Impacts of logging in Carnation Creek, a high-energy coastal stream in British Columbia, and their implication for restoring fish habitat

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Abstract: The land form, surficial geology, and hydrometeorology of the west coast of British Columbia cause streams in the region to be highly variable in flow and vulnerable to land-use disturbance. Carnation Creek, a small drainage in this region, was studied intensively for > 20 yr to examine the impacts of forest harvesting. Landslides and debris torrents modified steep slope tributaries and the mainstem of the creek. Bank erosion also altered the stream channel on the alluvial flood plain. These effects were additive in the system and reduced the quality of spawning and rearing habitat for juvenile salmonids. In streams like Carnation Creek, it is necessary to restore some stability to the hill slopes and gullies before attempting fish habitat improvements in the main channel. Salmonid production was limited by combinations of processes and conditions that were different for each species and life-history stage. Knowledge of the processes that limit fish production must be applied in habitat improvement work or the projects risk failure. Programs intended to restore natural function to systems or to improve habitat for fish must be planned, evaluated, and reported methodically if they are to succeed and provide information of use to future programs.

Résumé : Sur la côte de Colombie-Britannique, le relief, la nature des dépôts meubles et les facteurs hydrométéorologiques font que les petits cours d'eau ont un débit très variable et sont facilement perturbés par l'utilisation du territoire. Les impacts de l'exploitation forestière sur le ruisseau Carnation, qui draine un petit bassin-versant de la région, a été étudié intensivement pendant plus de 20 ans. Les glissements de terrain et les torrents de débris ont modifié les tributaires à forte pente et le tronc principal du ruisseau. De plus, l'érosion des berges a modifié le chenal du cours d'eau dans la plaine alluviale. Ces facteurs ont eu des effets additifs sur le système et ont réduit la qualité des frayères et des aires d'alevinage des salmonidés. Dans le cas d'un cours d'eau comme le ruisseau Carnation, il est nécessaire de rétablir une certaine stabilité des pentes et des ravins avant d'essayer d'améliorer l'habitat des poissons dans le chenal principal. La production de chaque espèce de salmonidé était limitée par une combinaison particulière de processus et de conditions. Une connaissance des processus limitant la production des poissons doit être appliquée aux travaux d'amélioration des habitats, qui risquent autrement d'échouer. Les programmes visant à rétablir la fonction naturelle des systèmes ou à améliorer l'habitat des poissons doivent faire l'objet d'une planification, d'une évaluation et de rapports méthodiques, si on veut qu'ils réussissent et produisent des données utiles pour les programmes à venir.
[Traduit par la Rédaction]

Introduction

Drainage basins of the west coast of British Columbia hold high resource values for forestry, fisheries, wildlife, tourism, and cultural heritage. The significance of the fisheries and forestry values within the drainages has been recognized for decades, and conflicts regarding the impacts of forest management activities on fisheries resources date back to the 1950s. While managing a high level of use of resources that share a common land base is challenging in itself, the situation in coastal drainages of British Columbia is made more difficult because they are located in mountainous terrain with shallow and unstable surficial material. Coastal drainages are also subject to high precipitation and severe storms, which cause hydrological regimes that vary with watershed size and elevation. Flow regimes in small and low-elevation streams are driven by winter rain, while those of higher elevation are driven by winter rain, rain on snow, and spring snowmelt events. Regimes may differ from one drainage to another, but in all cases the high hydrological energy, the extremely flashy nature of these streams, and the transport of sediment are key elements in the challenge of managing fisheries and forestry resources. These conditions also make watershed restoration and stream habitat improvement difficult.

In this manuscript, we use "restoration" to describe activities that attempt to return disturbed drainage basins to near predisturbance condition. "Habitat improvement" refers to specific efforts within the stream channel and riparian zone to enhance spawning, rearing, or feeding conditions for fish.

The impacts of forest management activities on stream ecosystems are complex and vary in timing and duration, depending on system type, forestry activity, and fish species present. The major groups of physical and biological processes studied

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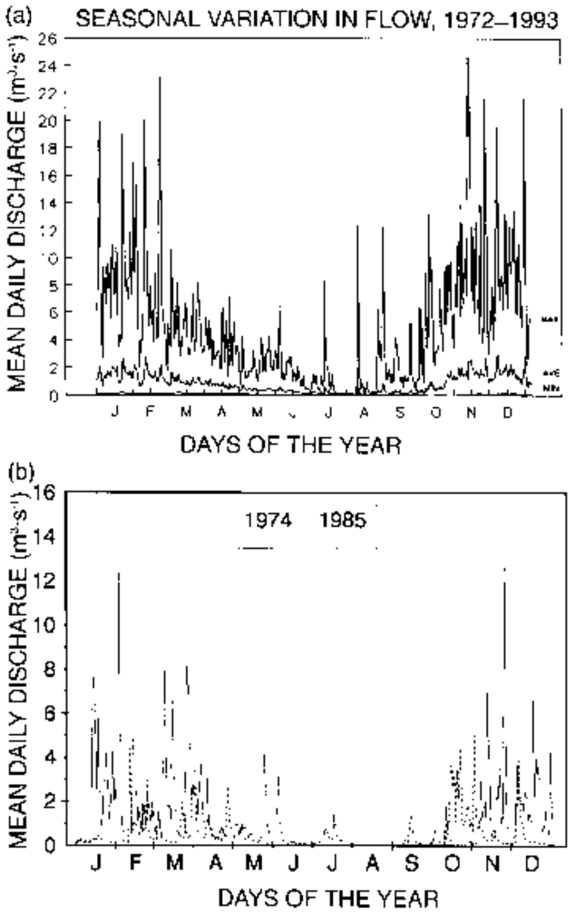


Fig. 1. (*a*) Daily variation of stream flow at B-weir in Carnation Creek, 1972–1993. (*b*) Mean daily flows during an example of a wet year, 1974, and a dry year, 1985.

at Carnation Creek included hydrological, fluvial-geomorphological, thermal, and trophic processes. Five generalizations emerged during the project:

(1) The processes were extremely complex and almost fully interconnected (Hartman and Scrivener 1990).

(2) Each species and life stage of salmon and trout responded differently to the impacts of forestry activities.

(3) Responses differed geographically. Watershed orientation or topography affected impacts. Some responses occurred ≥ 4 km downstream from the location of logging impact (Hartman et al. 1987; Meehan 1991).

(4) Responses differed in duration. Some persisted for a few years, while others continued longer than originally expected (Scrivener and Brown 1993) and may continue for centuries (Meehan 1991).

(5) Impacts of forestry activities may combine with conditions in the marine environment to limit fish population numbers (Hartman and Scrivener 1990).

In this paper we examine the implications of these generalizations to watershed restoration and stream habitat improvement programs.

To improve fish habitat, it is necessary to understand how various structures or in-stream improvements can affect the various life stages and species. Any primary limiting factors must also be understood for the species being enhanced. This paper illustrates the nature of some of the limiting factors for species in Carnation Creek and comments on how biologists determine limiting factors for habitat improvement projects. Terrain, hydrology, and stream productivity are also important elements that, over time, have influenced the evolution of successful life history strategies for a population. Enhancement should be tailored to limiting factors and life strategies of the target population.

The stream ecosystem: Carnation Creek

Physical conditions

Carnation Creek is ~8 km long and drains an area of 10 km^2. It is located in the Barkley Sound region of Vancouver Island. The bedrock consists principally of the Vancouver Island Intrusion, a Jurassic age batholith of granodiorite. Surficial materials are tills and colluvium that are frequently only thin veneers overlying bedrock (Jungen, no date; Alley 1975).

The terrain is steep and rocky and forested with western red cedar, coastal western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*), and red alder (*Alnus rubra*). Above 5 km from the mouth, the stream flows through a bedrock-controlled channel. Elsewhere, it passes through a 100–300 m wide alluvial flood plain, except for a short canyon reach, 3.1–3.5 km from the mouth. Before logging, channel structure was controlled by large woody debris (LWD) and by stream banks with erosion resistant vegetation. The amount, type, and role of LWD was described by Toews and Moore (1982), and the responses since logging were described by Powell (1988). Side-channel and tributary areas on the alluvial plain were characterized by Brown (1987).

Carnation Creek is, hydrologically, a high energy system. From 1970 to 1990, ~95% of the 210–480 cm annual precipitation occurred as rain, and most of it fell during storm events in the period between November and April (Hartman and Scrivener 1990). Stream flow increased rapidly in response to rainfall within storms whether they occurred during summer or winter (Fig. 1*a*). Because soils were saturated, water moved quickly to bedrock in the coarse shallow soils, and the ephemeral channel network expanded rapidly up the slopes (Hetherington 1982, 1995). Quick runoff was further enhanced by movement of water through soil macrochannels (subsurface channels left by decomposed tree roots). Because of these climatic and geological features, the stream reached flood levels within a few hours and water levels declined as rapidly after storms (Fig. 1*a*).

Minimum stream flows occurred during the summer months, although storms and high discharges could occur during any month (Fig. 1*a*). Large differences occurred between wet and dry years (Fig. 1*b*). Discharges, in summer, were low during both wet and a dry years, but the volume of discharge and the frequency of events with flows <2 $m^3 \cdot s^{-1}$ were much greater during a wet year, 1974, than a dry year, 1985 (Fig. 1*b*).

Streams on the west coast of British Columbia are usually low in biological production because of nutrient, light, and

Fig. 2. Schematic representation of the freshwater life histories of juvenile chum, pink, sockeye, chinook, and coho salmon and steelhead and cutthroat trout for as long as 5 years.

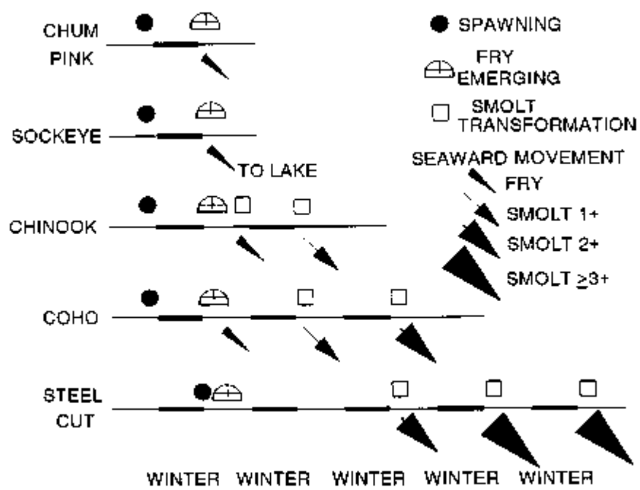
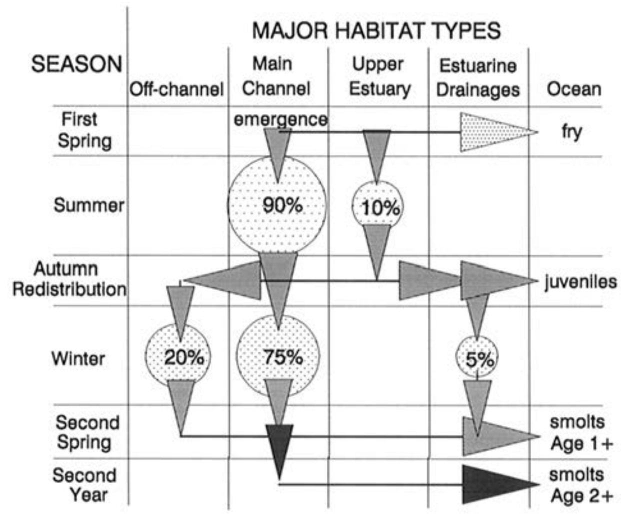


Fig. 3. Major habitat types and life history strategies that are used by coho salmon in Carnation Creek.



temperature conditions. In Carnation Creek, conductivity, an indicator of productivity, was low (20–60 μmhos·cm^{-2}) and inversely related to stream flow (Scrivener 1988). Bedrock did not weather rapidly to release minerals, and those released were flushed rapidly through the watershed. Only 24–47% of the total light available reached the stream under the old-growth forest (Shortreed and Stockner 1982). Therefore, stream autotrophic production was limited by low levels of light and nutrients, especially phosphate (Stockner and Shortreed 1976). Stream temperatures averaged only 9–11°C from May to September (Holtby 1988).

Fish populations

The fish fauna in Carnation Creek consists of coho and chum salmon (*Oncorhynchus kisutch* and *O. keta*), steelhead and cutthroat trout (*O. mykiss* and *O. clarki*), and two species of cottids (*Cottus aleuticus* and *C. asper*). The salmonid species demonstrate a variety of alternative life-history strategies (Fig. 2), the advantages and disadvantages of which are discussed.

Chum salmon limit their freshwater life to spawning and incubation stages (Fig. 2). They spend their full postembryonic growing period at sea, in an environment far more productive than that of their natal stream, but they are subjected to greater potential predation pressures in the ocean. Their reproduction is concentrated in the lower reaches of the stream. Thus, populations are at risk from the impact of major habitat disturbances such as elevated sediment loads and temperature regimes that reach lower parts of the stream. These disturbances have cumulative downstream effects that impact incubation success and marine survival (Scrivener 1991).

Juvenile coho salmon exhibit five different life history strategies in Carnation Creek (Fig. 3). They may hatch and rear in the main channel until smolt transformation at age 1+ or 2+ (Hartman and Scrivener 1990). They may hatch and rear in the main channel before moving, during autumn, into off-channel habitat on the flood plain. Coho fry may disperse downstream during March to June, remain in the estuary until October or November, grow rapidly, and then disperse to sea (Tschaplinski 1987), or move upstream to estuarine drainages (Scrivener and Brown 1993).

The success of a particular coho life-history strategy depends upon conditions in the stream during the winter. For example, during years when late winter and early spring water levels were low, juvenile coho survival and smolt production was low in the off-channel habitat (Brown 1985). Survival was better in the main channel. During winters with many storms, access and survival were high in the off-channel, but low in the mainstem habitat. These different patterns of habitat use provided stability of smolt production and additional options for habitat improvement.

Trout had a 2- or 3-yr residence in the stream (Fig. 2), but fewer habitat strategies than those that coho exhibited (Fig. 3). Steelhead used only the main channel, while cutthroat used some off-channel habitats (Brown and Hartman 1987).

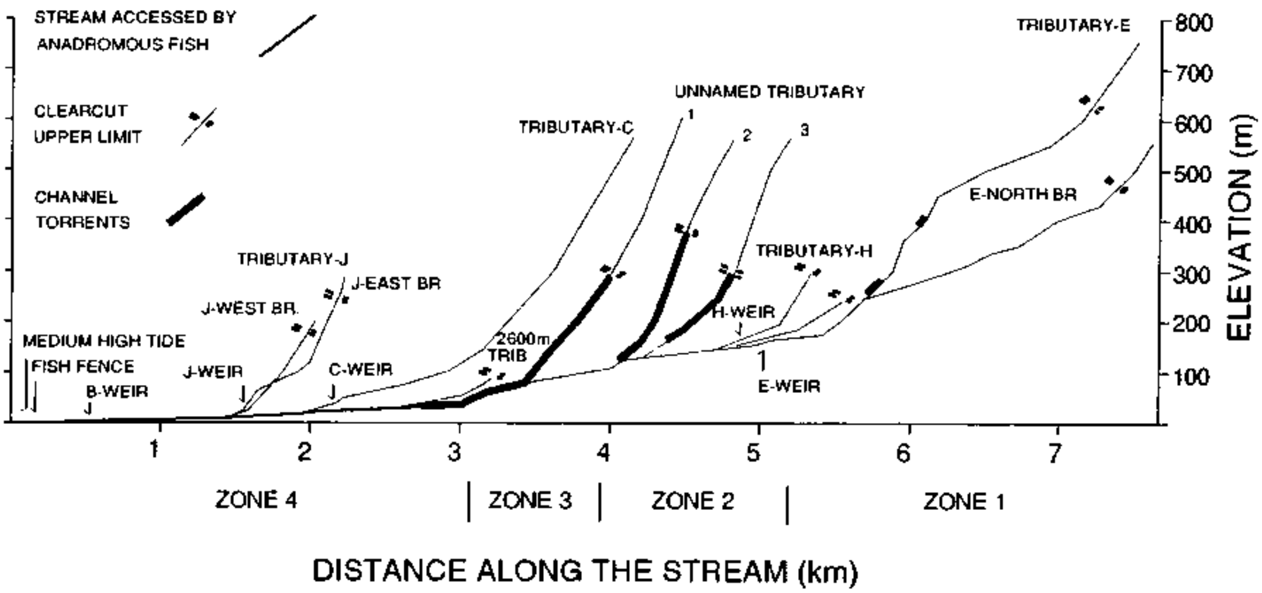
Characteristics of forest management impacts in west coast B.C. streams

Forest management affected the interrelated hydrological-geomorphological, thermal, and trophic processes in Carnation Creek (Hartman and Scrivener 1990). During phase I of the logging, 1976–1981, 41% of the basin was clear-cut. During phase II, 1987–1994, another 42% was cut. To date, ~61% of the length of headwater streams has been logged, requiring 38.5 km of road and 21 crossings of hillslope channels. This activity has caused changes to water routing and, deposition of ~25 480 m^3 of sediment, principally derived from landslides, into the creek (S. Chatwin, B.C. Ministry of Forests, Victoria, B.C., personal communication). The relevance of these changes and associated processes can now be discussed with regard to habitat improvement and restoration within this type of ecosystem.

Hydrological-geomorphological processes

Several changes in hydrological conditions in the Carnation Creek basin have occurred since logging. Annual water yield increased 9–16% following near total clear-cutting of a 12-ha sub-basin (H-tributary; Hetherington 1982), but an increase

Fig. 4. Gradients of Carnation Creek and tributaries, limits to clearcuts, and locations of debris torrents.



was not detected for the total basin following phase I. Following logging of this sub-basin, summer flow levels increased 78% and runoff peaks increased ~20%, but only for early autumn storms. Alterations of natural hydrological pathways such as loss of water interception by the canopy and compaction of soils along skid trail road, and ditch channels probably caused the increased yield and runoff (E. Hetherington, Canadian Forestry Service, Victoria, B.C., personal communication). After logging, groundwater levels were elevated in some areas of the flood plain, but declined at other locations when compared with control sites.

Hydrometeorological conditions strongly affected slope stability in the Carnation Creek watershed, and both hydrological and sediment transport processes affected structural changes in the stream channel. At Carnation Creek, Caine's (1980) criterion for susceptibility of slope failures was exceeded during rain storms with 2-yr return periods, even at undisturbed sites. Elsewhere in southwestern British Columbia, slope failures and debris torrents[2] have occurred at smaller rainfall intensities than those proposed by Caine (1980) when soil moisture has been increased by previous rainfall or snowmelt (Church and Miles 1987). All of these criteria were exceeded at some logging disturbed sites at Carnation Creek, even at short-duration rainfall intensities (Hartman and Scrivener 1990). The volume of landslide material has increased 12-fold since logging. This is about one third of the increase (34-fold), that was observed for watersheds on the Queen Charlotte Islands (Rood 1984, 1990). This is consistent with information from Swanson et al. (1987) who reported that frequencies of landslides and debris torrents were increased when forestry activities caused elevated water yields and shorter water runoff routes on steep hill slopes.

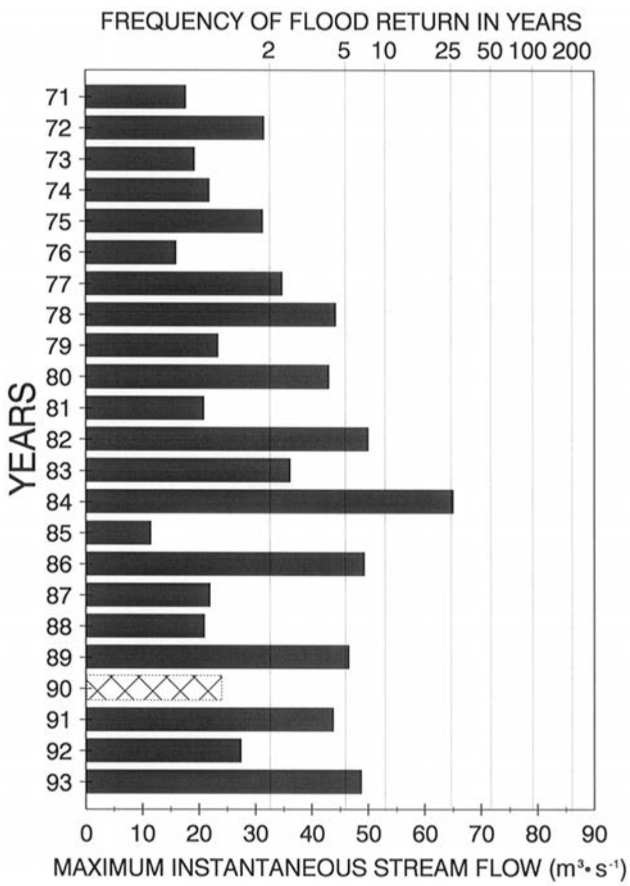
[2] A debris torrent is a mass movement of water-charged material that flows down a steep, confined, pre-existing stream channel (Swanston 1974; Van Dine 1985). The material includes rocks as large as several meters in diameter and wood, ranging from mulch to large logs.

Two sets of structural change occurred in Carnation Creek, which are temporally and spatially different. Although their effects were cumulative, they were caused by forestry activities in different parts of the basin. First, clear-cutting to the stream margin on the flood plain caused destabilization of LWD, erosion of stream banks, entrainment of sediment, widening of the channel, and deposition of sediment in the lower reaches (Hartman and Scrivener 1990). These events began following a major storm, 3 years after logging was initiated, and they accelerated for a decade. A second set of changes took place 5–8 yr after logging when a landslide occurred in the canyon and debris torrents came down three steep gullies (Fig. 4). These events occurred during a single storm with a calculated 25-yr return period (Fig. 5). There were three large piles of LWD on the banks and ~1500 m^3 of sediment remaining in the channel of Carnation Creek at or near the toe of the torrent.

Many changes occurred in the lower reaches of Carnation Creek after the destabilization of LWD and the large input of sediments. LWD volumes declined 50% within a few years in stream reaches with a clear-cut riparian zone (Toews and Moore 1982) and 0–20% within a decade elsewhere in the channel (Powell 1988). This pattern is typical of coastal streams (Fig. 6). Channel diversity (e.g., pool volumes) and sediment storage are directly related to the LWD volume (Bisson et al. 1987), so the channel became structurally more uniform (pool habitat filled) and stream sediments were more mobile. The additional sediments caused dewatering of some areas, transport of fines into spawning gravel, and disturbance of incubating salmon eggs (Scrivener and Brownlee 1989). Some of this sediment is stored in channels that have been recently abandoned by the stream. Some of it is stored above large LWD jams and then periodically released during storm events. Watershed-restoration and habitat-improvement projects must recognize and understand these multiple source problems and their cumulative effects before fish habitat improvement structures are added to the channel.

Sediment accumulating behind LWD has caused two relo-

Fig. 5. Annual peaks of stream flow at B-weir and their predicted reoccurrence in Carnation Creek. A Gumbel frequency distribution is superimposed on the graph to show probable return periods for peaks. The 1990 maximum was predicted with a correlation of annual peak flows from B- and E-weir (R^2 = 0.77).



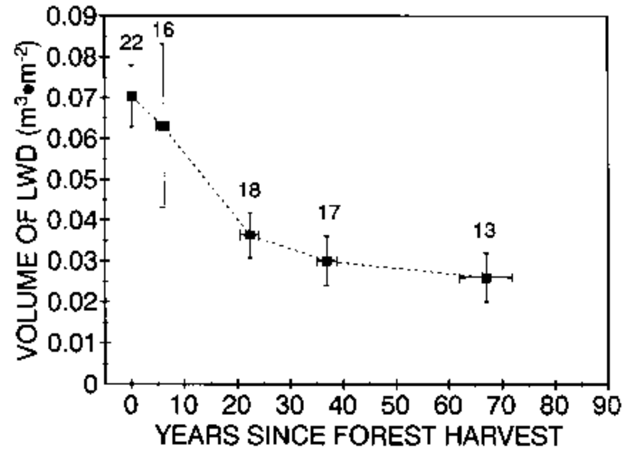
cations of the main channel of Carnation Creek. Gravel filled the old channel at km 1.3 and 1.7 (Fig. 4), and new 150 and 75 m long channels were scoured during 1986 and 1993 storms, respectively. These changes were caused by floods with ~7-yr return periods (Fig. 5). Fish habitat is now ephemeral in the old channels and additional sediment was mobilized when the new channels were formed.

The seven ephemeral tributaries and side-channels, located on the valley floor, were not altered by forestry activities as much as the mainstem of Carnation Creek. There was some deposition of debris and loss of aquatic vegetation within these habitats, but their structure was not altered (Brown 1985).

Thermal processes

Stream temperatures increased 0.5, 0.75, and 3.2°C during winter, spring, and summer, respectively, for the decade following logging of the riparian zone of Carnation Creek (Holtby 1988; Hartman and Scrivener 1990). During summer, elevated stream temperatures occurred when more radiant energy reached the stream. This type of impact has had deleterious effects on salmonids elsewhere (Brown 1971; Hall and Lantz 1969; Hall et al. 1987), but it enhanced fish growth in Carnation Creek (Holtby 1988). Increased stream temperatures during winter and spring caused rapid embryonic development and early emergence of salmonid fry in Carnation Creek (Hartman and Scrivener 1990). This had negative impacts on chum salmon, positive and negative impacts on coho salmon, and positive impacts on age 0+ trout.

Fig. 6. Mean volumes of large woody debris (10 cm diameter) and standard errors for 53 streams on Western Vancouver Island (DFO data, including Carnation Creek), for 6 streams on the Queen Charlotte Islands (from Hogan 1986) and for 27 streams on the Olympic Peninsula, Washington (from Grette 1985; Bisson et al. 1987). The numbers of streams used to calculate the means are also shown.



Trophic processes

Three changes occurred, following logging, that altered trophic conditions in the stream:

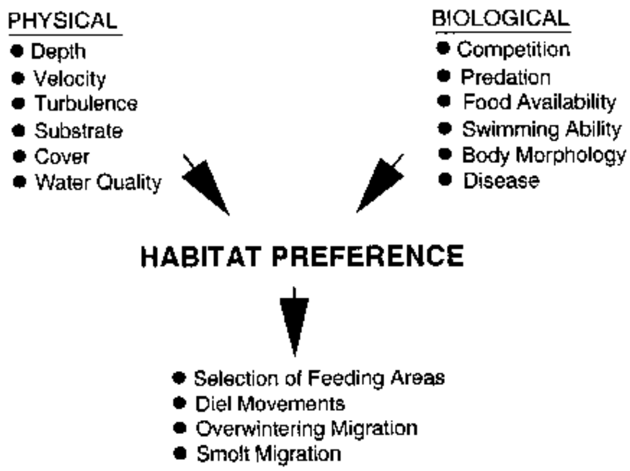
(1) The riparian forest was cut for ~2.25 km along the lower 5 km of stream and only a thin line of trees was left on one side of another 1.0 km of stream (Hartman and Scrivener 1990). Leaf litter input from these areas was stopped or reduced.

(2) Sunlight reached the stream and stream temperatures were increased (Stockner and Shortreed 1976; Holtby 1988).

(3) The flux of nitrates through the system was increased, particularly during winter freshets (Scrivener 1989). The increase in total phosphorus was very low.

Logging of streamside areas produced a statistically significant increase in primary production within the stream (Shortreed and Stockner 1982), but the increase was small when compared with other studies (Minshall et al. 1983; Gregory et al. 1987). The elevated stream temperatures and light intensities had little or no influence on algal production in Carnation Creek (Stockner and Shortreed 1976). Primary production was limited mainly by low concentrations of phosphorus. The algae that grew were partially removed by freshets during summer and almost totally scoured away during September and October freshets (Stockner and Shortreed 1976). Prior to logging, production was primarily heterotrophic, given the stream size and functional attributes described by Vannote et al. (1980). The input of leaf litter and its conversion to detritus were the basis for most of the macroinvertebrate production in Carnation Creek (Culp 1988).

Fig. 7. Physical and biological factors that determine habitat preference for fish, and the biological functions in which habitat preferences are exhibited (Redrawn from Bisson 1989).



The effects of logging on macroinvertebrate production was negative. Densities of seven taxa in summer (three genera of Plecoptera and Ephemeroptera, Chironomidae) and of five taxa during other seasons (two Ephemeroptera, two Plecoptera, Chironomidae) were lower in clear-cut sections than in leavestrip sections of Carnation Creek (Culp and Davies 1983). Total macroinvertebrate densities were reduced 41–50% when compared with densities during the prelogging phase and with densities from unlogged control sites. Culp and Davies (1983) hypothesized that increased transport of fine sediment, reduced stability of the channel, and decreased input of leaf litter were responsible for this effect.

Duration of impacts

Most forest harvesting impacts on streams fall into three duration categories. The first group is related to regrowth of watershed vegetation. In coastal streams, these impacts begin immediately after logging and they continue for 3–20 yrs until hydrological recovery is established and vegetation has begun stabilizing the soils and channels and reshading the stream. Examples are increased stream temperatures when logging allows more sunlight into the stream (Holtby 1988); changed concentrations of nutrients and dissolved ions in stream water when soil disturbance (slash burning, herbicides) permits more leaching of soils (Scrivener 1988, 1989); increased fine sediment when slope soils, road cuts, road surfaces, and road ditches are exposed to erosion (Beschta 1978); and decreased stream detritus when riparian vegetation is removed (Culp and Davies 1983). The second group of impacts does not begin immediately, but initiation depends on the occurrence of large flood events with 5- to 10-yr return periods (Fig. 5) or the deterioration of stump root strength, which occurs 3–5 yr following logging (Swanston 1974). Impacts accelerate for a decade and may persist for several decades. Examples include increased sediment production from hillslope failures and gully torrents (Fig. 4); increased erosion and transport of sediment and bedload when streambank integrity is lost (Hogan 1986; Scrivener and Tripp, in press); reduced streambed stability and channel diversity when more sediment enters streams (Powell 1988); and changed composition of spawning gravel when sediments are transported from upstream channels (Scrivener and Tripp, in press). The third group contains very long-term impacts that appear 10–20 yr after logging, and they continue throughout the forest rotation. An example is the structural and habitat changes caused by the loss of LWD in streams, which occurs over a long period in time (Fig. 6). Three centuries may be required before volumes of LWD recover in coastal streams (Gregory et al. 1987).

These comments show that restoration or habitat improvement programs may have to be of different duration depending upon the physical problem being treated. In some cases there may be no “quick fixes” for altered habitats, and it may be necessary to wait for natural recovery to begin before initiating treatment.

Impacts that limit populations

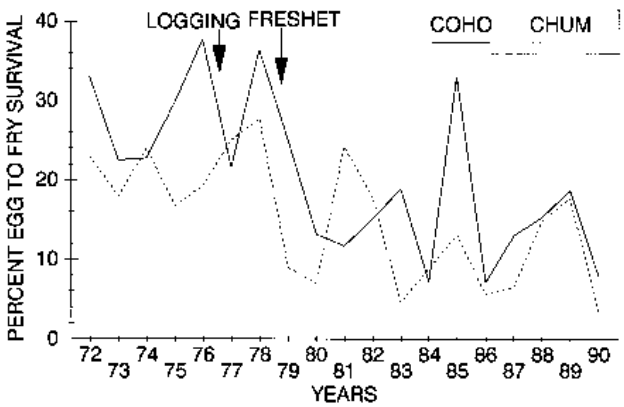
Identifying limiting factors

Many physical and biological features influence the abundance of salmonid populations and it is crucial to identify the factors that limit production (Reeves et al. 1991). There may be specific daily or seasonal periods relating to food, cover, water quality, or predation that control the size of a specific population. Examples include maximum daily stream temperature during summer, limited spawning habitat during autumn, and limited rearing habitat during winter. Therefore, we must understand how limiting factors might operate on a population and restoration and habitat improvement measures must focus on such factors, if they are to be successful (Koski 1992; Hall and Baker 1982; Everest and Sedell 1984; Bisson 1989).

In some cases a single factor may limit production. Examples include the absence of spawning habitat, the existence of barriers, or some form of serious habitat damage. In these circumstances, treatment of a single factor is appropriate. For example, in ~20 British Columbia projects, gravel placement has provided spawning habitat where little or none previously existed (Hartman and Miles 1995).

In most cases it is an oversimplification to attribute population limitation to a single factor. Overall abundance of a population is a reflection of the way the animals respond to the total environment. Several physical and biotic factors, acting alone or in concert, can potentially limit production (Bisson 1989). They shape habitat preference, determine patterns of behaviour (Fig. 7), and ultimately affect annual production levels. Habitat improvement projects must identify the major conditions and associated processes, from within a model of the type shown in Fig. 7. Bisson (1989) stressed that pitfalls can be minimized when doing a limiting factor analysis by obtaining (1) knowledge of the life histories of the species present, (2) detailed and accurate habitat inventory information of the area, (3) an appreciation of the complexity of the ecosystem, and (4) a perspective of processes occurring in the drainage. Case-history studies such as that done at Carnation Creek meet these requirements and provide a strong basis for understanding the factors that control fish population sizes. Examination of similarities and differences of watershed processes among drainages where case histories have been obtained and drainages where habitat enhancement is being planned should be carried out to evaluate assumptions about habitat needs (Bisson 1989).

Fig. 8. Egg to fry survival for chum and coho salmon in Carnation Creek. Streamside logging was begun during 1976, which was followed by the first large freshet during 1978 (see Fig. 5).



Factors that limited Carnation Creek fish populations

Within the Carnation Creek drainage, the numbers of all four salmonid species were limited by different sets of factors. However, for each species the critical control period occurred during winter.

Chum salmon numbers were affected by two major watershed changes. First, erosion of stream banks in the lower 3 km and transport of the fine sediment downstream caused a decline in the quality and stability of chum spawning gravel (Scrivener and Brownlee 1989). The entombment of alevins and the scour and deposition of spawning gravel caused a 41% decline of egg to fry survival (Fig. 8) and a reduction of fry size following logging (Scrivener and Brownlee 1989). Second, following logging, stream temperatures increased during January–March, accelerating embryonic development and emergence of the fry (Holtby 1988). Fewer numbers of fry, earlier emigration to the ocean, and smaller size of fry caused fewer adults to return after logging (Scrivener 1991). Chum salmon survival at sea was also dependant on ocean conditions that had nothing to do with logging. Chum salmon returns to unlogged streams on the west coast of Vancouver Island declined with poor ocean conditions, but increased when conditions improved. Populations in streams within logged areas did not recover when ocean conditions improved (Scrivener 1991). Here, limiting factors shifted outside of the realm of any enhancement or restoration activity. Therefore, evaluation of habitat-improvement programs must include the ocean environment or managers might consider a project a failure when in fact poor ocean conditions affected the level of adult production.

The decline of spawning gravel quality and stability, and the increase of winter stream temperatures produced similar impacts on juvenile coho salmon, but they did not limit production in the population. Reduction of egg to fry survival (Fig. 8) and of fry size and acceleration of incubation and emergence timing were similar to those for chum salmon (Hartman and Scrivener 1990). Mean numbers of age 0+ coho during postlogging years were < 50% in late May and < 75% by the end of summer, of what they were in the prelogging period (Table 1). During postlogging years, however, growth rates increased when densities were reduced (Holtby and Scrivener 1989). This effect, plus the lengthening of the summer growing season, caused by earlier fry emergence, produced much larger juveniles by autumn (Holtby 1988). These large age 0+ coho had greater overwinter survivals (Table 1) and greater rates of smolt transformation at age 1+. Prior to logging, 50–75% of the smolts entering the ocean were age 1+ and the remainder were age 2+. Following logging, 95% of the smolts were age 1+ (Hartman and Scrivener 1990). Postlogging smolt numbers were similar to or greater than prelogging numbers but their annual variability increased threefold (Table 1).

Numbers of age 0+ coho declined progressively from spring to autumn, and the final number of smolts produced was set during the winter period when cover was critical (Table 1). Numbers of juvenile coho per unit of stream length was positively correlated with the volume of LWD that provided cover during both summer (Forward 1984) and periods of winter freshets (Tschaplinski and Hartman 1983). Choice of cover habitat increased with structural complexity of the habitat (McMahon and Hartman 1989). During winter, coho numbers in the main channel appeared limited by the volume of LWD with the correct structural complexity. During 1980–1989 in Carnation Creek, the number of fry at the end of September was greater than the winter carrying capacity of the stream in all years except two (Table 1). If incubation conditions were much poorer or if number of spawners were much smaller, control of smolt numbers would have shifted from winter rearing conditions for age 0+ coho to incubation conditions and egg to fry survival.

Coho production limits were also affected by the balance of use of off-channel and main-channel habitat and by the yearly changes of survival in the two habitat types. Age 0+ coho entered the floodplain habitat during September–November, and they exited from it during April and May (Fig. 3; Brown 1985). These areas were not significantly impacted by logging. However, survival and production were limited by winter and spring water levels (Brown 1985).

The few coho that remained in Carnation Creek for a second year did poorly in the post-logging environment. Summer growth rates and autumn size declined under the warmer temperature regime (Holtby and Scrivener 1989) and reduced food supply (Culp 1988). Physical habitat no longer appeared to limit their numbers, because almost all coho were now resident for only a single year (Table 1).

The altered age composition and size of coho smolts affected production stability and the numbers of returning adults. Smolts from two brood years stabilized smolt and adult production during prelogging years when large age 2+ smolts had high marine survivals (Holtby and Scrivener 1989). The large 2+ smolts were, however, rare during post-logging years so marine survivals declined and were more variable. The earlier emigration also caused reduced survivals in the ocean (Holtby 1988). If habitat improvement is carried out after logging in situations like Carnation Creek, it must be directed to the limiting stage in these sequence of changes. For coho production the critical stages occurred during winter.

Although we regard the amount and quality of winter habitat as being most important in determining coho smolt output, periods of drought or an elevated stream channel can reduce the amount of summer rearing space as a result of channel dewatering (Dolph et al. 1992). The channel has aggraded in

Table 1. Numbers of coho fry at emergence and during stream surveys and fence counts in the lower 3070 m of Carnation Creek (1971–1982 data from Scrivener and Andersen 1984).

		Population estimation period			
	Population at emergence	Late May early June	Late July	Late September	Yearlings smots + resident
Prelogging period					
1970	—	—	16 004	14 129	2492
1971	157 400	37 030	29 188	11 842	3214
1972	50 320	33 556	15 578	9223	2509
1973	38 600	18 357	10 776	9071	2198
1974	37 420	17 580	14 589	12 460	1854
1975	44 770	14 605	14 092	11 482	2965
1976	58 800	46 662	19 173	12 327	2655
Mean	64 550	27 965	17 057	11 505	2555
SD	46 160	12 975	5905	1813	454
Logging period					
1977	23 460	15 767	14 338	10 602	5213
1978	39 825	26 148	23 120	10 927	4481
1979	30 400	26 347	19 702	13 227	5338
1980	48 625	—	25 756	20 953	5599
1981	17 200	6743	6995	6088	3152
1982	12 450	8648	8890	7337	3748
1983	27 650	17 304	11 720	10 184	3158
1984	6700	3209	4466	3423	1904
1985	15 000	12 589	12 303	6824	2850
1986	4150	2692	—	2916	2501
1987	14 606	6773	—	6584	2969
1988	8180	4242	—	5107	3753
1989	11 940	8780	—	7092	3217
Mean	20 014	11 603	14 143	8559	3682
SD	13 363	8243	7320	4784	1152

a few locations of Carnation Creek, isolating pools and inhibiting the movement of fish and aquatic insects especially during periods of low flows (Hartman and Scrivener 1990).

Impacts of logging on processes effecting cutthroat and steelhead trout were similar to that of coho salmon, but limiting factors were different. Trout spawned during the spring so when fry emerged early, the growing period was only lengthened by 1–2 wk. Their autumn size was significantly larger during post-logging years, but it did not increase overwinter survival or their transformation into smolts at age 1+ (Fig. 2). The size benefit gained during year 1 was lost during years 2 and 3 of stream residence (Hartman and Scrivener 1990). Cutthroat trout used the off-channel habitat both for spawning and winter rearing (age 0+, 1+, and 2+), so logging impacts on them were not as severe as for steelhead (Hartman and Scrivener 1990). Juvenile steelhead occupied only main-channel habitat. Coho, cutthroat, and steelhead had different patterns of distribution and use of the various parts of the watershed. Despite this, winter was the most critical period for production of each species.

Within Carnation Creek, the number of coho or trout smolts produced was controlled by complex interactions of both physical and biological processes, but factors that limited production were different for each species. Key elements that interacted to influence freshwater production were water temperature, condition of the incubation environment, amount of winter cover, and the balance of advantage and disadvantage of using off-channel habitat during any particular winter. Managers attempting to improve habitat must understand the relative importance and the interaction of these conditions before a project is begun.

Watershed restoration and habitat improvement: what does Carnation Creek tell us?

In the following section, we will discuss remedial strategies that could be used appropriately in watersheds like Carnation Creek. However, it must be recognized that headwater, hillslope, and channel conditions in this watershed are still changing rapidly at Carnation Creek.

Hillslope conditions and options

Conditions in the Carnation Creek drainage are still changing. Another 42% of the watershed was logged after 1987. This occurred in the steep headwater areas. More slides and debris torrents could occur in these areas, based on our experience during the first logging phase (Hartman and Scrivener 1990). To date, these areas have not been exposed to storm events with > 7-yr return periods (Fig. 5). Initial restoration projects should focus on road and slope stabilization. Attempts should be made to reduce further sediment supply by pulling back areas of unstable sidecast materials, diverting water off roads, removing culverts, reestablishing preexisting drainage channels and revegetating disturbed slopes. Removal of logging slash from torrent prone gullies may also be beneficial, if the remaining sediment and LWD is stable. It is, however, better to implement this kind of work immediately after logging, prior to the material being incorporated into the channel structure by processes of sediment deposition.

Riparian zone conditions

Conditions in the riparian zone have not stabilized at Carnation Creek (Scrivener and Tripp, in press). Areas of the alluvial floodplain that were logged to the stream bank 12 yr ago have not developed enough riparian vegetation to stabilize the banks. Restoration strategies here should assist with revegetation or wait for the volume of moving sediment to decline. Silvicultural practices to expedite the re-establishment of riparian shrubs and trees (including conifers and rapidly growing deciduous species) will eventually provide root-strengthened and erosion-resistant stream banks as well as a future supply of LWD. Measures to control localized bank erosion may be justified in some circumstances, particularly if this can be undertaken using bioengineering techniques (e.g., Schiechtl 1980). However, over the long term, the stream should be provided with a corridor within which it can freely migrate. Following restoration, few trees, if any, should be harvested from the riparian zone.

Habitat improvement within the channel

Once hillslope and riparian zone concerns have been addressed, it is appropriate to examine options for habitat improvement within the stream channel. However, it should be noted that a healthy or natural riparian zone would eventually produce a structurally diverse and productive stream channel, but it may require ≥ 90 yr after logging before these conditions are restored (Fig. 6). Therefore, work within the channel should expedite these natural processes and, as an interim measure, provide replacement habitat prior to its natural formation.

Keeley and Walters (1994) listed and evaluated a range of potential measures that might be used at Carnation Creek. LWD could be placed in sections of the channel that are devoid of it because of harvesting practices or subsequent removal by debris torrents, etc. These structures need to be well anchored and stable. They should provide areas of increased water depth and structural complexity for fish cover. However, they can also cause localized erosion of the stream banks either by redirecting stream flow or by causing sediment deposition, which redirects stream flow. Woody debris, placed in torrented streams on the Queen Charlotte Islands, provided habitat for young coho and steelhead with some success (D.B. Tripp, Tripp Biological Consultants, Nanaimo, B.C., personal communication). However, the LWD's anchors had to be buried 2 m below the streambed and their attached cables had to be 3.5 cm in diameter before the structures remained ≥ 5 yr. They captured floating logs, promoted sediment deposition, and attracted fish. If these structures had been placed in Carnation Creek, they might have exacerbated bank erosion and channel widening during 1984–1990. In some stream reaches, they would have been buried where large volumes of gravel were moving or abandoned when the channel relocated (Hartman and Scrivener 1990).

The complexity and location of LWD structures influenced the species composition of the stream community. Trout densities were less closely related to debris volume than were coho densities (Tschaplinski and Hartman 1983; Hartman and Brown 1987). Trout also tended to use plunge pools, caused by single, large, and partially buried logs, while coho salmon tended to use root wads and other structurally complex cover. In Kloyia Creek, coho preferred natural and artificial root wads that were near the banks, while trout preferred those that were away from shore (Shirvell 1990).

Placement of boulder clusters and log ramps (step dams) were listed as stream improvement techniques for small streams (Keeley and Walters 1994). In the Keogh River, boulder placement increased steelhead and coho densities (Ward and Slaney 1979). In the Chilliwack River, trout were more closely associated with boulder cover than were coho salmon (Hartman 1965). These methods appeared useful, but better design criteria are needed: specifically, involving studies to determine the rock size required for physical stability in different stream sizes, the rock densities at which stream sediment transport begins to alter significantly, and what kinds of stream environments are suited for enhancement with various types of structures (Lowe 1992; Rosgen and Fittante 1986). These structures might not be useful at this time in Carnation Creek, because they could compound problems caused by moving sediment, channel dewatering, and channel relocation.

Stream fertilization has merit as a stream habitat improvement technique. Its benefits have been shown in large streams like the Keogh River (Perrin et al. 1987; Johnston et al. 1990; Slaney et al. 1994). In Carnation Creek, low concentrations of natural phosphorus limited primary production (Stockner and Shortreed 1976). Production of periphyton and stream insects were increased by adding dissolved inorganic phosphorus to troughs at Carnation Creek (Mundie et al. 1991). Additions of nutrients might increase production of algae, insects, and fish. However, it should be demonstrated that production and food limit smolt output before substantial investment is made in enrichment programs. Mason (1976) increased the number of juvenile coho by artificial feeding. However, elevated numbers in autumn did not result in increased smolt production because winter habitat was limiting. Increased size of age 0+ coho, by autumn, improved overwinter survival in Carnation Creek. However, any gain achievable by enrichment may be limited by the amount of winter habitat. During winter, the relative importance of estuarine production and ephemeral satellite channels might become important for other watersheds (Cederholm et al. 1988).

Stabilizing stream banks with rip-rap may be regarded as a form of channel improvement. Studies on the Coldwater River (Lister et al. 1995) indicated that rip-rap can provide high quality juvenile chinook habitat if it is constructed of large rocks. However, rip-rap has not reduced bank erosion on agricultural land where valley bottom clearing and grazing have dramatically increased rates of channel shifting. Studies on the Deadman River, near Kamloops, B.C., indicated that prior to removal of riparian vegetation, the river channel was narrow, deep, laterally stable, and carried small amounts of bedload. Within areas of intensive grazing, the channel became wider, shallower, straighter, laterally mobile, and carried large quantities of coarse-textured sediments (Miles 1994). These studies suggested that attempts to control channel shifting by placement of rip-rap merely moved the area of active erosion downstream and further reduced fish access to a small number of remaining off-channel habitats. Here, a more appropriate strategy would have been to establish a corridor through which the river could freely shift, to provide fences to keep cattle from destroying riparian vegetation, and to replant the area stabilizing stream banks, providing shade and producing cover. Riprap placement would not improve channel conditions in Carnation Creek. However, providing a stream corridor, within which future logging was restricted or prohibited, would undoubtedly be beneficial from the perspective of both channel stability and fish habitat.

Off-channel habitat improvement

Streams with floodplain habitat hold some options for fish habitat expansion. Ponds and side channels might be built even if the main channel is very unstable. Overwinter survival and growth of coho and cutthroat were significantly higher in abandoned river oxbows and areas adjacent to wall-base channels[3] in tributaries to the Clearwater River, Washington, than they were in the main channel (Cederholm et al. 1988). It was an inexpensive technique that primarily benefitted coho salmon. In Carnation Creek, coho used sloughs and ephemeral tributaries on the floodplain, but cutthroat trout used only the ephemeral tributaries (Hartman and Scrivener 1990). Steelhead made little use of either habitats.

Off-channel construction in drainages like Carnation Creek would be less vulnerable than the main channel to the effects of elevated sediment loads, the deposition of pulses of sediment, and the erosion of stream banks. However, water on flood plains and terraces can be retained by a layer of fine sediments and decomposing vegetation that overlay the gravel (Brown 1987). Disruption of this layer could cause a loss of the perched water. Therefore, extreme caution is needed when doing construction in these habitats. Attempts at further enhancement in areas that already support fish might be limited to improving access. The optimum sites for creating new channels appear to be on fans, near the edge of the valley wall, or in areas where auxilliary water supply is available. In watersheds where coho salmon rear in the estuary, off-channel habitat might be built immediately upstream so that juvenile fish can move back into freshwater for the winter (Hartman and Scrivener 1990). Habitat would have to be constructed so that freshwater would flow through it during the winter. This type of project would enhance only coho salmon abundance, because most salmonids that use estuaries for summer rearing do not return to freshwater during autumn.

Expansion of estuary habitat might benefit spawning chum or pink salmon and rearing chinook salmon (Groot and Margolis 1991). Constructed areas of salt marsh (Adams and Whyte 1990), and zones of tidal shear and food production (Levings and Macdonald 1991) are used by juvenile chinook salmon.

If off-channel projects are envisioned for floodplain areas, either upstream or in locations close to an estuary, three requirements are necessary: (1) a water source to provide flushing and fish access; (2) sources of cover during cool winter temperatures; and (3) the project should not endanger existing water routing and availability.

Performance criteria for stream structures

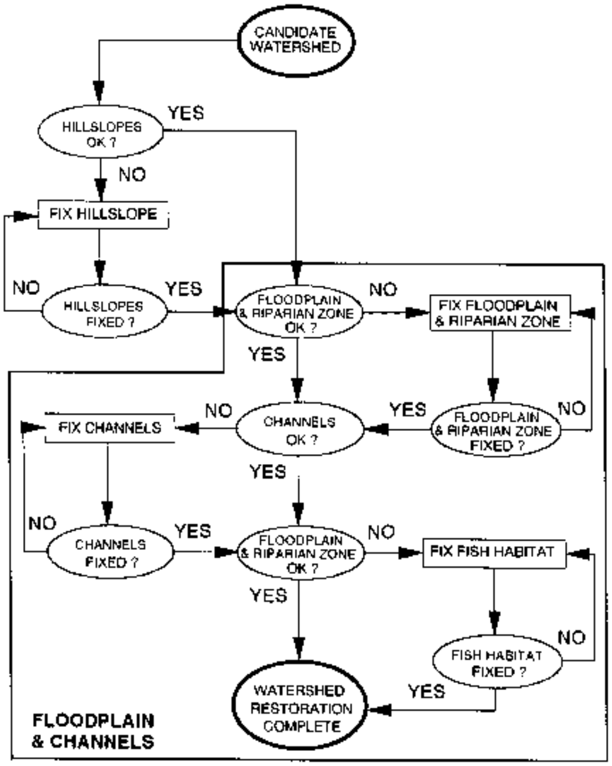
Installation of the types of structures listed by Keeley and Walters (1994) has value, but we also need to understand and to predict their performance. We are not prescribing LWD piece size or density criteria; however, it may be inappropriate to attempt to reestablish LWD structures to prelogging densities in Carnation Creek. Sediment transport and peak flows were higher, and bank stability was lower, during the post-logging period. Because of this a high (prelogging) LWD density could lead to sediment deposition, bank erosion and structure instability, or relocation of the channel. A recent review of ~350 habitat-improvement structures indicated that channel processes affected their stability and performance (Fitch et al. 1994). Even in the comparatively benign streams of southwestern Alberta, structures were more successful in streams that were laterally and vertically stable, that carried small quantities of coarse textured bedload in comparison to total sediment load, and that had banks > 2.5 m high. Similar results were presented for streams in the Pacific Northwest (Frissell and Nawa 1992). Thus, instream structures may not perform well in the vertically and laterally mobile channels that commonly occur in logging impacted streams such as Carnation Creek.

Practical problems for fisheries enhancement projects are the lack of engineering criteria for structure design and the lack of hydrologic, hydraulic, and geomorphic data. This reflects both a lack of engineering and geomorphological advice during project design and a paucity of postconstruction assessment studies. Many manuals of stream enhancement structures exist but with the exception of Lowe (1992), none provided dimensions, rock sizes, or other engineering specifications. Similarly, more analyses like those of Rosgen and Fittante (1986) are needed to determine what structures are suited or unsuited for particular types of stream channels.

Even with better design guidelines, it may not be practical to build instream structures that are sufficiently robust to function effectively in high-energy streams. For example, an analysis of boulder placements in southwestern Alberta streams indicated that they had to be ≥ 23 times larger than the streambed mean particle size before they would remain in place (Fitch et al. 1994). If these results are verified, it may be physically impossible to move boulders of sufficient size to be stable in many west coast streams. Flume studies have indicated that single roughness elements cause a maximum flow resistance when they cover 10% of the channel bed, but they have relatively little effect at ~1% (Koloseus and Davidian 1966). This implies that boulder densities should be quite low, ~1% of the bed surface, if significant changes in channel resistance and sediment deposition patterns with very high sediment loads are to be avoided for streams. Studies on the Coquihalla River, a high-energy stream in southwestern British Columbia, also indicate that a 20-yr return period flood can substantially entrain or even bury very large boulder groups (Miles and Associates Ltd. 1994). Thus, periodic monitoring

[3] Wall-base channels are floodplain channels that collect and transport runoff from the base of valley walls to permanent streams. They often develop along abandoned meander scars and swales.

Fig. 9. Decision making hierarchy proposed, by D. Hogan, for use in the Watershed Restoration Program which is being implemented in British Columbia (Redrawn from Moore 1994).



and repairs may be required to maintain instream structure performance.

The corridor required as a channel-meander zone should be determined by characteristics of the river and not by artificial rules, such as a 10–30 m wide leavestrip. Two approachs to this problem can be made using typical relationships of hydraulic geometry. The radius of curvature for a stream meander is typically 2.3 times the bankfull width of the channel. Thus, the corridor that would contain two opposing bends would be ~6 channel widths (Newbury 1994). Second, pool-riffle or meander bend sequences tend to reoccur every five to seven channel widths. Therefore, if one riffle-pool sequence was to form across the valley, a width of ≥ 6 times the bankfull channel would be required. A corridor as much as 10–14 channel widths might, however, be necessary for unstable streams to provide enough space for vegetation to form erosion-resistant banks.

Planning, building, and evaluating projects

Watershed restoration and stream improvement projects require steps of proper planning, construction, and evaluation. Programs with all three components are seen infrequently.

Planning

Planning of large-scale projects requires institutional arrangements that are seldom made. Project teams should be interdisciplinary and the individuals should work closely with some type of public advisory group. Large-scale watershed projects must include fish biologists, plant ecologists, hydrologists, geomorphologists, foresters, wildlife biologists, and economists. Small-scale habitat improvement projects involving placement of structures in stream should be developed with geomorphological and engineering advice.

Projects planned following logging require a systematic analysis to establish where effort should be focussed. The Watershed Restoration Program, under development in British Columbia, uses a hierarchical implementation sequence that attempts to examine and then restore hill slopes, riparian zones, channels, and fish habitat in this order (Fig. 9). Thus, a system is established that avoids channel work in unstable streams like Carnation Creek, until such times as hill slopes and riparian areas have been stabilized. The following kinds of information are necessary for a hierarchical analysis: (1) the potential sources of slides, sediment, and debris; (2) the nature of upslope processes; (3) conditions in steep gully tributaries; (4) the potential for transmission of impacts to downstream locations; and (5) processes that are occurring in the lower reaches of the stream channel.

If the analysis and planning process leads to a program of stream habitat improvement, to increase abundance of fish by replacing lost habitat or by improving habitat, two matters must be understood. First, the appropriate species must be selected for enhancement. Second, the life-history stage where primary limitation occurs, and the processes by which it occurs must be understood. Although it seems obvious that such assessments should be made, it is not always done. Frequently decisions about habitat needs are based on judgement or biological intuition. In the mitigation program for the Oldman River Dam Project in Alberta, the priority assigned to species, the decision about the target life stage, and the type of habitat improvement measures required (Dominion Ecological Consulting Ltd. and J.N. Mackenzie Engineering Ltd. 1988) were based on judgement and assumptions. The survey work was extensive, but there was no experimental analysis of population limitation even though this was a very large-scale program (FEARO 1991). A major program of remedial measures compensating for flow reductions in the Nechako River focussed on the provision of cover for juvenile chinook salmon. The decision to enhance this life stage of chinook in such a manner was based on judgement and intuition about needs and not on research information that identified the juvenile rearing stage as the one that limited population production (Anonymous 1987).

For small stream improvement projects in British Columbia, the life stages of fish species and the limiting factors that are targeted for enhancement are usually chosen from management experience and judgement. This is understandable because it may be impractical to do population analyses for limiting factors during small projects. However, the use of judgement or intuition are inappropriate where substantial sums of money are being spent.

Before any restoration project is approved for action, the timing of evaluations, their criteria, and the reporting sequence should be developed. Conditions for project abandonment should also be agreed upon. Small-scale projects should not be allowed to “fall between the cracks” because of staff changes. The planning process should be guided by policy that determines how intense efforts should be to increase fish numbers. In British Columbia, emphasis is shifting toward ecosystem management and concern about maintaining biodiversity. Historically, biologists and members of the public have expressed concern about a single-use philosophy that they perceived in the forest industry. The single use of streams as fish production areas may also not be appropriate; therefore, it may be inadvisable to construct large numbers of instream structures on specific river reaches, as was done in southern Alberta as part of the Oldman River Dam project.

Construction

Construction for watershed restoration projects is different than for stream habitat improvement and may involve more risk to personnel. Work on the hill slopes requires costly machine time and high skill level for activities such as road resloping and debris removal from steep gullies. There may be risks to workers when steep and unstable gullies are cleared, or when machines are placed on old road grades. Operational limitations should be understood before projects are designed.

Sound construction and appropriate design are both necessary components for stream channel improvement. Many techniques are described, including streambank stabilization, riparian planting, streambank fencing, gravel placement, gravel cleaning, construction of cover, fertilization, and off-channel development (Adams and Whyte 1990). The features that affect the biological merits of using such structures or techniques have been considered by Reeves et al. (1991). Keeley and Walters (1994) listed techniques for stream and riparian zone restoration and classified those most useful for small streams. Both evaluations assumed that the construction is sound. However, these assumptions are not always met. Forty-four percent of 100 structures built in British Columbia, and evaluated by Hartman and Miles (1995), were of limited durability or failed. It was not possible to separate the roles of design and construction in these failures. However, some boulder placement projects had used rocks that were too small. Other installations were successful because workers made the special effort of installing large boulders on carefully constructed pads of smaller ones. Some log placement projects failed because the cables used were too small. In the Mount Hood National Forest, structures that were installed with heavy machinery were more durable than those constructed by hand. After 15- to 20-yr floods, 90% of heavy equipment structures and 60% of the hand-built structures were still functional (Higgins and Forsgren 1987).

Preparation for construction must at least include (1) consideration of risk to workers, (2) determination that design materials are available and can be used, and (3) consideration of the method of installing structures that will provide the highest physical durability.

Evaluation

Evaluation should be done on all projects to determine the following.

Physical performance

(1) If roads were resloped and deactivated, if sediment and debris were removed from gullies, or if eroding slopes were reseeded in watershed restoration, did these measures succeed physically?

(2) If stream structures were built for habitat improvement, were they durable and did they remain in the physical context that was intended?

(3) If the structures or restoration were not durable, how much maintenance was required?

Biological performance

(1) Did the works accomplish what was intended?

(2) Did structures increase population production or simply change fish distribution?

(3) Did the structures cause loss of productivity of one species, while increasing that of another?

(4) What was the population increase if it occurred?

Economic benefits

(1) What was the value of the production increment over natural background levels?

(2) What was the amortized cost of construction?

(3) What was the cost of maintenance?

The economic evaluation must be of adequate intensity and duration to be valid. Projects targetting natural populations of salmonids probably require 6–7 yrs to produce population changes (Hunt 1976), so evaluation must extend over a period that detects such change. Evaluation is very weak, or absent, during most projects (Lowe 1992; Frissell and Nawa 1992; Miles 1994; Fitch et al. 1994). A small sample of mitigation projects was reviewed for the Oldman River Dam Project. Only 8 of 41 projects were evaluated for > 4 yrs (FEARO 1991). In British Columbia, only 2–5% of the small fisheries projects were reported on after 7 yrs.

The record of progress of projects must be available to the public. Sound evaluation is needed to provide this information. Funding and the continuation of programs depends upon public satisfaction and trust. People may accept a degree of openly reported failure. However, they may not continue to accept information that is vague or suggests incompetence.

Conclusions

The Carnation Creek studies provided some understanding of the types of processes that managers should be aware of or appreciate before entering into projects of watershed restoration or stream habitat improvement:

(1) There is a high level of complexity in natural ecosystems. We can not always judge correctly what the critical factors or times are in the life of populations of fish.

(2) Physical conditions caused by forestry activities change at different rates over time. There may also be sets of physical processes occurring that overlap and compound their effects.

(3) Forestry impacts have different effects on different species and life stages of fish.

Experience with a number of habitat improvement projects and consideration of processes in Carnation Creek indicate that (1) the planning and development phase of projects is often weak; (2) experimental design for evaluation of projects is weak or absent (even the Carnation Creek Project did not have a separate control watershed of similar size); (3) a hierarchical approach to planning watershed, riparian, and stream-channel improvement is a valuable and essential foundation.

Much of this paper has focussed on problems of doing stream restoration and habitat improvement. We do not wish to discourage this work. However, we believe that too much of it is done with little or no use of science. Good science and well-structured management programs must merge in any fish habitat improvement project. We must understand basic watershed ecology and use sound practical judgement to restore habitat.

Fisheries biologists must begin considering limits to stream improvement work. Many structures are unnatural and offend other stream users and even some people who fish. A broad sector of stream users must eventually decide the scale, type, and location of stream-improvement projects.

Finally, it may not always be possible to repair the damage caused by decades of irresponsible land use. We must understand that we may be able to destroy things more readily than we can repair them. Restoration is a poor substitute for habitat protection.

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