligotrophic streams in B.C. are P-limited and the low N content will not usually be of concern. Slow release fertilizer for use in N-limited rivers or streams will require additional nitrogen content, which is feasible (Pers. comm., B. Rehberg, Vice-President R&D, IMC Vigoro Inc., Winter Haven, Florida) to prevent N:P (atomic weight) ratios from decreasing to less than 10:1 at which point nitrogen may become limiting (Borchardt 1996).

Pond Fertilization With Slow Release Fertilizer

Pond fertilization is a relatively new strategy that is intended to temporarily increase the productivity of off-channel restoration projects (e.g., reopened side channels, new side channels, overwintering ponds and side channel-overwintering pond complexes) until sufficient escapement of anadromous salmonids becomes established. As previously noted, these ecosystems can often benefit from low-level nutrient addition as they have not been the recipients of marine-derived nutrients for many years (in the case of relict side channels) or never had any anadromous nutrient loading (as in the case of newly constructed channels and ponds). The development of slow release fertilizer has stimulated interest in fertilizing ponds due to the simplicity of once annual applications. Salmonid carcasses can also be used to fertilize ponds, providing there is a source of carcasses within the watershed that are available and would not detract from nutrients originally destined for some other stream in the watershed.

Figure 13-7. Slow release fertilizer distributed in riffle zone in Shop Creek, B.C.

The first step in pond fertilization is to conduct a low-level soluble reactive phosphorus (SRP) and DIN analysis of the water in the system during the growing season. SRP concentrations can be quite high (e.g., 5-10 $\mu g \cdot L^{-1}$) in certain groundwater-fed systems, and if SRP concentrations are greater than 3-5 $\mu g \cdot L^{-1}$ then additional phosphorus is not required. Dissolved inorganic nitrogen (NO_3-N + NO_2-N + NH_3-N) is typically not considered to be limiting in ponds due to the general ubiquitous nature of NO_3-N in groundwater and the usual presence of N_2 fixing deciduous trees and their associated leaf litter in off-channel riparian habitats. If the off-channel system is P-limited, and contains allochthonous organic matter that is low in P content, the addition of P should increase the rate of microbial decomposition of the allochthonous material (Peterson et al. 1993).

The next step, if SRP is found to be limiting, is to calculate the volume of the pond and its turnover time (i.e., pond volume divided by inflow volume). Sufficient slow release fertilizer briquettes of the original ($0.5\% \cdot d^{-1}$) or faster releasing (0.6-$1.5\% \cdot d^{-1}$) formulation (17.5-17.7% P by weight; Mouldey and Ashley 1996) should be added to the pond to increase the instantaneous SRP concentration to approximately 2-4 $\mu g \cdot L^{-1}$ assuming that the treatment is going to last for approximately 150 days ($0.5\% \cdot d^{-1}$ formulation) or 75 days (0.6-$1.5\% \cdot d^{-1}$ formulation). For example, a pond 20 m wide by 50 m long by 3 m average depth has a volume of 3,000 m^3. Assuming the turnover rate was negligible (low flow summer conditions), the slow release fertilizer requirement ($0.5\% \cdot d^{-1}$ formulation) for a 3 $\mu g \cdot L^{-1}$ treatment would be as follows:

(1) Volume (3,000 m^3) x 1,000 ($L \cdot m^{-3}$) x desired conc. (3 $\mu g \cdot L^{-1}$) x 1E-9 ($kg \cdot \mu g^{-1}$) = 0.009 kg P;

(2) P (0.009 kg) x 40/17.5 (where 40 = %P_2O_5 of slow release and 17.5 = %P) = 0.02 kg total P_2O_5;

(3) Total P_2O_5 (0.02 kg) x 100/40 x 5 (where 100/40 is P_2O_5 ratio of fertilizer and 5 is an expansion factor **that is subject to revision**) = 0.25 kg total weight of slow release fertilizer.

These calculations demonstrate that very small amounts of nutrients are required. Ponds with higher flushing rates will obviously require more fertilizer per unit volume than slow flushing rate ponds. Loading rates may be reduced by 75% in new channels to prevent excessive accumulation of periphyton while invertebrates are colonizing the system.

The slow release fertilizer briquettes should be spread in the inlet stream and around the shoreline zone within 0.25-0.5 m of the water level, but not placed in soft sediments where they will get buried. If a series of interconnected ponds is being used, then each pond should be individually treated and the briquettes should be placed in the interconnecting stream riffle areas if possible and around the shoreline. The seasonality of the application will depend on the salmonid species present. However, most applications will be likely made in mid-spring in order to stimulate primary and secondary production as long as possible. Care should be taken to not overfertilize, as this results in inefficient use of the nutrients, and may result in dangerously low dissolved oxygen concentrations from decaying algae if the ponds freeze over for an extended period of time.

Salmon Carcass Alternatives to Inorganic Nutrient Addition

Salmonid carcasses (e.g., salmon, kokanee) can also be used to fertilize streams and ponds, providing there is a source of carcasses (typically hatchery or spawning channel) within the watershed that are available and would not detract from nutrients originally destined for some other system in the watershed. Due to valid concerns of disease transfer, carcasses cannot be used outside of their local drainage basin. However, it should be realized that salmon carcasses are approx. 0.325% P and 3.0% N (wet weight) (Stansby and Hall 1965), and that considerably more carcass biomass (54-fold) is required than equivalent P and N loads from inorganic nutrients. For example, 500 kg of slow release fertilizer was applied to Shovelnose Creek in 1995 to obtain a P load of 87.4 kg. The equivalent P load of salmon carcasses would have been approximately 27 tonnes. In situations where stream access is by air only, inorganic nutrients are the only cost-effective nutrient replacement option. For example, 3 tonnes of slow release fertilizer was recently applied to the Cruickshank River and tributaries (Vancouver Island) in 3 hours by helicopter to obtain a P load of 524 kg P. The equivalent P load in salmon carcasses would have been approximately 162 tonnes, and with a lift capacity of 500 kgs (e.g., A-Star), the treatment would have taken 324 trips and several days and would not have been economically or logistically feasible.

The same procedure as above is utilized to calculate amounts of salmon carcasses to be utilized. The P content of the salmon should be considered to be approximately 0.325% (wet weight) (Stansby and Hall 1965) as compared to 17.5-17.7% P for the slow release fertilizer, hence considerably more weight (i.e., 54-fold) of salmon carcasses will be required and careful consideration of the logistics of such applications are required. Salmon should decompose at approximately 1.5%$\cdot d^{-1}$ at a mean water temperature of 4.2°C, and 4.9%$\cdot d^{-1}$ at a mean water temperature of 8.6°C (Minshall et al. 1991).

Stream Fertilization With Liquid Agricultural Fertilizers

Liquid inorganic fertilizer will likely be the preferred nutrient delivery strategy for larger rivers (> 10 $m^3 \cdot s^{-1}$ May to August flows) due to the cost advantage of liquid fertilizer ($230-370 per t) over slow release fertilizer (small research batches are currently $2,000 U.S. per t). A number of interrelated factors must be considered when designing an ecologically-based liquid fertilizer treatment. The six key variables are (1) concentration of applied nutrients; (2) nutrient formulation (i.e., SRP or poly P; NO_3-N, NH_3-N or urea); (3) seasonal timing of nutrient addition; (4) frequency of nutrient addition (i.e., continuous or intermittent); (5) location of application sites; and (6) N:P ratio of the fertilizer blend. All of these factors may be able to exert a significant influence on the community composition and biomass of the resultant periphyton community.

Concentration of Applied Nutrients and Limiting Concentrations: Soluble reactive phosphorus (SRP) concentrations will likely be quite low in coastal stream and river systems with granitic watersheds and high rainfall; however, if SRP concentrations are greater than 3-5 $\mu g \cdot L^{-1}$ during the growing season then additional phosphorus is likely not required. SRP concentrations of 0.3-0.6 $\mu g \cdot L^{-1}$ have been shown to saturate specific growth rates of unicellular periphytic diatoms (Bothwell 1988). However, relative peak biomass continues to increase with SRP additions from 1 to 25-50 $\mu g \cdot L^{-1}$ as the relationship shifts from cellular to community controlled growth rates (Bothwell 1989). Excessive periphyton biomass is reported to occur when SRP concentrations exceed 10 $\mu g \cdot L^{-1}$, therefore, target concentrations of SRP for stream and river fertilization (background plus nutrient additions) are in the 3-5 $\mu g \cdot L^{-1}$ (or parts per billion) range, or approximately 1/3 to 1/2 of potential nuisance concentrations but high enough to be effective over several kilometers. Uptake of SRP is rapid and concentrations are usually < 1-2 $\mu g \cdot L^{-1}$ within a few kilometers. Dissolved inorganic nitrogen (NO_3-N + NO_2-N + NH_3-N) is typically not limiting in non-lake headed systems, however, low-level analysis is still required to determine if seasonal DIN limitation situations exist. DIN concentrations below 20 $\mu g \cdot L^{-1}$ may become limiting (Bothwell 1988), hence minimum target DIN concentrations (background plus nutrient additions) are 20 $\mu g \cdot L^{-1}$. Most of the background DIN will likely be in the form of NO_3-N, as NO_2-N is usually found under anoxic conditions, and NH_3-N is not as mobile as NO_3-N in groundwater and generally undetectable in coastal riverine ecosystems.

Nutrient Formulation: The liquid fertilizers used most frequently in B.C are ammonium polyphosphate (10-34-0: N-P_2O_5-K_2O; % by weight) for phosphorus and urea-ammonium nitrate (28-0-0) as the principle nitrogen source. Phosphorus in 10-34-0 is in the form of 34% as phosphate, and 68% as polyphosphate. Nitrogen in the 28-0-0 (N-P_2O_5-K_2O; % by weight) is in the form of 50% as urea nitrogen, 25% as ammonia nitrogen and 25% as nitrate nitrogen. Due to the 10% (by weight) nitrogen content in the 10-34-0, 3.37 $\mu g \cdot L^{-1}$ of N is obtained for each 5 $\mu g \cdot L^{-1}$ of P added using 10-34-0. These fertilizers are standard agricultural grade fertilizer with extremely minute concentrations of metals when applied to water. They are relatively safe to handle, readily available in B.C. and inexpensive (i.e., approx. $231 per tonne for 28-0-0 and $366 per tonne for 10-34-0 in $1996). A more concentrated form of urea-ammonium nitrate is available (i.e., 32-0-0); however, problems have been encountered with this blend due to "salting out" in storage tanks and this blend is not recommended for use in temperate climates.

Seasonal Timing and Frequency of Nutrient Addition: Nutrients are typically applied during mid-spring to summer growing season (i.e., 3-4 months), following the descending limb of the hydrograph for the river or stream in question. For example, nutrients are applied on the

Salmon River from mid-May until early August (Slaney et al. 1994b) and from late June to early September on the Adam River and Big Silver River depending on the size of the snowpack and runoff regime (Toth et al. 1996). In the Central Interior, nutrient application is typically limited to a relatively short 60-day summer period (i.e., July and August) due to the late spring thaw and extended summer runoff period (Paul et al. 1996). Monitoring at the Salmon River demonstrated that a periphyton response continues for a least one month after cessation because nutrients are stored and cycled within the substrate. Until further research has been conducted, nutrients should either be applied continuously (manual or flow proportional systems) or intermittently at a minimum of 3 times per hour (i.e., every 20 minutes) (pre-programmed systems). Less frequent applications result in localized "spiking" of concentrations to relatively high concentrations that are undesirable (e.g., undesirable species of algae were favoured by 30-minute spiking of nutrients at the Upper Nechako River; Slaney et al. 1994a).

Location of Application Sites: The exact number and spacing of application sites has not been completely resolved as additional research on nutrient spiralling is still required. However, logistical reasons will play a key role in the location and number of application sites due to access requirements for fertilizer delivery and concerns about potential vandalism. On the Salmon River, four application sites were used, 4-6 km apart. A single tank site was located on the Adam River (10 km from the Eve River confluence) (Toth et al. 1997) and Big Silver Creek (13 km from Harrison Lake) (Toth et al. 1996). At the Mesilinka River, two tanks (one for 10-34-0 and one for 28-0-0) were installed at two drip stations, one about 66 km from Williston Reservoir and a second 46 km from the reservoir (Paul et al. 1996). Based on a target concentration of 5 $\mu g \cdot L^{-1}$, the effective distance in smaller rivers is a maximum of 15 km, based on that detected at the Salmon River in 1992 and Big Silver in 1994 and 1995. However, elevated periphyton accumulations were observed 35 km downstream of the lower Mesilinka River fertilizer site and 50 km downstream of the Nechako River fertilizer treatment site; hence nutrients can be transported significant distances in larger rivers (Slaney et al. 1994a). Thus, lower target concentrations (e.g., 3 $\mu g \cdot L^{-1}$) would be effective over proportionately less distance.

Nitrogen to Phosphorus Ratios: The "Redfield ratio", which is the cellular atomic ratio of C, N and P in marine phytoplankton, provides a benchmark for assessing nutrient limitation, most commonly between N and P (Borchardt 1996). Ambient N:P atomic ratios greater than 20:1 are considered P limiting, less than 10:1 are N limiting, and between 10 and 20:1 the distinction is equivocal (Borchardt 1996). Atomic weight ratios can be converted to weight:weight ratios by multiplying by the atomic weight of the element in question. For example, a 10:1 N:P atomic weight ratio is equivalent to a 4.5:1 N:P weight:weight ratio (e.g., 10 x 14/1 x 31 = 4.5; where 14 = atomic weight of nitrogen and 31 = atomic weight of phosphorus). Minimum target N:P ratios (weight:weight) should range from 5-10:1 (i.e., 20 $\mu g \cdot L^{-1}$ NO_3-N + NO_2-N + NH_3-N/2-4 $\mu g \cdot L^{-1}$ SRP). Actual N:P ratios will usually be greater than 5-10:1 (weight:weight) as background DIN in many coastal and interior streams and rivers in B.C. are typically in the 50-100 $\mu g \cdot L^{-1}$ range (Mouldey and Ashley 1996; Toth et al. 1996; Paul et al. 1996).

Application: Recent advancements in liquid fertilizer application technology have allowed the capability to maintain constant loading despite fluctuations in river discharge, thus significantly increasing the accuracy, ease and logistical requirements for liquid fertilizer applications (Larkin et al. 1997). Two different engineering designs have been developed for applying liquid fertilizer to rivers and streams: (1) a "flow proportional" system that uses a water pressure transducer to monitor the stage height of the river and an intelligent controller that interfaces with an existing stage-discharge curve to accurately apply the required amount of liquid fertilizer into the river via a programmable DC powered peristaltic pump, and (2) a low energy gravity fed system that dispenses a pre-programmed amount of fertilizer into the river based on an exponential decay curve derived from prior analysis of the descending limb of the hydrograph. The pre-programmed system has been designed to apply nutrients at 20-minute intervals by opening a valve for a sufficient time to allow a pre-calculated amount of fertilizer to drain out of the system and achieve an instantaneous low level concentration (e.g., 5 $\mu g \cdot L^{-1}$ of SRP). Changes in loading rates are obtained by a daily reduction of the period of valve opening according to a pre-determined exponential decay coefficient for the river.

The flow proportional system is reliable and accurate, but requires routine replacement or recharging of several deep cycle batteries and is relatively expensive (approx. $20,000). The pre-programmed system is considerably cheaper (approx. $3,000) as it uses gravity rather than a peristaltic pump, and the energy requirements are sufficiently low that a 30 ampere hour battery will last for two to three months. The pre-programmed design is most applicable to rivers with snowmelt-dominated watersheds as the descending limb of their hydrographs are quite predictable. Analysis of hydrographs indicated the errors in the flow volume passing monitoring stations as compared with flow volumes taken from fitted exponential curves were in the range of 12 to 14% for rivers with a significant percentage of their watershed located at high elevations. For lower elevation rivers, the error in approximating the decay curve were unacceptably large (23-32%) as the flows in these systems were rain-driven as much as snowmelt-driven during the summer months, hence the flow proportional systems are better suited to lower elevation watersheds (Larkin et al. 1997).

Logistically, the use of liquid fertilizer is quite simple requiring only a storage tank(s) of sufficient capacity, spill containment berm and liner, and plumbing associated with the fertilizer application system. Polyethylene tanks designed for fertilizer storage are available in a variety of sizes, and have sufficient strength and chemical resistance to safely contain the fertilizer. Separate tanks are required for the 10-34-0 and 28-0-0 as mixing the two solutions would likely trigger precipitation of solids in the tanks and distribution lines. Care should be taken during initial site reconnaissance to select a location that is near the river and an access road so that the tanks can be filled without too much difficulty and the distribution lines are not excessively long. The location should also be secure from potential river channel movement. Vandalism is a potential problem, and efforts should be taken to camouflage the tanks and fertilizer injection hardware.

CASE STUDY EXAMPLES OF STREAM FERTILIZATION IN BRITISH COLUMBIA

Fertilization experiments are currently being conducted on a series of oligotrophic coastal and interior rivers in B.C. to determine the effect of inorganic nutrient addition on water chemistry, periphyton and invertebrate community composition and biomass, as well as fish growth and abundance. These systems include the Salmon River and Adam River (northern Vancouver Island), Big Silver Creek (near Harrison Lake) and the Mesilinka River (280 km north of Prince George). The Nation River (near Mackenzie) is being studied as the external control for the Mesilinka River. The Keogh River (northern Vancouver Island), which was the site of the pioneering whole-river fertilization experiments in B.C. in 1984-86, will be added to this set in 1997 as a stream restoration evaluation site. These rivers represent a broad spectrum of stream types in differing geographical areas of B.C. and will allow for the assessment of nutrient additions on several types of fish populations under different climatic conditions.

Keogh River Case Study

Pioneering research studies of nutrients and their role in salmonid food chains were examined at the Keogh River in the 1980's. The Keogh is a humic-stained salmon and steelhead river located near Port Hardy on northeastern Vancouver Island; it is 33.5 km long (to mid-lake) within a 130 km^2 watershed, has a mean annual discharge of 5.3 $m^3 \cdot s^{-1}$ with a minimum in mid-summer of 0.1 $m^3 \cdot s^{-1}$ and a maximum in winter of 254 $m^3 \cdot s^{-1}$ (see Johnston et al. 1990 for details). Primary objectives of the Keogh River fertilization experiment were to determine the role of nutrients in benthic productivity and the effect of nutrient additions on the growth and abundance of anadromous salmonids in an oligotrophic stream.

Inorganic fertilization resulted in striking increases in the weights of steelhead and coho salmon fry during the main years of treatment (Johnston et al. 1990). In the 1981 pilot experiment, inorganic fertilization increased salmon and trout fry geometric mean weights by 1.6-1.7 and 1.9-2.1 fold greater, respectively, than the control. During the whole-river treatments from 1984 to 1986, larger size-at-age steelhead parr were detected. In 1984, mean weight-at-age of parr did not differ between one of three treated reaches and the control, but in the two other reaches in 1984 and within all three treated reaches in 1985 and 1986, age 1+ parr were 30% and 130% greater in geometric mean weight than parr in the upstream control section (Fig. 13-8). The older age 2+ parr were 41-63% larger in the treated reaches than in the control in 1985 and 1986. In 1981, mean salmonid biomass in the treated reach increased 1.8-fold from 35 $kg \cdot ha^{-1}$ to 65 $kg \cdot ha^{-1}$ as compared to the control reach.

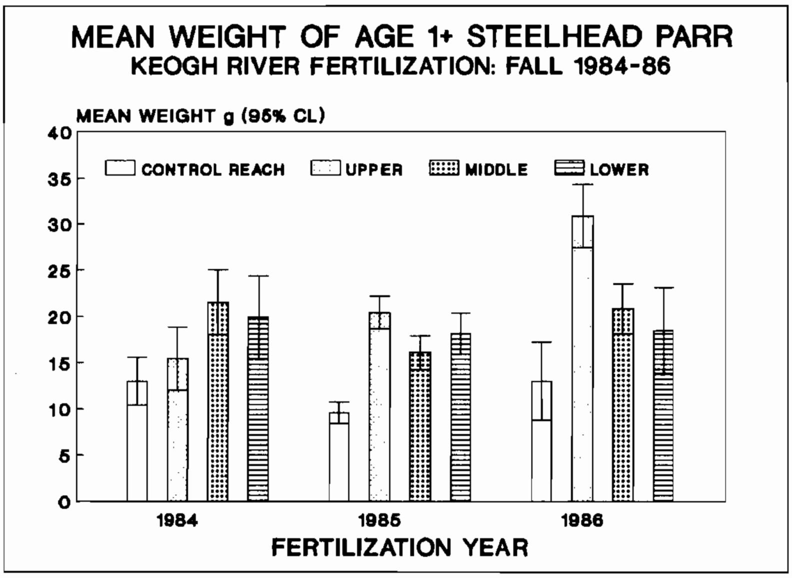

Figure 13-8. Mean weights of age 1+ steelhead parr in the upper river control and three treated reaches of the Keogh River during whole-river fertilization in 1984, 1985 and 1986 (Slaney and Ward 1993).

There was a suggested 21% increase in coho smolts resulting from fertilization. However, the presence of 16-19 tributaries and 6 small lakes, all untreated, confounded the treatment effects on mainstem coho production because most (~60%) coho are not produced in the mainstem. Mean coho smolt length (i.e., 104 mm) did not change as a result of the treatment. Steelhead smolts, as mainstem rearers, increased production by brood years by 62% over pre-treatment years. Fertilization also shifted the age class structure of the smolts as age 3 smolts dominated the annual pre-fertilization smolt yields, whereas age 2 smolts dominated the annual smolt production during fertilization, and age 1 smolts appeared for the first time in 1987 as a significant portion (i.e., 12%) of the annual yield (Fig. 13-9) (Slaney and Ward 1993). The smolt response peaked at 2.5 times the average smolt yield during the year the project was terminated (1987; Fig. 13-10). Fertilization had minimal effect on average smolt size, as mean smolt length in 1985, 1986 and 1987 was 175, 160 and 170 mm, respectively, or in two of three years, near the 1977-83 average size of 173 mm, and all three within the historical range of variation. Adult steelhead originating from smolt cohorts of fertilized years returned to the river from 1986 to 1990. Their numbers, and catch in the sport fishery, corresponded with the increased numbers and size-at-age of smolts, yet catch of wild steelhead at a nearby river showed little change (Fig. 13-11).

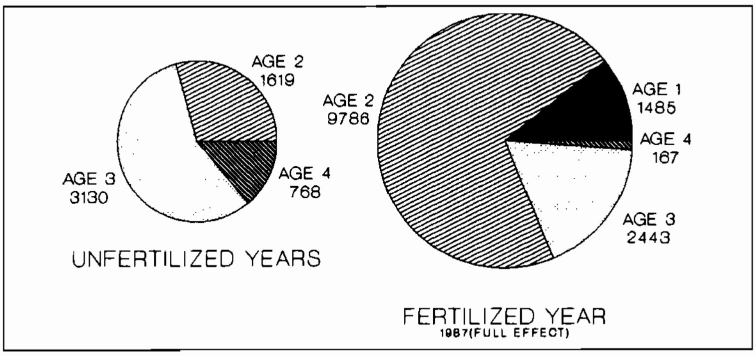

Figure 13-9. Age composition and numbers of steelhead smolts before (1977-1983) and during (1987; full effect) whole-river fertilization at the Keogh River (Slaney and Ward 1993).

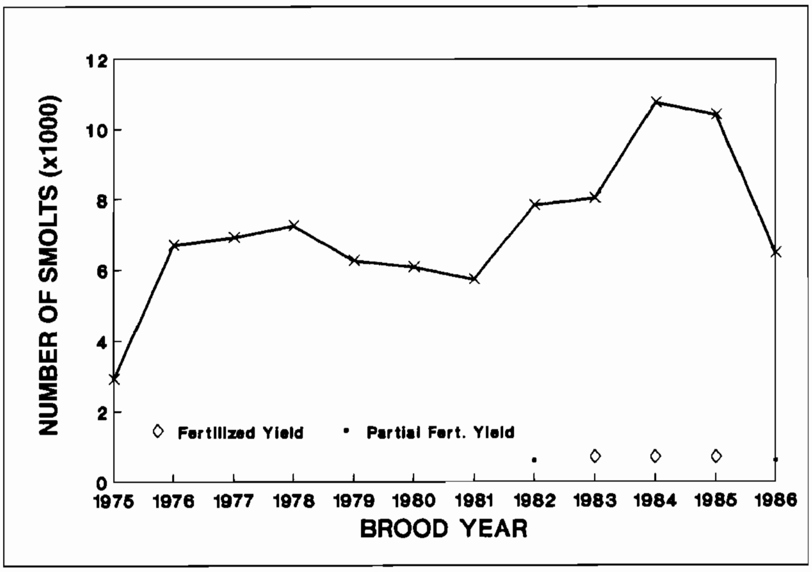

Figure 13-10. Number of steelhead smolts by brood year migrating from the Keogh River from 1975 to 1986. Broods affected completely and partially by whole-river fertilization are indicated above the x-axis (Slaney and Ward 1993).

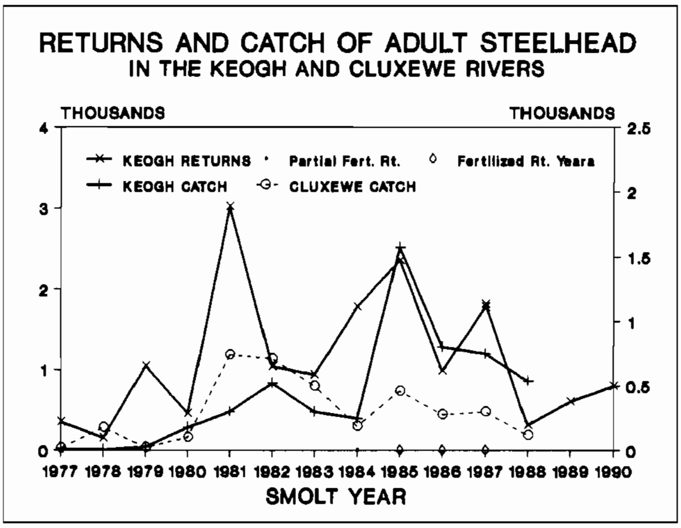

Figure 13-11. Estimated numbers of adult wild steelhead returning to the Keogh River and estimated catch of wild steelhead in the Keogh and Cluxewe River (unfertilized, by smolt years of 1977 to 1990). Smolt years partially and completely affected by whole-river fertilization are indicated on the x-axis (Slaney and Ward 1993).

Salmon River Case Study

The headwaters of the Salmon River are located about 30 km west of Campbell River, on the east coast of Vancouver Island; mean annual flow is about 13 $m^3 \cdot s^{-1}$, declining in spring to summer from 12 to 3 $m^3 \cdot s^{-1}$ whereas in Grilse Creek, a main tributary, average flow from early May to mid-summer declines from 3 to 0.5 $m^3 \cdot s^{-1}$. Water temperatures increase from 6-9°C in May, to 9-12°C in June, to 12-16°C in July to August, and are about 1 degree higher on average in Grilse Creek than the Salmon. Starting in 1989, Grilse Creek and the upper reaches of the Salmon River on northern Vancouver Island have been fertilized from mid-spring to mid-summer with inorganic agricultural dry and liquid fertilizer and more recently with slow release fertilizer to mitigate the impacts of intensive forest harvesting and hydroelectric diversion in the watershed on a renowned, but depressed, stock of steelhead. Peak algal chlorophyll *a* biomass in spring to summer initially increased 5 to 10-fold in response to nutrient additions at target concentrations of 5 $\mu g \cdot L^{-1}$ dissolved inorganic phosphorus and up to 20 $\mu g \cdot L^{-1}$ dissolved inorganic nitrogen, but since 1992 increased only 2 to 3-fold (Fig. 13-4). The mean biomass of benthic insects was on average 2 to 7-fold (1992) and 3.7-fold (1993) greater in fertilized sections than unfertilized spacial controls, indicating that grazers, dominated by mayfly nymphs and midge larvae, limited periphyton accrual to nominal biomasses (15-40 $mg \cdot m^{-2}$ as chlorophyll *a*) (Fig. 13-4). Fertilization resulted in 2 to 3-fold greater mean weights and standing crops of steelhead and rainbow trout in treated index sites than unfertilized index sites in warmer years, although the response was moderated (1.5 to 2-fold) in cool, wet years (e.g., 1993). The effective distance of fertilization downstream from a drip tank was at least 15 km (Slaney et al. 1994b). Overall, there has been a marked increase in the estimated total migration of parr and smolts counted at a smolt diversion screen at the Salmon River, which has been saturated with stocked fry, and more recently some wild fry, for the last decade (Table 13-2, from Hansen 1996).

Table 13-2. Estimated total steelhead smolt and parr migration from the Salmon River.

Year	1988[1,2]	1989[2]	1990	1991[2]	1992	1993	1994	1995	1996
Smolts	150	902	1041	1128	2265	1379	2414	3446	1931
Parr	500	763	447	490	718	1357	5593	5312	3403
Total	650	1665	1488	1618	2983	2736	8023	8758	5334

[1] Efficiency of smolt screen estimated at less than 50%.

[2] Trapping and enumeration started later than usual.

Big Silver Case Study

Big Silver Creek is located 35 km north of Harrison Hot Springs, originating in the Lillooet Range of the Coast Mountains and flowing for about 40 km in a southerly direction before emptying into Harrison Lake. Big Silver Creek was studied in 1992 and 1993 in order to determine representative prefertilization conditions in the system (Toth et al. 1993), fertilized for the first time in 1994 when 9.5 t of 10-34-0 (ammonium polyphosphate) was added in the Middle treatment zone (T1; 13 km upstream from Harrison Lake) and again in 1995 and 1996 with 9.5 t of 10-34-0 (Toth et al. 1996). Nitrogen (i.e., 28-0-0) was not required due to the natural high background concentration of DIN in Big Silver (Toth et al. 1993). During the 1995 growing season, Big Silver water temperatures ranged between 8 and 13°C, transparency between 1.5 and 5 m, and flow averaged 23.7 $m^3 \cdot sec^{-1}$ (40, 29, 17, and 8 $m^3 \cdot sec^{-1}$ in June through September, respectively). Water chemistry analyses indicated soluble reactive phosphorus concentrations increased downstream from the fertilizer input, relative to the control reach, and were higher than prefertilization (1993) levels. Chlorophyll *a* accrual in the fertilized reach also peaked at concentrations 3 and 4-fold those seen in the control reach over the same time period. Benthic invertebrate biomass in the fertilized reach were significantly higher than in the control reach over the same time period, and were significantly greater than the biomass observed in the same reach prior to fertilization, in 1993. Standardized electrofishing surveys indicated a juvenile rainbow trout biomass of 1.4 $g \cdot m^{-2}$ and a density of 0.12 $fish \cdot m^{-2}$ in the fertilized reach, 4 and 2-fold greater than the biomass and density measured prior to fertilization. As well, mean weights of age 0+ rainbow in the fertilized reach were significantly larger than fry from the control reach of the mainstem.

Adam River Case Study

The Adam River is an oligotrophic coastal trout stream located 80 km northwest of Campbell River on Vancouver Island, and originates from the Vancouver Island Range, flowing 50 km northwest to where it joins with the Eve River, which together flow for 3 km into the Adam River estuary at Johnstone Strait. The Adam River was studied in 1992 and 1993 in order to determine representative prefertilization conditions in the system (Slaney et al. 1993), fertilized for the first time in 1994 when 2.3 t of 10-34-0 (ammonium polyphosphate) and 1.03 t of 28-0-0 (urea-ammonium nitrate) were added in the Lower treatment zone (T2; from the mainline logging bridge to the waterfalls barrier, approx. 8 km) and again in 1995 and 1996 with the same type and amount of fertilizer (Toth et al. 1997). Adam River water temperatures ranged between 8 and 16°C, and flow averaged 13.2 $m^3 \cdot sec^{-1}$ (11.3, 8.0, 6.5, and 2.3 $m^3 \cdot sec^{-1}$ in June through September, respectively) during the 1995 growing season. Water chemistry analyses indicated there were no increases in nitrogen and phosphorus concentrations within the fertilized reach, relative to the non-fertilized reaches. However, peak chlorophyll *a* concentrations were 2 to 5-fold greater, and benthic invertebrate biomass was significantly higher during June and July, within the fertilized reach, as compared to values in the unfertilized reaches, suggesting rapid uptake of the additional nutrients into the food chain. In 1995, fertilizer addition rates were closely matched to river flow using a new flow proportional injection system which functioned well and ensured target addition rates were achieved. Standardized electrofishing surveys indicated a juvenile salmonid density and biomass of 0.082 fish·m^{-2} and 0.624 g·m^{-2}, respectively, in the fertilized reach during 1995. Both were similar to values recorded in the fertilized reach in 1994, and were greater than the 0.011 to 0.073 fish·m^{-2} density, and 0.177 to 0.314 g·m^{-2} biomass recorded in the unfertilized reaches during 1993-95 sampling.

Mesilinka Case Study

The Mesilinka River is a large northern river (mean summer flow, 112 m^3·sec^{-1}) located 280 km north of Prince George. The headwaters of the Mesilinka originate in the Omineca mountain range and flow east for 120 km to B.C.'s largest body of water, Williston Reservoir (1,775 km^2), which empties into the Peace River. It is one of several oligotrophic streams inhabited by migratory and resident salmonids that were affected by construction of the reservoir, thereby flooding the lowermost and most productive stream reaches. Mean spring to summer flows (1982-91) were 74, 180, 108, 49 and 35 m^3·sec^{-1} during May, June, July, August and September, respectively, and water temperatures in summer average 10-13°C. Following two years of pre-fertilization monitoring (1992 and 1993) in control and treatment reaches (Koning et al. 1995), 14.1 t of 10-34-0 and 15 t of 28-0-0 were added in 1994 in the first treatment zone (T1; 66 km upstream from the reservoir) and 14.1 t of 10-34-0 only in the second treatment zone (T2; 46 km upstream from the reservoir) (Paul et al. 1996). The Mesilinka was fertilized in 1995 and 1996 with an additional 15 t of 28-0-0 being added to the second (i.e., T2) treatment zone due to a fertilization induced shift to N limitation in the T2 reach. Target in-river concentrations were 5 μg·L^{-1} dissolved inorganic phosphorous and 20 μg·L^{-1} dissolved inorganic nitrogen. Preliminary results (1995) from 5-8 km index reaches suggest rainbow trout and mountain whitefish numbers have increased 2-fold and 5-fold, respectively. By 1995, weight-at-age of rainbow trout (age 4+ fish only) increased in the treated reach (T2) compared to the control (34%). The response of the food chain, indicated by periphyton accrual, was detectible for >15 km below the fertilizer drip stations (Paul et al. 1996).

Summary of Case Studies

The results to date, based on the responses of the Keogh, Salmon, Adam, Big Silver and Mesilinka rivers, strongly indicate that low-level addition of limiting nutrients can increase the productivity of oligotrophic rivers. The periphyton and invertebrate biomass responses are similar across all systems, and preliminary results (i.e., Adam, Big Silver and Mesilinka) indicate the biomass of resident juvenile salmonids has increased. The Salmon and Keogh experiments indicate increased size and weight-at-age of juvenile anadromous trout and salmon, while the Keogh has shown increased steelhead smolt output with corresponding adult returns in response to inorganic nutrient treatment. Completion of the Adam, Big Silver and Mesilinka experiments in 1997 should provide the additional evidence to evaluate the effect of nutrient treatment on both resident and migratory populations of salmonids.

RESEARCH NEEDS FOR FUTURE ADVANCES IN FERTILIZATION

A considerable amount of research has been conducted on the effects of low-level nutrient addition in the Pacific Northwest and other regions; however, several areas require additional research, either independently or in combination with ongoing long-term studies. An interdisciplinary approach between fisheries biology, limnology and environmental engineering should prove beneficial, and will likely result in significant improvements in our understanding of the long-term effects of low-level additions of limiting nutrients and improvements in the cost-effectiveness of this restoration technique.

Effects of Forest Practices on Nutrients: A key research area that requires further investigation is the impact of various forest harvesting and silviculture practices on the export of nutrients from the watershed and subsequent effects on stream productivity. Data collected from the Carnation Creek experiment indicates clear-cut harvesting caused an initial pulse of nutrient export which declined after 3-5 years as new vegetation began to sequester the nutrients (Scrivener and Brown 1993). Periphyton are very effective at sequestering nutrients (particularly soluble reactive phosphate) at extremely low concentrations (i.e., $< 1\ \mu g \cdot L^{-1}$; Bothwell 1989), hence subtle shifts in nutrient export could potentially influence algal species composition (Stockner and Shortreed 1978). The impact of temporal changes in nutrient export, stream C:N:P ratios and its effect on stream biota have not been thoroughly researched. In addition, silvicultural practices may involve forest fertilization with urea and phosphorus, which can influence adjacent aquatic nutrient loadings due to watershed runoff, hence there is potential for integration of forest and stream fertilization practices (Perrin et al. 1984).

Trends in Marine Derived Nutrients: A recent review of 42 years of salmonid escapement records for Georgia Strait, the west coast of Vancouver Island and the mainland coast of B.C. has identified a disturbing trend that indicates past land use practices and commercial salmon harvesting may have reduced the availability of salmonid carcasses to some streams, resulting in a decline in marine-derived nutrients and carbon sources for stream-rearing salmonids, including coho and chinook salmon, steelhead and cutthroat trout and char (Larkin and Slaney 1996). The marine nutrient evidence collected to date, although not definitive, has sufficient merit and has identified such a significant risk to wild salmon production, that it should be expanded to a complete review of all B.C. stocks at medium risk, high risk and special concern. In addition, the analysis should be conducted over a longer time period as both commercial fishing and habitat degradation due to forest harvesting practices were well established since the turn of the century (Hilborn and Winton 1993).

Stable Isotope Analysis of Food Web Pathways: Analysis of food webs using natural stable isotope tracers (^{15}N and ^{13}C) has provided convincing evidence of the importance of marine derived nutrients in maintaining the productivity of freshwater environments (Kline et al. 1993). An important research question arising from these studies is the generality of the conclusions. For example, Bilby's observations (Bilby et al. 1996) may only be valid in small, heavily canopied streams where autotrophic production is limited by spawner density, low light levels, short day lengths, cold temperatures and frequent streambed scouring. Autotrophic production has been shown to be a significant energy pathway in experimentally fertilized tundra streams (Peterson et al. 1993) and Vancouver Island rivers (Johnston et al. 1990). Therefore, a synoptic survey of stable isotopes in different salmonid habitats and species complexes is required to determine if these results are applicable over a wide range of habitats.

Microbial Ecology and the Hyporheic Zone: One of the least studied aspects of stream ecology is the effect nutrients have on the "microbial loop" and meiofaunal community. Meiofauna is defined as organisms in the 50-1,000 μm size range, such as protozoans and nematodes (Bott 1996). The relative importance of the microbial loop remains controversial (Bott 1996). However, microbial loops dominate carbon flow and nutrient cycling in oligotrophic lakes (Weisse and Stockner 1992) and it is possible that microbial loops exist in oligotrophic stream and river systems that introduce additional steps in the flow of energy and nutrients from microbes to macroinvertebrates and fish (Bott 1996).

Salmonid Species Complexes: A review of the various salmonid species complexes should be conducted to determine if certain salmonids act as "keystone species" by biogenically influencing the productivity of the freshwater environment for related or non-salmonid species (Willson and Halupka 1995). In the Keogh River, a distinct two-year periodicity has been observed in steelhead smolt size that is likely related to steelhead parr feeding on eggs from the even year spawning migrations of pink salmon (Ward and Slaney 1988). Therefore, salmonids that return in large numbers and die after spawning (i.e., semelparous species - sockeye, pink and chum) may improve the productivity of the habitat for unrelated salmonids that spend extended periods of time rearing in the freshwater environment (e.g., coho, steelhead, cutthroat).

Invertebrate Grazer Response: Invertebrate grazing activity can significantly influence algal biomass in streams and rivers, and serve as the key link between autotrophic production and fish communities. Two important topics requiring further investigation are (1) the effects of low-level nutrient addition on invertebrate biomass and community composition (in response to changes in periphyton biomass and community composition), and (2) the presence and duration of temporal lags in invertebrate production in response to increased autotrophic production.

Optimizing Fertilizer Applications: The key variable in designing automated application equipment is the frequency and volume of nutrient application as this directly translates into energy and cost requirements. Additional research is required to determine if the frequency of nutrient application has any impact on periphyton community composition as the injection frequency changes from continuous to intermittent slug flows. Also, organic micronutrients may improve the response and need to be experimentally examined.

Release Rates and New Formulations of Slow Release Fertilizers: A variety of macro and micronutrients can be added to the slow release formulations to compensate for local variations in limiting macro and micronutrients. These could be developed into slow release products if assessment procedures identified a particular nutrient(s) as limiting in a watershed, particularly N-limited watersheds where additional N is required.

Nutrient Synergy with Instream Structures: Several studies have demonstrated that stream rearing salmonids may be limited by the availability of their preferred habitat in summer and winter (Ward and Slaney 1993; Slaney et al. 1994a), and that placement of instream structures (i.e., large woody debris and boulders) in hydraulically-suitable structure deficient streams is a valuable restoration technique (see Chapters 8, 9 and 10). Phosphate mines in northern Idaho can provide large (i.e., 1 m dia.) raw phosphate ore boulders, and if transportation costs were not excessive, this would form the basis of an interesting experiment to determine if the slow nutrient leaching from the phosphate boulders would result in an incremental improvement in habitat capability over regular boulder clusters.

Salmon Carcass Application Strategies: In the small nutrient-limited streams described by Bilby et al. (1996), addition of inorganic nutrients may not be as effective due to low light levels, short day lengths, cold temperatures and frequent streambed scouring. Hence, direct application of salmon carcasses may be a more cost-effective restoration technique for transferring allochthonous marine nutrients to the ecosystem. This concept requires research to determine its cost effectiveness relative to inorganic nutrient additions, but within watersheds where there are minimal concerns of disease transfer, road access and a readily available supply of carcasses (i.e., hatcheries).

Chapter 14

Augmenting Minimum Streamflows in Sediment Deposition Reaches

J. Alex Wood[1]

INTRODUCTION

Streamflow is a major environmental factor affecting the survival and production of coastal anadromous and resident salmonids. Extended periods of low flows can delay the movement of adults into streams, draining their limited energy reserves, affecting upstream distribution and spawning success. High winter flows can cause egg mortalities by scouring and/or sedimentation of the spawning beds. Low winter flows can result in the freezing of eggs or stranding of fry and impact on the overwinter survival of juvenile fish from the loss of winter habitat. Prolonged periods of low flow in the summer reduce available rearing areas for juveniles. Water temperatures can also rise resulting in mortalities and stress for fish, including juvenile steelhead and coho.

Past forest practices have created hydrological changes in watersheds resulting from clear cutting, removal of vegetation along river banks, construction of logging roads as well as inadequate restoration of disturbed logging areas. The higher runoffs result in debris flows from logged hillsides causing erosion and greater sediment load, which infills fish habitat and restricts the interchange of oxygenated water into spawning beds.

In some watersheds highly disturbed by historic logging practices, the entire streamflow subsurfaces at much higher flows in the sediment accumulation zone in comparison to the steeper gradients upstream. Summer flows are also lower as a result of hydrological changes in watersheds impacted by logging. This results in a reduction of rearing area for juvenile salmonids and resident fish populations.

The focus of this chapter is to address the site-specific need for augmenting low summer flows and to review suitable techniques for increasing minimum streamflows in the summer that have been seriously reduced by sediment deposition from past logging practices.

FLOW CONDITION ASSESSMENT

There are many coastal and interior streams and rivers that have been impacted by past logging practices. Some of these streams could be candidates for increasing the minimum summer flows. Prior to completing a detailed assessment of a specific watershed, a preliminary review of a number of streams should be carried out and a short list established for further investigation. Fundamental items that should be investigated prior to "short listing" candidate streams for further investigation are:

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Preliminary Assessment

1. Examine the past, present and future logging status of the watershed contributory to the stream or river under investigation of a critical low flow period. If there is no active logging, the Ministry of Forests (MOF) should be contacted to determine the history of the area including any plans for the future. If the area is being actively logged, also discuss past and current logging operations with the forest licensee. Inspect the stream upstream of the alluvial sediment deposition zone and within the zone during summer.

2. Many streams and rivers in British Columbia have been metered by the Water Survey of Canada. For some rivers and streams continuous records are available and for others there may only be a few years of records. Obtain copies of these flow records to assess historic flows and current trends associated with critical low summer flows. It should be noted that instream flow monitoring techniques are not very accurate to assess very low flows. Visually compare minimum summer flows within the sediment depositional reach to an upstream reach above the zone.

3. Obtain mapping and aerial photographs to assess whether the watershed under preliminary study has deteriorating logging roads, obvious erosion and deposition areas, landslides and dormant or active side-channels, a lake or pond in the watershed. Adjacent land use is also an important factor when assessing a stream for fisheries access.

4. Obtain a history of past and present fish populations, stream utilization and any limiting factors to fish production from the local and regional offices of the Department of Fisheries and Oceans (DFO), and regional fisheries biologists of the Provincial Fisheries Branch. On larger systems the resource management agencies may also have some information on seasonal water temperatures. Input from local fish and game clubs, or similar organizations is also a valuable source of local information on flow and channel conditions.

5. Some river systems have water storage facilities already installed in the headwaters for potable or industrial use. Often these systems can be used as a multiple water-use facility where one of the uses is the summer release of flow to improve downstream conditions for the production of fish.

After the preliminary assessment is complete and one or more streams are suggested as candidates for summer flow augmentation, a more detailed analysis of the basin is required. This will require an on-site inspection of the entire stream channel including headwater ponds or lakes and existing side-channels. The assessment of the latter should emphasize intercepting the groundwater and/or subsurface component of the flow. In particular, the following should be carried out before proceeding with project approvals under Section 7 (revised to Section 9) of British Columbia's Water Act.

Detailed Site Assessment

1. Further assess the impacts of logging activity with particular emphasis on the stability of existing and abandoned logging roads and associated items such as culverts, bridges, slides and washouts. This is required to determine if past and present logging practices will continue to impact on the stream. Flow augmentation may have to be deferred until hillslopes are "storm proofed" under the Watershed Restoration Program (WRP).

2. Assess the portion of stream channel that is accessible to fish for impacts as a result of past logging practices. Hydrological changes in the watershed result in higher peak flows causing sedimentation of habitat, and deposition of bedload. Major bedload deposition usually occurs when there is an abrupt change in stream gradient and often results in the minimum summer flows subsurfacing with no flow on the surface. The areas should be recorded and flagged for summer flow augmentation as discussed in the following section of this chapter.

3. Record the gravel size and condition of sedimentation throughout the various reaches. The normal maximum velocity can be roughly estimated by the size of the gravel substrate. For example, if the gravel size in a given reach is in the order of 10 to 20 mm, the maximum velocities are likely in the range of 1 to 1.2 m $\cdot sec^{-1}$ (3 to 4 ft $\cdot sec^{-1}$). Similarly, if the substrate is 100 mm, the velocity likely exceeds 3 m $\cdot sec^{-1}$ (10 ft $\cdot sec^{-1}$) sometime during the year (Chow 1959). This can be a valuable tool to determine if summer flow augmentation will enhance a specific reach without any other habitat improvements.

4. Measure minimum low summer flows. Even a single flow measurement during the historic low flow period is a good indication of what to expect each year and provides a basic flow value from which to build on for increasing the summer base flow. An assessment of pool and riffle area should also be carried out as there is direct correlation between the quantity of pool-riffle habitat to the production of such species as coho, steelhead and resident trout. For example, an increase in summer base flows of 50% may increase the effective pool and riffle area (rearing habitat) by 30% with a corresponding increase in fish production. *(Methods for determining the minimum summer flow augmentation are discussed later in this chapter.)*

5. If the selected stream includes a lake or pond in the headwaters, the lake area, depth and potential storage volumes should be determined. In addition, the environmental impacts of raising or lowering the water levels over natural lake levels should be assessed and the impacts addressed. The outlet from the lake must be surveyed and access to the site resolved. Some sites may be accessible by public road or existing logging roads, other sites may only be accessible by helicopter. Many coastal and interior lakes are controlled at the outlet by bedrock, while others are founded in stable fluvial deposits. The type of control structure will depend on the outlet conditions, access and the amount of storage required or available.

As outlined under item 4 above, there are a number of methods for determining instream flow needs (IFN) for fisheries requirements as part of an overall water management plan for a stream environment. The first three types have been referred to by previous authors (Annear et al. 1984) as basically office methods, which do not require field surveys. The three methods for determining IFN for fisheries are briefly described below:

Size of Watershed	Uses basin-wide information such as size of watershed to recommend streamflow requirements.
Average Annual Flow Method	This is also referred to as the "Montana Method" (Tennant 1976) and identifies a percentage of the average annual flow for IFN for fisheries.
Flow Characteristics	Incorporates a flow duration curve for the stream. IFN are based on flows that have historically occurred 80 to 90% of the time.

The **wetted perimeter method** involves a relationship between the discharge and the wetted perimeter of the stream. The recommended IFN is often identified as the point where an increase in discharge does not result in a significant increase in wetted perimeter.

For smaller projects, involving relatively low capital investments and a restricted time frame for project assessment and construction, the **Fixed Percentage Method** or **Montana Method** can be used. This method has been field tested over the last 30 years in the United States and Canada. The field studies indicated that the condition of aquatic habitat is remarkably similar on most of the streams carrying the same portion of the average flow (Tennant 1976).

Table 14-1 summarizes the Montana Method for estimating the instream flow requirements for fish (from Tennant 1976).

Table 14-1. Recommended instream flow requirements for fish based on a percentage of the average annual flow (Montana Method).

Comparative Description of Flows	Recommended Base Flow October - May	Recommended Base Flow April - September
Flushing or Maximum	200% of the average flow	
Optimum Range	60% - 100% of the average flow	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or Degrading	10%	30%
Poor or Minimum	10%	10%
Severe Degradation	10% of average flow to zero flow	

The "Montana Method" has primarily been used for interior streams and rivers. For applications to B.C. coastal streams, it is recommended that the wetted cross-section be measured at a few key areas in the stream under investigation. Preferably this should be done at approximately 5, 10 and 30% of the average annual flow. In addition, it has been recommended by Wesche and Rechard (1980) that the initial design flow determined by the Montana Method should also be compared to the average 10-day and 30-day natural low flow values for the stream. This is required to ensure that the proposed increase in summer flow is realistic and will result in a significant increase in wetted area and associated fish habitat.

For purposes of summer flow augmentation it is recommended that 30% of the average annual flow be established as an initial goal for rehabilitation of a depressed stream resulting from subsurface flow in a depositional reach. As discussed in the next section of this chapter, the recommended design flow may have to be modified to suit physical constraints imposed by available system storage, as well as other methods to augment summer flows.

METHODS TO AUGMENT MINIMUM SUMMER FLOWS

There are a number of methods to increase the minimum summer flows for an entire stream or for a specific section of stream that has been seriously impacted by low flows. These methods include (1) water storage in the spring with controlled release from headwater lakes in the summer, (2) interception of groundwater or subsurface flow particularly in side-channels, (3) restructuring the stream channel by reshaping and/or gravel removal to restore surface flow that formerly passed through the deposition area as subsurface flow.

Water Storage

The most common method for flow control is to increase the storage capacity of a lake or natural impoundment in the headwaters. The storage is the volume of water between the lowest and highest water elevations. A dam can be constructed across the outlet of a lake to raise the water level, and the outlet structure can be constructed below the natural lake outlet to lower the minimum water level elevation.

Large flow control projects such as the Big Qualicum River Project on Vancouver Island and the Fulton River Project on Babine Lake are instructive examples but are outside the scale required to offset logging impacts.

An example of a medium-sized project is shown in Figure 14-1. A rock cut was carefully excavated into the bedrock that formed the outlet from Wolf Lake, which forms the headwaters of Headquarters Creek, a tributary of the Courtenay River System. A concrete wall fitted with a sluice gate was then installed. The structure had sufficient capacity to release 0.5 to 1 $m^3 \cdot sec^{-1}$ (18 to 35 cfs) for a 4 to 6-week period each summer. The increased summer flows provided improved habitat for rearing juveniles and improved flow conditions for migrating fish. The cost in 1996 dollars would be approximately $120,000. The interesting point to note about this project was that the existing lake outlet section was not disturbed, which resulted in the maximum lake levels not exceeding pre-controlled levels.

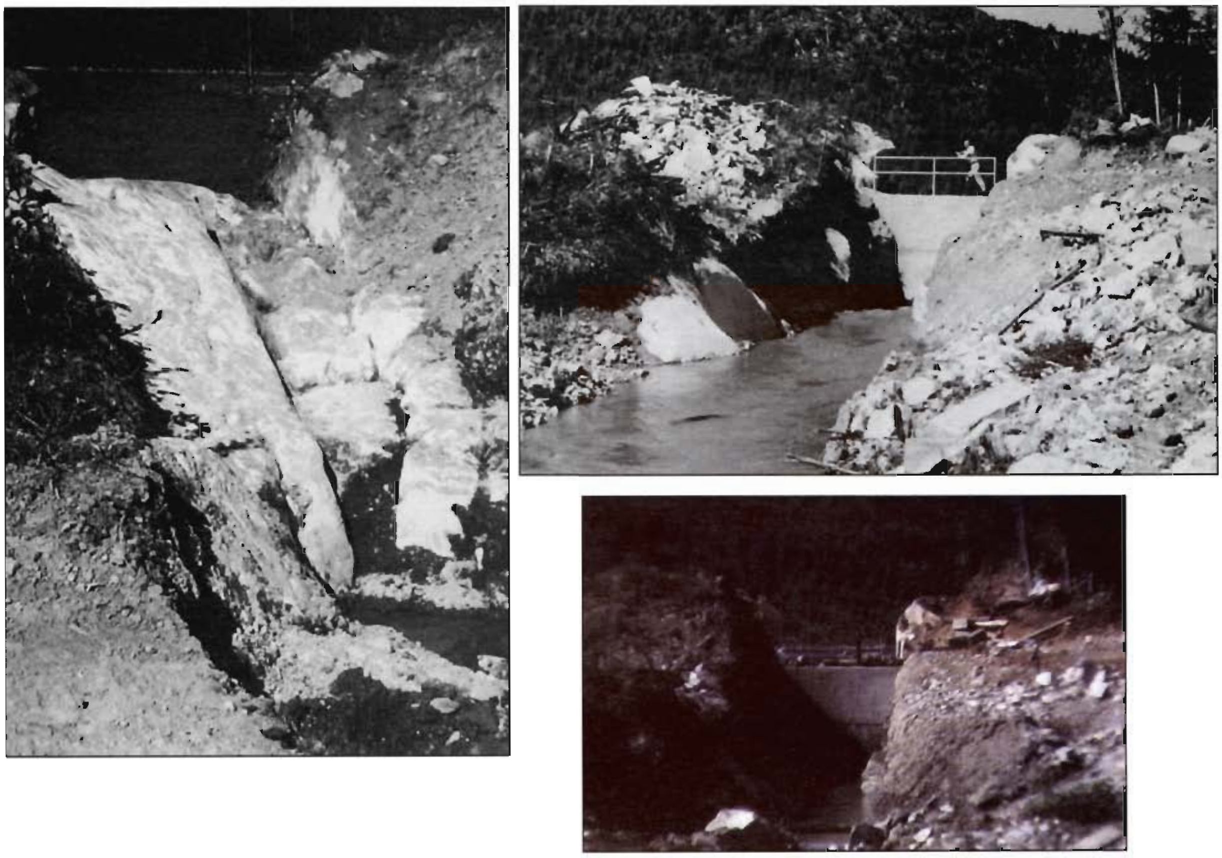


Figure 14-1. A small flow control structure provides increased flows during the summer and early fall to improve spawning conditions and rearing habitat for coho and steelhead juveniles. The left photograph shows the initial construction stages of an open-cut channel which was blasted through bedrock to allow water to be drawn from the lake. The right photograph shows a simple, reinforced concrete wall installed with a manually-operated sluice gate to control the discharge from the lake.

With today's technologies this same project could have been constructed using directional drilling or "micro-tunnelling techniques". Directional drilling involves driving a horizontal or inclined pilot hole with an articulated drill bit containing a microprocessor-based location device. The drilling direction of the bit can be changed as the drilling advances and the depth and location of the hole advance can be monitored at the surface. The pilot hole is then back or forward-reamed to the desired size. The cost of micro-tunnelling varies considerably depending on the access and the proximity to contractors specializing in this work. The cost to drive a 500 mm diameter tunnel would likely range between $1,000 to $2,000 per meter. For the previously described Wolf Lake project, which had good access to the site, the cost to drive 50 meters of micro-tunnel complete with pipe liner and control valve would also cost in the order of $120,000. The micro-tunnel approach results in virtually no visible structures; however, the surficial bedrock must be sufficiently competent to allow the drill bit to advance without encountering excessive fracture zones.

The more common method to augment minimum summer flows is to construct a dam at the outlet from a lake. An example of this is the small one-meter high dam at Matheson Lake on Vancouver Island (Fig. 14-2). The dam was constructed with hand-mixed concrete and boulders, and impounded a 28 ha (69 acre) lake. The flow was controlled between 0.04 to 0.06 $m^3 \cdot sec^{-1}$ (1.5 to 2 cfs). This provided improved rearing conditions during the later summer months when the creek was almost dry.

Another example of a flow control structure is a small flow control dam at the outlet to Keogh Lake on northern Vancouver Island because minimum flows decline in summer in the lower river to < 0.1 $m^3 \cdot sec^{-1}$ (Fig. 14-3). A small concrete structure was anchored into the gravel-hard pan section in the outlet by a seepage cutoff. Manually operated stop logs and an adjustable fishway were installed to improve the summer releases by 0.1 $m^3 \cdot sec^{-1}$ to the Keogh River downstream. (Fig. 14-4). Cost in 1996 dollars for a simple flow control structure is $40,000.

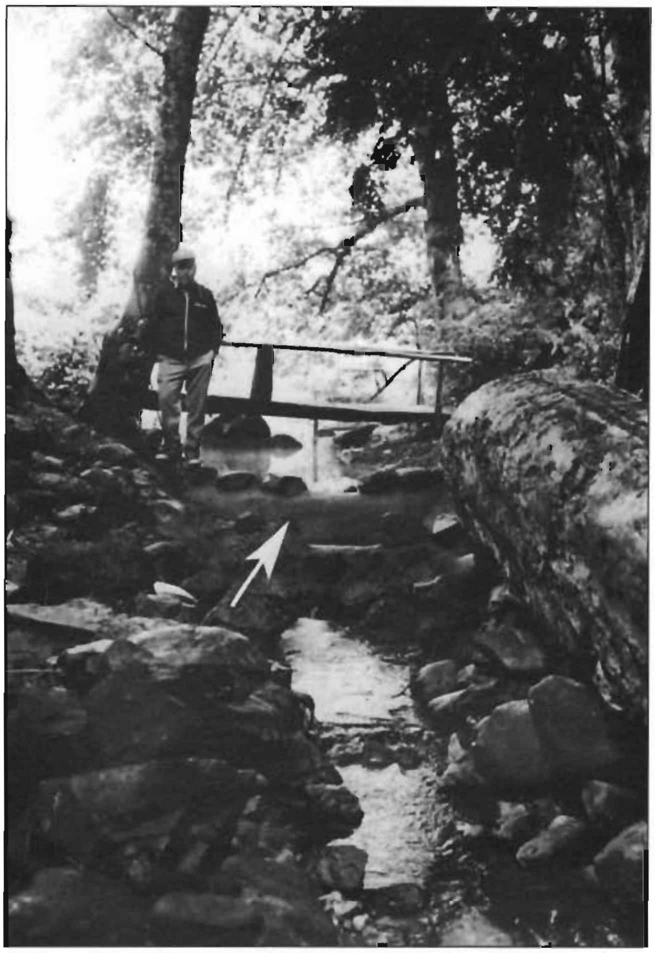


Figure 14-2. A one-meter high dam constructed of hand mixed concrete and boulders. The dam provided storage in 27 ha (69 acre) Matheson Lake, Vancouver Island, to increase summer flows for rearing juvenile coho and trout.

Figure 14-3. A small concrete control dam with a manually operated control gate, located at the outlet of Keogh Lake on northern Vancouver Island.

Figure 14-4. Manually-operated stop logs and an adjustable juvenile fishway were installed to improve summer flow releases to the Keogh River from Keogh Lake on northern Vancouver Island.

Water impoundments by beaver dams provide another opportunity to augment streamflows. This approach involves the installation of pipes through the dam as shown on Figure 14-5. Usable storage is the volume of water between the crest of the dam and the outlet of the pipe. Based on successful installations in eastern United States, the key is to seal the inlet end of the pipe and allow water to enter the pipe through fine slots. Using this approach the beavers were unable to detect the source of water loss.

Design Considerations and Cost of Storage

The approximate volume of water that can be stored in a small lake or pond can be estimated by knowing the area of the lake and the average depth of water that falls within the zone of live storage. The flow that can be produced from this storage depends on the length of time over which the water will be released. For example, the number of days that a controlled flow of 1 $m^3 \cdot sec^{-1}$ would be calculated follows:

No. of $m^3 \cdot sec^{-1} \cdot days$ = lake area (ha) x available storage depth in meters (m) x 0.116.

Note: The following conversions:

One $m^3 \cdot sec^{-1}$ = 35.3 cfs,
One cfs = 450 U.S. gal $\cdot$ min^{-1}

Summarized below are a number of other design criteria that should be considered when constructing a small dam.

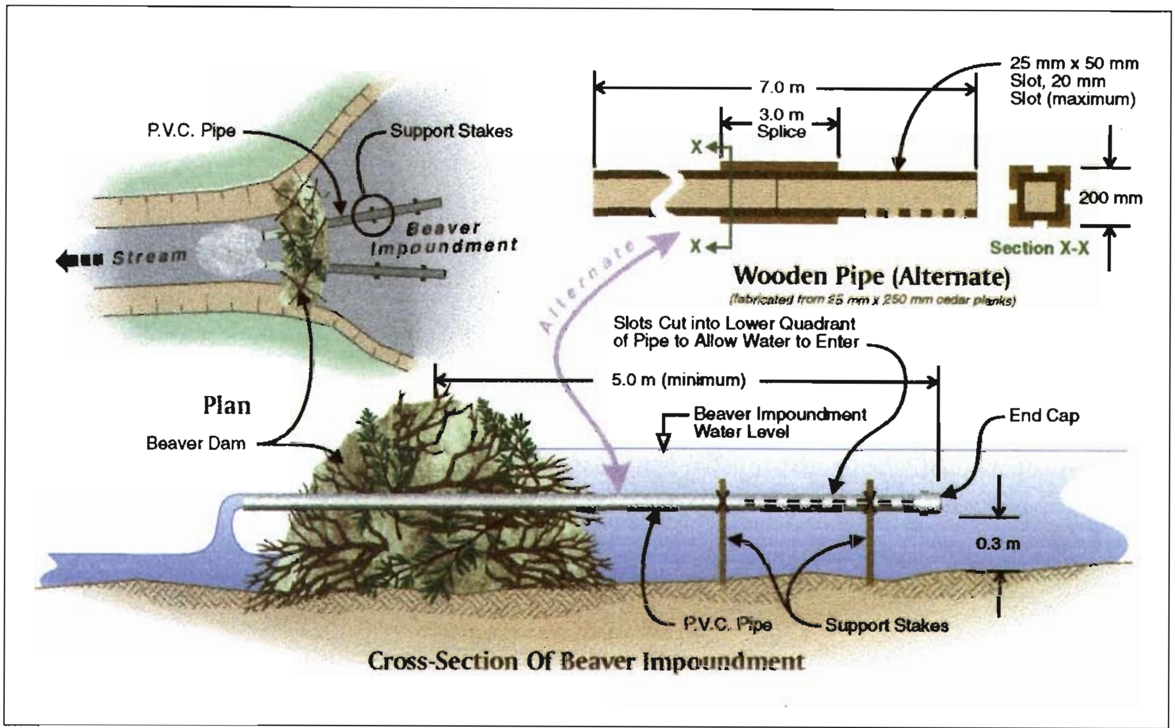


Figure 14-5. To augment low summer flows, water impounded above beaver dams can be released through a slotted P.V.C. pipe. The submerged end of the pipe must be capped to prevent beavers from intercepting the flow.

Criteria for Siting and Design of Small Dams

1. Constructing a dam in a lake outlet would result in higher peak lake levels, and in some cases the flooding of valuable timber and property. Land may have to be purchased or long-term leases secured to compensate for land impacted by the higher water levels.
2. Most dams should be designed for unobstructed fish passage. This often requires a small fishway between the lake and the stream below (Fig. 14-3). There are sites where this is not a consideration. A typical example is a dam built high in a watershed at the crest of a natural obstruction.
3. Topography and foundation affects the size and type of construction. A narrow valley or gorge founded in competent bedrock is ideal for concrete construction. A small footprint results in an economical structure relative to a dam constructed in a broad valley or outlet.
4. Dams must be anchored to the foundation with sheer keys and seepage cutoffs. Dams on fluvial soils must be sufficiently downset into the base to prevent blowout from seepage forces. The spillway section must be designed for a minimum 200-year storm flow event (i.e., a peak flood flow with a statistical frequency of occurrence of once in 200 years). The channel downstream of the spillway must be adequately protected from erosion of the foundation materials. **Most impoundment structures will require design input from a professional engineer specializing in this field.**

5. Control gates and valves must be accessible and protected from the flow over the spillway. Coarse screens should be installed on the intake to prevent debris from plugging the valve or sluice gate. Where automatic control valves are installed, fine screening such as stainless steel wedge wire intake screens should be included at the entrance to the outlet pipe to prevent the small water passages in the valve from plugging (Fig. 14-6).

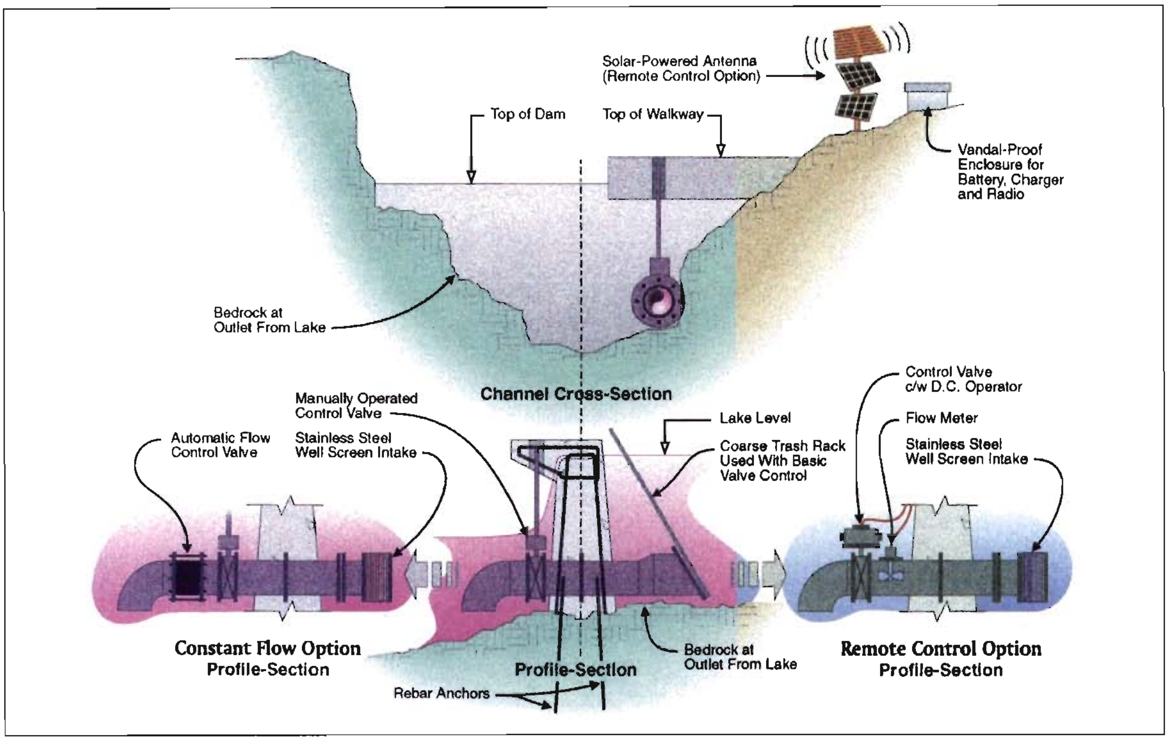


Figure 14-6. Conceptual design of a concrete low head dam constructed on bedrock.

Costs for small dam structures will vary considerably primarily depending on location, access and geometry and foundation materials at the outlet. For example, a small concrete dam located at a high elevation lake, located in a relative narrow rock gorge would require approximately 7 m^3 of concrete with a maximum height of 2.4 m at the deepest section (Fig. 14-6) If existing access is available to the site, the basic structure including a simple valved outlet, but excluding a fishway, would cost approximately $25,000. An identical structure constructed at a remote site but utilizing a helicopter to transport all construction personnel and materials would cost approximately $55,000. The cost to transport concrete to a remote site by helicopter is approximately $100 per km for short flight distances (< 8 km) and $70 per km for longer transport (>12 km). These costs are based on utilizing a Bell 204 helicopter and include an allowance for hover time, fuel and all applicable taxes. For the previous example, the cost of transporting concrete was based on an assumed return trip distance of 18 km. The cost of redi-mix concrete will vary between $125 to $200 per m^3 depending on the quantity of concrete being transported and the proximity to the redi-mix plant.

On remote installations it is often desirable to release a constant flow regardless of the elevation of the water in the lake. To achieve this, a constant flow valve (such as a Griswold Valve) will automatically control the flow to within 5% of the design value over a water level range in the lake upstream of 0.9 to 14 m (3 to 46 ft). The minimum cost to install a 300 mm diameter flow control valve over the basic "valved outlet" would be $3,800 for the automatic control valve and $3,500 for the stainless steel intake screen. The total installed cost would be approximately $10,000.

For larger installations, when it may be preferred to vary the flow over the summer and fall months, the lake level, amount of flow released and valve opening can be monitored and regulated from a remote location using UHF radio (direct line of sight). The cost of the radio equipment, remote and local control stations, flowmeter, solar panels, battery chargers, 30-day standby battery capacity for inclement weather and 24-volt DC powered butterfly valve would cost approximately $45,000 including installation. This would be an additional cost to the basic installation. One application where this may prove beneficial is on inaccessible high elevation multiple water-use storage dams where a minimum flow release has been mandated for fisheries mitigation.

Where the outlet from a lake is located in fluvial deposits, a small low head dam or control structure can be constructed from timber, concrete or precast concrete blocks. A low level (1.5 m) control structure could be constructed with precast concrete Lock Blocks weighing 2,000 kg each (Fig. 14-7). This type of structure should only be considered where good access is available to the site and the precast concrete blocks are readily available. The cost to construct the structure shown on Fig. 14-7 is in the order of $30,000 to $35,000. If volunteer labour and equipment is provided the cost could be as low as $15,000 to $20,000.

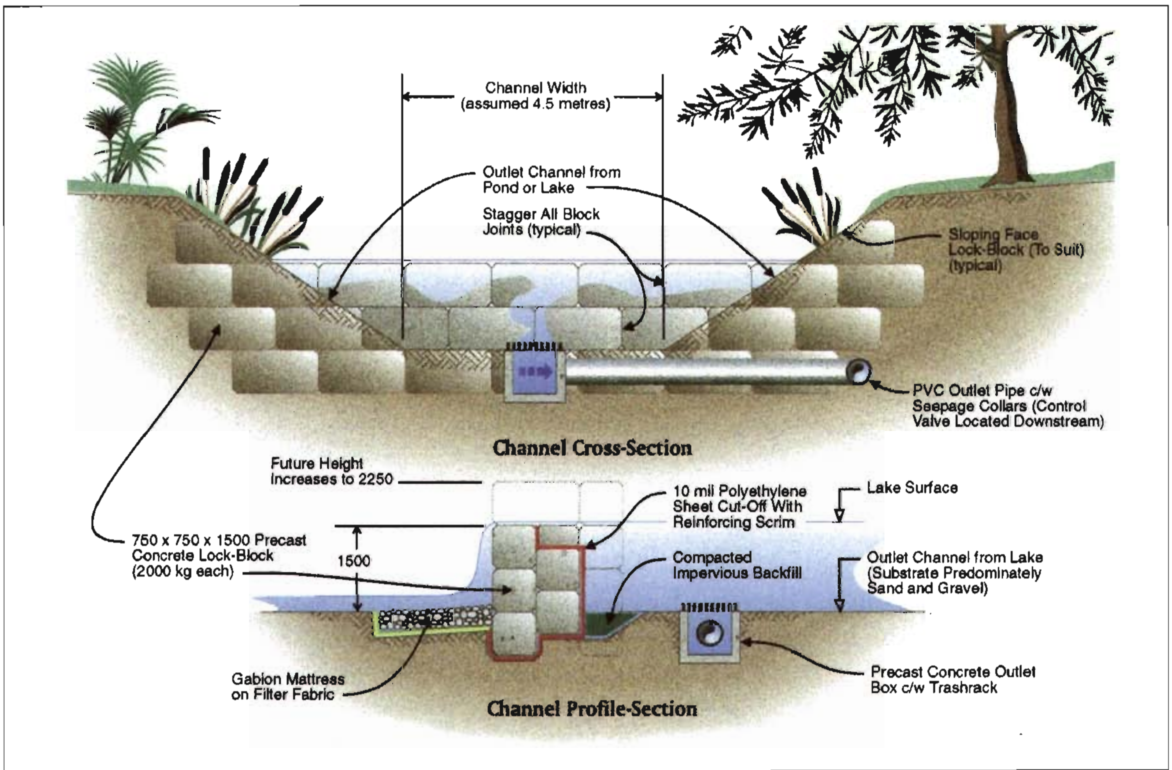


Figure 14-7. Conceptual design of precast concrete (lock-block) low head dam founded in fluvial deposits.

Interception of Groundwater and Subsurface Flows

Another method to increase base summer flows is to increase the groundwater component and intercept subsurface flows. This work is normally carried out in an existing side-channel.

Many side-channels are connected to the main channel at their upstream and downstream ends. Groundwater-fed channels are connected to the main channel at the downstream end only. Interception of subsurface and groundwater flows provide a stable flow of water of consistent quality. Improved flow conditions when combined with other habitat improvements discussed in this guide will improve spawning, rearing and overwintering conditions for several species of fish. For a more detailed discussion of side-channel development, including habitat improvements, recommended flow and velocity regimes, flood protection and food sources, see Chapter 7, as this chapter primarily focuses on increasing the base summer flows.

As an example, an existing side-channel was excavated adjacent to the Fording River in the east Kootenays to offset habitat losses to cutthroat trout (Fig. 14-8). The improvements to the channel included increasing the base flow by 50%, providing spawning gravel above and below pocket pools, and improving instream cover including transplanting riparian vegetation along the banks. The side-channel also included overwintering ponds with floating cover for adult cutthroat trout, which were highly utilized as a refuge from harsh winter (anchor ice) conditions in the mainstem.

The base flow in the channel was increased by deepening the headwater pond and installing pocket pools along the channel approximately 6 m long, 4 m wide and 1.5 m deep. Consideration was given to intercepting subsurface flow by installing polyethylene cutoffs below the channel invert, but this was not necessary as the installation of the pools and deepening the existing channel provided the increased flow. A few small groundwater seepage zones were also intercepted and directed into the side-channel under development.

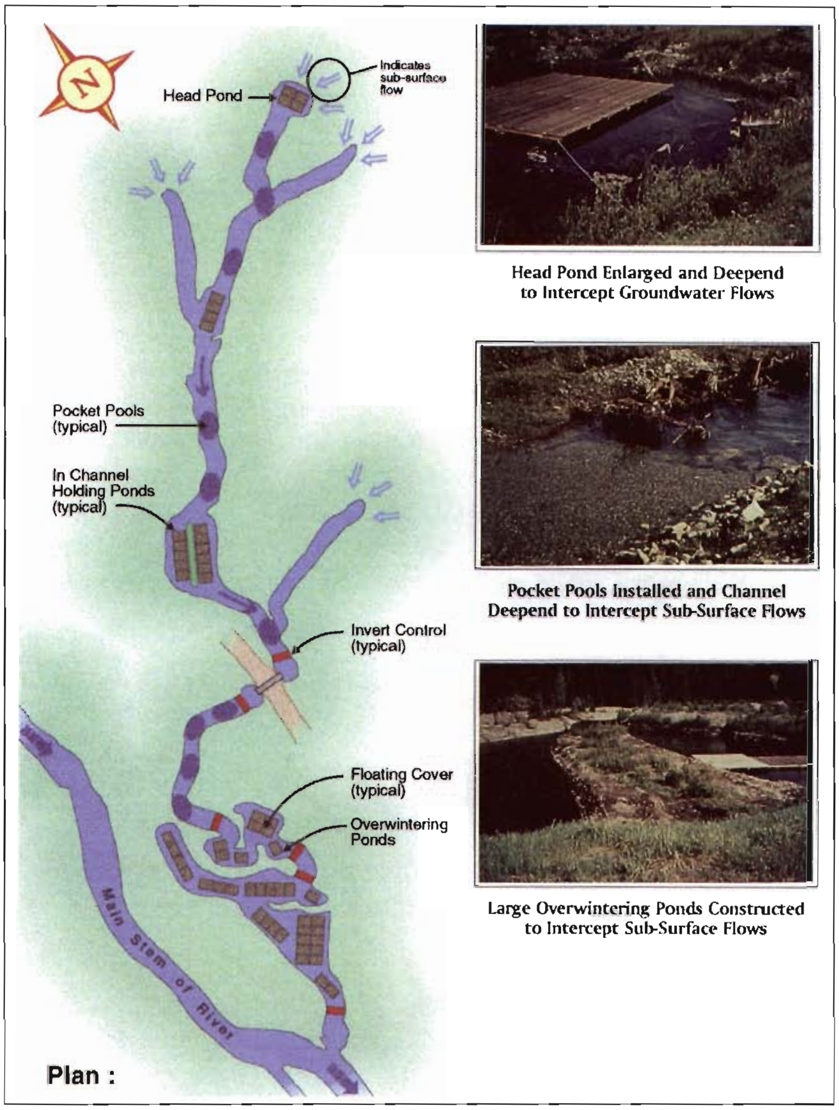
The intercepted subsurface flow was likely a mixture of groundwater with the major component of the flow from the main channel upstream, which had subsurfaced as a result of gravel deposition. In the winter, the average temperature of the water varied between 1 to 2°C. In comparison to the mainstem which was at 0°C, this was attractive to adult cutthroat (2+), which overwintered in the ponds in large numbers. One other advantage to increasing the base flow in the side-channel was that it also provided a modest increase in the baseflow in the main channel immediately downstream of the entrance to the side-channel.

The side-channel shown on Fig. 14-8 included the following features:

- 600 m of enhanced side-channel complete with transplanted vegetation along each bank, 8 pocket pools approximately 24 m^2 in area and 1.5 m deep complete with LWD and rock placements for cover;
- 2 medium-sized instream pools complete with LWD, rock placements and floating cover;
- 2 large overwintering ponds varying in depth from 2 to 3 m complete with floating cover;
- 130 m^2 of spawning gravel located either upstream or downstream of each pool.

The total cost of the project was in the order of $200,000, of which $40,000 was applicable to increasing the base flow in the side-channel.

In conclusion, base flows can be increased by intercepting subsurface flows by cutoffs, constructing deep pools, lowering the channel invert, and diverting groundwater seepages into the head of a blind side-channel.



Head Pond Enlarged and Deepend to Intercept Groundwater Flows

Pocket Pools Installed and Channel Deepend to Intercept Sub-Surface Flows

Large Overwintering Ponds Constructed to Intercept Sub-Surface Flows

Figure 14-8. Typical side channel development for cutthroat trout showing methods used to increase base flow.

Replacement of the Channel to Restore Minimum Surface Flows

As a result of hydraulic changes in the watershed, primarily as a result of past logging practices, annual deposition in the bedload accumulation zones increases as a result of higher peak flows. The bedload accumulation zones normally occur at abrupt changes in stream gradient when the stream transitions from a steep valley to the relatively shallow gradient of the floodplain. In most streams utilized by fish the floodplain gradient would be in the range of 0.5 to 2%. Another area of annual deposition is in the estuary where the stream velocities approach zero as a result of backwater from the ocean.

During the low summer flows these deposition areas are often completely dry or have a minimum surface flow that is not conducive to supporting fish habitat. In the past, gravel removal programs in the estuary have been justified on the basis that the surface flows are restored. However, this condition only lasts for one or two seasons until the area once again infills with gravel. This method to augment surface flows is not recommended, particularly if other opportunities exist.

A better approach would be to work around the deposition area and investigate side-channel opportunities where the minimum summer flows, both surface and subsurface, can be intercepted and collected. Side-channels can be surface-water-fed, deepened to intercept subsurface flows or a combination of both methods. This approach has been proposed for High Falls Creek (upper Squamish River) where hillslope impacts of past logging practices have deposited large volumes of gravel on the floodplain (R. Finnigan, pers. comm.).

When a surface water intake is proposed for a side-channel adjacent to a major deposition area, the intake must be designed to eliminate high flows and resultant gravel depositions. There are a number of ways to design a surface-water intake to minimize bedload deposition within a channel. These include flow diversion structures, hollow weir intakes with flushing chambers, settling ponds and simple float-operated gates that minimize the flow entering a side-channel as the water level in the mainstem of a stream rises. These methods are discussed in further detail in Chapter 7.

Another advantage to developing side-channels, in lieu of excavating and channelizing the actual deposition area, is that stable side-channels can also incorporate other habitat features. These include streamside vegetation for cover, pools and riffles for rearing, and instream LWD or boulder complexes for instream cover.

SUMMARY OF FLOW CONTROL PROJECTS IN B.C.

Large Projects

Weaver Lake, B.C. During low flows in the fall, water can be withdrawn from below the lake outlet elevation utilizing a siphon. The water is released to Weaver Creek to ensure adequate flow to the Weaver Creek spawning channel. A small concrete fishway was incorporated into the outlet from the lake.

Pinkut Creek, Babine Lake, B.C. A low head control dam was constructed at the outlet from Pinkut Lake to augment low summer flows to the natural creek and a large spawning channel complex downstream.

Medium-sized Projects (Summer Flow Augmentation)

Cameron Lake, Vancouver Island, B.C. A low head concrete control dam was installed at the outlet to the lake to augment the summer flows in the Little Qualicum River and associated spawning channels downstream.

Wolf Lake, Vancouver Island, B.C. A flow control structure was constructed adjacent to the outlet from Wolf Lake to increase the base summer flow in Headquarters Creek and the Tsolum and Courtenay Rivers. All storage was below the normal outlet from the lake (Fig. 14-1).

Elk Creek, Chilliwack, B.C. The intake from the Elk Creek reservoir was redesigned by DFO and the Municipality of Chilliwack to provide a minimum flow for fisheries. The minimum flow release is controlled by a V-notched weir set below the normal water intake from the lake.

dam building responses. For each of the various designs of screening devices, wire mesh with square openings of 15 cm will allow fish passage but prevent beavers from entering the cage. It is also necessary to maintain a minimum desired depth of water in the pond at the lowest levels of flow. This may require construction of a weir or ramp, using rocks, gravel or wood, at a point just below the downstream end of the culvert. The weir or ramp must be passable to the target fish species (see Chapter 5 on culvert passage criteria).

Of the various screening devices described here, the small tubular wire cage is the easiest to assemble using rolled wire mesh (Fig. 15-3). This design may be appropriate for small streams but beavers may be able to detect water movement and attempt to block the flow. The cylindrical wire cage (Fig. 15-4) makes it more difficult for beavers to detect water movement. Legs can be attached to the cage for structural support.

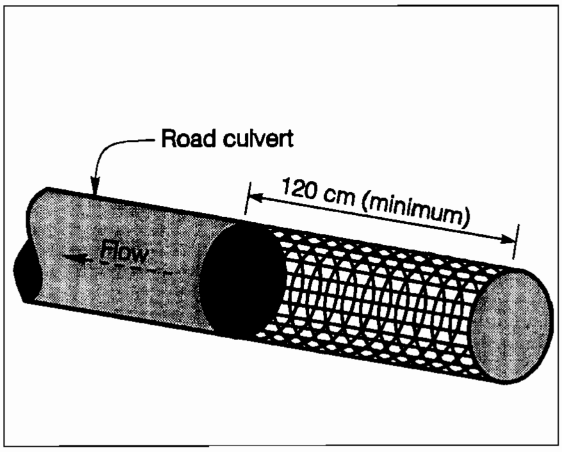


Figure 15-3. Tubular wire mesh cage.

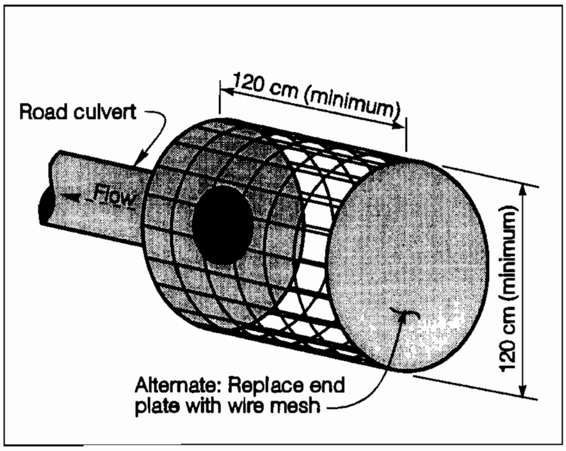


Figure 15-4. Cylindrical wire mesh cage.

Triangular wire mesh cages (Fig. 15-5) are a variation of the cylindrical and rectangular cages. Flat concrete reinforcing mesh fastened to welded aluminum or steel frames can be used.

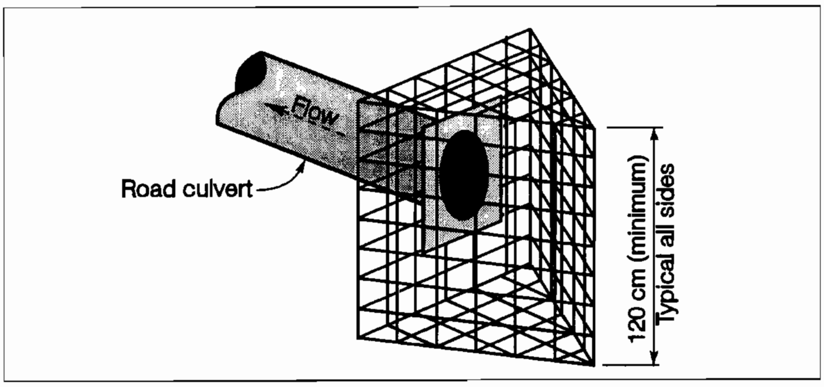


Figure 15-5. Triangular wire mesh cage.

Rectangular wire mesh cages (Fig. 15-6) can be assembled using rolled wire mesh or the stronger flat concrete reinforcing mesh. The mesh is attached to aluminum or steel frames. Legs will be required to support the heavy cages above the pond floor.

Rectangular cages with treated plywood sides and wire mesh top and bottom (Fig. 15-7) are designed to avoid winter damage to cages in instances where ponds freeze and ice cover is

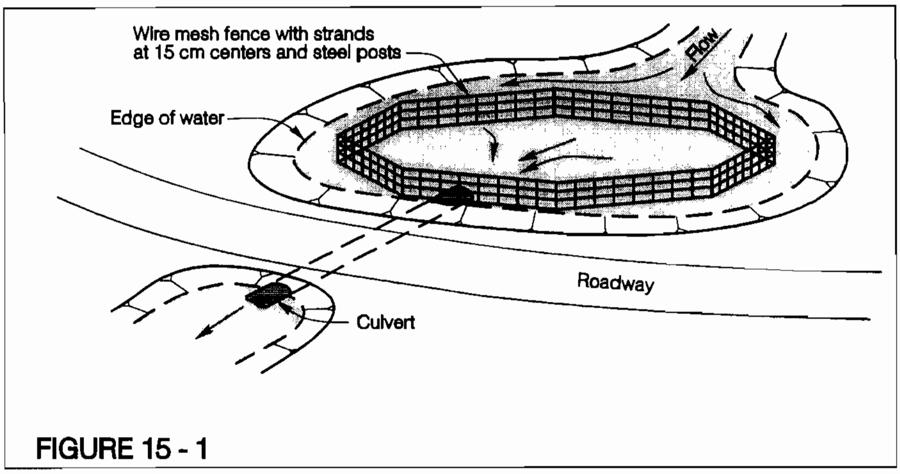


Figure 15-1. The O-shaped fence prevents access by beavers to the upstream end of the road culvert.

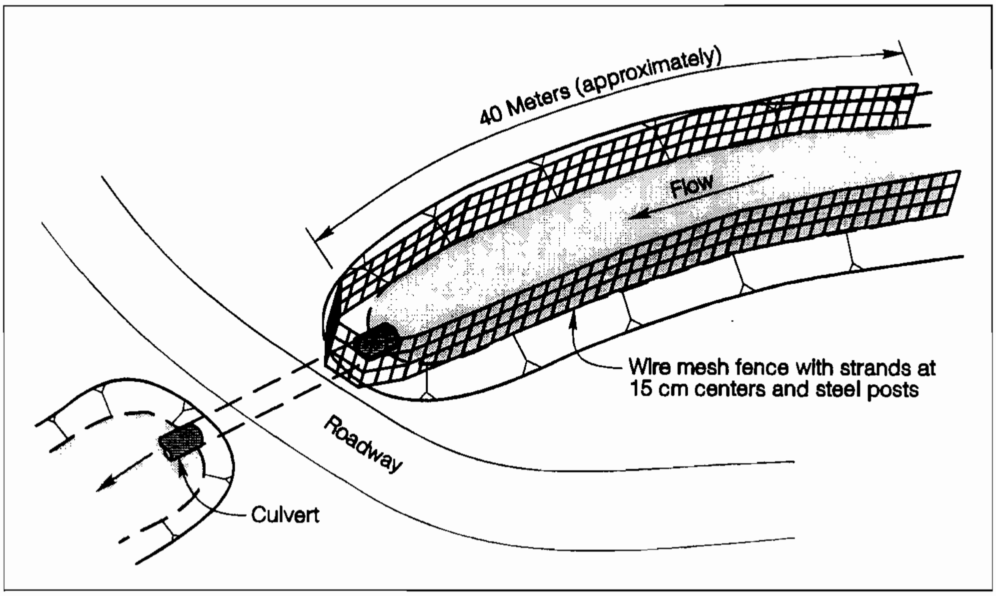


Figure 15-2. The U-shaped fence restricts access by beavers to the upstream end of the road culvert.

Screening Devices

Screening devices of various designs can be attached to the intake end of a culvert to deter beavers. These cage-like structures (Figs. 15-3 to 15-7) allow fish to pass while limiting the beavers' ability to block water flow. Some of these conceptual designs are simple applications that may be only temporary solutions because they can be eventually sealed by beavers. They are appropriate only where a pond (natural or man-made) exists at the upstream end of the culvert. The culvert, before attachment of the screening device, should "gun-barrel" at least one meter into the pond. The screen surface on the bottom of the cages should be elevated at least 0.5 m above the pond floor, which makes it difficult for beavers to anchor their dam-building materials and block the flow of water. The cages may also deter beavers in another way, by preventing them from getting close enough to the culvert opening to detect a velocity gradient or hear the sound of moving water. Velocity and sound are considered to be the beavers' cues that trigger rivulets flowing overland around the ends of dams, or they may access the impoundments from waters upstream. The latter would be possible if resident adult fish of the preceding generation spawned above the dams, or if migratory adult fish of the preceding generation were able to ascend the dams to reach spawning beds upstream. Rarely are beaver dams a barrier to juveniles migrating downstream. Fish passage conditions, both upstream and downstream, improve during freshet when dams are overtopped. Coho salmon, which typically spawn at the time of fall rains in the upper reaches of small streams, are generally successful in ascending beaver dams, hence juveniles are often found in abundance in beaver impoundments. Other important fish species that spend part or all of their lives in fresh water in British Columbia and are frequently found in beaver impoundments include chinook salmon, cutthroat trout, rainbow trout (both sea-going and resident), grayling (in northern regions) and char.

MANAGING BEAVER IMPACTS

While the positive aspects of beaver activities are emphasized in this chapter, these can sometimes be outweighed by the negative impacts; for example, the barrier to fish migration, the backwatering of spawning beds or trout rearing habitats, and the flooding of roads and lands. Unfortunately, the necessity of opening dams and clearing culverts is laborious, frustrating work and ineffective in the long term because beavers are generally undeterred and respond by repairing a breach almost immediately. Fortunately, there are technologies that can be employed to cope with beaver problems. The technologies are not without some maintenance requirements, but these are considerably less onerous than the alternative of fighting the beavers "head-on". Where possible, techniques should be employed that accommodate beavers. In the long term mutually beneficial coexistence is a sound ecological approach.

BEAVER CONTROL AT ROAD CULVERTS

Beaver Fences

The O-shaped wire-mesh fence configuration (Fig. 15-1) encircles the intake end of the culvert and prevents beavers from approaching the opening. The wire mesh should have 15 cm square openings, large enough to allow the passage of adult salmonids but too small for beavers. The surface area of the encircling fence should be in proportion to the maximum volume of stream flow. Debris will accumulate on the fence over time, hence the larger the surface area the less frequent the maintenance requirement. Since winter freeze-up could damage the fence if there is significant horizontal or vertical movement of pond ice, repairs may be necessary in spring. It should be emphasized that the O-shaped fence concept is appropriate only at sites where a pond (rather than a stream channel) exists immediately above a culvert. Similar designs have been used in Maine and New Hampshire (e.g., Laramie 1963).

The U-shaped wire-mesh fence configuration (Fig. 15-2) is appropriate only where a stream channel (rather than a pond) exists immediately above a culvert. The fencing is erected at the water's edge along both banks, beginning at the culvert and extending upstream approximately 40 m. The fence is left open at its upstream end and drifting debris floats downstream unimpeded. The fence prevents beavers from obtaining woody material from sources nearby to block the culvert. Instead, it makes it necessary for beavers to drag the woody material overland from a source near the upstream end of the fence, and then through shallow water for a distance equal to the length of the fence to reach the culvert. It is not known if the deterring factor is the difficulty of the task or if the beavers sense their vulnerability to predators if they are required to work without the safety of a nearby pond.

Beaver impoundments have been found to improve the quality and diversity of riparian habitat, which can benefit some species of fish and wildlife and make it more appealing to recreational users. The original riparian vegetation not used by beavers for food or dam building soon dies after flooding and is replaced by plant species better adapted to wetland soil conditions. This invasion of new vegetation is gradual and will continue long after beavers have vacated the site if dams remain intact. The accumulation of sediments and organic detritus in the still waters of the impoundments is part of this process, providing the nutrient-rich soils to sustain the new vegetation. Aquatic plants, such as yellow pond lilies and cattails, may eventually become established along with water-tolerant shrubs including willow and alder. A diverse aquatic and riparian vegetation community contributes to fish production by providing escape cover, thereby minimizing mortality from predators; by attracting terrestrial insects, some of which fall to the water surface and are eaten by fish; and, in the case of submerged vegetation, by providing suitable habitat for aquatic insects and other invertebrates that are the principle source of food for fish.

The activities of beavers are also much involved in nutrient cycling which, in terms of fish production, may be as important as the role they play in moderating stream flows. Beaver impoundments function somewhat like a gardener's compost heap, acting as a repository for leaf litter and other vegetation that originate from riparian plants adjacent to and upstream of impoundments. The vegetation contributes to the food supply of aquatic insects and other invertebrates in beaver impoundments. Vegetation not consumed contributes to the food supply indirectly by decomposing, thus releasing the key elements limited in aquatic ecosystems: phosphorous and nitrogen. These elements are bound-up in the mud at the bottom of the pond and are slowly released back into the water column, providing the essential nutrients for growth and reproduction of algae (periphyton and phytoplankton) at the base of the food chain. The nutrients become fish food a few links farther up the food chain in the form of stoneflies, midges, caddis flies and other aquatic insects and invertebrates. Beaver droppings are another factor in the enrichment of the impoundments. An average-sized beaver may eat up to 1,100 kg of leaves and twigs a year (Bergstrom 1985), the nutrient-rich end result being deposited in the impoundments and surrounding areas.

The productivity of beaver ponds is reflected both by the numbers and growth rates of the juvenile fish they support. In a controlled study of beaver pond productivity at Fish Creek in Oregon, juvenile coho salmon planted in late November were large enough to smolt and migrate to sea by the following March (Bergstrom 1985). In only four months they grew to a size equal to the largest wild smolts found in other nearby streams. The combination of an abundant food supply and moderate water temperatures in the pond resulted in a 6-fold increase in weight over the winter, three times the weight gain of juveniles rearing in the main channel of Fish Creek. Similar findings have been reported from other studies in southeast Alaska (Bergstrom 1985). Also, a review of salmonid densities in all types of ponds indicated an average number of about one fish per m^2 in smaller ponds (1000 m^2) although less ($0.35 \cdot m^{-2}$) from larger ponds (1 ha) (Keeley et al. 1996).

Another analysis of data in the literature on coho smolt yields for 27 streams, ponds and side channels in British Columbia, Washington and Oregon indicated that production in ponds was similar to small streams on an area basis but much greater on a centerline or perimeter length basis (Marshall and Britton 1990). Based on this analysis, average smolt yield for small streams and ponds were calculated to be 0.73 smolts per m^2 or $4.6 \text{ g} \cdot m^2$.

Most fish species present in streams colonized by beavers will rear in impoundments if accessible. Juvenile fish can sometimes ascend from waters downstream via one or more small

BEAVER BIOLOGY

The basic unit of beaver society is the family group, referred to as a colony, usually consisting of a pair of adults and one or two generations of offspring. In the fall, for example, a colony of nine beavers might consist of the adult pair, three yearlings and four kits. Five to seven beavers per colony is quite common. Such colonies may build and maintain more than one lodge and several dams, but will usually stockpile only one cache of winter food (Hatler 1988). The dominant pair in a thriving colony typically produces one litter of three or four kits each year. Generally, two-year-old juvenile beavers leave the colony and set out on their own in late spring, just before birth of the colony's next litter. The departure of the two-year-olds eases the pressure on the local food supply and reduces the risk of in-breeding. This also leads to colonization of new territories, sometimes in adjacent watersheds.

The prime habitats for beavers are along the slower-moving sections of rivers and streams, in existing ponds and along shores of small lakes not exposed to wave action. Stable streams, such as groundwater-fed side channels and those draining small lakes, are better suited than those where water levels and velocities fluctuate widely. On flowing streams, the foraging area used by a colony will usually extend further upstream from the lodge than downstream, probably because it is more difficult to move food and building material against the flow. A study conducted on backwater sloughs in Alaska found that the maximum distance between a food cache and the cutting site was 800 m (Boyce 1981). Safe and efficient foraging distance inland from the water's edge is considered to be about 50 m. In cold climates where ponds freeze over in winter, sufficient depth must exist beneath the ice cover to provide the beavers access to their cache of woody vegetation.

Beavers feed on a variety of plants including grasses, the leaves of shrubs and the roots and leaves of pond lilies, but their main food source, especially during the long winter season, is typically the bark and tender twigs of deciduous trees and shrubs, such as aspen, alder, cottonwood and willow. The most productive food sources include stands of cottonwood and alder that naturally regenerate on old sedimentation bars along large rivers and in forest clearings created by fire, blowdown, insect-kill and logging. In areas where aspen is predominant, regrowth may support population expansion for beavers as early as eight to 10 years after a burn, although it may take 20 to 30 years to produce trees of a size that will provide the maximum supply of food (Hatler 1988). Willow thrives in the moist and nutrient-rich soil conditions on the banks of beaver ponds, and its growth is often vigorous enough to extend the beaver's food supply a few more years after the aspen has been exhausted.

ECOSYSTEMS CREATED BY BEAVER IMPOUNDMENTS

The most productive fish rearing streams are those that are not frequently subjected to upper and especially lower extremes of flow. Spring-fed and lake-fed streams are examples, as are small streams that have been colonized by beavers. In the latter example, beaver impoundments stabilize stream flows in two ways: first, they act as reservoirs, increasing the water-holding capacity of the watershed, thus slowing the rate of runoff; second, flooding of land in the vicinity of beaver colonies raises the level of the water table and the stored groundwater is slowly released back into the stream, which helps to maintain flow during long periods of drought. Studies conducted in late summer and fall in small coastal streams in Oregon revealed that up to 25% of water during low flow periods may be held in beaver ponds (Bergstrom 1985). Depth of even a few centimeters of stored water will enable some fish to survive until fall rains replenish the flow.

Chapter 15

Managing Beaver Habitat for Salmonids: Working with Beavers

Rheal J. Finnigan[1], David E. Marshall[2]

INTRODUCTION

Beavers are just one of several animal species that have increased in numbers as a result of logging. Like the black-tailed deer (*Odocoileus hemionus columbianus*) of coastal forests and the mule deer (*O. h. hemionus*) native to drier interior woodlands, beavers have benefited from the removal of the mature coniferous forest on river bottom lands and its replacement with faster-growing deciduous trees and shrubs. The new vegetation is the preferred food of beavers and, like deer and other animal populations, their numbers tend to increase with the abundance of their food supply. In time the conifers will return as the dominant tree species and beaver populations will return to original levels, but in the absence of aggressive beaver population control and/or reforestation practices this will be a very slow process.

Beavers qualify for special recognition as the hardest working of forest animals. By cutting down trees and shrubs and using this woody material to construct dams, beavers convert long sections of streams into deep ponds. The ponds provide beavers safety from predators and easy access to their woodland food supply. But their efforts inadvertently impact on other plant and animal species, notably the fish that occupy the same stream. For instance, a dam can sometimes be a barrier to adult and juvenile salmonids: adults passing upstream to spawning grounds, or juveniles moving upstream or downstream in search of suitable rearing habitat. In addition, some trout species are vulnerable to beaver encroachment. Resident rainbow and cutthroat trout and juvenile steelhead frequently rear in faster waters among boulders, large woody debris and at the heads of pools. This type of habitat is readily eliminated by beaver ponds on small streams. Beavers are also a problem to people — often a costly one — when their persistent dam building causes flooding of roads, timberlands, farms and other public and private property.

On the positive side, however, researchers and resource managers have found that beaver impoundments, both occupied and abandoned, support a variety of terrestrial and aquatic plant and animal communities, creating productive ecosystems. The impacts of beaver colonization are now considered an important factor in the health and diversity of riparian ecosystems. It appears then, that beaver activities can be beneficial in some cases and detrimental in others, depending upon where a family unit chooses to set up a colony.

The first section of this chapter describes briefly the life history of beavers and how their activities, mainly through damming small streams, affect stream hydrology, riparian vegetation, the nutrient cycle and ultimately fish production. The second section describes technologies that have been employed to facilitate fish passage at beaver dams without destroying the integrity of their ponds. Techniques are also described that discourage beavers from blocking culverts, a common problem that impedes fish access and leads to flooding of adjacent roads and lands.

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Small Projects (Summer Flow Augmentation)

Keogh Lake, Vancouver Island, B.C. A concrete low head dam was constructed at the outlet from Keogh Lake to increase summer flow in the Keogh River (Fig. 14-3 and Fig. 14-4).

Quatse Lake, Vancouver Island, B.C. As above to augment flow in the Quatse River and the Quatse Hatchery.

Matheson Lake, Vancouver Island, B.C. A small dam approximately 1 m high was constructed at the outlet to the lake by a public involvement group. The dam was constructed of boulders and concrete and flow releases were controlled by an adjustable plate over the end of the pipe (Fig. 14-2).

Demaniel Creek, Vancouver Island, B.C. A seasonal dam was constructed of sand bags at the outlet from the head pond of Demaniel Creek. Water was released by an adjustable plywood weir to increase the base rearing flow primarily for coho smolts. The dam was replaced each year by a dedicated resident in the area.

subject to significant vertical movement. The smooth plywood surfaces prevents ice from adhering, thus allowing movement to occur without damaging the cages. The buoyancy of the wood must be offset by attaching weights such as large rocks to the cages, or by anchoring to a "deadman" or large rock below the cages.

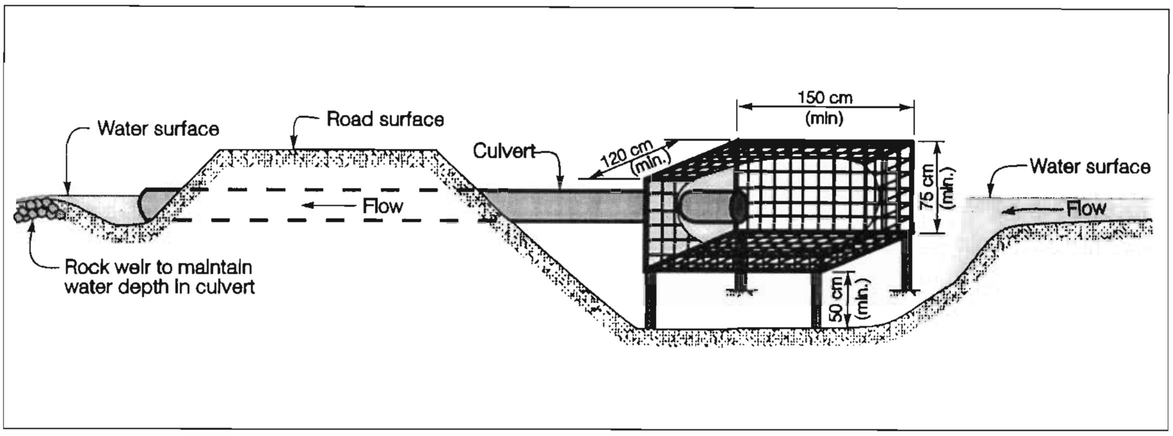

Figure 15-6. Rectangular wire mesh cage.

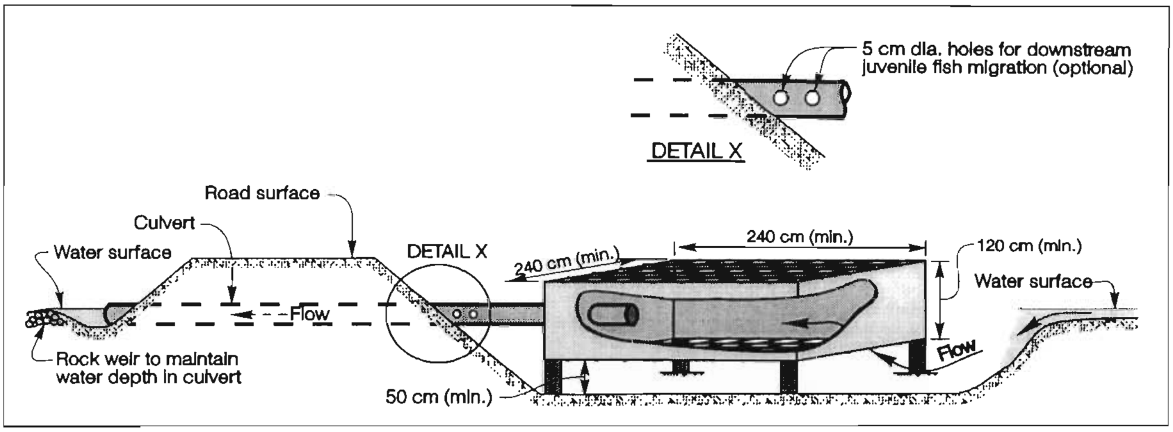

Figure 15-7. Rectangular cage with treated plywood sides and wire mesh top and bottom.

Excavating the accommodating deep holes and installing cages can be easily accomplished using a large track-excavator (Figs. 15-8, 15-9 and 15-10). It should be noted that although this design has been successful in facilitating upstream fish passage, difficulties to downstream migrant smolts seeking the pond outlet have been recorded (D. Bustard, pers. comm.). Hence, it may be necessary to provide small openings on each side of the culvert near the shoreline as shown on Figure 15-7 (DETAIL X) to facilitate fish movement at the time of the downstream smolt migration in spring. The rate of flow and proximity of the cage to the shoreline are the probable critical factors in smolts being able to locate the outlet.

Figure 15-8. Installation of plywood cage with wire mesh top and bottom.

Figure 15-9. Dewatered plywood cage attached to upstream end of culvert.

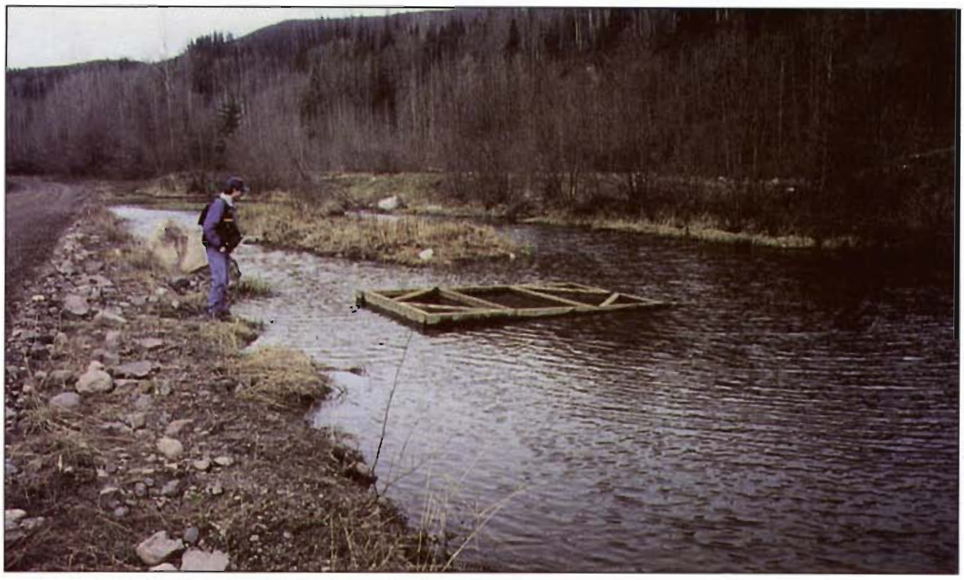

Figure 15-10. Plywood cage at normal operating water level.

FISH PASSAGE AT BEAVER DAMS

Fisheries workers carrying out spawning ground surveys frequently encounter beaver dams which must be breached to enable migrating adult salmonids to reach natal spawning areas upstream. If beavers rapidly repair the breached dam, delayed spawners may spawn elsewhere in less productive areas or may die unspawned. Because spawning migrations usually span a period of several weeks, dams must be breached repeatedly, a formidable task in remote areas. Access by juveniles seeking habitat suitable for summer and/or overwinter rearing is an additional problem that dams create. A concept for coping with the problem of fish access over beaver dams at non-culverted sites is the Telkwa design (Fig. 15-11). This concept has been tested on a small spring-fed tributary of the Telkwa River in northern British Columbia. The project addresses the hydrological needs of the resident beavers by maintaining a constant water level in the impoundment while providing for the two-way movement of fish.

At the Telkwa project, the width and height of an existing beaver dam were increased to minimize leaks and prevent overtopping. A large track excavator was used to obtain fill by digging deep holes in the beaver pond and side-casting the granular material onto the top and the outside sloping face of the dam. Next, a meandering channel, approximately 100 m in length, was excavated to accommodate the outflow from the pond. Because of its great length relative to its rise in elevation, the channel provides an access route with a low gradient (< 2%) enabling juveniles to ascend from the Telkwa mainstem. The final excavation work involved the construction of a 2-meter-deep, 5-meter-wide and 30-meter-long section of channel connecting the meandering outlet channel to the pond. A wire-mesh fence was erected along both banks of this connecting channel and the upstream reach of the meandering channel (Fig. 15-11). The connecting channel was filled with large floating woody debris, which was kept from drifting downstream by a barrier log spanning the channel. The combination of the fence and the floating debris makes it difficult for beavers to access the top riffle of the meandering channel and renew dam-building activities. The meandering channel was also provided with woody debris and other complexing to add to the rearing potential. The project has been operating successfully for four years (to 1996) with beavers having made no attempts to block the outlet channel. The average annual mark-recapture population estimate of coho salmon pre-smolts in the pond and channel combined from 1992 to 1996 has been 2,123.

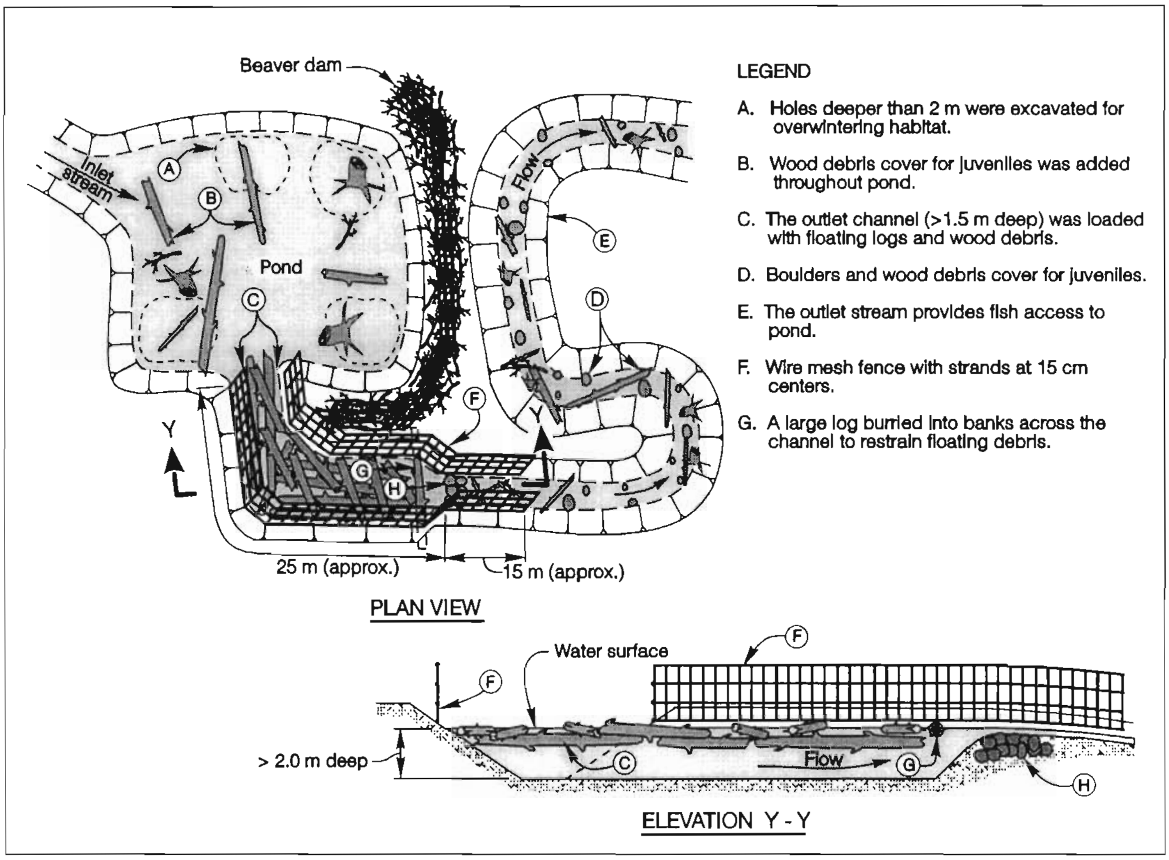

Figure 15-11. The Telkwa design concept. The outlet stream provides fish access into the beaver pond. Wire fence and floating logs restrict beaver access to the outlet stream.

The Telkwa design can also be applied to two or more ponds in series (Fig. 15-12). The meandering outlet channels can be appropriately located and aligned to suit the surrounding topography. Short (5 m-long) riffles with suitable instream cover (boulder and LWD) will accommodate stream dwelling species such as juvenile trout. It is recommended that the connecting channels be constructed without pools to deter beavers from erecting new dams in these channels. If beavers persist with building new dams, it may be necessary to fence the entire length of the outlet channels on both sides.

The Telkwa design concept can also be adapted to deter beavers from blocking road culverts (Fig. 15-13). A 1.5-meter-deep by 15-meter-long channel should be excavated to contain the floating woody debris, but measures should be taken to ensure that the debris does not drift downstream and block the culverts.

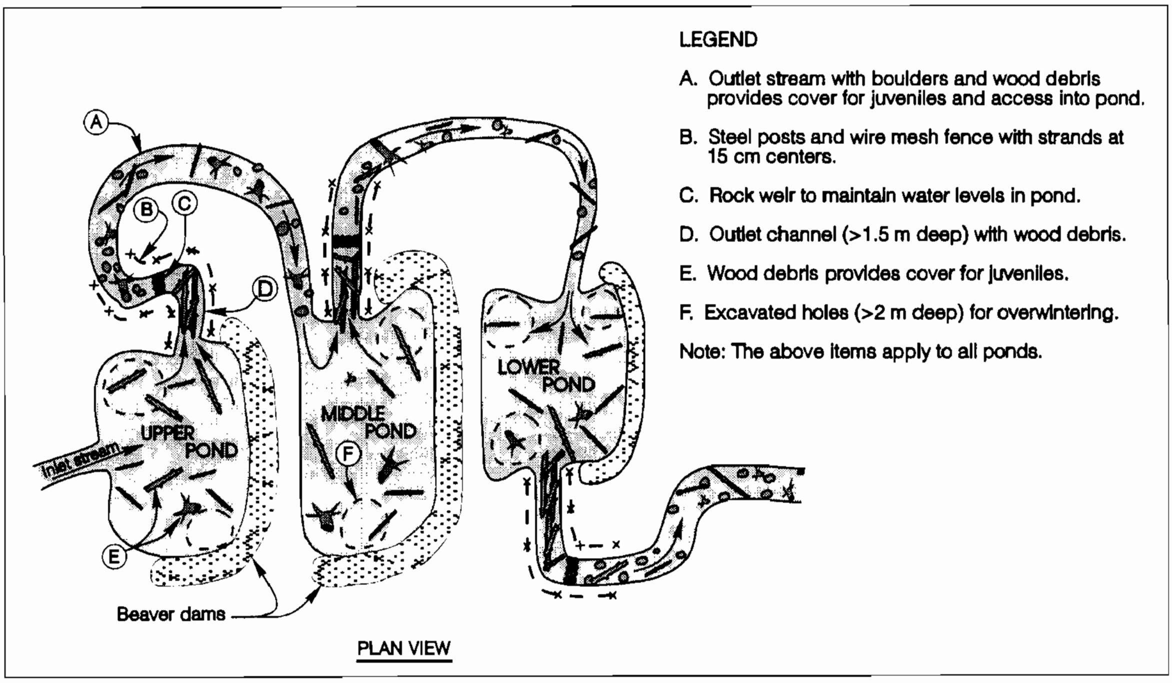

Figure 15-12. The Telkwa design concept adapted to three beaver ponds.

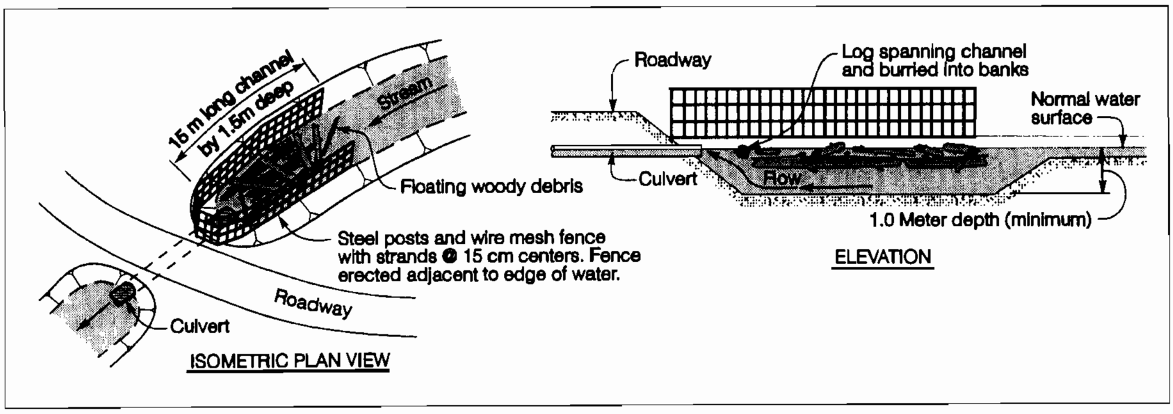

Figure 15-13. The Telkwa design concept adapted to a road culvert.

Glossary

Abandoned channel: A surface channel along which water no longer flows, such as on an alluvial fan or on a floodplain.

Aggradation: The geologic process by which streambeds, floodplains and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported from other areas. It is the opposite of degradation.

Alluvial deposit: An accumulation of predominantly coarse grained soils, deposited during post glacial time by running water, such as a stream or river, in the bottom of the water course, on a floodplain or delta, or on a fan at the base of a mountain slope. The material is generally well sorted and stratified. Also referred to as a fluvial deposit.

Alluvial fan: A relatively flat to gently sloping landform composed of predominantly coarse grained soils, shaped like an open fan or a segment of a cone, deposited by a stream where it flows from a narrow mountain valley onto a plain or broad valley, or wherever the stream gradient suddenly decreases.

Anadromous: Fish that breed in freshwater but live their adult life in the sea. On the Pacific coast, anadromous fish include all the Pacific salmon, steelhead trout, some coastal cutthroat trout and Dolly Varden char, lampreys, and eulachons.

Anchor Ice: Ice formed below the surface of a stream, on the streambed or upon a submerged body or structure.

Armouring: (a) The formation of an erosion-resistant layer of relatively large particles on the surface of the streambed that resists degradation by water currents. (b) The application of various materials to protect stream banks from erosion.

Backwater: (a) A pool type formed by an eddy along channel margins downstream from obstructions, such as bars, rootwads or boulders, or as a result of back flooding upstream from an obstructional blockage. Sometimes separated from the channel by sand/gravel bar. (b) A body of water, the stage of which is controlled by some feature of the channel downstream from the backwater, or in coves or covering low-lying areas and having access to the main body of water.

Bank erosion: A loosening and wearing away of soil and rock by water from the edge of a body of water, usually resulting in an enlargement of the body of water.

Bed erosion: A loosening and wearing away of soil and rock by water from the bottom of a body of water, usually resulting in a deepening of the body of water.

Channel bank erosion: A loosening and wearing away of soil and rock by water from the side of a channel, usually resulting in lateral shifting of the channel.

Channel bed erosion: A loosening and wearing away of soil and rock by water from the bottom of a channel, usually resulting in deepening of the channel.

Channel erosion: A loosening and wearing away of soil and rock by water flowing in a well-defined drainage course.

Channelization: Straightening of a stream or the dredging of a new channel to which the stream is diverted.

Condition assessment: An objective procedure to characterize the present state of a natural resource in a watershed and to diagnose resource impairment that can be remedied by restoration activities.

Conifer: Any of a large family of evergreen shrubs and trees, characterized by needle-shaped leaves and cones, such as pines, firs, hemlocks and spruces.

Debris: An accumulation of loose, predominantly coarse grained soil and rock fragments, and sometimes with large organic material such as limbs and trunks of trees, that have become mixed together in an unsorted fashion. Sometimes the term is used to refer solely to organic material, as in "logging debris".

Debris flow: A type of landslide characterized by water-charged, predominantly coarse grained soil and rock fragments, and sometimes large organic material, flowing rapidly down a pre-existing channel. Sometimes referred to as channelized debris flow, debris torrent, or mudflow.

Deciduous tree: Any of a large family of shrubs and trees, such as maple, birch, cottonwood and alder, whose leaves shed annually.

Deflector: An artificial erosion-resistant point bar. The purpose of deflectors is to keep the current moving swiftly in a sinuous course. When properly located and constructed, they can keep a stream channel moderately deep and allow the current to scour pools at stream bends.

Degradation: The geologic process by which streambeds and floodplains are lowered in elevation by the removal of material. It is the opposite of aggradation.

Discharge: Volume of water flowing in a given stream at a given place and within a given period of time, usually expressed as $m^3 \cdot s^{-1}$.

Eddy: A circular current of water, sometimes quite strong, diverging from and initially flowing contrary to the main current. It is usually formed at a point at which the flow passes some obstruction or on the inside of river bends. Often forms backwater pools or pocket water in riffles.

Energy dissipation: The loss of kinetic energy of moving water due to bottom friction, pools, large rock, debris and similar obstacles that impede flow.

Erosion: A process or group of processes whereby surface soil and rock is loosened, dissolved or worn away, and moved from one place to another, by natural processes. Erosion usually involves relatively small amounts of material at a time, but over a long time can involve very large volumes of material.

Fisheries sensitive zones: Side and back channels, ponds, swamps, seasonally flooded depressions, lake littoral zones and estuaries that are seasonally occupied by overwintering anadromous fishes (refer to the Forest Practices Code).

Forest resources: The Forest Practices Code of British Columbia Act defines forest resources as "resources and values associated with forests and range including, without limitation, timber, water, wildlife, fisheries, recreation, botanical forest products, forage, and biological diversity".

Flooding: The covering or inundation of land with a high level of water.

Floodplain: The low-lying, topographically flat area adjacent to a stream channel which is regularly flooded by stream water on a periodic basis and which shows evidence of the action of flowing water, such as active or inactive flood channels, recent fluvial soils, rafted debris, or tree scarring.

Fluvial: Of or belonging to rivers.

Forest Practices Code of British Columbia: A system of legislation, regulations and guidebooks intended to change the way provincial forests are managed. The *Act* is the foundation of this new forest management system. It makes five main contributions:

- a clearer, more legally enforceable management framework
- stronger compliance and enforcement powers, including administrative penalties and offense provisions
- a new legislated forest planning framework
- powers to regulate managed private forest lands and botanical forest products
- new administrative bodies like the Forest Practices Code, the Forest Appeals Commission and the Forest Practices Advisory Council that help ensure proper forest management.

Freshet: A rapid rise in river discharge and level caused by heavy rains or melting snow.

Gabion: A galvanized wire basket with a removable top. The basket, filled with selected stones, is used to stabilize banks to control erosion in streams and to prevent stream gravel from shifting.

Geomorphology: The branch of geology that deals with the origin and nature of landforms. The active forces that shape landforms are water, ice, wind and gravity.

Glide: A slow-moving, relatively shallow type of run. Calm water flowing smoothly and gently, with moderately low velocities (10 to 20 cm/sec), and little or no surface turbulence.

Gradient: (a) The general slope or rate of change in vertical elevation per unit of horizontal distance of the water surface of a flowing stream. (b) The rate of change of any characteristic per unit of length.

Groyne: A barrier built, usually of large boulders, out from the shore to protect against erosion and sand movement.

Gully: A long, linear depression incised into steep hillslopes, where the overall gradient is at least 25%, with a channel confined in a V-notch ravine with banks higher than 3 m, sideslopes steeper than 40% and an overall length greater than 100 meters.

Hardwood: The fully mature stem of a deciduous tree or shrub.

Hydraulic jump: An abrupt, turbulent rise in the water level of a flowing stream, normally occurring at the transition from shallow, fast flow to deeper and slower flow.

Hydraulics: Refers to water, or other liquids, in motion and their action.

Incised channel: A stream that through degradation has cut its channel into the bed of the valley.

Infilling: A process where humans use a variety of materials to increase the building grade within a floodplain. As the area infilled increases, the potential flood level of future floods also increases.

Large woody debris: Any large piece of relatively stable woody material having a diameter greater than ten centimeters and a length greater than three meters that intrudes into the stream channel. Synonym: LOD, large organic debris, log. Specific types of large organic debris include:

- Affixed logs: Single logs or groups of logs that are firmly embedded, lodged or rooted in a stream channel.
- Bole: Term referring to the stem or trunk of the tree.
- Large bole: Ten meters or more in length; often embedded, remains in the stream for extended periods.
- Small bole: Less than ten meters, usually sections of bole; seldom stable, usually moves downstream on high flows.
- Deadheads: Logs that are not embedded, lodged or rooted in the stream channel but are submerged and close to the surface.
- Digger log: Log anchored to the stream banks and/or channel bottom in such a way that a scour pool is formed.
- Free logs: Logs or groups of logs that are not embedded, lodged or rooted in the stream channel.
- Rootwad: The root mass of the tree. Synonym: butt ends.
- Snag: (a) A standing dead tree. (b) Sometimes a submerged fallen tree in large streams. The top of the tree is exposed or only slightly submerged.
- Sweeper log: Fallen tree whose bole or branches form an obstruction to floating objects.

Types of large organic-debris accumulation:

- Clumps: Accumulations of debris at irregularly spaced intervals along the channel margin, not forming major impediments to flow.
- Jams: Large accumulations of debris partially or completely blocking the stream channel, creating major obstructions to flow.
- Scattered: Single pieces of debris at irregularly spaced intervals along the channel.

Mass wasting: Landslide processes, including debris falls, debris slides, debris avalanches, debris flows, debris torrents, rockfalls, rockslides, slumps and earthflows, and the small scale slumping collapse and raveling of road cuts and fills.

Mean annual precipitation: The total precipitation (rain and the water equivalent of snow) recorded per year and averaged over many years.

Meandering: Characterized by a clearly repeated pattern of curvature as seen from above.

Mitigation: Activities taken to offset for the impairment of natural resources where restoration or, hierarchically, rehabilitation is not feasible. Mitigation, as a last recourse may not replace "like with like" and may not be undertaken in the same watershed but may reserve species or stocks at risk.

Off-channel pond: A pond, not part of the active channel, but connected to the main stream by a short channel. Generally occurs in old flood terraces, but also refers to wall-based channel ponds when located near the base of a valley wall.

Oxbow: A looping river bend cut off from the main flow by a new channel broken through the neck of its enclosed peninsula.

Point bar: A deposit of sand, gravel or other material on the inside of a stream bend, which causes some obstruction to the flow.

Pool: (a) A portion of a stream with reduced current velocity, often with water deeper than the surrounding areas, and which is frequently used by fish for resting or cover. (b) A small body of standing water, e.g., in a marsh or on the floodplain.

Backwater: see **Backwater**.

Corner: A lateral scour pool resulting from a shift in channel direction.

Dammed: Water impounded upstream from a complete or nearly complete channel blockage, typically caused by a logjam, beaver dam, rock slide or stream habitat improvement device, such as a boulder berm, gabion, or log sill.

Eddy: see **Eddy**.

Flat: A wide, shallow pool of low turbulence. Sometimes used synonymously with glide.

Lateral scour: Formed by the scouring action of the flow as it is directed laterally or obliquely to one side of the stream by a partial channel obstruction, such as a gravel bar or wing deflector.

Plunge: (Also falls pool, plunge basin.) A pool created by water passing over or through a complete or nearly complete channel obstruction, and dropping vertically, scouring out a basin in which the flow radiates from the point of water entry.

Pocket water: A series of small pools surrounded by swiftly flowing water, usually caused by eddies behind boulders, rubble or logs, or by potholes in the streambed.

Secondary channel (see **Side channel**): Relatively small, sometimes isolated pools in a smaller braid of the main stem and usually associated with gravel bars.

Slack water: Pool-like depressions along the stream margin and on the floodplain that contain water only during high flow or after floodwaters recede. More transient in nature than secondary-channel pools, they may contain water for only a few days or weeks.

Trench: A pool characterized by a relatively long, slotlike depression in the streambed, often found in bedrock-dominated channels.

Under scour: Formed by scouring under a stream obstruction, such as a log. Sometimes called upsurge pool.

Pool-Riffle ratio: The ratio of the surface area or length of pools to the surface area or length of riffles in a given stream reach, frequently expressed as the relative percentage of each category.

Rain on snow event: A rainfall that occurs when there is already snow on the ground. Depending on the temperature, the rain melts the snow and the resulting runoff can be substantially greater than that from just the rain.

Rehabilitation: Returning to a state of ecological productivity and useful structure, using techniques similar or homologous in concept (e.g., boulders replacing root masses); producing conditions more favourable to a group of organisms or species complex, especially that economically and aesthetically desired of native flora and fauna, without achieving the undisturbed condition.

Restoration: Bringing back to a former or original condition (e.g., the pre-logging state). In this manual the term "restoration" is meant to include rehabilitation.

Revetment: A facing of stone or broken rock pieces placed on a stream bank to prevent or minimize erosion from high velocity flow.

Riffle: A shallow rapids where the water flows swiftly over completely or partially submerged obstructions to produce surface agitation, but standing waves are absent.

Riparian area: The land adjacent to the normal high waterline in a stream or lake whose soils and vegetation are influenced by the presence of the ponded or channelized water. Riparian management areas are administratively-defined strips of land adjacent to certain stream channels; consult the Forest Practices Code and regulations for their definition.

Rootwad: The root mass of the tree. Synonym: butt ends.

Roughness: A measure of the irregularity of streambed materials as they contribute to resistance to flow. Commonly measured in terms of Manning's roughness coefficient.

Run: An area of swiftly flowing water, without surface agitation or waves, which approximates uniform flow and in which the slope of the water surface is roughly parallel to the overall gradient of the stream reach.

Salmonid: Refers to a member of the fish family classed as Salmonidae, including the salmons, trouts, chars, whitefishes and grayling.

Scour: The downward or lateral erosion by swiftly moving water or by a debris flow.

Sedimentation: The process of subsidence and deposition of suspended matter carried in water by gravity; usually the result of the reduction of water velocity below the point at which it can transport the material in suspended form.

Side channel: Lateral channel with an axis of flow roughly parallel to the main stem, which is fed by water from the main stem; a braid of a river with flow appreciably lower than the main channel. Side-channel habitat may exist either in well-defined secondary (overflow) channels or in poorly defined watercourses flowing through partially submerged gravel bars and islands along the margins of the main stem.

Sinuous: (a) The ratio of channel length between two points on a channel to the straight line distance between those same points; (b) The ratio of channel length to valley length (1.5 = meandering; close to 1.0 is straight).

Smolt: A seaward migrating juvenile salmonid, which is silvery in color, has become thinner in body form and is physiologically prepared for the transition from fresh- to saltwater. The term is normally applied to the migrants of species such as coho, sockeye, chinook and steelhead that rear in freshwater for a period before migrating to sea.

Stream: A natural watercourse containing flowing water at least part of the year, supporting a community of plants and animals within the stream channel and the riparian vegetation zone. Streams in natural channels may be classified as follows:

a. Relative to time

Ephemeral: One that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

Intermittent or seasonal: One in contact with the ground water table that flows only at certain times of the year as when the water table is high and/or when it receives water from springs or from some surface source, such as melting snow in mountainous areas. It ceases to flow above the streambed when losses from evaporation or seepage exceed the available stream flow.

Perennial: One that flows continuously through the year. Synonym: permanent stream.

b. Relative to space

Continuous: One that does not have interruptions in space.

Interrupted: One that contains alternating reaches that are perennial, intermittent or ephemeral.

c. Relative to groundwater

Gaining: A stream or reach of stream that receives water from the zone of saturation.

Insulated: A stream or reach of stream that neither contributes to nor receives water from the zone of saturation. It is separated from the zones of saturation by an impermeable bed.

Losing: A stream or reach of stream that contributes water to the zone of saturation.

Perched: Either a losing stream or an insulated stream that is separated from the underlying groundwater by a zone of aeration.

d. Other

Incised: A stream that through degradation has cut its channel into the bed of the valley.

Stream bank: The portion of the channel cross section that restricts lateral movement of water at normal water levels. The bank often has a gradient steeper than 45 degrees and exhibits a distinct break in slope from the stream bottom. An obvious change in substrate may be a reliable delineation of the bank.

Lower bank: The periodically submerged portion of the channel cross section from the normal high waterline to the water's edge during the summer low-flow period.

Upper bank: That portion of the topographic cross section from the break in the general slope of the surrounding land to the normal high waterline.

Streambed: The substrate plane, bounded by the stream banks, over which the water column moves. Synonym: stream bottom.

Stream order: A scale-dependent property of drainage networks that describes the position and approximate size of a stream segment in the network. First order streams are headwater streams that have no tributaries. A second order stream is formed where two first order streams join, a third order stream is formed where two second order streams join, etc. Note that the confluence of a second order stream with a first order stream remains a second order stream.

Stream reach: A homogeneous segment of a drainage network, characterized by uniform channel pattern, gradient, substrate, and channel confinement.

Substrate: The mineral and/or organic material that forms the bed of the stream.

Thalweg: The path of maximum depth in a river or stream. This path normally follows a meandering pattern, back and forth across the channel.

Velocity: The time rate of motion; the distance traveled divided by the time required to travel that distance.

Watershed: An area of land (the catchment or drainage basin), bounded peripherally by a topographic height of land, that delivers water along a stream channel to a common outlet. Watersheds are the natural landscape units from which hierarchical drainage networks are formed.

Weir: A low dam or fence constructed across a stream or river primarily to control water levels or to divert water into another facility.

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