Pacific Fisheries Resource Conservation Council

BACKGROUND PAPER NO. 2000/3

Sand and Gravel Management and Fish-Habitat Protection in British Columbia Salmon and Steelhead Streams

Prepared by

Dr. Marvin L. Rosenau

BC Ministry of Environment, Lands and Parks

Mark Angelo

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Executive Summary

Sand, gravel and other sediments within and adjacent to spawning and rearing streambeds are fundamental to the productivity of salmon and steelhead stocks. The high levels of production formerly seen in many of British Columbia's chum, pink and sockeye populations were, in part, the result of the conditions of the spawning sediments, primarily gravel, available for these fish. For instance, the quality of the freshwater rearing environment for coho, chinook and steelhead is more crucial than the amount of spawning area.

In-stream gravel, cobbles and boulders constitute the high-quality sediments in salmon habitats. Stream habitat is essential to maintain sufficient levels of rearing capability for these species, as their young must undergo a period of rearing in freshwater before they migrate to the sea.

During the past century, however, human activities have degraded many of the best spawning and rearing streams by disrupting the basic processes that regulate the recruitment and revitalization of their sediments and associated riparian features. The activities include mining for aggregate or metals, damming of rivers, dredging for navigation and flood protection, and diking, armouring and straightening of rivers for the protection of property. As a result, the character and composition of the gravel and other sediments in many streams have often been changed, usually reducing their capability to produce salmon and steelhead.

Historically, the mining of sand, gravel and cobbles from streams by the aggregate industry, and placer mining, was done with little regard for fish. Sediment extraction from stream areas was a method used to provide flood protection by increasing the flow-carrying capacity. Usually, this occurred where humans encroached onto floodplains, and where normal stream flows during floods would otherwise inundate properties. Over time, the line between flood-proofing and extraction for industrial purposes became blurred.

A number of notable collapses of salmon and steelhead stocks in British Columbia followed upon such in-stream extractions of gravel where this activity was extensive. These mining activities have led to losses in available spawning area, increased levels of fine sediments that smother the river bottom and decreased quality and productivity of salmon and steelhead rearing habitat. While sand and gravel are vital to the composition of roads, buildings and other structures, their removal from streams normally has far-reaching biological, economic and social implications in terms of losses in salmon productivity.

In many instances, sand and gravel is still mined from sensitive locations adjacent to or within stream areas. Plans continue to be put forward to expand extraction in British Columbia for projects that would affect additional stream habitats.

The economy continues to grow, and aggregate is needed to accommodate this growth. It is suggested that region-wide integrated aggregate management plans are necessary to ensure that supplies are available for commercial use without compromising the protection of salmon and steelhead. Any new mines must be located where they will not degrade fisheries values as a result of: (1) impacts of the "footprint" of the mining; (2) interrupting stream processes; or (3) entraining fine sediments streams.

In British Columbia and elsewhere around the world, humans have encroached upon floodplains where streams historically meandered and naturally flooded. However, billions of dollars worth of property have been developed on the floodplains of streams. As a result, the diking and armoring of stream banks and the straightening of many streams have been common practices to prevent flooding or to allow further development to occur. Important salmon spawning and rearing gravels have been, without exception, affected by these flood-protection measures that have undermined the productivity of the fish. Federal, provincial and regional governments are increasingly expected to engage in effective planning and initiate measures to minimize these impacts.

Human impacts to sediment abundance and quality and to streambed structure can also occur as a result of dredging for navigational purposes. In British Columbia, this activity occasionally occurs in salmon streams, albeit not as extensively as in other parts of North America. Notably, the lower Fraser River in the "sand reach" of this stream downstream of New Westminster is routinely dredged for shipping. In recent decades, this removed far more sediment than was naturally recruited by the stream. These dredging activities for navigation affect the fish habitats by changing the shape of the streambed to which many fish and aquatic insects are adapted. We know that the streambed of the lower Fraser River in the shipping channels downstream of New Westminster has degraded significantly over the last two decades. However, inventory is inadequate, assessment is lacking and biological impacts are not well understood.

Similarly, the Fraser River in the "gravel reach" of the stream between Hope and the confluence with the Sumas River upstream from Mission has been scuffle-dredged, or scraped deeper, in order to provide adequate draft for log-boom towing. Even less is understood about the effects of scuffle dredging in the gravel reaches of the Fraser River, but it must be presumed that fish habitat is affected.

Good inventories and assessments of the impacts are required to make appropriate habitat-management decisions, but they are lacking in these two instances. Because the shipping of goods along the lower Fraser River is important to British Columbia's economy, fisheries regulatory agencies have been expected to protect fish habitat while accommodating the transfer of cargo and logs. This continues to be difficult in the absence of good knowledge of the impacts to fish habitat.

The construction of dams affects the quality and abundance of important spawning and rearing sediments in downstream areas. This can occur when a dam disrupts sediment processes by interrupting or trapping the naturally recruited, larger-diameter bed-load sediments. This can cause the river downstream to become much coarser and a less desirable habitat for certain life stages of the fish, such as spawning and incubation. Furthermore, dams which either store or divert water and cause downstream discharges to become much less than before impoundment can reduce downstream flows to an extent that they no longer flush out the very fine sediments. These fine materials can smoother the spawning grounds and ruin the juvenile rearing habitats that normally require clean substrates.

The construction of dams has been economically vital in the development of British Columbia, performing a variety of functions ranging from flood protection to storage, as well as generation of hydro-electricity. Some of these dams, however, are now obsolete and their social costs outweigh their benefits. In these cases, decommissioning should be more seriously considered.

Where decommissioning is not an option, changes in dam operations may provide significant social and environmental benefits by resolving some of the problems associated with the downstream recruitment of gravel.

Because the storage of water and the operation of dams are regulated under the *British Columbia Water Act*, there are opportunities for governments to require that these facilities be operated in a more environmentally and socially responsible manner that takes issues, such as sediment management, into consideration. Long-range planning exercises for old and new dams could enable the transition needed for recovery of existing perturbed habitats. At present, the province is proceeding with a formal process for all of the dams for which BC Hydro holds water licences; this is known as the water use planning process. The intent of this effort, in part, is to address and resolve issues related to salmon and steelhead habitats. The redressing of sediment issues is an aspect of the planning process in some instances.

1. Introduction

Salmon and steelhead (*Oncorhynchus mykiss*) populations in the Pacific northeast have experienced reductions in abundance over the last 150 years and particularly steep declines in the past five decades. The losses have been especially dramatic from central California to Campbell River, British Columbia (Nehlsen et al. 1991; Slaney et al. 1996). In the continental western United States, salmon are now extinct in 40% of their historic range (Lichatowich 1999) and listings and potential listings under the US *Endangered Species Act* continue to occur regularly. Population losses to levels of extinction for salmon and steelhead are also occurring in unprecedented numbers in the southern region of British Columbia.

It is no coincidence that the disappearances and declines in salmon and steelhead stocks have coincided with the period of massive influx and growth of human populations in western North America, specifically from the Georgia Basin in British Columbia to an area past the Sacramento River in California. Fisheries managers view the decline in numbers of salmonids, the biological family to which salmon and steelhead belong, to be directly related to human activities along the West Coast. Various reasons have been put forward for these losses including:

1) lack of recruitment of adult salmon to spawning grounds due to overharvest (Walters and Korman 1999, c.f., Ricker 1954);

2) reduction in freshwater productivity due to a failure to replenish marine-derived nutrients, as a result of declining salmon escapements (Bilby et al. 1996, Larkin and Slaney 1997, Cederholm et al. 1999);

3) change in Pacific Ocean temperatures and productivity which may be due to global warming (Beamish and Bouillion 1993); and

4) major anthropogenic changes to the western North American terrestrial and aquatic landscapes, resulting from settlement, agriculture and resource extraction, that have resulted in the wholesale habitat destruction of salmon and steelhead watersheds (Lichatowich 1999).

These four points describe what are now considered by fisheries scientists to be the major contributors to the decline of salmon and steelhead populations. While some stocks of fish have collapsed as a result of one of the above, combinations of the listed factors are implicated in the demise of many of the populations. The observations of declines are consistent with the statements by Moyle et al. (1998) that biodiversity is being lost in aquatic environments even faster than it is being lost in terrestrial environments, and the problem is particularly acute in streams and rivers.

Of particular interest for this report is the impact of human disturbance to freshwater salmon and steelhead habitat and, specifically, to streams. Lichatowich (1999) provides a startling statistic when he states that, since the turn of the twentieth century, the natural productivity of Pacific salmon in the continental US has declined by 80% due to destruction of stream habitat. A similar decline was noted in Canada, in a report entitled "Wild, Threatened, Endangered and Lost Streams of the Lower Fraser Valley" that indicated that of the 779 large, medium and small streams in this area, 117 no longer exist. Most of those remaining are under significant stress and are classified as threatened or endangered (Precision 1997).

Extensive settlement in western North America led to dramatic changes in the landscape. These alterations modified water flows and water chemistry, as well as changes to in-stream, riparian and up-slope conditions of many salmon and steelhead watersheds.

With humans manipulating the landscape of western North America, the natural processes that regulated the sediment inputs and outputs to streams over thousands of years, and to which salmon and steelhead had been evolutionarily adapted to, were affected. This was a more or less sequential process. It first occurred through trapping and eliminating most beaver populations, then through clearing land for settlement. It was followed by development of agriculture, in-stream and riparian mining, forest harvesting and, more recently, damming for hydro-electric production.

A basic feature of a stream environment is its physical shape, which is structured primarily by its underlying sediments — clay, silt, sand, gravel, cobbles, boulders — as well as bedrock. All salmon and steelhead stream habitats are linked to these basic materials. It is, therefore, important to examine how current and historic human activities have disrupted fundamental stream sediment processes and affected fish.

Stream sediment disruption by humans is caused, in large measure, by mining, diking and damming activities and by dredging for navigation and flood protection. Because of the importance of sediments to the maintenance of salmon and steelhead habitats, this report first reviews what constitutes in-stream fish habitat. The authors then discuss the resulting impacts by the above-listed human actions to salmon and steelhead habitats in British Columbia. Since these behaviors are regulated by governments, this report goes on to examine government agency roles, responsibilities and activities, including those meant to ensure no-net-loss of habitat, as they relate to legislation, policy and regulation. The report also discusses how British Columbia and other jurisdictions around the world are dealing with their problems. Finally, this report relates some of the opportunities to protect and restore salmon and steelhead habitats impacted by stream-sediment disruption.

2. The Influence of the Ice Age on Sediments in Salmon and Steelhead Streams

To a great degree, the richly textured diversity of British Columbia's landscape arose as a result of its geographic location on the western edge of the North American continent. Multiple events of glaciation, a high degree of climatic variability, including a great range of rainfall rates, and ancient tectonic and geological histories shaped the physical and biological tapestry. Even now, these processes continue to facilitate the evolution of the extraordinarily diverse river systems in which vast and rich aquatic ecosystems have evolved. These attributes include the biologically, socially and economically important runs of salmon and steelhead.

Many of these same processes produced the rich salmon rivers in the Pacific Northwest of the United States, and Lichatowich (1999) discussed this by stating that "[r]ivers of all sizes wind their way through this complex mosaic. The rivers, through their natural, seasonal flow patterns, are continuously rearranging the river channels, rebuilding and maintaining the basic structure of salmon habitat. The interaction between land and water produces a diverse array of habitats, reaching from the lowlands to headwaters in a continuum of connected places...[W]ithin this crazy quilt are thousands of microhabitats, each with its own challenges to the salmon's survival."

British Columbia, Alaska and the Pacific Northwest looked very different 18,000 years ago during the Wisconsin Ice Age when glaciers covered the landscape as far south as Puget Sound. Indeed, during this time, the present-day location of Seattle had a layer of ice over 1,000 metres thick and the lower mainland of British Columbia was covered up to twice that thickness (Armstrong 1981). Then, sometime around 10,000 years ago, the ice retreated and a myriad of streams, lakes and valleys was formed. Vast amounts of boulders, gravel and dust were created and distributed by the immense moving ice sheets and were then left in the wake of the glaciers. During the Ice Age, salmon and steelhead populations remained in isolated fringe refuges in Alaska, British Columbia and to the south, but these fish soon followed the melting and retreating ice up into the newly created watersheds and colonized the lakes and streams for spawning and rearing.

Many of the stream bottoms and valleys constructed by the retreating ice became storehouses of clay, silt, sand, gravel, cobbles and boulders, and these are the parent components of modern day salmon and steelhead watersheds. It has been hypothesized that the first post-glacial streams were quite harsh environments for fish because of the unstable and barren natures of the recently created watersheds. However, Pacific salmon and steelhead in western North America did not really become abundant until about 4,000 years ago when the riparian and upslope landscapes became vegetated and began to stabilize (Lichatowich 1999).

The old growth forests and others in Alaska, British Columbia and the western United States had vast integrating root systems and large inputs of woody debris into streams. They were crucial in stabilizing the up-slope, riparian and in-stream areas of many of the silty, sandy and gravely post-glacial rivers and valley-bottoms (c.f., Hogan et al. 1998). This vegetation also became a biological linkage between the land and water through the uptake and storage of nutrients and their redistribution in the form of leaves and needles. Once leaves and needles enter streams, they become food for many aquatic invertebrates. The importance of vegetation to the evolution of salmon and steelhead populations in western North America cannot be overstated. Beschta (1998) remarks that "[f]rom an ecological perspective, streamside vegetation performs a variety of functions including thermal moderation of stream water by overstory canopies, production of leaves, needles, and other organic matter that provides a food base for numerous aquatic organisms, cycling of nutrients and the recruitment of large woody debris which can locally affect channel morphology and create important microhabitats for fish and other aquatic species (Salo and Cundy 1987, Sedell and Beschta 1991). In addition, the below-ground root systems provide a means of binding soil particles and resisting the erosive forces of flowing water while the above-ground stems and branches hydraulically slow overbank flows, causing sediment deposition and the long-term accretion of floodplain soils. Thus, streamside vegetation typically has an important role in the bank and bed morphology of gravel-bed river systems."

As a result of the interaction between vegetation, land and water, some of these post-glacial and now-stabilized watersheds include the most productive coastal and interior salmon and steelhead streams.

3. The Role of Sediment in Salmon and Steelhead Streams

3.1 SEDIMENT IN STREAMS DEFINED

Streambeds are normally comprised of inorganic materials of varying sizes including clays, silts, sands, gravel, cobbles and boulders (Table 1). These are collectively known as sediments. In aggregation, these fundamental inorganic components of our landscape define the morphology, or shape, and the quantity and quality of habitat for all salmon and steelhead streams. Sediments are originally derived through primary geologic processes but, at some point, the parent materials are reduced and shaped by physical, chemical or biological means. This produces the size fractions that we now observe in both our aquatic and terrestrial environments.

Streams are formed around their parent geology and hydrological conditions that collectively result in stream-specific sediment yields (Reiser 1998). Over time, the general movement of sediments is in a downhill or down-stream direction. The grain-size distribution of sediments in a particular flowing body of water is the result of the past and recent history of the area. It is also influenced by local and up-stream geology and topography, by watershed hydrology and climate, as well as by current and historic human impacts.

Table 1:

Classification of sediment-particle sizes. Based on categories from Parsley and Beckman (1994).

Class	Minimum (mm)		Maximum (mm)
Boulder	250	-	<4000
Cobble	64	-	<250
Gravel	2	-	<64
Sand	0.062	-	<2
Silt/Fine Sand	0.004	-	<0.062
Clay	0.00024	-	<0.004

Thus, the areas that in-stream sediments recruit from are not only within the wetted perimeter of the stream, but also include the surrounding riparian and up-slope areas. Ultimately, however, the habitat richness and complexity provided by these in-stream sediments is directly the result of the movement of sediments by the river itself (Church and McLean 1994). That is, sediment which continues to be entrained, transferred and deposited by the discharge of the river defines the shape of the stream and the habitat quality and abundance. Furthermore, the survival and production of various salmonid species and life-histories are linked specifically and functionally to the quality and quantity of particular sediment sizes. Reiser (1998) states that: "...[a]quatic biota present in these systems have evolved around such conditions [of sediment yield], which may explain the presence or absence of certain species or assemblages of species."

Sediments in a stream contribute to the structure of both the micro- and macro-habitat features for rearing, spawning, incubation, migration and holding of fish and other aquatic organisms. The quality and abundance of each habitat is determined by the depth, velocity and substrate composition and, to some degree, each of these parameters are interdependent with one another. There is a very rich body of scientific literature that attempts to provide predictive relationships for determining the quality and abundance of habitat for fish and aquatic habitat (e.g., Bovee 1982, Orth and Maughan 1983, Moyle and Baltz 1985, Raleigh et al. 1984, Raleigh et al. 1986). Nonetheless, the quality and abundance of the sediments, and how the sediments are distributed and contribute to the formation of pools, riffles, and runs, define the ability of a stream to produce salmon and steelhead.

3.2 ROLE OF IN-STREAM SEDIMENTS IN SALMON AND STEELHEAD SPAWNING

Salmon and steelhead are evolutionarily adapted to spawn in a bed of gravel permeated with flowing water. They reproduce primarily by burying their fertilized eggs into the sediments of streams, and then allowing them to incubate under the protective surface of a semi-pervious layer of small cobbles, gravel and sand. The survival and production of these species are, in part, a function of their spawning beds having a distribution and abundance of sediment diameters of a specific range (Kondolf 2000). However, this can vary and depend upon what is available in the stream (e.g., Table 2), the hydraulics of the area, the size of the fish, and the species. Generally, the larger the individual salmon or trout, or the larger the species, the greater the size of sediment the female chooses to build her nest. However, too many fine sediments intermixed within the gravel matrix will reduce incubation success (Kondolf 2000).

The choice of the spawning location by the female salmon or steelhead is not made at random. She first selects a site that is characterized, not only by a specific range of sediment sizes, but by particular depths and water velocities as well. The female then digs a depression, or nest, in this site. This is accomplished by using the motion of her tail and body in a series of exaggerated flexing movements, while lying horizontal to the streambed.

During the act of digging the nest, the water currents differentially wash away the finer particles, such as silt or sand, from the nest (Kondolf 2000). Then, with one or more males releasing milt to fertilize the eggs, the female releases the eggs from her body into the depression in the stream bottom. Once the spawning act is completed, the female covers the fertilized eggs with gravel. She digs from an upstream direction using a similar series of digging motions. This dislodges material downstream into the nest depression by using the currents to carry the substrate. A number of nests are usually constructed by the same female in a contiguous area, and the aggregation is referred to as a redd. Salmon and steelhead construct their redds with a specific design that enhances the hydraulics of the oxygenated water passing from the stream through the semi-impervious bed-sediments and over the embryos (fertilized eggs) or alevins (hatched, but not-yet-free-swimming yolk-sac larvae) (Fig. 1).

Salmon and steelhead seek out substrates with sediments of a size range that tend to be comprised more of gravel and small cobbles than silt and sand. Substantial

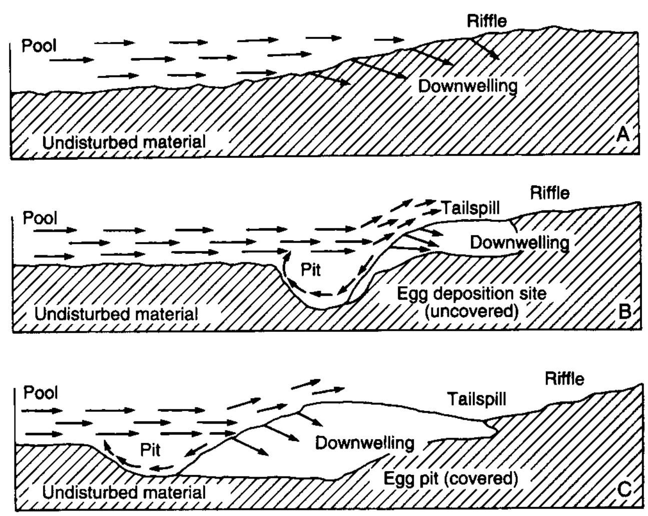
Table 2:

Size comparisons of sediment composition for streambed material from pink salmon spawning grounds in five Sakhalin Island streams. From Heard (1991) as reported in Rukhlov (1969). Note that they include a size category that is intermediate between their gravel and cobble which is termed "shingle"

	No. of Samples	Sand	Gravel	Shingle	Cobble
			Percentages		
Spawning grounds	126	14.7 1.5-40.3	34.4 0-55.1	43.5 0-74.8	7.4 0-59.1
Redds	61	11.5 2.7-40.0	36.2 0-61.6	39.6 0-65.0	12.7 0-49.1

Figure 1:

Longitudinal section of the construction of a salmon spawning redd. Drawing and explanations from Sandercock (1991) as reported in Reiser and Wesche (1977).



A: The change in depth from a pool to a riffle in a stream forces water to percolate through the gravel (downwelling) in the shallower riffle.
B: The female salmon excavates a pit (nest) in the sediment at the downwelling near the riffle causing an increase in discharge through the gravel; fertilized eggs are released into the nest.
C: The nest is covered with sediment and flow percolates through the redd.

amounts of fine sediments in or on the redd are normally detrimental to incubating embryos and alevins (Birtwell 2000). In a comprehensive review, it was suggested that survival rates of salmonid embryos and alevins are negatively related to increasing percentages of fine sediment in or on the spawning gravel (Chapman 1988). Furthermore, Reiser and White (1988) found that sediments smaller than 0.84 mm were the most detrimental to developing salmon and steelhead embryos. In the Yukon, chinook embryos had survivals that ranged from 86-91% when they were exposed to 10% fine sediments but this decreased to less than 35% when the embryos were exposed to 40% fine sediments (Seakem Group Ltd. 1992, as cited in Birtwell 2000).

There are two primary reasons why fine sediments can cause a reduction in survival of embryos and alevins incubating in redds.

1) Fine sediments that enter the stream after spawning may physically cap or cement the surface of the redd. This can prevent the small fry from breaking forth through the now-impervious surface sediments when it is time for them to become free-living.

2) An overabundance of fines within the sediment matrix of the spawning redd can cause a decreased flow through the redd as a result of these sediments plugging up the spaces between the gravel. This may result in a reduction in oxygen levels of the water reaching developing embryos or alevins.

There are also upper limits to the particle sizes that salmon or steelhead use for spawning. They may be too big for the fish to move in order to construct its redd.

Fine sediments occur naturally in streams and, even under pristine conditions, they can impact on the survival of incubating fish. Nevertheless, humans are particularly prone to increase the levels of these materials through the disturbance of either terrestrial or alluvial landscapes. Some human activities can cause a detrimental increase in the fine sediments in spawning habitats. Conversely, other anthropogenic actions, such as damming or channel straightening, can cause a loss of those medium-sized sediments which are most desirable for reproduction, leaving only materials that are too large for use by spawning salmon.

3.3 ROLE OF IN-STREAM SEDIMENTS IN PRODUCING INSECTS FOR FOOD FOR FISH

Chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon, as well as steelhead, normally rear in streams as juvenile fish before migrating to sea for further growth. This stream-rearing phase allows the young fish, called smolts, to reach a size that conveys a much greater survival rate for each juvenile that goes to sea. This compares to chum (*Oncorhynchus keta*) and pink (*Oncorhynchus gorbuscha*) salmon whose very small fry go directly to salt water or an estuary almost immediately after emergence from the spawning gravel.

The moving water of a stream conveys energetic advantages for each of the young salmon or steelhead because the flow acts like a conveyor belt, bringing food to a more or less stationary individual. In contrast, young sockeye salmon usually have a freshwater rearing phase in a lake before going to sea, but these young fish have to swim about the lacustrine environment in their hunt for their food, thus expending effort and energy.

The young stream-rearing salmon and steelhead rely extensively on a variety of organisms (e.g., insects, oligocheates or worms, crustaceans) that are recruited from the terrestrial/riparian areas or produced in the stream itself. The latter include aquatic invertebrates, and these organisms are highly dependent on the structure of the stream and the accompanying types of sediments that they must live upon or within.

The aquatic invertebrates that are eaten by juvenile salmon and steelhead are themselves generally dependent on two sources of food. One arrives from the terrestrial or riparian areas in the form of leaves or tree needles, and this is referred to as an "allochthonus" source. The other is grown within the aquatic environment itself, including bacteria and algae, and this is referred to as an "autochthonus" source.

Normally, there are interdependent relationships amongst current velocity, substrate size and dissolved oxygen levels in streams. Those aquatic invertebrates that are especially important for salmon and steelhead are generally associated with, and are adapted to, faster flows, larger sediments and well-aerated water. This includes mayflies (Ephemeropterans), stoneflies (Plecopterans) and caddisflies (Tricopterans), as well as other species (Gurtz and Wallace 1984, Lancaster and Hildrew 1993, Scarsbrook and Townsend 1993, Stewart and Stark 1993, Stone and Wallace 1998, Wallace 1990, Wiggins 1996).

Many of these fast-water adapted species wedge themselves between rocks and the bottom of the stream where they are protected from being washed away. Other aquatic insects attach themselves to the surface of stable and clean substrates, such as gravel, cobbles and boulders, where they filter out food from the moving water in the form of small organisms or bits of organic material. Normally, when in-stream gravel and cobbles are replaced by silt and sand, a decline in invertebrate bio-diversity generally occurs and insect communities can be observed to become less species-abundant. The current-loving and larger-substrate adapted species (mayflies, stoneflies, caddisflies) are often replaced by midges (chironomids) (Reiser 1998, Steve Macdonald, Fisheries and Oceans Canada, personal communication). Midges are a large family of insects and they can tolerate the lowered levels of oxygen that are often found within the fine substrates that they live in (Hilsenhoff 1991, Coffman and Ferrington 1996).

The size of the in-stream substrate is important for providing food for insects, with coarser sediments generally being more productive than fines. The larger stream sediments create more back eddies, cracks and crevices which can act as traps for the allochthonus and other organic material that many stream insects feed on (Reiser 1998). This may occur in the form of fine organic particulate matter (FOPM, or tiny bits of material), as well as coarse organic particulate matter (CPOM, such as leaves and tree needles). Furthermore, larger in-stream substrates (gravel or cobbles versus silt and sand) have better surfaces to which algae and bacteria can attach. Many other aquatic invertebrates use these micro-organisms as food. The term for these small organisms is periphyton, and they can be seen as the green-brown "slime" covering the surface of cobbles and gravel in streams.

Increases in fine sediment, whether suspended or moving along the bed, reduce the production of stream-aquatic insects in a variety of ways. Van Nieuwenhuyse (1983 cited in Birtwell 2000) found that increasing the turbidity in streams by 15 to 20 mg/litre could decrease the algae production in a shallow stream by 3-13%. An increase in fine sediment from 75 to 100 mg/litre could decrease algae from 13-50%. The reduction in light penetration caused by the sediment reduces growth rates in these uni-cellular plants that are dependent on sunlight for respiration. The impacts of entrainment of fine sediments into or on stream beds include: (1) smothering of stream-bed bacteria, algae and insect communities; (2) clogging of interstitial cracks and crevices between larger substrate sediments which affects the micro-habitat of aquatic insects; and (3) abrasion of respiratory surfaces of invertebrates and interference of food uptake for filter-feeding insects (Birtwell 2000).

3.4 ROLE OF IN-STREAM SEDIMENTS FOR FISH-REARING HABITAT

Sediment size plays an important role in defining the suitability of the physical attributes utilized by those species of salmon and steelhead that rear in streams. Firstly, the quality and quantity of macro-habitats, including the pools, runs, and riffles, are affected by the composition of the substrate. Juvenile salmonids prefer a particular range of macro-habitat characteristics depending on species. This changes as the fish becomes larger and older. The abundance of pools, runs or riffles can be modified by increasing or reducing the volumes and size-classes of sediment inputs to a stream.

Water depth, water velocity and substrate size are the primary variables of micro-habitats which, together, comprise macro-habitats. Generally, for stream dwelling salmonids, a greater variety of micro-habitats is available for fish when the larger size-fractions of gravel, cobble and boulders are present than when sand and silt predominate in the substrates. This is because large substrates are used by salmonids for cover from predators and competitors (e.g., Heggenes 1988). Bjornn et al. (1977 cited in Birtwell 2000) found that fewer juvenile salmonids remained in study streams when fine sediments were added to pools that initially contained large rocks. The untreated habitats had an abundance of interstitial cracks and crevices and the spaces were used as cover by these fish.

Griffith and Smith (1993) also found that, when cobble and boulder habitat was heavily embedded by fine sediments, the numbers of juvenile trout were reduced. This compared to those habitats that did not have such an abundance of fine material, but retained cleaner interstitial spaces. Other research has shown that maintaining spaces amongst substrate particles is important for stream-rearing salmonids during winter (Cunjak 1996). Embedding these spaces with fine substrates reduced the locations where fish could hide.

4. How Sediment Processes in Streams Create Salmon and Steelhead Habitat

The morphology (shape) of an alluvial channel is governed principally by the factors of streamflow, sediment load, physiographic setting, and history (Kellerhals and Church 1989). Similarly Kern (1998) notes that "...[r]iver systems evolve over geologic time periods, governed by the prevailing geologic, tectonic and climatic conditions." The geometry of an evolving stream is the result of interplay amongst flow, the quantity and character of sediment being transport by the stream, the character of the bed (e.g., the slope) and bank material, and the in-stream and riparian vegetation. Because the streams are not static, but dynamic and subject to a continuing suite of inputs, present-day sediment processes define the current salmon and steelhead habitat abundance and health of a stream, and govern the distribution, size and abundance of these particles which determine these parameters.

The river channel and the flood plain are dynamic and constitute a single water and land unit characterized by frequent movements of water and sediment between the two parts. The failure to appreciate the integral connection between flood plain and channel underlies many environmental problems in river management. All rivers have at least some capacity to move sediment. The volume of flow and the channel slope are proportional to sediment size and yield (Lane 1955). This means that, along the gradient of a stream, there is a balance between producing sediment and the stream's ability to keep it moving.

In considering the structure of sand and gravel in rivers, the bedload (the material that moves along a stream bottom) is the most important fraction of the sediment load. The various components of the bed do not travel uniformly over the whole width of the channel. The majority of the material travels in a sinuous path between and over bars on alternating sides of the channel. When the flood declines, a poorly sorted mix of sediment starts to settle out on the bed and bars of the channel. Sand particles are winnowed out of the surface layer by the declining floodwaters, leaving a coarse lag or "armor" layer.

Sediment can enter the bedload of a stream in a variety of ways. Collins and Dunne (1990) suggest that it can be recruited by:

1) the assortment of mass wasting processes, including land sliding and soil creep, by which gravity moves soil and rock downslope;

2) erosion of hillslopes by water; and

3) erosion of rivers of their beds and banks.

Any or all of these can be exacerbated by human activities such as land clearing, tree harvesting in the riparian zone and dredging within the alluvial boundaries.

Once within the influence of flowing water, sediments in rivers have the potential to be mobilized. Furthermore, and over time, these alluvial materials may be continually deposited or eroded as a result of the energy of the flowing water. However, the water flow must have enough power to move the material, and this will occur only after a certain discharge is attained for a given stream of a particular set of characteristics.

In some rivers, the bulk of transport of sediment down the stream precedes the peak of a flood. In other situations the material follows the peak. This has a lot to do with the size of the material and whether or not the surface of the streambed is protected by an armouring layer (e.g., large gravel and cobbles), as well as how it is consolidated (NCASI 1999). For example, if a stream has not had a flood in some time, accumulated fine material on the surface of the bars will be quickly mobilized and washed out. However, the larger material may be difficult to erode due to the "cementing" effect of the small sediments between the bigger substrate pieces, as well as the orientation of the cobbles and gravel which may make up the bulk of the armour layer. Once the stream bottom has been disturbed by the first flood of the season, the increasing discharge of the next flood may find it easy to move the streambed sediments before the peak has been reached.

For West Coast salmon and steelhead streams, an important site of sediment storage is behind log jams and other large woody debris (LWD) particles that have accumulated within streams that are in or near forested areas (Hogan et al. 1998). These sediment-storage sites are only temporary, and the length of time that the material is stabilized depends on how long the wood remains, is removed or decomposes. The rate of development of replacement jams is critical to the overall stream-sediment storage capacity of smaller and medium-sized forested streams (Hogan et al. 1998). Log jams can store up to 15 times more sediment than is delivered annually to the mouths of basins in yield (Megahan 1982). Roberts and Church (1986) showed that the residence time of sediment in these wedges in streams in the Queen Charlotte Islands can be five to 150 years.

Where logging has taken place to the edge of a stream, it takes centuries to replace these riparian trees which will eventually fall into the water and become LWD. They first have to become large enough to provide the bulk and strength to hold the sediments in place (i.e., old growth trees). In undisturbed coastal streams, these LWD structures constitute critical components for salmonid ecosystems by ensuring that the stream is stable, maintains good spawning gravel and provides complexity and cover. The extent of the importance of LWD in maintaining sediment stability for a particular small stream on the Oregon coast is described by Beschta (1979) who calculated that depths of scour averaged almost a metre after LWD was taken out. The scouring of this stream produced over 20 cubic metres of material per lineal metre.

The shape and dimensions of gravel-bedded streams typically consist of wandering, multi-threaded channels separated by bars and vegetated islands. These features are normally dynamic and do not generally stay static or fixed in position over time. These complex inter-connections are dictated by sediment erosion and deposition events that are often variable and stochastic in the short term (that is, they are not usually predicable), but in the medium or long term may have very clear, repeatable patterns.

Over time, the events of erosion and deposition in undisturbed streams can leave the river in a dynamic equilibrium. The term "dynamic equilibrium" has been defined as the balance maintained by the changes in flow and sediment supply around average conditions of the system in an evolving stream. When in equilibrium, the stream may, however, adjust its width, depth, slope or other characteristics to counterbalance another event in order to ensure that equilibrium occurs. A stream in a state of dynamic equilibrium is one that may lose habitat features at one location, due to erosion or deposition of sediment, while over time re-create equivalent habitat at another nearby site, thus ending up with a zero-sum difference over time (Knighton 1984).

The gradient, bedload supplies of sediments stored in the stream-banks, and the amount of water (in terms of total volume and distribution of that volume over time), define how a stream will ultimately look. Nevertheless, there are physical constraints as to how sediments can behave in a stream. For example, important variables defining the ability of a river to transport sediment of a particular size include the water depth and the surface slope of the water. This is articulated in a mathematical formula as follows:

$$\mathbf{DIAMETER}_{\mathrm{SEDIMENT}} \propto \mathbf{DEPTH}_{\mathrm{WATER}} \times \mathbf{SLOPE}_{\mathrm{WATER}}$$

DIAMETER	diameter of the particle of sediment to be moved
DEPTH	depth of the water
SLOPE	dimensionless statistic describing the ratio of the change in channel water-surface elevation over a given distance
$\propto$	is proportional to

Specific to the $\mathrm{DEPTH}_{\mathrm{WATER}}$ variable in the above mathematical relationship, the ability of a stream to move material of a particular size down river decreases as: (1) the discharge decreases; or (2) the stream becomes less confined and there is more room for the water to spread out. The discharge magnitude and the width of a stream regulate the $\mathrm{DEPTH}_{\mathrm{WATER}}$ variable in the equation above. Discharge normally fluctuates under natural conditions, but it may be only during flood events that the river can move substrate particles. However, discharge can also be reduced by human intervention through damming and water abstraction. Channel width naturally increases when a mountain stream, which is confined by steep hillsides, enters a wide valley bottom, thereby decreasing the variable $\mathrm{DEPTH}_{\mathrm{WATER}}$ and the ability of a stream to carry material. Conversely, confining a stream by diking and channeling can increase the $\mathrm{DEPTH}_{\mathrm{WATER}}$ variable causing scour and erosion of sediments that are important to fish habitat.

The other variable in the above relationship is $SLOPE_{WATER}$. As streams flow from highlands or mountains to lowlands, they typically become less steep and the $SLOPE_{WATER}$ becomes shallower. The ability of a stream to move sediment becomes diminished as the stream gradient ($SLOPE_{WATER}$) becomes flatter, such as in a valley bottom. As a stream becomes less steep, the larger sediment particles, such as cobbles, begin to drop out on to the stream bed and, eventually, gravel, sands and silts are precipitated.

In most streams, there are three primary zones of sediment movement: (1) an upstream, headwater zone dominated by erosion and sediment production; (2) a middle zone of sediment transport; and (3) a downstream zone of deposition. In the transport zone, the river acts like a conveyor belt and, although a gravel bar may remain from year to year, sediment removed from one end of the bar may be continually replaced by material recruited from upstream.

As a stream flows further down the hillsides towards the ocean, and the $SLOPE_{WATER}$ becomes less steep, the material that can be moved by the stream becomes limited. As a result, the bed of the channel begins to aggrade or build up in elevation. Human activity can change the $SLOPE_{WATER}$ of a stream by dredging and affecting the shape of the stream bottom, as well as through channelization and confinement by diking.

This recruitment of sediment and associated rise in stream and valley bottoms provide what may be perceived to be "problems" or "opportunities," People are often interested in settling near rivers and desiring flood protection, by diking or removing material for flood control, or wanting to extract non-fisheries resources, such as gravel for aggregate. These human activities are usually to the detriment of the fisheries resources.

The deposition of sediments in streams is in the form of bars, when the coarser fractions are deposited outside of the low-water channels. In some circumstances, these deposition zones can occur in mid-channel, or they may be on the inside of the bend of the stream (Fig. 2). As bars get bigger, they tend to push the force of the water to the opposite bank where there is a tendency for the stream to erode it (Fig. 3). When islands and bars begin to build up as a result of sedimentation, these structures may also cause the water to shift its direction. Consequently, both the point and the power of erosion and the location of the resulting deposition may also change.

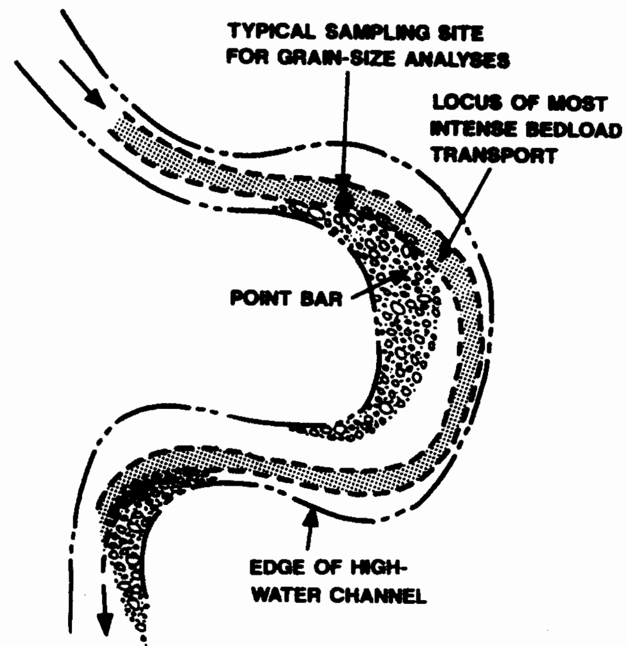


Figure 2:

Plan-view diagram of a meandering stream showing the transport path of most intense bedload movement through a bend. From Collins and Dunne (1990).

Where a gravel stream in an unconstrained valley bottom is eroding its stream bed, the cross-section of the stream generally moves in a lateral direction across the valley until it reaches the non-erodable valley wall. At some point of the collision of the stream with the solid-valley wall, the stream reverses its direction of lateral erosion and starts to move back across the valley in the opposite direction. These movements by a stream, back and forth across a valley or plain, are normally very slow and may occur over decades, centuries or millennia, although sometimes during floods the erosion can happen very rapidly. The generalized ultimate shape of the stream in an unconfined valley bottom is that of a continuous 'S'.

Brown et al. (1998) suggest that alluvial gravel streambeds, though complex, usually have rather predictable geometries (see also Brussock et al. 1985 and references therein). For example, it is well known by fluvial geomorphologists (stream geographers) that riffles (the shallow, rippled part of the stream) often occur at

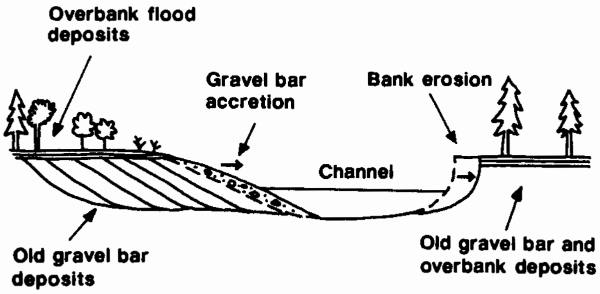


Figure 3:

Cross-sectional diagram of lateral channel shifting at the bend of the river. Addition, or accretion, of gravel in bars and of fine sediments deposited by floodwaters on the gravel creates new floodplains on the inside of the bend of the stream. Undermining of the side of the stream occurs on the outer bank. From Collins and Dunne (1990).

intervals of five to seven bank-full widths (Leopold et al. 1964). Because erosion and deposition in streams have a generalized downhill direction, the final longitudinal channel configuration of a gravel-bedded stream is one that can move back and forth like a snake in the form of a meander or wave. Interestingly, the periodicity of the complete wavelength tends to be constant in a flowing medium, such as water, regardless of the size of the stream (and this is normally about 12 times the normal bank-full width of the stream.

The beds of gravel streams are formed when discharges occur to at least channel-forming flow levels, and repeated flow events eventually provide the ultimate shape a stream channel adopts as it carves its way through alluvial gravel deposits (see Keller 1971; Richards 1982). In gravel-bed streams that are in dynamic equilibrium, the channel-forming flow, or 'dominant discharge,' is the amount of water that is responsible for the characteristic size and shape of the channel over time and which transports the majority of the sediment. The 'bankful discharge' is the water volume that fills the channel from bank to bank before flooding over the floodplain. For channels in dynamic equilibrium, the bankful flow is similar to the channel-forming flow. In wet environments, these discharges commonly have return periods of about a year and a half.

Once the formation of a three-dimensional channel occurs, and it has a shape that is consistent with the path of the flowing water and the surrounding landscape, movement of the bedload is minimal (Brown et al. 1998). However, alteration of the shape of the stream channel, either naturally or through human activity, has important consequences. Once the channel shape has been disrupted, the stream spends considerable hydraulic energy to realign the channel during subsequent high flow events, in order to re-establish normal riffle-pool spacing and meander pattern. Brown et al. (1998) suggest that gravel-bed streams are less resilient than many other flowing waters as a consequence of their predictable natures.

If bedload is taken from the wetted perimeter of the gravel stream, the remaining hole is filled by sediment moving into it. Through this activity, the stream is attempting to restore the appropriate water surface gradient. Because the human removal of gravel bedload can alter the riffle-pool spacing and other physical attributes that are normal for the reach (such as the meander), the stream will continue to attempt to rearrange available in-channel or bank sediments until the shape is in harmony with flow patterns at the bankful stage. A "reach" of stream is a homogeneous stretch of water with similar gradient characteristics.

Sediment can be moved by water along the bed (bedload) or within the water-column of the stream (suspended load). Bedload moves by rolling, sliding or bouncing along the bottom of the stream and normally includes the larger diameter materials. Suspended load is the part of the material maintained in the water column because of the swirling nature of the water, as well as the sediment that is far too small to settle in the channel bed (wash load). Gravel-bedded rivers normally move their substrates only at certain times when the flows get large enough and powerful enough. Sand-bedded rivers will move material at relatively small changes in flow, as the streambed material is much easier to move for a given discharge and slope, than the sediment which makes up the bottom of a gravel or cobble stream.

It is important to note that the difficulty in understanding these sediment processes in a particular stream is simply because our observational time scale is normally too short. Supporting this notion, Kondolf (1994b) remarks that transportation of sediment may be continuous on a geological time scale, but episodic on a human scale. The stocastic or highly variable nature of the rate of bedload movement is further discussed by Kondolf (1994b) when he states that "...[s]ediment transport occurs as a power function of discharge, so high flows transport proportionally greater sediment loads than moderate flows." Most sediment transport is accomplished by flows that occur over a small percentage of the time. For example, on average, 97% of sediment transport on the Santa Clara River in California occurs 1.2% of the time or about four days per year (Kondolf 1994b). Because of the large inter-annual variability in discharge and sediment load, a river might have to be monitored for years before sediment transport can be quantified.

In summary, there is a linkage between the stream-geomorphic processes and salmon and steelhead. Stream shape and the processes that give rise to the shapes define the quality and quantity of the fish habitat. When the shape of the stream is reformed, fish habitat is transformed, and this may be in either a positive or negative direction. Complex macro-habitats such as side-channels, back-channels and slack-water areas can also be the result of these changes, creating diverse and productive habitats for a variety of fish and other aquatic organisms (Rempel 1999).

5. Man-Made Changes to Rivers: How Sediment Transport, Stream Shape and Fish Habitat are Affected by Human Activities

5.1 EXTRACTION OF SEDIMENTS

5.1.1 Mining Gravel for Aggregate

Sediments found within floodplains of streams have long been considered a ready source of aggregate material for the construction industry and the development of property. Aggregate is a term that refers to sand, gravel and rock — materials used for constructing dams, roads, buildings and other structures. Aggregate constitutes the largest mineral commodity used and mined in the province, by volume.

Aggregates are essential components in British Columbia's economy, and gravel of stream origin is particularly sought after. River gravel is especially desirable for many construction applications due to the fact that streams tend to reduce fractured rock into elements that provide a superior product for stress-sensitive applications (Meador and Layher 1998). A further advantage is that the various fractions are already graded, to a degree, by size.

Aggregate in itself is normally a very cheap commodity, but the processing and transportation costs are major components of the pricing structure. Costs are exacerbated when settlement and agriculture sterilize parts of the landscape that might otherwise be used to mine aggregate, and the industry has to search farther and wider for sources of these sediments. The transportation of aggregate usually is the largest cost associated with the product in both the United States and British Columbia (Meador and Layher 1998, Anon. 2000).

The amount of aggregate used in British Columbia is currently estimated to be 50 million tonnes per year, and most of this is consumed by infrastructure in the form of roads, sewers, homes, schools and hospitals (Anon. 2000). The British Columbia Ministry of Transportation and Highways was the single largest user of aggregate in 1999, taking a total of eight million tonnes worth about $44 million. The private-sector aggregate businesses include both large and small companies, and they pay almost $6 million per year to the Province in the form of royalties when this material is taken from Crown land.

British Columbia's annual per capita consumption ranges from 13 to 16 tonnes with the Lower Mainland, Southern Vancouver Island and Okanagan regions being the areas of highest aggregate use (Anon. 2000). Because of their high growth rates, these three geographic areas are currently running out of cheaply available supplies of sand and gravel (Anon. 2000). Historically much of the gravel for development came from alluvial sources. Increasing concerns by the public and the fisheries agencies began to restrict its extraction. However, British Columbia is fortunate that many areas requiring aggregate have land-based post-glacial-outwash deposits for use in place of stream-derived sediments.

While many aggregate applications require coarse forms of material, the use of fine sediment is also an important part of British Columbia's development industry. For example, a current source of conflict between fish and aggregate mining occurs in the sand reach of the lower Fraser River. Much of the population growth that has occurred in the Lower Mainland over the last decade has been in the low-land parts of the Fraser River-based communities of Delta, Richmond, Surrey, New Westminster and Pitt Meadows. These communities have grown, in part, due to the availability of cheap and easy-to-build-on land within the floodplain of the Fraser River. Current development of properties that lie within the floodplain must now comply with flood hazard regulations for that area. Usually, this means that a structure must be able to withstand the height and power of any flood that statistically occurs up to once in 200 years. Lower Fraser River alluvial sand, from Mission downstream, is particularly desirable for providing material in order to increase the elevation upon which buildings can be constructed. This is due to its characteristics for compaction and because it is geographically and cheaply accessible to these communities.

Volumes that have been removed from within the wetted perimeter of the lower Fraser River during the 1970s and 1980s greatly exceeded the amounts that were being naturally recruited by the river, and the health of the estuary was being compromised. The Fraser River Port Authority (FRPA) in the lower river sells the sediment by-product of its navigation dredging to the development industry in order to help pay for its business operations. This is a continuing incentive to extract as much as is economically feasible. As a result, pressures are placed on the fisheries regulatory agencies to accommodate the FRPA. Issues surrounding the over-abstraction of this material by dredging interests, in the sand reach of the Fraser River, are discussed in a later chapter of this report.

While sand and gravel extraction and associated aquatic environmental impacts are significant issues in British Columbia, they have consequences that are also found around the world. With the global expansion in human populations over the past 50 years, the needs of the aggregate industry have grown worldwide and have caused environmental problems related to extraction of river-derived sediments. Sear and Archer (1998) indicate that commercial-gravel extraction from river beds is a global phenomenon because rivers have historically been an attractive source of gravel supply where they have existed close to the point of use.

About 10-20% of the sand and gravel mined in the United States in 1974 came from streams (Meador and Layher 1998). Construction utilizes about 96% of the material, while around 43% of this amount is used for buildings in that country. To place aggregate use in context, about 91,000 kg of sand, gravel or crushed stone are required to construct a six-room house and 14 million kg of aggregate are required to construct a school or hospital. Like British Columbia, road building in the United States accounts for a high level of aggregate use, with 24% of the sand and gravel volumes directed to this purpose. Around 60 million kg of aggregate are normally used in building 1.6 kilometres (1 mile) of a typical four-lane US highway (Meador and Layher 1998).

The largest aggregate producer of any US state is California. Furthermore, the extraction of sediments for aggregate is its largest mining industry. Around 100 million tonnes, or 30% of the current US production, are extracted in California for a value of US $700 million (Kondolf 1995). Because of the lack of alternative sources, virtually all of the mined material in California is derived from alluvial deposits. This amount is considerably greater than the volumes recruited into the state's streams through natural erosion. For comparison, Kondolf (1998a) has estimated that the total annual natural creation of bedload throughout the whole landscape of California is 13 million tonnes, or about one order of magnitude smaller than what has been taken by industry from stream derived deposits. It is worthwhile noting that Kondolf (1998a) has estimated that in California the doubling of the cost of delivered aggregate for a $150,000 home would increase the construction cost by only 2%. This suggests that alternate options of aggregate production, such as using crushed rock or recycled concrete, may be viable at times instead of using river gravel.

Closer to home and in contrast to California, Washington State has many aggregate deposits that are the result of the outwash from the melting of ancient glaciers near many of its markets. This alternative source to stream gravel, coupled with government discouragement of in-stream gravel extraction, seems to have limited and reduced the number of mines from active river channels in Washington to four. There are, however, some additional floodplain pits in the state (Kondolf 1998a).

In many parts of the world outside of North America, sediment mining from alluvial sources continues to be a source of aggregate. However, for some countries, moratoria have been put into place in order to deal with gravel mining in and about rivers, and due to the recognition that sediment mining under these circumstances has severe physical and ecosystem impacts. This includes the United Kingdom, Germany, France, The Netherlands and Switzerland, although for some of these countries, existing mines have been grandfathered until their permits expire (Kondolf 1997). This type of aggregate mining is also prohibited or reduced in Italy, Portugal, New Zealand (Kondolf 1997) and Norway. In Kenya, for example, where sand is harvested from river beds and accounts for about 90% of its national consumption, the government realized as early as 1982 that uncontrolled mining was causing widespread damage to river ecosystems (Rowan and Kitetu 1989).

5.1.2 Removal of Floodplain Sediments for Flood Protection

While removal of sediment for aggregate purposes has been a problem for fisheries habitat regulators, a second and potentially more difficult issue has arisen in recent years with regards to the removal of in-stream or floodplain sediments in order to increase stream capacity for flood protection. This is particularly an issue for flood-prone streams near populated areas with high recruitment of bedload. The buildup of material in the stream bed can cause dike over-topping during flood events, with the attendant destruction of life and property. A simple-minded way to deal with the problem has been to remove sediment from the channel in order to increase the water conveyance. Often, in the cause of expediency and cost, this method is undertaken by floodplain managers. In centers of high population, where gravel supplies are already short and the demand is high, the aggregate industry is more than happy to remove the material at minimal cost, or even pay a significant royalty for the material. Regulatory agencies are pressured to allow the removal of gravel from within the floodplains of salmon and steelhead streams in excess of what realistically may be needed. Further complicating matters, the aggregate industry readily provides its removal capability to government agencies for the ostensible purpose of reducing an actual or perceived threat of flood. The resulting alliance between industry and government officials often undermines the support that fisheries regulators require to protect salmon and steelhead habitat.

In British Columbia, the removal of sand and gravel in order to increase the floodway capacity for the purpose of public safety and flood control occurs under the aegis of the provincial Water Management Branch, and usually with some level of input from the senior fisheries agencies and the local communities.

On Vancouver Island, the Cowichan and Chemainus rivers have recently undergone sediment removal to reduce flood problems. Alluvial material has also been removed from Haslem Creek (Nanaimo River watershed), Nanaimo, Englishman and Oyster River on Vancouver Island. In the Lower Mainland, the Cheakamus, Vedder, Fitzsimmons, Norrish, Coquihalla, Silverhope and Fraser rivers, to name a few, have been subject to gravel removal for flow conveyance purposes over the past decade. Furthermore, all of the streams mentioned above are salmon and/or steelhead watersheds. Streams in other parts of the province have also been, and continue to be, affected in this manner.

The projects by public and flood protection agencies, to increase floodway capacity by removing sediment, appear to be on the rise in British Columbia. This is occurring for a number of reasons:

1. The cumulative impacts of 100 years of settlement on floodplains, and the associated confinement of streams over the last 50 years, have gotten to the point where gravel and sand buildups now have to be dealt with.

2. There continues to be wide-scale urbanization of lowland areas due to high human population growth. The perimeters of the floodplains are often the last to be settled; this is because, although they are cheapest in terms of cost, they are the most difficult and expensive to protect from flooding.

3. The construction of buildings between dikes continues, with the acceptance of regulatory agencies. Relaxation of building restrictions within the floodplain often occurs where the proponent builds on a pad to a specified floodproofed elevation.

4. Flood-protection managers are under pressure to cut costs. It is normally much easier to dredge out sediment and sell it to recover costs than to raise dikes.

5. Many of the floodplains that are now settled were initially logged to the edge of the stream banks. In these circumstances, there are no old-growth trees to maintain stream-banks with their root structures, or to recruit new boles into these water bodies. The in-stream old-growth LWD that had been stabilizing and controlling the sediment for hundreds of years is now at its final life stages, rotting and releasing the stored sediment and causing stream aggradation down-river. This may also be exposing unconsolidated material to erosion for input into streams.

6. Wide-scale terrestrial changes, due to logging, agriculture and urbanization, have led to increased peak-flows, greater erosional power and accelerated mobilization of sediments. This may be exacerbated by changes to global climates and subsequent increases in water yield.

5.1.3 Physical Effects of Removal of Sediments from Deposits in Alluvial Environments

The implications of dredging material from streams to salmon and steelhead habitat have rarely been considered in the first half of the 20th century in British Columbia. In the past, gravel removal was not thought to signficantly harm fish habitat, and the fisheries resources seemed unlimited. Some amount of habitat destruction seemed inevitable given the growth the province was going through but this activity was thought not likely to change the numbers of fish in any meaningful way. For example, in the 1950s and 1960s, gravel was routinely removed from within the wetted perimeter of some of southwestern British Columbia's richest salmon and steelhead streams including the Vedder, Alouette, Coquitlam and Fraser rivers. It was not until some significant declines had taken place to fish populations at mining locations that people began to link the issue of diminishing fish numbers to in-stream sediment removal.

Subsequently, in the 1980s and 1990s, fisheries agencies in British Columbia became somewhat more conservative regarding the removal of material for aggregate purposes. Indeed, sediment removal solely for aggregate has been almost ruled out for most small rivers with salmon and steelhead. Nevertheless, gravel mining from non-anadromous rivers continues at locations where natural land-based sources of aggregate are limited, such as the Peace River and Fraser River, where large volumes are easily accessible. Furthermore, it is often difficult for a fisheries agency to stave off requests for approvals for extraction from these sources when the information, to date, on impacts to fish habitat is often mostly lacking.

Extraction of alluvial deposits from within the wetted perimeter of a stream channel usually occurs through either one of two different modes. The first is by scraping or scalping material off of the top of a dry gravel bar when the water drops to a low flow, usually in late winter or during late summer (bar scalping). The second is by dredging material from within the wetted perimeter of the channel, usually with a dragline or clamshell dredge, or by suction. Mining can also occur within the infrequently wetted floodplain in the form of pits; this can cause problems for fish and aquatic habitat if the stream channel re-routes itself into these pits as a result of erosion, or if it strands fish and aquatic invertebrates after a flood. Table 3 summarizes many of the impacts of these methods.

Table 3:

Summary of the effects of gravel extraction in streams. From Collins and Dunne (1990) and Sear and Archer (1998).

Impacts to Habitat and Natural-Stream Attributes

1. In-stream mining causes disruption of bed sedimentology.
2. Removal of sand and gravel from streams causes disruption of sediment movement continuity.
3. Extraction of bed material in excess of replenishment by transport from upstream causes the bed to lower (degrade) upstream and downstream of the site of removal.
4. Degradation may change the morphology of the riverbed, which constitutes one aspect of the aquatic habitat.
5. Degradation can deplete the entire depth of the gravelly bed material, exposing other substrates that may underlie the gravel which, in turn, affects the quality of the aquatic habitat.
6. If a floodplain aquifer drains into the stream, groundwater levels can be lowered as a result of bed degradation.
7. Lowering of the water table can destroy riparian vegetation.
8. The supply of overbank sediments to floodplains is reduced as flood heights decrease.
9. Rapid bed degradation may induce bank collapse and erosion by increasing the heights of banks.
10. The reduction in size or height of bars can cause adjacent banks to erode more rapidly or to stabilize, depending on how much gravel is removed, the distribution of removal, and on the geometry of a particular bend.
11. Removal of gravel from bars may cause downstream bars to erode if they subsequently receive less bed material than is carried downstream from them by fluvial transport.
12. Degradation may continue up tributaries following a main river's degradation.
13. Increased levels of downstream turbidity may occur as a result of the action of removal, exposing sediments or causing erosion into deposits of fine sediments.

Human-related Effects

1. Bed degradation can undermine bridge supports, pipelines and other structures.
2. In rivers which sediments are accumulating on the bed (aggrading) in the undisturbed condition, gravel extraction can slow or stop aggradation, thereby maintaining the channel's capacity to convey flood waters. Flooding is reduced as bed elevations and flood heights decrease, reducing hazard for human occupancy of floodplains and the chance of damage to engineering works.

Bar scalping can have a substantial effect on aquatic ecosystems by creating a wide, flat cross section and eliminating any defined low-flow channels; the result of this is a thin sheet of water across the channel at base or lowest flows. Importantly, bar scalping can also remove the surface congruity, or armoring, and this layer is important in regulating the rates of bedload transport. When the armoring is removed, it normally exposes finer subsurface material which may be entrained into the water even at non-flood flows. These fine sub-surface materials may be transported downstream into pools where they differentially settle out and negatively impact on organisms that use this macro-habitat feature (Kondolf 1994b). The armoring surface layer can also provide salmon and steelhead attributes that are not in the sub-surface layers, such as a larger average grain size of sediment which is important for some spawning and rearing.

Bar scalping has been commonly used in British Columbia. But, unless the bar is very large, water engineers attempting to increase channel capacity for flood control purposes or aggregate operators trying to maximize revenues normally do not prefer to use this technique as a gravel source because the yield of sediment is usually quite small. Deep pits are the preferred extraction technique. Furthermore, salmon and steelhead habitat biologists now recognize that the high points on these bars normally constitute juvenile rearing habitat during high-water periods. These bars also provide recruitment of gravel to downstream spawning and rearing areas and maintain stability of the channel. Because of these recognized impacts to fish, routine authorizations for scalping have fallen out of favour with the fisheries regulatory agencies.

The most dramatic effects of in-stream sediment extraction occur, however, when pits are excavated within an active stream channel (Kondolf 1994b). Once a deep pit is excavated within the wetted perimeter, the profile of the streambed is no longer in equilibrium with the size of sediments in the bed. This is because the relationships among the stream slope, water depth and sediment diameter are now artificially altered; the channel shape and size must re-adjust through erosion of the bed as the water enters the locally steeper gradient at the upstream end of the pit (Fig. 4). The steeper gradient of the side of the pit increases the stream power at the point where the water enters. This results in bed erosion as the river then tries to re-establish its former gradient.

There are a number of ways that the stream attempts to compensate for the disruption of the equilibrium between its slope and sediment size. One way is the erosion of streambed material in an upstream direction, known as headcutting or knickpoint migration. Under certain conditions, the erosion may continue upstream for kilometres (Scott 1973; Stevens et al. 1990 cited in Kondolf 1994b). Or, if the pit is located within the pathway of the streambed sediment, much of the incoming sediment load may be trapped in the pit until the equilibrium slope is achieved. However, the water exiting the downstream end of the pit will be deprived of its normal sediment load due to the upstream entrapment. The term "hungry waters" is used to describe the discharge flowing from the pit, where it "expects" sediment from upstream sources but no longer receives it due to the entrapment of these sediments within the pit. As a consequence, the excavation of a pit within the normally wetted channel of a stream may also induce erosion or incision in a downstream direction due to this "hungry waters" phenomenon (Kondolf 1994b). One of the consequences of downstream incision is that it tends to coarsen the bed (Kondolf 1998a) and this can be negative to fish habitat if important spawning gravel is being eroded away.

Another effect of digging pits in a stream is that this can cause channel instability by initiating lateral erosion into banks. This, in turn, can result in channel migration into formerly stable parts of the floodplain (Kondolf 1998a). Because the bedload-free 'hungry water' now has excess energy in its downstream locations, it typically erodes its banks in a horizontal direction to regain, at least in part, its sediment load, so as to restore the former slope. Stream channel instability and stream bank erosion can cause a loss of the important riparian vegetation. Stream-side vegetation shades and covers channels, as well as providing effects to wildlife and other ecological attributes. Indeed, the vegetation itself can be important in trapping fine sediments during flood flows.

Finally, channel incision may cause the alluvial water table to be lowered (Kondolf 1998a). Because the banks are effectively drained to a lower level as a result of a lowered streambed, riparian vegetation and other organisms that depend on the water being at a certain height can be affected.

In summary, the excavation of an in-stream pit can cause vertical erosion or incision that can propagate both upstream and downstream: upstream by nickpoint migration and downstream by sediment starvation (Fig. 4). Bed coarsening, lateral erosion and water table lowering are collateral impacts that may also occur.

In order to safeguard a river from having too much material removed during a mining operation, the amount of new material coming into the system should be accurately estimated in order to determine the replenishment rate. Estimates of bedload recruitment or transport can be made in a number of ways. For example, this can be done empirically by using a bedload sampler which is a device that traps material moving down the stream. However, this is expensive and time consuming, and it cannot always get accurate data during brief, episodic flood events.

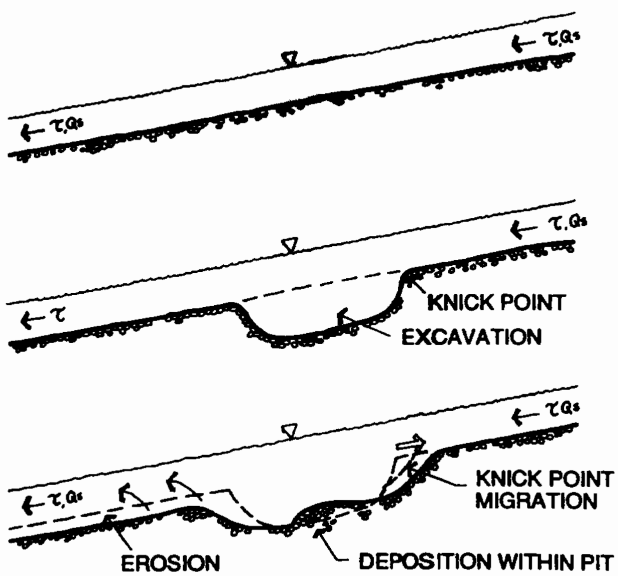


Figure 4:

Upstream (headcutting) and downstream (degradation) erosion in a stream occurring as a result of instream mining. A: the pre-extraction condition in which the stream's sediment load (Qs) and the force available to transport sediment, the shear stress (T), are continuous through the reach. B: the excavation creates a knickpoint on its upstream end and traps sediment while interrupting the transport of sediment through the reach. Downstream, the river still has the capacity to transport sediment (T) but has no sediment load. C: the knickpoint migrates upstream and hungry water erodes the bed downstream causing incision upstream and downstream. Both the diagram and explanation are taken from Kondolf (1994b).

Fluvial geomorphologists and river engineers also use mathematical models, inputting such parameters as the grain-size distribution of the bed material, channel cross-section, slope of the water surface and relationship between water depth and discharge. These are used to develop a rating curve for which material recruitment can be estimated if the discharge patterns for the stream are known. Rating curves are not applicable for very steep streams. Channel surveys can also be used to determine the net changes in erosion and deposition and the net accumulation or erosion along a reach. This involves creating a three-dimensional map of the stream bed. However, this is also time consuming and expensive.

The National Council for Air and Stream Improvement (NCASI) (1999) indicates that individual sediment transport measurements, load estimates, and determinations of mean annual sediment yields are usually of rather low accuracy for most studies. They suggest that this lack of accuracy can be attributed to the high temporal and spatial variability of sediment transport, the poor or inconsistent sampling efficiencies, and low sampling intensities. This brings an element of error into the use of gross sediment budgets to determine the availability of gravel that may be removed in a watershed.

Some jurisdictions consider an appropriate amount of allowable gravel mining to be a proportion of the incoming volumes, typically somewhere around 100%. However, Kondolf (1993, 1994b) dismisses the common belief that in-stream gravel extraction can be conducted safely so long as the rate of extraction does not exceed the rate of replenishment. This approach to managing in-stream gravel extraction fails because it does not account for the upstream/downstream erosional effects that change the channel morphology as soon as the gravel extraction begins. In addition, Kondolf (1993, 1994b) suggests that because flow and sediment transport for most rivers and streams is highly variable from year to year, an annual average rate figure is often meaningless.

5.1.4 Physical Observations From Around the World

In the United States Colins and Dunne (1989) recorded the gravel-extraction impacts to three gravel-bed streams in southwestern Washington. They found that the amounts of material removed from these rivers were exceeded for up to three decades, and often by a volume of more than an order of magnitude greater than the natural recruitment. For the Lower Mississippi River, various studies have shown that in recent years there were significant changes in both the size and gradation of the bed material due to mining (Lagasse et al. 1980). Much of this change seems to be related to the removal of the coarse fraction of the bed material that results from the dredging of the limited gravel resources.

Overseas, the effects of gravel mining have also been seen to be dramatic. Excessive harvesting of sands and gravel occurred in the Rhone River near Lyons between 1970 and 1980, causing a substantial lowering of the streambed. In this instance, there was also a collateral drop in the elevation of the water table that precipitated ecological consequences in the alluvial plain, as well as domestic water supply problems (Petit et al. 1996). In the UK, Sear and Archer (1998) found that there were substantial effects resulting from gravel extraction on the stability of Northumberland gravel-bed rivers. While this activity occurred over a 50-year period, it led to the incision of the stream-beds of up to nine metres, in addition to a metamorphosis of channel planform from a laterally active wandering gravel-bed river to a largely single-thread, sinuous channel.

For Japanese streams, Kira (1972) discussed the effects of "gravel gathering" on rivers in that country and noted that at that time about 80% of the total annual consumption was derived from alluvial gravel deposits. It was suggested that, because of indiscriminate digging or gathering of gravel, alluvial resources were being exhausted and "river course calamity due to river-bed degradation" had become a public concern. Galay (1983) has also provided numerous examples of the destructive and negative impacts to rivers and properties around the world where man had intervened in the fluvial processes by changing the stream channel slope and causing streambed degradation. Galay's paper provides some of the most compelling published evidence of the destructive effects of interfering with in-stream fluvial processes or taking gravel from a stream. This study makes a powerful case for not removing gravel from streams.

Ironically, some of the most visually dramatic impacts resulting from poorly regulated alluvial mining are of a human infrastructure nature. Incision has been shown to cause the undermining of piers and bridge pilings and the exposure of buried pipeline crossings and water supply facilities. In California, the Department of Transportation has estimated that 1% of the state's 12,000 bridges over water are critically threatened by scour, and many of these are associated with aggregate extraction from the channel (Kondolf 1998a). Another extreme example where gravel mining caused excessive impacts to a stream occurred in the Russian River, California, during the 1960s and 1970s. There, the sediment removal caused channel degradation in excess of three to six metres over a distance of 11 kilometres (Kondolf 1997).

5.1.5 Observations of Biological Impacts Resulting from Experimental Sediment Removals

While many studies have looked at the physical aspects of in-stream sediment removal, few have identified the direct biological impacts of gravel mining. This is normally difficult because of the inherent variability of aquatic ecosystems and the difficulty in developing a scientifically controlled experimental design. One of the more detailed published experiments that has application to salmon and trout streams, and that integrated the biological with the physical, was undertaken by Brown et al. (1998). This study undertook an detailed examination of the impacts of gravel mining on physical habitat, fine-sediment dynamics, biofilm, invertebrates and fish in three different gravel-bed streams in the Ozark Plateaus. The experimental design included looking at the upstream, downstream and on-site effects of a large mine on each of three streams. In other words, this was an attempt to undertake a controlled scientific experiment, something that is rarely done when attempting to assess the impacts of alluvial mining.

Brown et al. (1998) found that gravel mining significantly altered the geomorphology, fine-particle dynamics, turbidity and biotic communities of streams. The stream channel form was altered as a result of increased stream bankful widths — pools became longer and riffles became smaller where the mining affected the streams. Due to the aggregate extraction, less fine particulate organic matter (FPOM), important food for insects, was transported from the riffles to the pools. Biofilm organic matter, an invertebrate food, decreased on the flats and increased on the lower number of riffles that had been left. The study also found that the numbers and biomass of large invertebrates, and the density of small invertebrates, were reduced when the mining occurred repeatedly at small sites. A study by Brown et al. (1998) showed that the densities of fish in pools were reduced as a result of mining at large sites and the densities of game fish in pools and riffles were also less. Those species of fish that are sensitive to silt were less numerous downstream of the mining sites.

The authors of this comprehensive study suggested that attempts to mitigate or restore stream ecosystems impacted by gravel mining may be ineffective because the disturbances result from changes in physical structure on the streambed over distances of kilometres upstream and downstream of mining sites. The stream shape, the authors contended, was changed by a lack of bedload, not by how the material in the bed was removed. As a result, it is their opinion that mining gravel from stream channels at the levels observed in their study results in irreconcilable multiple-use conflicts.

5.2 IMPACTS TO STREAM SEDIMENTS RESULTING FROM HUMAN ENCROACHMENT ONTO FLOODPLAINS

For streams that are bed-load rich, the natural discharges continually move material down the watershed so the stream bed or valley bottom increases in elevation. The consequence of this net deposition is that the valley bottom, or flood plain, must accommodate the water that spills out of the existing stream in order to provide room for a new channel. Over time, these new channels are created over top of, and through, these sand and gravel accumulations, albeit at a higher level. This is the result of deposition and erosion.

Throughout geological time, the addition of sediments to alluvial stream bottoms and floodplains have not been a problem to fish, vegetation and other living organisms living in these watersheds. They have simply moved or adapted to these cyclically changing sedimentary and morphological conditions. Indeed, much of the richness of some of the best salmon and steelhead streams is a result of the constant renewal of stream habitat due to flooding and sediment reconfiguration. However, human activities in floodplains and upslope areas (e.g., forestry, clearing, agriculture) have now exacerbated sediment loads and increased run-off peaks and water yields over natural levels to many of watersheds (Larkin et al. 1998).

Rivers have formed the focus of human settlement since pre-historic times and many of the earliest civilizations settled on floodplains where they have attempted to control hydrologic regimes since about 5000 BC (Welcome 1985). Although salmon and steelhead have inhabited many of British Columbia's streams since the last ice age 10,000 years ago, it has only been in the last 100 years that humans began to develop the floodplains to any extent. Furthermore, it was not until there was a dramatic increase in numbers of native and non-indigenous peoples, who began to live on the floodplains in this province in a permanent way, that in-stream habitat conflicts began to arise between fish and humans. As the communities began to grow, permanent infrastructures came to encroach significantly upon the lower-elevation, alluvial areas. Anthropogenic changes included clearing land for agriculture, as well as constructing permanent buildings, building transportation routes and forming towns.

Natural flow regimes normally involve over-bank flooding from time to time. With collateral damage to infrastructure, people began to protect their investments by controlling flood flows. Large floods in 1894, 1948 and 1972 caused substantial damage to property throughout many parts of British Columbia. As a result, settlers began to dredge, channel, dike and dam streams and, in doing so, salmon and steelhead habitat began to be impacted through the disruption of natural sediment processes.

There are 140 diking arrangements in British Columbia for a total length of over 1,000 kilometres, protecting 120,000 ha of land. In the lower mainland, half of the entire population and $13 billion worth of property and developed land are behind 600 kilometres of dikes. The 1948 floods caused numerous dike failures and about 30,000 ha were flooded, damaging or destroying 2,300 homes (Woods 1996). The standard flood design for southern British Columbia is based on the 1894 flood event, the largest one in the province's recorded history. This event is thought to have a return period of about 1:200 years.

Flows in many British Columbia streams have also changed over time and this has important implications for moving sediment. Human clearing of the landscape over the last 100 years has exacerbated natural flow volumes. Annual water yield in Carnation Creek, for instance, increased 9-16% following a clear-cutting of a 12-ha tributary sub-basin (Hartman et al. 1996). Furthermore, a long-term study in Oregon suggests that peak discharges increased by as much as 50% and 100% in large river basins where the forest harvesting included 100% clear-cutting as well as 25% clear-cutting, with the addition of roads (Jones and Grant 1996). Higher peak flows move disproportionally more sediment than lower discharges.

One method of controlling water on floodplains has been to channel and straighten streams. This often occurs in conjunction with lowering the stream bottom by dredging in-stream sediments. This means that the stream is deepened and straightened, the sides are protected or armoured with rock or other hard material and the channel cross section is made rectilinear. This prescription increases the land base for human use and it confines water within a clearly defined perimeter. This is, however, normally devastating for aquatic ecological communities.

Worldwide, channelization has been shown to be detrimental to fisheries and salmonids (Welcome 1985). For example, an impact arising from channelization of the Missouri River was that its straightening subtracted 120 kilometres between the years 1890 to 1947. This reduced the water surface area by 50% from 1879 to 1972 (Welcome 1985). Groen and Schmulbach (1978) showed that, as a result, the fish catch per mile was two to 2.5 times greater in the unchannelized reaches of the Missouri River.

Like dredging, the straightening of stream banks also affects how sediment particles are deposited or are dispersed. In the process of confining and straightening the stream, the flowing portion of the streambed becomes shortened and the slope increases. Because the slope is now greater, some of the constituent streambed particles are now smaller and cannot be retained at this location in the face of the stream's normal range of water discharge. The greater slope means that the smaller component of the in situ range of sediments will now be carried from this location in the stream, potentially eroding important spawning gravel and coarsening the bed.

Habitat quality and abundance in salmon and steelhead streams is a function of a physically diverse stream. Channelization removes much of the physical diversity that would have been present under natural conditions, including meanders, sediment grain sizes, and physical structure, such as LWD. Furthermore, because full meandering under natural conditions requires an adequate river corridor, channelization limits rehabilitation of rivers and streams in most cases. Once channelization has occurred, the corridor available for restoration is dictated by land use, rather than by calculations of river engineers or geomorphologists.

To stabilize shore lines, rip-rap, stone paving or non-natural hard materials are often used, in both channelized and non-channelized river reaches. Hardening of banks reduces stream variability due to the restriction of natural erosion and deposition processes. It also causes the subsequent loss of recruitment of fresh sediments, including spawning gravel. The hardening of natural banks also eliminates the opportunity to develop meanders. Astonishingly, even the Fraser River in the salmon-rich gravel reach between Sumas and Agassiz, has had over 50% of its banks hardened by rip-rap. The long-term consequence of this will be a major shift in the quality and quantity of the habitat for those species that rear and spawn therein. Indeed, because it is cheap, quick and easy to install, and gives a false sense of accomplishing river management, rip-rap is sometimes referred to as the "crack cocaine" of river engineering because its addictive qualities make it one of the most heavily used and abused tools by floodplain managers.

Engineering work in gravel- and sand-bed rivers, in order to use more of the floodplain of these streams, has historically has been based on the concept that man could control the forces of nature (Klingeman 1998). With respect to rivers, these forces included floods, bank erosion and sediment deposition. As a result, throughout the 20th century, humans were stabilizing and "correcting" rivers through engineering solutions. Hey (1998) makes the point that for centuries, and in response to society's needs, engineers have managed rivers for flood control, land drainage, water supply, navigation and power generation, and have also carried out river training to stabilize them. As an example, Hey (1998) indicates that in England and Wales up to 41% of main rivers in the Thames basin have been engineered to some degree (see also Brookes et al. 1983).

Much of the engineering has been counter-productive. By modifying rivers and their flow regimes, many engineering schemes have promoted instability, both within the engineered reach and adjacent sections, which then requires expensive and long-term maintenance (Hey 1998). Unfortunately, the more that was done to alter a river, the more attention it seemed to need, to the point where it lost all character and semblance of being a river (Klingeman 1998).

Bathurst and Thorne (1982) sum up the problems of human attempts to master rivers by articulating the following: "[The]...natural character of many alluvial channels has been significantly affected by river and catchment development projects...channels have been straightened, flows regulated and banks stabilized and raised...catchment development...has considerably altered the quantity and quality of sediment and water carried into river. Many of these changes have had serious effects on rivers, either by promoting instability at, for example, meander cut-offs, downstream from dams and in the vicinity of river intakes and outfalls, or by adversely affecting ecological habitats and recreational potential through unsympathetic management practices. Such repercussions are economically expensive and aesthetically unpleasant. Future developments should therefore ensure that the natural character of river channels is preserved..."

Impacts to salmon and steelhead habitat can be lessened under these floodplain circumstances by constructing dikes that are set back far enough from the normally wetted perimeter of the stream. Set-back dikes allow more of the natural stream processes than those located immediately adjacent to the wetted perimeter. Set-back dikes also lessen the need to harden the stream banks with the ecologically-destructive rip-rap protection. The effectiveness of the set-back dike approach to protect property and ecosystems nevertheless depends on the distance of the dike from the wetted perimeter. The subsequent need to purchase property for set-backs adds an additional diking cost to governments.

5.3 EFFECTS OF DAMS ON SEDIMENT IN STREAMS

The damming of a river has been termed a cataclysmic event in the life of a stream ecosystem. Dams change the flow of water, volumes of sediments, nutrients, energy and biota. They interrupt and alter most of a river's important ecological processes (Ligon et al. 1995).

When dams are constructed, they normally interrupt and trap sediment, limiting material to downstream reaches. Unless special provision is made to bypass sediment, the reservoir eliminates the supply of sediments coarser than clays and silts. Those coarser sediments would normally provide habitat for many aquatic species, including spawning and rearing habitat for salmonids (Wilcock 1998).

Both storage and diversion dams can cause a change in peak flows, often reducing the high flows required for flushing and removing fine, deleterious sediments from spawning and rearing gravel downstream (Kondolf 1995). Thus, the sediment-transport capacity of rivers downstream of reservoirs can often be reduced as a function of the reduction of flood magnitudes. However, the subsequent morphological response of the channel downstream of the dam depends in a complex fashion on the relative decreases in transport capacity and sediment supply (Wilcock 1998). If the decrease from pre-dam sediment supply is large, relative to the transport capacity, the downstream response is bed degradation, as well as armoring and coarsening of the sediments. Conversely, if the transport capacity is reduced more than the sediment supply, the downstream channel will undergo aggradation, typically with finer grained sediment that passes through the reservoir, or those which are supplied from downstream tributaries (Kern 1998, Wilcock 1998). In some instances, even though the sediments in the stream channel are sufficient to provide habitat, there will be essentially no transport of bed sediment downstream of the dam because the flows are now too weak to move the material. Kondolf (1995) provides examples demonstrating the variability in sediment response for two streams in California. The Big Bear River had post-damming flows of 98% of pre-dam discharges, and this resulted in a coarsening of the bed. In the Merced River the discharge regime had a pre-dam value of 12%, yet it still retained abundant spawning gravel.

Until recently, little thought was given to the impacts of interrupted sediment processes occurring in steams in British Columbia as a function of the changes in flow regime resulting from dams. Government agencies, however, are now considering, studying and attempting to rectify this situation through water use planning for a number of dammed watersheds, including the Campbell, Cheakamus, Alouette, Stave, Theodosia and Capilano rivers.

5.4 EFFECTS ON RIVERS RESULTING FROM DREDGING OF SEDIMENTS FOR NAVIGATION

Only a few British Columbia salmon and steelhead streams are dredged for navigational purposes, but a notable exception is the Fraser River. Downstream of New Westminster (Fig. 5), both sand- and silt-sized sediments are routinely removed from the shipping channel. As a result, this activity impacts habitat in the extraordinarily rich rearing and feeding areas of the Fraser River estuary. It has been hypothesized that effects on habitat may be occurring as a result of the disruption of the stream-bed shape and/or a subtle change in the diameters of the fine sediments on the river bed to which aquatic organisms are specifically adapted (McLaren and Ren 1985).

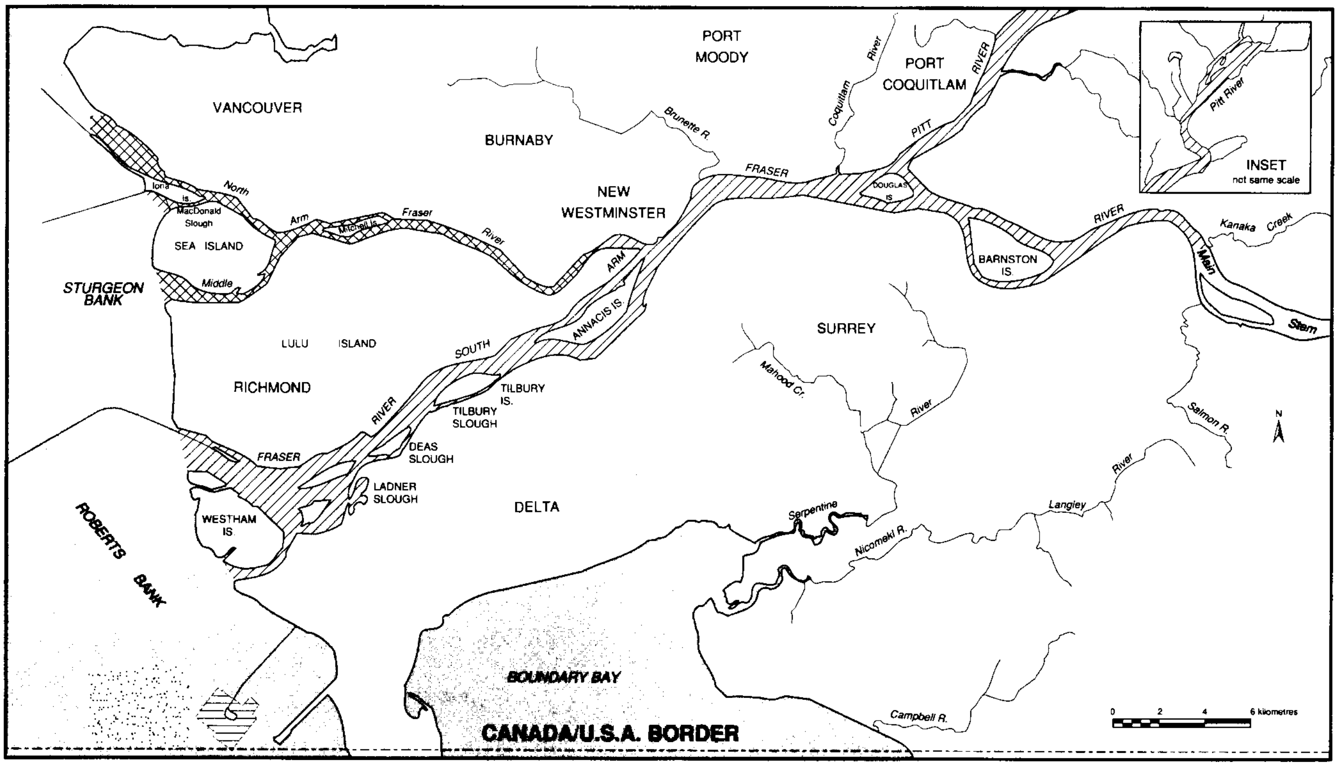


Figure 5:

The Fraser River estuary and the jurisdictional boundaries for the various port authorities in the area. From NHC (1999); horizontal hatches refer to Vancouver Port Authority; diagonal hatches refer to Fraser River Port Authority; cross hatches refer to North Fraser Port Authority.

A second location where navigational dredging occurs in the Fraser River is upstream of the confluence with the Sumas River, to Hope, in the gravel reach of this stream (Fig. 6). Here, sediments are scuffle dredged (cast aside from the navigational channel, but left within the streambed perimeter) in order to provide adequate channel depths for tugboats and log booms. This area has an exceptional number of fish species using these habitats as migration and/or spawning and/or rearing environments. Thus, these habitats are vulnerable to this activity.

Because both the extraction of sand and the scuffling of gravel in the Fraser River cause harmful alterations, disruptions or destruction of fish habitat, they are of concern to fisheries agencies. Issues relating to the disruption of sediment processes and the agency management of both the sand- and gravel-reaches of the Lower Fraser River will be discussed in detail in Chapter 7 of this report.

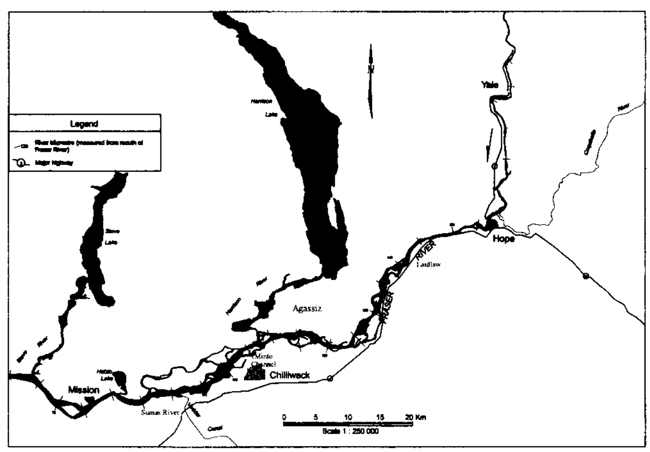


Figure 6:

The Fraser River from Mission to Hope in the gravel-bedded reach of the stream.

6. Agency Jurisdiction Over Sediment Management in Salmon and Steelhead Streams in British Columbia

6.1 ROLES AND RESPONSIBILITIES

Various statutes, policies and regulations apply to the management of human-related disruptions of sediment processes within alluvial salmon and steelhead habitats in British Columbia. Some deal directly and specifically with matters of fish habitat, including the *Canada Fisheries Act* and its No-Net-Loss and Net-Gain habitat policies and the *British Columbia Fish Protection Act.* Other legislation and policies regulate how humans can influence sediment processes, but do not specifically deal with fish habitat, even though the activity sanctioned or regulated may have collateral and negative impacts to salmon and steelhead. For example, the *BC Lands Act* and the *BC Mines Act* allow for the extraction of sediment in Crown land alluvial environments, but the statutes only obliquely specify how gravel is to be taken in a manner that protects fish habitat.

The agencies and levels of government that have relevant legislated authority include: Fisheries and Oceans Canada; British Columbia's Ministry of Environment, Lands and Parks and Ministry of Agriculture, Food and Fisheries; British Columbia Assets and Land Corporation; as well as regional and local governments.

First Nations are also becoming more involved in issues surrounding sediment extraction or stream-bank protection where this occurs within their traditional territories. Furthermore, quasi-governmental groups act as co-ordinating bodies to facilitate activities. For instance, the Fraser River Estuary Management Program is involved in the dredging of sand for navigation, and the Fraser Basin Council is active in gravel and flood management issues.

Below we provide a brief overview of some of the more pertinent legislation regarding sediment and salmon and steelhead habitat.

6.2 *CANADA FISHERIES ACT*

The *Canada Fisheries Act* is relevant to sediment to streams in two ways. The introduction of fine sediment into a fish-bearing waterway can be considered a pollutant. And the introduction of, or disturbance to, in-stream sediments may constitute a harmful alteration, disruption or destruction of fish habitat.

By way of background, the *Fisheries Act* defines fish habitat as encompassing those environments where fish live, including the "...spawning grounds and nursery, rearing, food supply and migration areas on which fish depend directly or indirectly in order to carry out their life processes" (Section 34(1)).

Section 34 of the *Fisheries Act* defines what deleterious substance is and, under many circumstances, regulatory agencies have considered the release of fine sediment to be a harmful substance to fish (Table 4). Fine sediment has also been viewed as deleterious to fish by the courts in some cases. The introduction of fine sediments into fish-bearing waters can be the result of disturbance to riparian and other terrestrial areas (e.g., land development, forest harvest, gravel mining, road building). It can also be a direct result of industrial activity on the riparian areas (e.g., aggregate washing), or due to an activity within a stream (e.g., dredging). Fine sediment can clog gills and detrimentally affect fish and invertebrates. Following from this, Section 36 makes it illegal to release a deleterious substance into fish-bearing water (Table 4).

Table 4:

***Canada Fisheries Act* legislation relating to sediment in streams.**

Deleterious Substances
Section 34(1): For the purposes of sections 35 to 43, "deleterious substance" means

(a) any substance that, if added to any water, would degrade or alter or form part of a process of degradation or alteration of the quality of water so that it is rendered or is likely to be rendered deleterious to fish or fish habitat or to the use by man of fish that frequent that water, or

(b) any water that contains a substance in such quantity or concentration, or that has been so treated, processed or changed, by heat or other means, from a natural state that it would, if added to any other water, degrade or alter or form part of a process of degradation or alteration of the quality of that water so that it is rendered or is likely to be rendered deleterious to fish or fish habitat or to the use by man of fish that frequent that water, and without limiting the generality of the foregoing includes

(c) any substance or class of substances prescribed pursuant to paragraph (2) (a),

(d) any water that contains any substance or class of substances in a quantity or concentration that is equal to or in excess of a quantity or concentration prescribed in respect of that substance or class of substances pursuant to paragraph (2)(b), and

(e) any water that has been subjected to a treatment, process or change prescribed pursuant to paragraph (2)(c).

Destruction of Fish Habitat
Section 35(1): No person shall carry on any work or undertaking that results in the harmful alteration, disruption or destruction of fish habitat

Section 35(2): No person contravenes subsection (1) by causing the alteration, disruption or destruction of fish habitat by any means or under any conditions authorized by the Minister or under regulations made by the Governor in Council under this Act.

Pollution of Fish Habitat
Section 36(3): Subject to subsection 36(4), no person shall deposit or permit the deposit of a deleterious substance of any type in water frequented by fish or in any place under any conditions where the deleterious substance or any other deleterious substance that results from the deposit of the deleterious substance may enter any such water.

Section 36(4): No person contravenes subsection 36(3) by depositing or permitting the deposit in any water or place of

a) waste or pollutant of a type, in a quantity and under conditions authorized by regulations applicable to that water or place made by the Governor in Council under any *Act* or other that this *Act*; or

a deleterious substance of a class, in a quantity or concentration and under conditions authorized by or pursuant to regulations applicable to that water or place or to any work or undertaking or class thereof, made by the Governor in Council under subsection 36(5).

The release of fine sediment into fish-bearing water constitutes an act of pollution. However, it can also cause what has been termed a HADD (harmful alteration, disruption or destruction) of fish habitat (Section 35, Table 4). This has been described by the Department of Fisheries and Oceans as "...any change in fish habitat that reduces its capacity to support one or more life processes of fish." Following from this definition, there is an assumption that the capacity to support life processes is linked to the capacity of the habitat to produce fish. While the *Fisheries Act* deals with fish habitat *per se*, the No-Net-Loss or Net-Gain principles of Fisheries and Oceans Canada Habitat Policy connects fish habitat and productive capacity, which is specifically related to the production of fish.

The input of fine sediments into a stream may suffocate salmon or steelhead redds which contain incubating embryos or alevins, smother algae which is important food for insects, or inundate overwintering juvenile habitat, thus causing a loss in the productive capacity of a stream. These are examples of a HADD. It may also occur as a result of physically changing the structure of a stream through the direct rearrangement or removal of sediments, thus altering or destroying fish habitat. An example of a direct, or footprint, impact would be the extraction of gravel from a salmon or steelhead spawning bed, or the dredging of a riffle used as rearing habitat by young fish.

Continuing from this, it is our view that a HADD may also take place not only as a result of the footprint impact, but also when the sediment processes, which form, create and maintain salmon and steelhead habitat, are disrupted. This means that a human activity may not directly impact on fish habitat during the time of the activity or at the location of the footprint disturbance, but may have consequences that harmfully alter, disrupt or destroy fish habitat later or in some other area of the stream.

An example of this would be the removal of gravel from the top of a dry bar. Even though the sediments might be taken from above the wetted perimeter of the spawning bed and may not directly affect gravel where embryos and alevins would then be incubating, the effect would still trigger a HADD. This is because the sediment removal eliminates the opportunity for that bar-top material to recruit downstream and reform into other spawning beds. Likewise, removing gravel from the top of a dry bar during the summer may impact on the capability of that bar to perform as juvenile rearing habitat during the next spring when high water run-off would inundate the area.

In most cases, the hardening of stream-banks for erosion protection (i.e., rip rap placement), will also result in a HADD because of its nearly universal propensity to disrupt the natural erosion and deposition of sediments. Because spawning and rearing gravel and cobbles can be stored in the stream banks, and are naturally and slowly released into the alluvial environments as a result of erosion, hardening of the banks can starve the stream of sediments. Hardening of the banks can also reconfigure the depth and slope profiles of the water, changing the abundance and distribution of micro- and macro-habitats (e.g., pools, riffles) due to new erosion patterns. This is a serious concern on the lower Fraser River where about half of the banks from Agassiz to Sumas, the highly valuable pink salmon spawning reach, have been hardened for protection from erosion by rip-rap placement (McLean 1990).

In summary, if an activity affecting sediment processes triggers a HADD, and habitat could be destroyed in a manner that could not be mitigated, an authorization is required under Section 35(2) of the *Canada Fisheries Act* (Table 4). If an authorization is required, then the *Canadian Environmental Assessment Act* (CEAA) applies and compensation may be necessary (Department of Fisheries and Oceans 1998).

6.3 *CANADA ENVIRONMENTAL ASSESSMENT ACT*

The *Canadian Environment Assessment Act* is designed to ensure that thorough assessments are undertaken for projects that may affect the environment and fisheries habitat. Losses of habitat that cannot be mitigated, from either small or large projects, are covered under this *Act*. Projects requiring federal approval or authorization, occurring on federal land, receiving federal funding, or proposed by a federal department or agency are considered by the *CEAA*. Screening identifies the projects that require the full-scale review, and small issues are dealt with through an authorization to harmfully alter, disrupt or destroy habitat process, subject to compensation. Fisheries and Oceans Canada is now starting to consider sediment mining from streams under the aegis of Section 35(2) of the *Fisheries Act* and the *CEAA*.

6.4 *CANADA NAVIGABLE WATERS PROTECTION ACT*

This *Act* is federal legislation respecting the protection of navigable waters. It authorizes the development of "works" in navigable waters, such as bridges, booms, dams, piers, etceteras, as well as the dumping of fill or excavation of materials from the bed of a navigable water. The development of these works can impact on fish habitat and sediment processes.

6.5 *BC FISH PROTECTION ACT*

The *Fish Protection Act* is one component of British Columbia's Fisheries Strategy, and it was passed in July of 1997. This legislation is meant to deal with a variety of issues, including directives on streamside protection, designation of sensitive streams for fish sustainability and stream-flow protection licences. However, the section relating to no-new-dams across a number of listed rivers was the only part of this legislation to come into effect immediately. From a sediment perspective, restricting dams on streams provides the opportunity to maintain their sediment movements.

The remainder of the *Act* was to be implemented through the development of regulations, policies and procedures in a series of phases. The Streamside Protection Policy Directives are part of this legislative initiative and are currently being developed. Once implemented, these Directives should provide the opportunity to ensure that effects of development on natural sediment processes are minimized by providing set-back buffer zones between the stream and the development of adjacent land.

6.6 *FOREST PRACTICES CODE OF BRITISH COLUMBIA ACT*

In June 1995, the *Forest Practices Code of British Columbia Act* was proclaimed as law. The *Code* is the delivery component of the *Act*, and it consists of enabling legislation, regulations and guidebooks that govern forest planning, harvesting and silviculture on crown lands. These documents include the Riparian Management Area Guidebook, Watershed Assessment Procedures, and Terrain Stability and Gully Stability Assessment Procedures. The *Code* does not apply to private lands.

Provisions provide the opportunity to help protect stream-sediment processes. They involve: (1) discretionary and mandatory Riparian Management Areas around fish bearing streams, lakes and wetlands, including the riparian Reserve Zone and Riparian Management Zones; (2) discretionary limits to the size of harvested areas and the rate at which wood can be harvested, including green-up and silviculture regulations; and (3) regulations on road building to help reduce slope disturbances, limit the effects on the hydrology, and protect streams and wetlands.

6.7 *BC WATER ACT*

The *British Columbia Water Act* is the single most influential piece of legislation affecting fish habitat in this province. With the exception of forest harvesting, it regulates most of the activities in and about a stream that have the potential for impacting on sediment processes.

The provincial Crown owns all water at any time in any stream, except where private rights have been established in licences issued, or approvals given, under the *Water Act*. Specific to sediment processes in streams, the *Water Act* provides certain authority. Firstly, it can authorize changes in and about a stream. This includes damming, modifications to the morphology (e.g., dredging, channelization, diking, protecting banks from erosion) and changes to the adjacent land and vegetation. Secondly, the *Water Act* can also authorize the diversion, extraction, use or storage of water. As noted earlier in this report, reducing water volumes and impounding stream discharges has the potential for disrupting natural sediment processes.

The primary authorizing document issued by the British Columbia Water Management Branch is a water licence. This can entitle its holder to divert and use beneficially an amount of water for the purpose and time stipulated on the licence, as well as store water, maintain the works associated with the use and alter or improve a stream or channel for any purpose. Works in and about a stream and temporary diversions of water may also be authorized through an order of the Comptroller of Water.

6.8 *BC ENVIRONMENTAL ASSESSMENT ACT*

The *British Columbia Environmental Assessment Act* (BCEAA) is legislation designed to assess environmental, economic, heritage, health and social effects of large development projects, including gravel mines. It addresses effects that relate to provincial government responsibility. Where other legislation covers impacts to the environment, this *Act* does not apply. For example, forestry impacts are normally covered under the *Forest Practices Code*. Smaller, non-threshold level projects can be reviewed under this *Act* at the discretion of the Minister of Environment, Lands and Parks through a Section 4 designation. There is also a harmonization agreement that can apply where the *CEAA* and *BCEAA* overlap.

6.9 *BC MINES ACT*

The *BC Mines Act* regulates the methodology and operational components of aggregate extraction. This *Act* defines a mine as "...a place where a mechanical disturbance of the ground or any excavation is made to explore or produce....rock, limestone, earth, clay, sand or gravel." The permitting of gravel removal from a mine is undertaken by the Chief Inspector of Mines. Conflicts over gravel extraction have arisen when mining has been approved by the BC Ministry of Energy and Mines for an alluvial site, but has not been given approval by Fisheries and Oceans Canada.

6.10 *BC LAND ACT* AND *LAND TITLE ACT*

These *Acts* regulate how Crown land is managed and/or dispersed from the Crown, and how it may be subdivided once it becomes fee simple. On Crown land, aggregate material extraction is subject to the *Land Act* and managed by the British Columbia Assets and Land Corporation which will license and lease land for the development of aggregate resources, but will not sell it for this purpose. That is, Crown land is not to be disposed of if the Minister believes it to be suitable for sand and gravel mining. Of note, extracted river gravel from Crown land is subject to royalties. Aggregate is not considered to be a mineral under the *Mineral Tenure Act* and, therefore, it belongs to private owners when taken from private land. However, if that private land is within the normally wetted perimeter of a river, the *Water Act* and *Fisheries Act* still apply.

In order to protect riparian areas, the Crown can place restrictions on the use of land being disposed of for fee simple. Under the *Land Title Act*, the Minister of Environment, Lands and Parks can designate flood plain areas for the purpose of minimizing potential damage that might be caused by flooding should a party want to subdivide a parcel of land. That is, the provincial government can refuse to allow an area near a river that contains fish habitat to be developed if water normally inundates it.

The *Land Title Act* can also provide for the registration of a covenant when a property is being subdivided for the purposes of protecting an "amenity." An amenity can include riparian attributes having value as fish habitat.

6.11 *BC MUNICIPAL ACT*

6.11.1 Aggregate Extraction

The *Municipal Act* is a statute that provides the authority for municipalities to create legislation with regards to land use within their areas of jurisdiction. Aggregate extraction is not considered by law to be a land use and is, therefore, not directly subject to local government land-use zoning under the *Municipal Act*. To complicate matters further, the BC Ministry of Energy and Mines can authorize sediment extraction under the *Mines Act*, even though the fisheries regulatory agencies may object or a municipality may zone land for other purposes. Nevertheless, zoning requirements can be used by municipalities to manage aspects of aggregate production, such as processing and trucking. Municipalities can affect aggregate operations on private lands through soil removal bylaws.

6.11.2 Development of Property

Intensive development of property within a watershed creates the likelihood that sediment processes of streams within the area will be affected, thus impacting fish habitat. The primary methods of ensuring that sensitive habitats are not disrupted involve requirements that development not occur where they would influence sediment.

The *Municipal Act* is a primary statutory vehicle allowing development to be controlled in an orderly way through local legislation. These local laws must integrate with federal and provincial legislation. Rosenau and Angelo (1999) discuss more completely the following tools within the *Municipal Act* that influence how sediment is managed in and about a stream with respect to development:

- Official Community Plan (OCP) — This is a broad-brush tool determining where and how development will occur in a community.

- Development Approval Information — Sections 879.1 and 920.1 — Local governments have the ability under these sections to require impact assessments for land use and development proposals.

- Environmentally Sensitive Areas (ESAs) — This can restrict development in areas that are important for fish habitat.

- Development Permits — These can be used to provide special requirements that apply to development or redevelopment, including the protection of the natural environment, its ecosystems, and biological diversity.

- Zoning — Bylaws regulate how land can be used, density of use, parcel size, siting of buildings, and structures and uses on a parcel (see Sections 903, 904 of the *Municipal Act*).

- Soil Removal Bylaws — The *Municipal Act* permits local governments to regulate how fill will be removed or placed, and this has implications for habitat if this activity is to take place near a fish sensitive zone.

- Stream and Riparian Protection and Management Bylaws — Fish protection regulations and requirements can be placed into a single bylaw to: prohibit pollution (Section 551); enable tree protection (Sections 708 to 715); regulate soil, sand and gravel deposit and removal (Section 723); manage runoff control (Section 907); require vegetation planting and maintenance (Section 909); and provide flood plain construction requirements (Section 910).

- Stormwater Management — The impacts of land development on natural hydrographs and stormwater drainage systems can significantly affect sediment processes, and the *Municipal Act* empowers local governments to manage stormwater.

7. Case Study: The Management of Sediments in the Lower Fraser River for Flood Control, Navigation and Aggregate

7.1 THE LOWER FRASER RIVER SETTING

Most people in this province are aware that the Fraser River has had a huge role in shaping the social, geographic and biological diversity of today's British Columbia. Few, however, actually appreciate the extent or the richness and complexity of the river itself, particularly with regards to fisheries resources.

Much of the character of the Fraser River is related to the volume of its water flows. The average annual discharge of the Fraser River is about 3,400 cubic metres per second, and it has a mean annual spring flood of almost 10,000 cubic metres per second (Fig. 7). The largest flood in recorded history was in 1894 and was estimated to reach 17,000 cubic metres per second. The Fraser River drains about 230,000 square kilometres of the province, and this accounts for the yield of such a large volume of water. The greatest mass of the water is released during late-spring/early-summer (Fig. 7) because of the high-elevation source of much of the run-off.

The enormous power of the Fraser River is a function of the large yield of water, and this volume allows the river to move vast amounts of sediment. These sediments are the particles from the landscape that has eroded over the millennia and range in size from the smallest diameter clays to boulders. While most of the materials that are carried by the river are glacial till, glaciolacustrine silt and silty-debris-flow deposits, a much smaller volume comprises the sand and gravel that ends up being predominantly deposited downstream of Hope (Ashmore and Church 1998) (also compare Tables 5 & 6, Figs. 8 & 9).

The total sediment supply of the Fraser River can be divided into two primary components: suspended load and bed load. The suspended load is comprised of fine sediments held in the water column. A large fraction of the suspended load includes the wash load, made up of the very finest of materials that do not settle, but end up in the Strait of Georgia.

Table 5:

Composition of total sediment load, Fraser River at Mission, 1966 - 1986. Adapted from Ferguson 1991.

Sediment Type	***Percent Composition***
Clay	15.5
Silt	47.7
Fine Sand <0.177	18.8
Sand >0.177 mm	17.9

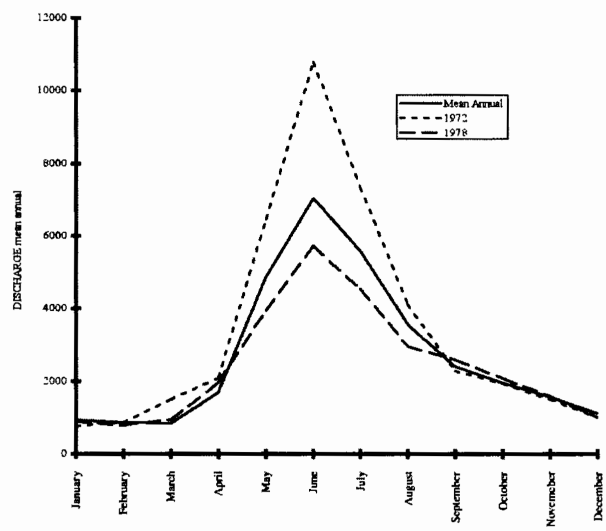


Figure 7:

Mean monthly hydrograph of the Fraser River for high (1972), low (1978) and mean annual discharge years at Hope. Data from the Water Survey of Canada (1989).

Table 6:

Estimated range of sand inflows and removal limits for the lower Fraser River. Data from NHC (1999).

Inflow Magnitude	*Total Load of Sediments of all Sizes (weight in millions of tonnes)*	*Bed Load >0.177 mm (weight in millions of tonnes)*	*Bed Load >0.177 mm (volume in millions of cubic metres)*	*Removal Limit 0.7 x Bed Load (volume in millions of cubic metres)*
Average Fraser River inflow	16.10	2.81	1.76	1.23
High Inflow (1972)	30.95	8.86	5.37	3.88
Low Inflow (1978)	12.30	1.19	0.75	0.52

To estimate sediment volume, divide sediment weight by 1.6.

Bed load makes up the second component of the total supply of sediment material. Because it is heavy, it remains in contact with the bed of the river, and includes materials that roll and bounce along the bottom. Bed load is normally made up of particles that are sand-sized or greater in diameter. Bed-load material in the Fraser River predominantly moves downstream for a period of several weeks between late May and late July in most years when the flow is above 4,000 m^3/s (Ashmore and Church 1998). At any given time, some of the finest materials in the bed load may be incorporated into the suspended load while some of the largest suspended materials may end up dropping into the bed load through saltation. For most rivers, the bed-load material does not travel a great distance compared to the wash load, and the Fraser River is consistent with this observation.

One of the most physically and biologically diverse parts of the river is at the Canyon near Hope, 160 kilometres from the ocean (Fig. 6), where it encounters a transition zone in its structure. Here, the more-or-less straight-running, bedrock-controlled stream opens into a valley and becomes a meandering cobble/gravel-bedded river downstream to its confluence with the Sumas River, a distance of about 70 kilometres. From here, the gradient of the Fraser River undertakes a sharp change and flattens out, and sand becomes the predominant bed feature. At the river's terminus, at the downstream end of the sand reach, the channel breaks up into a number streams that

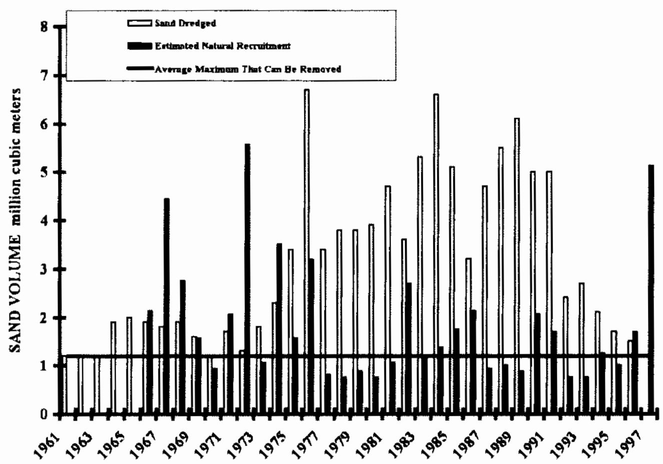


Figure 8:

Sand budgets and dredging for navigation and borrow in the lower Fraser River. Sand-particle sizes only include diameters greater than 0.177 mm, and all data and estimates are from Northwest Hydraulic Consultants (1999). "Sand Dredged" refers to amount moved for both channel maintenance and borrow dredging. Not all of the channel maintenance material always physically left the wetted perimeter of the river. "Estimated Natural Recruitment" refers to modeled weight of sand fraction (>0.177 mm) that is transported past Mission. "Average Maximum That Can Be Removed" refers to calculations of volume that can be taken from the river downstream of Mission without stream-bed degradation.

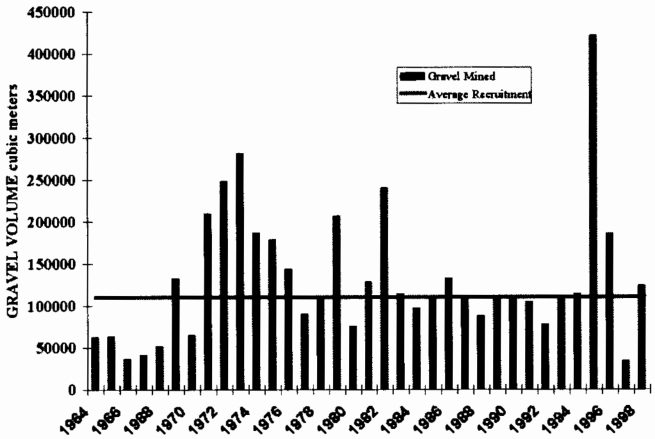


Figure 9:

Volumes of gravel removed from the Fraser River between Hope and Mission, British Columbia, 1964–1998. From Weatherly and Church (1999).

comprise part of the estuary. The Lower Fraser River estuary includes the North Arm, Middle Arm and Main Arm (Fig. 5).

Gradient and valley width become highly defining features in the character of the Fraser River downstream of Hope. To a great degree, they control the size-distribution of the sediments comprising the stream-bed. The slope of the river at Agassiz (the mid-point of the gravel reach) is 0.0005 while at Mission (just downstream of Sumas and in the sand reach) the slope is 0.00005, or one order of magnitude less than the former (Church et al. 1990). As discussed in Chapter 4, the $\text{DIAMETER}_{\text{SEDIMENT}}$ that can be moved by a stream is proportional to the $\text{DEPTH}_{\text{WATER}}$ multiplied by the $\text{SLOPE}_{\text{WATER}}$. Downstream of Hope, these variables define the gravel- and sand-bed reaches of this part of the stream. While the channel widths are somewhat similar at Agassiz and Mission, the severe reduction in slope as the river approaches Mission causes the coarser sediments to drop out onto the river bed before reaching the confluence of the Sumas River, leaving only sand at the latter location. Thus, in the Fraser River, the gravel and sand reaches are physically two very different streams. Distinct and rich ecosystems have taken up residence in each of them.

Subsequent to the extensive growth of human communities along the perimeter of the Fraser River, both the sand and gravel reaches have been dredged, mined, entrained and diked for transportation, industry, construction and flood protection. Because of the magnitude of these activities, they have the potential to radically disrupt aquatic ecosystems and reduce fishery values. While much is still not understood about the site-specific effects on fish ecosystems in the Fraser River, there can be little doubt that impacts have occurred over time and most, if not all, have been negative.

Part of the problem is that the Fraser River is a large and fast flowing waterway and, until recently, few people have had the resources to study it adequately. Because the quality and quantity of fish habitat is strongly related to sediment size and abundance, and because the fish ecosystems are quite different between the sand and gravel reaches for the lower Fraser River, we will discuss the issues surrounding sediment management for each reach separately.

7.2 THE GRAVEL REACH

7.2.1 The Sediment Resource

Downstream of Hope at Laidlaw, the Fraser Valley opens up and the gravel-bedded part of the Fraser River starts to meander (Fig. 6). Unlike upstream canyon areas, the channel shape now includes numerous side channels and islands. Over long periods of time, these channels shift from one spot to another, are lost to erosion or sediment deposition, and then are created again in time at a nearby location. The amount of gravel stored in the floodplain of the river is very large and volumes of 750,000 to one million cubic metres of material can be moved every year, albeit over very short distances (McLean and Mannerstrom 1984). Because much of this stored material is exposed as dry gravel bars during low-water periods in the winter, people have been given the false impression that there are almost unlimited amounts of aggregate material for the taking. At Agassiz, some 35 kilometres downstream of Hope, the total amount of material moving through the Fraser River is about 18.4 million tonnes per year. About 99% of the sediment moving downstream is suspended in the water column as wash load (small sand, silt and clay), with the remainder rolling along the bottom as bed-load material. The latter are primarily large grains of sand, gravel, and cobbles.

The sediments found within the floodplain in the gravel reach are mostly comprised of ancient materials derived from marine deposition and remains from the retreat of glaciers, as well as recruitment of alluvial material over hundreds and thousands of years. While the bulk of the gravel seen in the river bottom is very old, some new material is brought into this reach every year. It is thought that this "new" gravel, over and above the glacial or marine-derived deposits that currently exist in the floodplain, is recruited from the local tributaries from Hope downstream, as well as some sediments that pass through the Fraser Canyon. The amount of "new" bed material appears to be small, and comprises only about 176,000 tonnes (or 110,000 cubic metres: assume that 1.6 tonnes equals one cubic metre of sediment) moving past Agassiz each year (Church and McLean 1994).

Eventually all of the larger diameter sediments, such as gravel and cobbles which are traveling downstream, deposit in the floodplain somewhere above the Sumas River confluence. For example, the movement of gravel in the Fraser River past the confluence of the Harrison River, 15 kilometres from Agassiz, is only in the order of 100,000 tonnes (or 62,500 cubic metres) per year (McLean 1990). The reason why the Fraser River transport of bedload sediment past the Harrison River is less than the transport of bedload sediment at Agassiz is that the difference, or 76,000 tonnes (47,500 cubic metres) of material amount, drops out onto the river bed between these two points. That is, the alluvial floodplain between Agassiz and the Harrison River is also a zone of net deposition. It is important to note that the Harrison River contributes no sediment to speak of because large lakes in this watershed trap the material.

Although the part of the gravel reach between Agassiz and the Harrison River confluence is a zone of deposition, the increase in bed elevation must be very slow, assuming the amount of recruitment of new gravel that has been estimated in McLean (1990) and Church and McLean (1994) are correct. For example, the average stream width of the Fraser River between Agassiz and the Harrison River confluence is roughly two kilometres over this distance. Multiplying this by the river distance of 15 kilometres between these two points gives rise to a total surface area of 30 square kilometres, or 30 million square metres. The average rise of the river channel per year spread evenly over this distance, for an annual rate of deposition of 47,500 cubic metres is 1.58 mm. This means that the stream bed of the Fraser River between Agassiz and the Harrison River will rise a total of 16 cm or 6.3 inches over 100 years. These metrics have implications from a diking and flood-protection viewpoint and the rate of recruitment must be put into perspective relative to cost and environmental values.

7.2.2 FISH-HABITAT VALUES OF THE GRAVEL REACH

The gravel reach of the lower Fraser River is a biologically productive and diverse part of the landscape and is an extraordinarily rich habitat for fish. Indeed, the section of river from Hope to the Sumas River confluence probably holds the greatest variety of fish of any freshwater ecosystem in British Columbia. It comprises at least 28 different species (Table 7). About ten of those are from the salmonid family and, along with the remainder, make this a veritable Serengeti of the freshwater-fish world. While some of these species, like sockeye salmon (***Oncorhynchus nerka***), use the mainstream Fraser River primarily as a migration pathway between feeding or spawning areas, the majority of those listed in Table 7 use the stream, including its seasonally watered side channels, for spawning and/or rearing. The species using the gravel reach for spawning include chum and pink salmon, and juvenile chinook salmon rear here in large numbers.

In-stream habitats for fish, including salmon and steelhead, are largely defined by water depths and velocities and by substrates. There are broad ranges for these parameters and exceptional habitat diversities in the gravel reach of the Fraser River. These are functions of: (1) the change in the gradient of the stream by an order of magnitude between Hope and the confluence with the Sumas River; (2) the width of the Fraser Valley which allows the stream to spread out; (3) the considerable variability and abundance of parent substrate materials in the alluvial floodplain; and (4) the river's large yearly-discharge volume.

Habitat richness in the gravel reach of the Fraser River is also due to the fact that it is a relatively stable stream, both from a structural perspective and in terms of flow. For example, the bedload movement in this part of the river is fairly modest considering the absolute magnitude of the discharges. Furthermore, the ratio of the smallest to largest flows throughout a year is moderate and the maximum is normally only about ten times the minimum (Fig. 7). This is not great compared to some of British Columbia's smaller coastal salmon and steelhead streams which can have a range that is three orders of magnitude in difference. Water temperatures are also buffered because of the enormous volume of water that flows down this stream. Thus, because there is such a wide choice of niches, many species can be found in this part of the river.

Table 7:

List of fish species known, or thought, to occur in the gravel reach of the Fraser River from Hope to Mission.

Common Name	Scientific Name	Rearing	Spawning	Migratory	Native or Introduced	Common or Rare
sockeye salmon	Oncorhynchus nerka	yes (limited)	no	yes	native	common
chinook salmon	Oncorhynchus tshawytscha	yes (extensive)	no	yes	native	common
chum salmon	Oncorhynchus keta	yes (transistory)	yes, mostly in side channels	yes	native	common
coho salmon	Oncorhynchus kisutch	yes (limited)	no	yes	native	common
pink salmon	Oncorhynchus gorbuscha	no	yes (extensive)	yes	native	common
steelhead trout	Oncorhynchus mykiss	yes (limited)	no	yes	native	common
cutthroat trout	Oncorhynchus clarki	yes	yes (limited)	yes	native	common
bull char	Salvelinus confluentus	yes	not likely	yes	native	moderately common
Dolly Varden char	Salvelinus malma	yes?	not likely?	yes?	native	unknown
Rocky Mountain whitefish	Prosopium williamsoni	yes	unknown	yes?	native	common
eulachon	Thaleichthys pacificus	no	yes	yes	native	common
largescale sucker	Catostomus macrocheilus	yes	unknown	unknown	native	common
mountain sucker	Catostomus playrhynchus	yes	unknown	unknown	native	moderately common
bridgelip sucker	Catostomus columbianus	yes	unknown	unknown	native	moderately common
northern squawfish	Ptychocheilus oregonensis	yes	unknown	unknown	native	common
peamouth chub	Mylocheilus caurinus	yes	unknown	unknown	native	common
redside shiner	Richardsonius balteatus	yes	unknown	unknown	native	common
leopard dace	Rhynichthys falcatus	yes	unknown	unknown	native	moderately common
longnose dace	Rhinichthys cataractae	yes	unknown	unknown but likely	native	common
prickly sculpin	Cottus asper	yes	likely	likely	native	common
coastrange sculpin	Cottus aleuticus	yes	likely	likely	native	common
three-spine stickleback	Gasterosteus aculeatus	yes	likely	yes	native	common
white sturgeon	Acipenser transmontanus	yes	yes	yes	native	common
carp	Carpio cyprinus	yes	unknown	unknown	introduced	rare
brown bullhead	Ameiurus nebulosus	yes	unknown	unknown	introduced	rare
black crappie	nigromaculatus	yes	unknown	unknown	introduced	rare
river lamprey	Lampetra ayresi	unknown	unknown	yes	native	rarely caught
Pacific lamprey	Entosphenus tridentatus	unknown	unknown	yes	native	rarely caught

Despite the social importance of many of the species in the gravel reach, our knowledge of their habitat requirements is very limited. Around the world, large rivers have not been studied extensively, compared to small streams and lakes. This is because the former are more difficult to sample (Johnson et al. 1995), and there is no theoretical basis for how large river ecosystems operate (Davies and Walker 1986). The lower Fraser River has been no exception. Indeed, it was only in 1998 that fertilized white sturgeon (*Acipenser transmontanus*) eggs were first discovered and spawning habitat was identified. Likewise, in the same year, mountain suckers (*Catostomus platyrhynchus*) were discovered in the gravel reach of this river.

A species about which some knowledge has been gathered over the years with regards to habitat utilization is the pink salmon. One of the more remarkable fisheries phenomena is the pink salmon run that spawns in the mainstem of the gravel reach of the Fraser River during odd-numbered years. It is nothing short of amazing to visit the banks of this river at Agassiz or Chilliwack during the autumn to watch the hundreds and thousands of fish leaping from the water simultaneously for weeks on end as they go through their spawning rituals. Currently, this is one of the largest spawning escapements of any salmon species or stocks in the province and has exceeded five million fish in recent years (Fig. 10). Without question, the extensive beds of fine, loose, gravel make this area one of the largest natural spawning channels for pink salmon. Furthermore, the relatively stable flows that occur in the Fraser River during the fall-to-spring incubation period (Fig. 7) provide for high survival rates during the pink salmon development from embryos to alevins to fry. Unlike some other species, these small pink salmon head immediately to sea after leaving the spawning redds, hardly stopping even at the food-rich estuary in the lower river.

Another species of interest that spawns in the Fraser River between Sumas and Hope is the chum salmon (*Oncorhynchus keta*) (Fig. 11). While pink salmon tend to dig their redds along the gravel-rich bars and deep-water areas of the mainstem river, chum salmon spawn predominantly in the downstream ends of blind, groundwater fed side channels. These side-streams are isolated from the main flows, but remain wetted in their lower areas during the spawning and incubation periods due to sub-surface groundwater recharge. While these two species of salmon segregate their spawning areas by using different habitats (mainstem versus side channels), they both rely extensively on the abundant resources of gravel and water that the Fraser River has to offer. However, because Fraser River

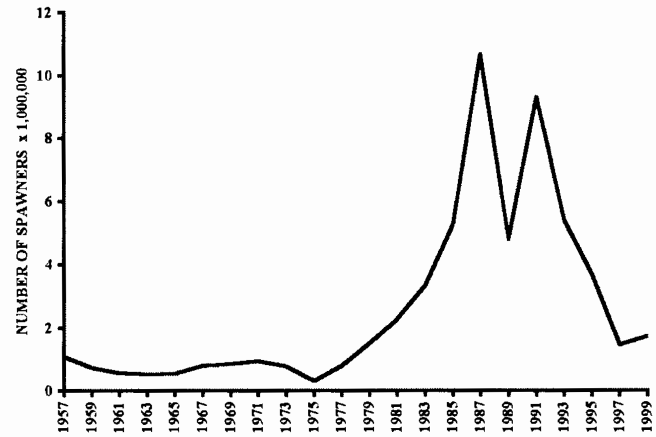


Figure 10:

Pink salmon spawning escapements to the mainstem Fraser River between Sumas and Hope, 1960-1999. Source is Farwell et al. (1987) and N. Schubert, Fisheries and Oceans Canada, pers. comm.

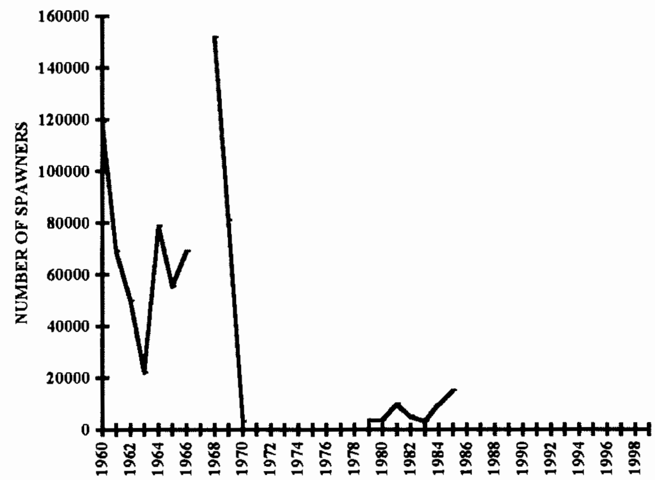


Figure 11:

Chum salmon spawning escapements to the mainstem Fraser River between Sumas and Hope, 1957-1999. Source is Farwell et al. (1987) and N. Schubert, Fisheries and Oceans Canada, pers. comm.

chum use groundwater, the cross-sectional shape of the side-channel is absolutely critical in ensuring that the specific required conditions for sub-surface flows. Disruption of the configuration of these side channels can have, and has had, seriously negative effects on the incubation of chum embryos. It should also be noted that, like pink salmon, chum fry do not use the gravel reach of the Fraser River for any protracted rearing. Chum fry do, however, extensively use the estuarine part of the downstream sand reach for rearing before migrating to sea, and this habitat will be covered in a subsequent section of this report.

One species that uses the gravel reach of the Fraser River for rearing is the chinook salmon and the young fish rear extensively in this part of the stream throughout the whole year. These young fry are not the progeny of adults that have spawned in the mainstem Fraser River, but are offspring of some of the many different chinook salmon populations that reproduce in the various tributaries of this watershed. Healy (1991) suggested that chinook salmon fry often use a life-history strategy where they will move in a protracted and downstream direction after emerging from the gravel, utilizing the mainstem rivers before going to sea. This is consistent with the observation that chinook juveniles in the lower Fraser River routinely use non-natal habitats for rearing prior to smolting (Murray and Rosenau 1989).

While these young chinook fry may be quite opportunistic when choosing the geographic location for their freshwater rearing, they clearly discriminate the kinds of micro-habitats that they use in the gravel reach of the Fraser River. For example, current studies indicate that chinook fry preferentially select micro-habitats with large substrates, including gravel and cobbles, compared to other areas of the stream bed which are comprised primarily of the smaller diameter sediments (Fig. 12). It is hypothesized that these small fish are choosing this kind of habitat because coarse substrates convey survival benefits to stream-rearing salmon compared to habitats with substrates comprised of finer materials (Heggenes 1988).

It is also important to note that while these chinook fry in the lower Fraser River are choosing habitats with distinct substrate criteria, other species are utilizing different micro-habitats, or niches, within the same areas. For example, recent research has shown that inter-species segregation occurs between juvenile chinook salmon and redside shiners (*Richardsonius balteatus*) in the gravel reach. The type of substrate that each prefers to associate

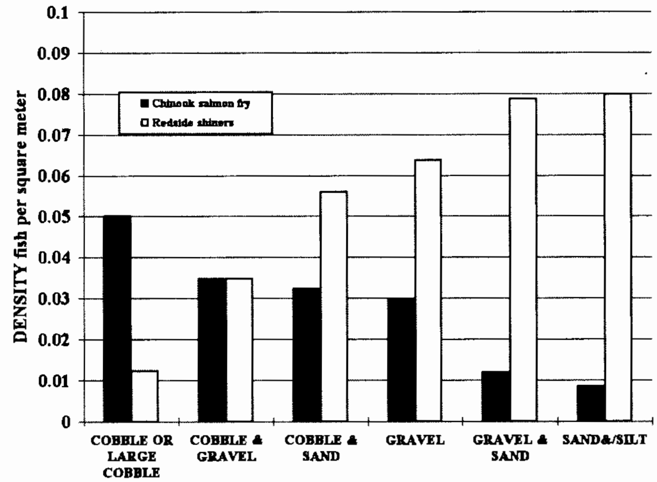


Figure 12:

Chinook salmon and redside shiner habitat utilization with respect to substrates. Unpublished data from L. Rempel (PhD thesis) and M. Rosenau.

with is very different; chinooks choose coarser sediments, while redside shiners prefer substrates comprised of sands and silts (Fig. 12). It is the theory that when species segregate macro-habitats, competition is reduced; consequently, a greater number of species with roughly similar, but still distinct, living requirements can all live within a macro-habitat area. From these observations, the conclusion that can be made is that disruptions or major changes in the grain-size distribution of sediments will ultimately affect the fish-species composition of the gravel reach.

This gravel reach of the Fraser River is also home to the largest freshwater fish in North America, the white sturgeon (*Acipenser transmontanus*). These large fish live in the lower Fraser River and are known to grow as large as 700 kilos and live for more than 100 years. Many of the juveniles and adults live and rear in both the main stream and the side channels for most or all of their lives. They do not migrate for more than a few kilometres during that time, as shown by tagging studies (Lane et al. 1994, RL&L 2000). Other Fraser River white sturgeon may travel over hundreds of kilometres and have extensive home ranges (Veinott et al. 2000).

Despite large gaps in our knowledge of this species, we are aware that the habitat requirements of white sturgeon throughout the year and over its life varies considerably in the gravel reach of the Fraser River (Lane et al. 1994, RL&L 2000). Of particular interest has been the search for an understanding of white sturgeon spawning habitat in this stream. From recent scientific investigations, white sturgeon in the gravel reach spawn near the peak flows of the spring runoff and on the decline of the hydrograph (RL&L 1996, RL&L 2000, Perrin et al. 1999, 2000a). Using radio-tagging and egg- and larval-sampling techniques, these studies have shown that, from Hope to the Sumas River confluence, large side channels constitute the primary spawning habitats for lower Fraser River white sturgeon, apparently preferring them to the main river (Perrin et al. 1999, 2000a). The substrate composition in the streambed of these channels where spawning takes place is predominantly gravel and cobble (Fig. 13).

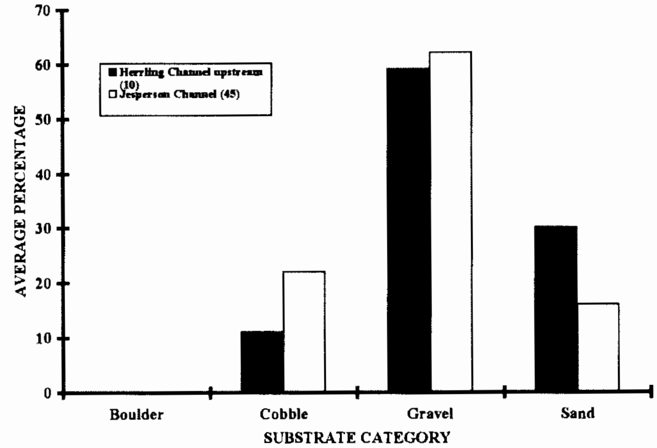


Figure 13:

Average percentages of particle sizes for sturgeon spawning substrates in the Fraser River side channels of the gravel reach where eggs or egg cases were found. Data from C.J. Perrin, personal communication.

In conclusion, we know relatively little about how the wide variety of fish species utilize the various habitats in the gravel reach of the Fraser River. Because of the number species in this area, they segregate into a multitude of different niches. These habitats are differentiated according to depth, velocities and substrates. It is clear, however, that that changes to the channel morphology and sediment particle-size distribution, by humans or otherwise, affect the quality and abundance of the in-stream fish habitat.

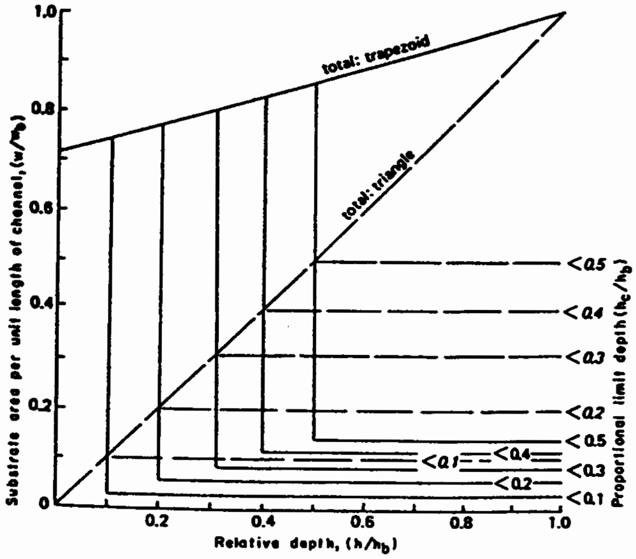
7.2.3 Navigation in the Gravel Reach

From the 1950s onward, the Fraser River between Mission and Hope has been used extensively by tugboat operators for log-boom towing to mills in the lower river. In recent years, over 300,000 cubic metres of wood from Harrison Lake, and over 150,000 cubic metres from Hope, have been towed by tugs down the Fraser River (Lauga & Associates 1994).

Until 1996, Public Works and Government Services Canada had been maintaining navigation channels by dredging in the gravel reach of the Fraser River where shallow spots and locations of difficult navigation were known to occur. This is because of the tendency of the river to continually shift its channels by filling in old ones and scouring new ones at certain locations. The rationale behind the dredging was to increase the draft, or depth of water, so that a vessel could reach an upstream point or pull logs downstream without being stranded. The forest industry is interested in reviving this practice.

For the most part, the maintenance of these navigational channels has been undertaken using a scuffle dredge. This means that the material blocking the navigational channel is simply pushed or "scuffled" out of the main part of the stream in order to deepen and widen the river. The material is normally dragged downstream from the shallow spots using a bucket or a large blade. That is, the material does not leave the streambed, but is scraped to the side and/or downstream in order to provide low-water navigation. Thus, the gravel is left within the alluvial floodplain and the shallow riffles are deepened.

Because the tugs and log-boom bundles have a draft of 2.1 metres, the design dredge grade is established at 1.8 metres below local low water levels. This is to ensure sufficient depth for the towing season which is outside of the months with the lowest stream discharge. Channel width and length is based on the log boom width and length, as well as the curvature of the river bends. Established dredge-area design parameters specify a dredge cut of up to 46 metres in the river bottom width along straight sections, and up to 70 metres in bends. The length of the dredge cut may vary up to a maximum of 200 metres (Public Works and Government Services Canada memo to Ministry of Environment, Lands and Parks, 1996). On average, 80,000-90,000 cubic metres of sediment were moved for these purposes (Public Works and Government Services Canada memo to Ministry of Environment, Lands and Parks, 1996), although Kellerhals et al. (1987) estimated between 54,000 and 82,000 cubic metres from 1979 to 1986.



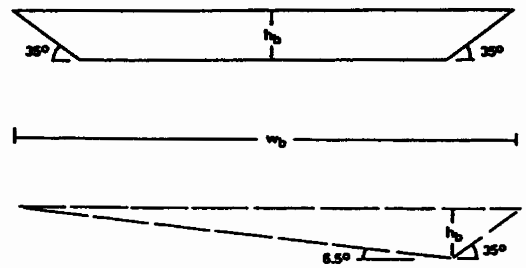


Figure 14:

Depth-area plots for ideal trapezoidal and scalene triangle sections (plots are non-dimensional). The triangular shape represents and un-mined channel bottom (bar) while the trapezoidal shape represents a mined stream bed. Taken from Kellerhals and Church (1989).

The impacts to fish and aquatic resources due of scuffle dredging have not been determined but, at face value, there are at least three direct impacts and one potential major collateral effect. Firstly, there is a significant change to the channel morphology, and this affects the distribution and abundance of depths and velocities in the stream. Kellerhals and Church (1989) discuss the depth and velocity variability of an idealized stream-cross section which corresponds to a dredged channel (trapezoid) versus an un-dredged section of stream that more closely represents a triangle (Fig. 14). The un-mined channel provides a much larger area of shallow water at any given time, except for the absolute lowest of flows, and a more varied range of depth and velocity at all flows. As was pointed out in the preceding section, depth and velocity are critical parameters in defining habitat quality and quantity in the Fraser River gravel reach. The un-mined areas provide greater opportunities for niche diversity, important factors in a stream that has 28 different species of fish that must be accommodated.

While no substantial assessments have been undertaken to determine which species are affected as a result of this navigational dredging, Laidlaw and Rosenau (1998) attempted to determine if white sturgeon spawning habitat was being disrupted. Using Public Works and Government Services Canada pre-dredging water depth, water velocity (Fig. 15) and substrate profiles collected at

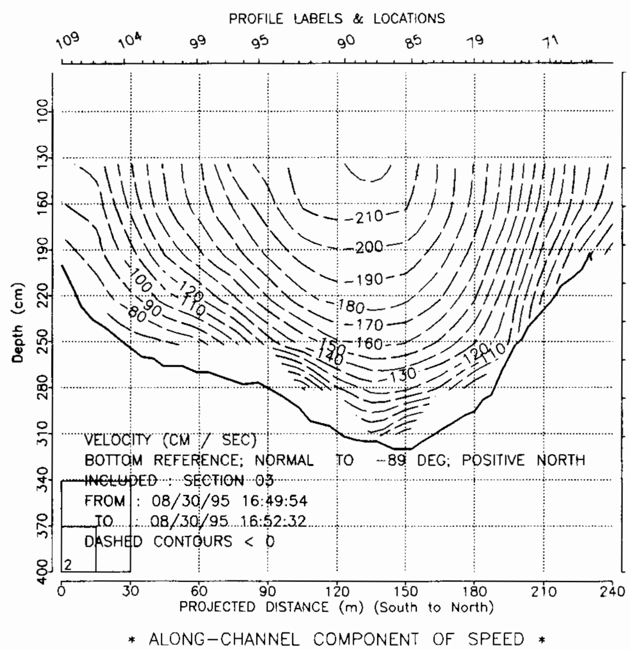


Figure 15:

Typical cross-section of Fraser River channel in the gravel reach, to be scuffle dredged, showing stream width, depth and velocity isovels. Public Works and Government Services Canada (1995).

scuffle-dredging sites, they compared the empirical physical data to published suitability-of-use curves for white sturgeon spawning from the Columbia River (Parsley and Beckman 1994). Their assessment of the dredging was that scuffle dredging may be disrupting white sturgeon spawning habitat. Recent work by Perrin et al. (1999, 2000a) indicates that the Fraser River sturgeon downstream of Hope prefer somewhat smaller substrates and spawn primarily in the large side channels along this river.

A second impact of navigational dredging is encouragement of water to flow down a single channel rather than multiple streams. That is, scuffle dredging generally causes the river to change from a multi-channeled structure to a narrower, single and deeper one (Kellerhals et al. 1987). If the passages are continually dredged, they increasingly constrain the river to a single stabilized channel. The result is that many of the productive side channels become isolated and/or dewatered. These changes in physical diversity are thought to impact on the diversity of fish habitat, including those areas where salmon spawn and rear in this part of the Fraser River.

The third effect of scuffle dredging is to disrupt the armouring layer in the thalweg (deepest part of the channel). This presumably encourages increased sediment movement over and above the actual physical removal of bed material. This has implications for entraining fine sediment into downstream habitat areas, as well as upstream and downstream degradation and destabilization of the stream channel. That is, breaking through the armouring layer that protects the stream from exacerbating erosion encourages further movement of material. Fish habitat is presumably changed to a degree, but the extent of it in the gravel reach of the Fraser River is not understood.

Based on the scientific literature reviewed in this report, scuffle dredging has the potential to cause upstream erosion, downstream incision, and aggradation and lateral erosion. Some of the sites are dredged repeatedly year after year, so the effects over time can be cumulative.

We feel that questions have to be asked with regards to the role of this activity in floodplain management and protection of salmon habitat. Virtually no analysis has been undertaken by the government agencies to understand the impacts of repeated dredging on the capacity of the channel to remain stable, aggrade or destabilize. Nor have there been any significant studies with regards to impacts to fish habitat. Still, fisheries and flood-protection agencies have continued issuing approvals.

7.2.4 Gravel Extraction

In recent years, there have been growing public controversy about gravel extraction in the reach of the Fraser River from Hope to the Sumas River. This seems to revolve around two primary issues. First, the aggregate industry has historically had easy access to the material. But, this access has been declining as the detrimental impacts of the mining on fish habitat have become apparent. The result is a growing conflict between industrial and conservation interests.

The second issue is about flooding. Because the channels of the river are shifting and the riverbed may be slowly rising at some locations due to long-term sediment accumulations, there is the perception that there will be an eventual over-topping of flood waters onto the developed flood plain due to a lack of dike freeboard. The removal of gravel and the lowering of the river bottom have been touted as ways of providing greater free-board for this part of the river.

Over 300,000 people live and work in the floodplain of the upper Fraser Valley. More than $2 billion in infrastructure assets are located behind 90 kilometres of dikes (Neil Peters, BC Water Management Branch, pers. comm.). A current computer-modeling exercise indicates significant shortfalls from the design criteria in the diking system at certain locations on both the Chilliwack and Agassiz sides of the river (UMA 2000). The cause of the apparent lack of freeboard is not clear, but it may be that the dike design in the 1960s did not have sufficient information to determine the appropriate stage-discharge elevation for the assumed 1-in-200-year flood volume.

An engineering solution that has been put forward for flood protection in the gravel reach is to reduce the amount of material within the channel by mining it. This would attempt to lower the elevation of the stream bottom to maintain or increase channel capacity. While sand and gravel removal may be technically easy to accomplish, there has been little consideration, so far, of what would happen to fish and other species or the long-term effect of destabilization of the alluvial sediments.

In order to protect the integrity of the aquatic ecosystem, it is important to understand the volumes of material that have been removed. Gravel mining from Crown land has been regulated by the provincial government to whom royalties are paid. As a result, there are fairly accurate records of prices and the amount of material extracted (Weatherly and Church 1999). Unfortunately, government agencies have not had the same level of accurate measurement of gravel extracted for their own use. The BC Ministry of Transportation and Highways, the province's largest user of gravel, has not kept good records of its extraction amounts (Weatherly and Church 1999). Gravel removal from private land encroaching into the Fraser River has also not been required to record its extraction volumes by the provincial government. The Department of Fisheries and Oceans began to require records of volumes in the early 1980s due to the concerns surrounding the potential impacts to fish habitat, so there is some recent information from that source. The University of British Columbia Geography Department has recently undertaken a comprehensive review of the gravel extraction inventory for the Lower Fraser River from Mission to Hope from 1964 to 1998 and it is from this report that much of the following information is derived (Weatherly and Church 1999).

About 4.6 million cubic metres of gravel were removed from within the yearly wetted floodplain of the reach of the Fraser River from Sumas River to Hope since 1964.

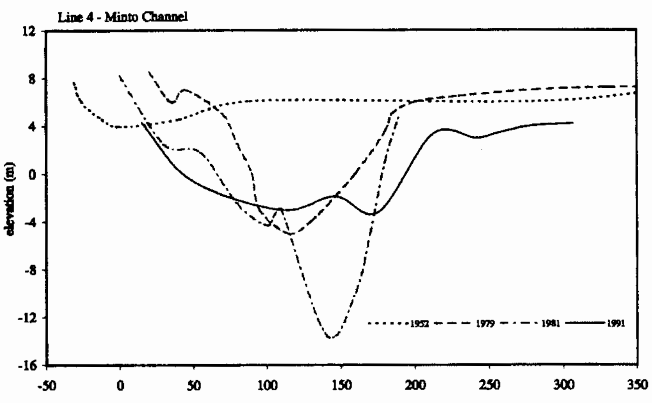


Figure 16:

Cross-sectional elevations of the downstream portion of Minto Channel bottom showing extreme example of degradation of the stream bed as a function of the gravel mining. Line 4 of Church and Weatherly (1998.)

This constitutes a mean value of about 130,000 cubic metres per year (Fig. 9). This amount has, on average, exceeded the published values for natural recruitment of gravel downstream of Agassiz of 110,000 cubic metres per annum (Church and McLean 1994). Within this area, Minto Channel, a large side-stream near Chilliwack, has been mined for over 50 years and 2.7 million cubic metres of material taken out alone from 1966 to 1998 (Church and Weatherly 1998).

While gravel does not naturally move through this reach of the Fraser River in a homogeneous fashion (i.e., spreading out in an even, well distributed layer), it has also not been evenly excavated from the river by the aggregate industry. Thus, sites where multiple removals have taken place over years have shown significant impacts with regards to changes to channel morphology. A documented example of these impacts is at Minto Channel. This channel is located adjacent to a physically and biologically rich complex of islands and channels near the mouth of the Harrison River. Minto Channel had already been seriously degraded by 1991, presumably as a result of the extensive gravel mining for over 40 years (Fig. 16). Currently, it appears that the downstream portion of the channel is deeper than it would naturally be and, therefore, has a larger conveyance capacity for water (Fig. 16). Fish species that found the pre-mining conditions in Minto Channel to be highly suitable as habitat are unlikely to find the existing depth, velocity and substrate conditions and physical diversity (Kellerhals and Church 1989; Fig. 14) to have the same level of suitability of use.

At a second, nearby site that had been mined as recently as 1995, there is also information showing the impacts of sediment extraction on the channel morphology. The gravel extraction-enterprise removed approximately 300,000 cubic metres of sediment at that date (Church and Weatherly 1998). At the time of the writing of this report five years later, the stream bed at the mining site had still not recruited the equivalent amount of material that was lost due to sediment extraction and, indeed, has lost material through erosion (Fig. 17). The conclusion is that gravel recruitment and channel reconfiguration in this reach of the river can be exceedingly slow.

Kellerhals et al. (1987) discussed the impacts of sediment removal from the gravel reach of the Fraser River and they concluded that gravel mining had the potential for significant effects to salmon habitat. Like other researchers, Kellerhals et al. (1987) suggested that the removal of these sediments, whether from in-stream excavation or from bars, reduced the diversity of river habitats and recommended that for the Fraser River gravel extraction volumes should not exceed 10-20% of the bedload. Kellerhals et al. (1987) suggest that removal of armour layers may also have detrimental effects and that excessive removal can have upstream and downstream effects. Interestingly, Fisheries and Oceans Canada had apparently instigated a long-term moratorium on gravel removal at the writing of the Kellerhals et al. (1987) report but, based on the information in Fig. 9 below, the moratorium was not particularly successful.

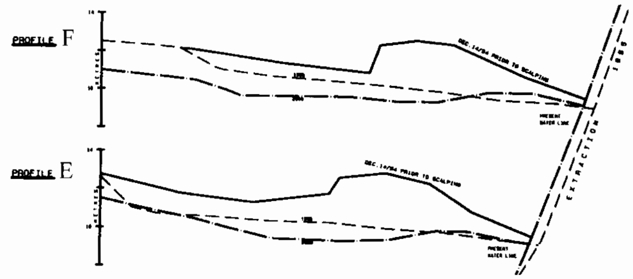


Figure 17:

Pre- and post-gravel extraction stream-bed elevations at Foster's Bar on the Fraser River, 1995 and 2000. From unpublished Ministry of Environment, Lands and Parks data, 2000, provided by Tunbridge and Tunbridge, BC Land Surveyors.

A recent study by Church et al. (2000) indicates that the streambed between Laidlaw and Sumas is degrading in elevation. The authors of the report suggest that more sand is being eroded from this reach than is being replaced by gravel. They speculate that the reason for the net erosion of sand is due to the diking and hardening of banks. By hardening the banks and narrowing the river, there is less opportunity for sediments to deposit and a greater propensity for the finer sediments to be washed out of the reach. Church et al. (2000) temper their statements by indicating that their analyses were not absolutely complete, but the trend appears to be real and is consistent with observations in other streams when channels have been narrowed.

7.2.5 Diking and Stream-bank Protection

Diking for flood protection and rip-rap placement for bank protection has been extensive since the 1948 flood. By the middle of the 1970s, the total length of rip-rap was 54 kilometres between Hope and Sumas and, as a result, nearly half the banklines have been protected (McLean 1990). There are 620 square kilometres of floodplain in the Fraser Valley. The area near Chilliwack has 90 kilometres of dike protecting much of its low-land district, and one-third of these dikes have erosion protection. Bank protection using large blasted bedrock typically costs $1-2 million per kilometre (Neil Peters, BC Water Management Branch, pers. comm.). Substantial hardening of the banks has occurred since the 1970s.

Diking in the upper Fraser Valley has caused enormous changes to sediment processes and aquatic ecosystems in the Fraser River by disrupting flow patterns through side channels. Table 8 lists most of the channels that have been isolated from the main channel at one or both ends. The total lineal distance of the side channels listed in Table 8 equals 103.5 kilometres. Because little or no water now enters these channels as a result of mainstem inputs, the water source is from groundwater, surface run-off and tributaries. The sediment sources for these channels are primarily from riparian, terrestrial and tributary locations and, for most of the channels, the size of the material is sand or finer. Aquatic and terrestrial vegetation has encroached in a significant way in most of these channels. The aquatic community that was formerly in the un-diked side channels has now changed. Aquatic ecosystems, which were adapted to the mostly turbid main-river waters have shifted to a more clear-water ecosystem (e.g. coho salmon), although some species of fish (e.g., redside shiners) seem to do well in either ecosystem. Any sturgeon spawning habitat that may have existed in these channels is no longer functional.

As indicated earlier, much of the sediment transport in the gravel-bedded river reach between Hope and the Sumas River is associated with the erosion of floodplain banks, as well as the buildup of gravel bars and new flood-plain surfaces (Kellerhals et al. 1987). Because much of the river's flood-plain bank has been hardened and protected from erosion by the placing of rip-rap rock, the sediment processes are no longer able to maintain the level of habitat quality and abundance in the gravel reach of the Fraser River. The hardening of the riverbanks, as a result of the capping of exposed surfaces, eliminates the recruitment of new sediments and causes local vertical scour and coarsening of stream-bed surfaces. Placing rip-rap on banks in the Fraser River and disrupting natural fluvial processes clearly cause the "harmful alteration, disruption or destruction" of fish habitat, as defined by Section 35 of the *Canada Fisheries Act*. The long-term hardening of the surfaces leads to a narrower, more stable

Table 8:

List side channels which have been isolated from one or both ends of the lower Fraser River due to diking. All of these water bodies are now referred to as sloughs. River kilometre follows Perrin et al. (2000a).

Slough Name	River Kilometre	River Bank	Lineal Distance kilometres
Bristol Island	156-154	left	1.1
Highway	153.5-152.5	right	0.9
Johnson		right	2.1
Maria	138-127	right	13.8
Ferry Island	122-120.5	left	2.1
Island 32	121	left	0.5
Cheam	122-119	right	4.7
Agassiz	116-115	right	6.8
Hope	122-103	left	21.5
Camp	120.5-111	left	10.3
Nelson	114-109	left	4.0
Gravel	111	left	1.0
Bell	110-108	left	4.3
Shefford	104-101	left	3.5
Coco-oppelo	101-100	left	1.0
Zaitscullachan	99	right	3.3
Quaamitch	95	right	2.0
Nicomen	105-86	right	20.8
			Total: 103.5

channel with a reduced bed load and further potential for reduced habitats for fish (Kellerhals et al. 1987). The rip-rapping of flood-plain river banks has possibly had the most destructive effect on fish habitat in the gravel reach of the Fraser River since the extensive cutting off of side channels in the early part of the 20th century.

7.2.6 The Fraser River Study

A number of levels of governments are responsible for flood protection in the gravel reach of the Fraser River, including the British Columbia Ministry of Environment, Lands and Parks and the District of Chilliwack.. Flooding has been of particular concern to residents living on the floodplain since the large floods of 1894 and 1948. A considerable amount of diking was undertaken since 1948 to protect properties that had been developed over time. In particular, a major flood protection program in the late 1960s developed the current dike-elevation profiles. Because of recent concerns that the riverbed elevation was increasing, due to sediment buildup in the floodplain between the dikes, and that there was a corresponding loss in freeboard, the Fraser River Study was established. The Study is being coordinated by the Fraser Basin Council, and is looking at these issues, as well as the biological impacts of various flood-protection scenarios.

One of the components includes an assessment to determine the 1-in-200-year flood stage-discharge elevations in the gravel reach of the Fraser River. This work indicated that significant portions of the dike were below adequate design grades (UMA 2000). Another study has shown that, while there has been aggradation at specific locations, the net change in the river from Laidlaw to Mission has been one of stream-bed degradation (Church et al. 2000). Finally, another study conducted by a University of British Columbia graduate student is determining the relationship between fish distribution and abundance, and their utilization of various habitats within the river.

It is not clear how the various levels of government will respond to the issue of dike freeboard deficiencies. However, the proposed gravel mining to increase the stream-conveyance capacity is still considered by some to be an option to raising dikes. This mining, if undertaken, would have potentially enormous ecosystem consequences to the Fraser River, depending on the volumes removed.

Table 9:

List of aquatic organisms entrained as a result of dredging action in the sand reach of the Lower Fraser River. Values rounded and expressed in thousands.

Species / Citation	1.	2.	3.	4.	5.	6.
crago shrimp	1,000	>0.1	1,000			
sandlance	216.9		77.5			
hagfish	21.8			0.1		
eulachon	6.5	69.2	6.7	0.9	186.5	0.9
chum fry	4.3	1.0	2.4	1.9		
starry flounder	2.7	4.3	1.8	3.7		
lamprey	2.5	24.7	5.6	10.8	0.1	0.4
spiny dogfish	1.3		0.5			
threespine stickleback	1.1	24.9	1.1	0.9	0.3	
sculpin	1.1		0.8	0.9	0.1	0.1
sand sole	0.9		0.2			
Pacific tomcod	0.4	>0.1	0.2			
crab	0.2					
toadfish	0.2					
butter sole	0.1		0.1			
lemon sole	0.1					
chinook fry	0.1	0.1				
Pacific prickleback	0.1		0.1			
pollack	0.1					
sockeye smolt	0.1		0.9			
shiner	0.1					
sturgeon poacher	0.1					
sturgeon	0.1	>0.1	0.3		0.1	
English sole	<0.1					
Dover sole	<0.1					
snailfish	<0.1					
sanddab	<0.1		0.1			
midshipman	<0.1					
crayfish	<0.1	0.2	0.1			
seal sucker	<0.1					
longfin smelt	<0.1		0.1			
whitebarred prickleback	<0.1					
squawfish		0.3				
tadpole		0.1		0.6		
peamouth chub		0.1				
rainbow trout		0.1				
coho fry		>0.1		0.6		
sockeye fry		>0.1				
shad		>0.1				
worms						3.3

Citation 1.

Sookachoff (1977) — mobile suction hopper dredge Department of Public Works "312" dredging the Main Arm of the Fraser River from New Westminster to Sandheads, the western extremity of the river from March 14 to June 1, 1977.

Citation 2.

Sookachoff (1977) — stationary hydraulic suction dredge Department of Public Works "322" dredging Annacis Channel March 1 to April 14, 1997.

Citation 3.

Sookachoff (1979) — mobile suction hopper dredge Department of Public Works "312" at Steveston Cut of the Fraser River South Arm from April 17, 1979 to May 15. Relocated to St. Mungo's Bend from May 16 to May 25, 1979. Relocated back to Steveston Cut May 28 to May 30, 1979.

Citation 4.

Sookachoff (1979) — stationary hydraulic suction dredge Department of Public Works "322" at Mitchell Island of the North Arm of the Fraser River April 5 to April 24, 1979. Relocated to Annacis Channel May 1 to May 31, 1979.

Citation 5.

Sookachoff (1979) — North Arm of the Fraser River dredging commenced April 14 to June 1, 1979.

Citation 6.

Sookachoff (1979) — Bedford Channel of the Fraser River at Fort Langely commenced March 25 to June 1, 1979.

7.3 THE SAND REACH

7.3.1 Biology and Geography of the Sand Reach of the Lower Fraser River

The sand reach of the Fraser River extends from the confluence of the Sumas River (Fig. 6) to the Strait of Georgia (Fig. 5). This part of the river includes the biologically rich estuary and delta through which all of the Fraser River's salmon runs must pass. Juveniles of some of the salmon species, such as chum and chinook, use the estuary extensively for feeding grounds prior to leaving the river for the ocean. An extraordinary number of other fish species also use this part of the river (Table 9).

The sand and silt substrates, and channel morphology, in the estuary contribute to the habitat conditions that make this a rich feeding environment. However, since the 1800s about 70% of the estuary's original tidal wetlands have been lost to diking, dredging, draining and filling. Nevertheless, the Fraser River estuary still makes up over half of the mud and sandflats found along the coastline of British Columbia; these habitats are relatively rare in this province and the Fraser River estuary provides an important part of them.

The present Fraser River estuary and delta were formed following the Fraser Glaciation which reached its zenith around 26,000 years ago. Once the glaciers retreated, the land where the present delta sits rebounded in elevation as a result of being relieved of the weight of the ice. The primary building blocks of the estuary are the enormous volumes of fine sediments that come down the river and deposit there every year (Table 5). Deposition of sediments occurs due to the flatness of the gradient. Because of the shallow slope from Sumas River and downstream, the streambed of the Fraser River is comprised of sand and silts.

The volume of sand, silt and finer particles moving through the lower river is directly related to the magnitude of the run-off freshet, or spring flood. (NHC 1999, see also Fig. 7). The bedload that moves through the estuary is transported downstream in a variety of ways. Much of it moves as large sand dunes of up to three metres in height, travelling 25 to 40 metres per day during freshet (Hay and Co. 1990).

The lower Fraser River carries an average annual sediment load of over 16.1 million tonnes (Table 6). From the confluence of the Fraser River and the Sumas River, and down to New Westminster, the stream-channel neither increases nor decreases in elevation due to the fact that it is a flow-through zone for these particles. That is, the river between these two points simply acts as a conveyor belt for the bedload, so there is no long-term aggrading or degradation of the stream. The bulk of the material that passes through the lower Fraser River is smaller than sand (Table 5), and not much of that is deposited in the river, but is dispersed into the Strait of Georgia. However, around 1.76 million cubic metres of sand-sized sediment is deposited downstream of New Westminster during an average spring freshet each year. It is this material that causes problems for navigation as the shipping channels begin to fill with sand. This part of the sand-reach of the river is extensively dredged of sediments annually.

7.3.2 Dredging the Sand Reach for Navigational Purposes

The lower Fraser River is one of the historic gateways to the interior of the province with boat traffic playing an important role. Navigation channels have been maintained in the Lower Fraser River since the 1800s when a buoy system was established. Originally, the draft for ships was 2.7 metres at low water. A dredging program was implemented and, as ships began to get bigger and the ports at New Westminster and Surrey became larger, more channel changes occurred (Ferguson 1991). By 1949, a total of 24.5 million cubic metres of material had been dredged from the river, and 19,500 metres of river control works had been constructed. By the 1960s, the dredging and training had developed a channel that allowed vessels up to 8.6 metres in draft, through a channel 150 metres wide (Ferguson 1991).

Until 1957, the federal government most of the dredging was undertaken by, but private contractors became involved in the 1960s. The Canadian Coast Guard is responsible for establishing the ultimate design specifications for this channel. Over time, three primary techniques have been used to remove the sand: hopper dredging (suction from the bottom onto a hopper for transfer); clamshell bucket; and cutter-suction dredge (a large pump creates a slurry of sand near the bottom and the material is piped ashore using suction).

In the early 1900s, authorities began to train the river using jetties and other structures to deepen and maintain a channel for shipping. River-training structures fall into the classes of works known as breakwaters, dikes and walled pilings. They concentrate flow patterns in order to increase water velocities and scour out sediments that would otherwise accumulate at specific locations.

Recently, a major river training structure was constructed at the New Westminster Trifurcation (three-channel split) which provided a significant amount of self scouring (Ferguson 1991).

The dredging volumes increased substantially during the 1970s and 1980s (Fig. 8), and coincided with the growth of population in the Greater Vancouver area. Much of this increase was to provide construction material rather than for navigation purposes, and up to half of the yearly volume in some years went towards development. The sand dredging in the lower Fraser River peaked between 1975 and 1991, with the navigation and "borrowed" volumes for construction reaching up to seven million cubic metres in some years (Fig. 8). In total, about 120 million cubic metres of sand were dredged from the river in the past 35 years (NHC 1999) and, in recent years, about 70% of the total was pumped ashore for land development or resale purposes (Ferguson 1991).

The New Westminster area of the sand reach of the lower Fraser River is an important port facility for British Columbia. It receives more than 50 million tonnes of river, coastal and deep-sea cargo per annum (Ferguson 1991). In order to provide passage for the PANAMAX-class vessels that the port is designed for, fine sediments must be removed from the river each year to provide a draft of 10.7 metres. The George Massey Tunnel, midway between New Westminster and the sea, restricts the ultimate potential depth of the channel to 12.8 metres with tidal aid.

7.3.3 Impacts to the Sand Reach as a Result of Dredging

The Fraser River delta is one of the richest salmon rearing areas, and its shape and substrate composition are important in determining the productivity of this habitat. Despite the extraordinary value of the estuary, there has been almost no inventory or assessment of fisheries resources impacted by dredging within the low-water portion of the channel. Nevertheless, the richness and biodiversity of the area are evident in the 30 different species of fish (Table 9).

As the rate and scope of dredging and training of the river increased over the years, it became apparent to the regulatory agencies and the public that there was a requirement to manage this activity in order to protect the estuarine ecosystems in the lower river. There are significant aspects related to fish and habitat (Ferguson 1991).

1. Sediments to be removed near industrial sites, located adjacent to the river, are sometimes contaminated and, thus, require special consideration and handling.

2. Entrainment of aquatic organisms (fish and invertebrates) into the suction intakes of the dredges had to be addressed; of particular concern were salmon and eulachon.

3. Over-removal of sediment had the potential to impact on the integrity of the estuary; that is, if too much material were removed, the delta could begin to erode and lose its integrity.

4. The physical removal of sediment from the river bottom results in increased turbidity or re-suspension of sediments in the water column, possibly having harmful effects for aquatic life.

5. The smothering of organisms that live on or next to the bottom of the river and provide food sources for fish populations could occur with fine sediment.

6. Direct destruction of bottom structure and organisms, as well as spawning habitat, could take place.

7. Changes could take place to main river and side-channel flows, reducing spawning and rearing habitat area and productivity.

In order to address the first concern, the federal government brought in the Disposal Regulation and Interim Contaminant Testing Guidelines to protect humans and ecosystems from contamination of dredged spoil materials. The sediments must be sampled prior to dredging to identify constituents such as mercury, cadmium, polynuclear aromatic hydrocarbons (PAHs), total organic carbon and particle size.

The regulatory agencies have also implemented restrictions that address the second issue — entrainment of fish. Close to a billion young salmon may pass through the Lower Fraser River during their downstream migration. Fisheries and Oceans Canada has implemented regulations that the dredging industry must follow to minimize entrainment. Specifically, from March 1 to June 1 in the upper half of the estuary, and from March 1 to July 15 in the lower half, there can be no suction dredging in water less than five metres deep, measured at daily low water. Also, pink salmon fry only emigrate from the Fraser River in even-numbered years, and they are particularly vulnerable as they are very weak swimmers. When juvenile pink salmon are migrating through the Fraser River, there can be no suction dredging at any location for approximately one month between March 1 and June 1.

Emerging concerns regarding eulachon migration, spawning, incubation and larval dispersal may bring on more restrictions to the timing and methods of dredging as new information becomes available.

With regards to the third issue in the list above, it was recognized in the 1990s by government agencies and the public that sediment removal in the lower Fraser River was dramatically exceeding incoming supply. Past dredging and training works had radically changed the profile of the river (NHC 1998) and presumably caused impacts to fish habitat. Physical surveys of the stream showed that impacts resulting from the dredging included degradation in both upstream and downstream directions. Upstream headcutting develops as a result of the locally steepened water surface slope near the hole, and degradation occurs as a result of the decreased sediment supply downstream of the hole as it acts as a sediment trap (Fig. 4, NHC 1998).

Due to the extensive sand dredging in the Fraser River in previous decades, the streambed had degraded upstream as far as Douglas Island (Fig. 9) and lateral changes due to erosion were also being seen (Ferguson 1991). Furthermore, the effect of all of this dredging had been to lower the water levels at New Westminster to about 0.7 metres in 25 years and cause a decrease in the bottom of the river of almost 2.5 metres since 1955 (Ferguson 1991, NHC 1999).

Other physical impacts from extensive mining activities caused questions to be raised about the long-range stability and structure of the delta. For instance, using the results of sediment trend analysis, MacLaren and Ren (1985) suggested that sand deposition over most of the intertidal flats was no longer the result of normal deltaic processes. Their study also indicated that the biologically important intertidal mud flats are becoming starved of sand. That is, the diameters of sediments in the estuary have changed and become smaller as a consequence of a reduction in the amount of larger-sized sand now passing through the lower river as a result of dredging. According to these authors, the evident paucity of sand on the tidal flats could be attributed principally to channelization and removal of river sands by dredging. Additionally, the extensive development of the various causeways and jetties crossing the banks may be a contributing factor in modifying sediment compositon.

MacLaren and Ren (1985) suggested that, over time, the extensive dredging of the lower Fraser River could affect the structure of the estuary and substrates in subterranean waters. A study by Stewart and Tassone (1989) suggested that there were areas of the delta front that were retreating subsequent to the initiation of extensive dredging in the lower Fraser River, but the authors of this work maintained that it was not significant. Church et al. (1990) also suggested that the foreshore could be flattening as a consequence of a change in sediment availability.

Issues 4-7 in the above list have yet to be significantly addressed by the regulatory agencies. Both river-training structures and dredging impact on the stream-bed morphology and this results in altered depths, velocities and substrates, the primary components of fish habitat. Like dredging in gravel streams, dredging reduces the physical diversity of the stream. Kellerhals and Church (1989) discussed the change in distribution of depths and velocities, as a result of changing the channel morphology from a triangular cross section (natural bottom) to a trapezoid (dredged bottom), subsequent to dredging. They pointed out that the depth/velocity relationship of a trapezoidal stream bottom has a much smaller area with shallow flow. Light penetration to the bottom is more restricted than an undredged or triangular section that has a much more varied range of depth and velocity at all flows (Fig. 15).

Levings (1982) recognized that our knowledge of impacts to benthic environment as a result of dredging is almost non-existent. He recommended that basis ecosystem research to determine losses of benthic production for fish be accelerated. One of the few studies to assess the impact of dredging on habitat in the sand reach of the Fraser River was undertaken by Perrin et al. (2000b). Almost 0.5 million cubic metres of sand were removed in 1998 from a site near Mission. It was estimated that the pit would take at least two years to recover its former elevation. Invertebrate production decreased by 84% at the time of dredging of which 98% was one species of chironomid. A period of ten months was required before the invertebrate population at the dredge site recovered.

In conclusion, all points of evidence indicate that sand dredging for navigation or other purposes in the lower Fraser River constitutes a harmful alteration, disruption or destruction of fish habitat (HADD) and requires a *Canada Fisheries Act* Section 35(2) authorization. It is not clear how the regulatory agencies will address this issue, since no HADD authorizations have been required to date.

7.3.4 Managing Sand Dredging Using Sediment Budgets

In response to the over-extraction of sand from the lower river, the Fraser River Estuary Management Program (FREMP) became involved in developing dredge-management guidelines for the lower river. FREMP was given the task of ensuring that impacts resulting from the removal of material for navigation and borrow would be mitigated to the fullest extent possible.

As a partnership amongst federal, provincial and regional government bodies, FREMP undertakes coordinated and sustainable management of activities in the Fraser River from Sandheads to Kanaka Creek and the mouth of Pitt Lake. FREMP was established in 1985 and now consists of:

- Fisheries and Oceans Canada
- Environment Canada
- BC Ministry of Environment, Lands and Parks
- Fraser River Port Authority
- North Fraser Port Authority
- Greater Vancouver Regional District

The organization clearly set out its vision, goals and action plan for improving the environmental, economic and social health of the Fraser River estuary. The plan reflects a consensus among a broad range of stakeholders concerning how the water, shoreline and upland resources in the estuary should be managed. This includes the issues surrounding extraction of sand and the maintenance of the navigational channel.

FREMP has a number of guiding principles for dredge management.

- Habitat values and fisheries resources must be preserved.
- Navigation channels are to be maintained.
- The development industry's demand for sand must be met on an environmentally sustainable basis.
- Disposal of contaminated dredge material must be properly managed and appropriate upland and offshore disposal sites are to be used.
- Public health and safety needs are to be met.

The plan also contains an action program for navigation and dredging. In 1996, a FREMP task group began to develop guidelines for dredging of the estuary to accommodate continued navigation and the construction industry to the extent possible, while maintaining the environmental and structural integrity of the estuary as a whole. Part of this work was to determine, by scientific and analytical means, how much sand is deposited in the lower estuary and how much could be removed without causing degradation.

For FREMP management purposes, this material, called "sand," has a diameter ranging from 0.177 to 2.00 mm. Smaller material than this normally simply goes out to sea while the large stuff drops out of the water column before it arrives down-river at Mission. The regulatory agencies, with the co-ordination of FREMP, engaged in a computer modeling exercise to determine how much sand could be removed from the river without compromising the integrity of the estuary.

The amount of bed material at Mission can be predicted using the following equation (NHC 1999):

$$S_{in} = 1.304 \times 10^{-10} V_{HOPE}^{2.08} P_{MISSION}^{1.530} - 124{,}000$$

where

S_{in} is the volumetric bed material load in metres³/year

V_{HOPE} is the freshet flow volume (April–September) at Hope in 10^6metres³

$P_{MISSION}$ June flow at Mission in metres³/second

The net dredging volume will be maintained at about 70% of the incoming bed material. The sand is of a range from 0.177 mm to 2 mm. This volume is estimated to be the maximum amount that can be taken out without degrading the estuary (Fig. 8, Table 6), and equals 1.23 million cubic metres in an average year. No borrow dredging is currently being undertaken upstream of Patullo Bridge at New Westminster, although a transfer pit site is being proposed at the time of writing of this report.

8. Other Jurisdictions

8.1 INTRODUCTION

With respect to the protection of aquatic ecosystems, initiatives in other parts of the world have also taken into consideration the management and regulation of sediments in streams. For example, some parts of the United States have far more rigorous stream habitat protection when determining whether or not to allow dredging to take place within alluvial channels. Below, we provide some of the approaches and observations in other jurisdictions in continental North America.

8.2 UNITED STATES

Mines that remove sand and gravel from alluvial environments must follow various federal and state regulations (Meador and Layher 1998). The US Army Corps of Engineers may require a permit for dredge-and-fill operations. Permits, for instance, may be required for gravel extraction under the US *Clean Water Act*, *Rivers and Harbors Act* of 1899, or *Fish and Wildlife Coordination Act*. Gravel extraction projects that do not fall under the above legislation may still be reviewed, subject to a county or state hearing. The Magnuson *Fishery Conservation and Management Act* can also address effects that changes to habitat may have on a fishery. The *Endangered Species Act* may also require compliance with respect to sediment mining. In short, an array of legislation could be relevant to changes in stream sediment in the United States.

The National Marine Fisheries Service (NMFS) is responsible for protecting, managing and conserving marine, estuarine and anadromous fish in the United States. It also has the task of developing policies regarding fish habitat protection. In its policy statements, the NMFS recognizes that there can be significant fish habitat impacts associated with gravel removal in alluvial environments (National Marine Fisheries Service 1996). It has written a national policy document that outlines issues of concern regarding the mining from or near streams and its position is that: "...[a] policy document on gravel extraction is necessary because extraction in and near anadromous fish streams causes many adverse impacts to fishes and their habitats." Their policy articulates eight points outlining what the NMFS sees as the potential effects of gravel mining in streams including:

1. Extraction of bed material in excess of natural replenishment by upstream transport causes bed degradation.
2. Gravel extraction increases suspended sediment, sediment transport, water turbidity and gravel siltation.
3. Bed degradation changes the morphology of the channel.
4. Gravel bar skimming significantly impacts aquatic habitat.
5. Operation of heavy equipment in the channel bed can directly destroy spawning habitat and produce increased turbidity and suspended sediment downstream.
6. Stockpiles and overburden left in the floodplain can alter channel hydraulics during high flows.
7. Removal or disturbance of in-stream roughness elements during gravel extraction activities affects both the quality and quantity of anadromous fish habitat.
8. Destruction of the riparian zone during gravel extraction operations can have multiple deleterious effects on anadromous fish habitat.

Of particular interest in this NMFS policy document is the following quote: "Gravel removal quantities should be strictly limited so that gravel recruitment and accumulation rates are sufficient to avoid extended impacts on channel morphology and anadromous fish habitat." Recruitment, in this case, is the rate at which bedload is supplied from upstream to replace the extracted material. While this is conceptually simple, annual gravel recruitment to a particular site in streams is, in fact, highly variable and not well understood. Kondolf (1993, 1994) argues that removal based on this formula is often fraught with difficulties and leads to biological and physical impacts that are not predicted in such a management plan.

8.2.1 State of California

Extraction of gravel from California streams is of particular interest for its comparisons with British Columbia. California's coastal rivers historically had anadromous fisheries of exceptionally high value. Most of these stocks are now a mere fraction of pre-European settlement, or are now extinct. Due to the excessively high growth rate of the human population, there has been an exceptional demand for aggregate for the state's development industry throughout the past half century. This came after many rivers had already been extensively placer-mined for gold, with the attendant disruption of alluvial sediments.

Unlike British Columbia, where there are large deposits of post-glacial outwash gravel, California's aggregate sources have been primarily derived from streams. As a result, California's options to protect anadromous fish by using non-riverine sources have been much more limited. Kondolf (1998a) indicates that aggregate extraction from California rivers has caused massive, poorly documented alterations of river form and process in that state. He states that sand and gravel are removed from floodplains in California at rates far exceeding supply from catchments, and this is estimated to be by an order of magnitude or greater.

According to Kondolf, vast areas of floodplain continue to be transformed from woodland or agriculture to open-water gravel pits, mostly without hydrological or ecological planning or design. An extreme California example has occurred at Stoney Creek, a tributary of the Sacramento River. Alluvial mines have been taking from the alluvial floodplain an average of 1.3 million tonnes of gravel per annum compared to the annual recruitment average of 0.16 million tonnes. This is almost 40 times that of the current gravel recruitment, and has resulted in channel incision up to five metres (Kondolf 1995).

From a regulatory perspective, the mining of gravel from alluvial environments in California is bureaucratically very complex (Kondolf 1998a). In the state, there are at least 15 different federal, state and local agencies playing a role in regulating gavel mining. The principal regulatory tool dealing with impacts by gravel mining in streams is the California *Surface Mining and Reclamation Act* (SMARA), and the California *Environmental Quality Act.* The latter is triggered by use permit applications under *SMARA. SMARA* requires that all surface mines to submit reclamation plans to the local lead agencies, describing the transition to subsequent productive use.

Kondolf (1994) indicates that despite numerous regulatory requirements, the cumulative impacts of gravel mining in California are rarely recognized or analyzed. Impacts are usually analyzed on an individual project basis in response to proposals for mine-specific sites. In Kondolf's view, it would be more appropriate that a regional or statewide approach be taken, given the large number of lead agencies involved in regulating the issue. Also, Kondolf (1998a) suggests that none of the regulatory agencies has adequate resources to conduct a comprehensive analysis of cumulative impacts of in-stream mining and all are constrained by the short time required by law to provide permits. Furthermore, the regulators lack the proper training in geomorphology and hydrology needed to assess projects (Kondolf 1998a).

Kondolf (1994b) indicates that the environmental costs of alluvial-gravel removal are not normally factored into the costs of production. So, despite the apparent requirements to protect the environment, aquatic ecosystems continue to be destroyed in California.

8.2.2 State of Vermont

Vermont's General Assembly recognized in its flood control policies and programs that there was a need to provide a balance between protecting the environment and protecting public and private property, specific to gravel removal from alluvial locations. A policy statement prepared for the Vermont General Assembly (Vermont Agency of Natural Resources 1999) declares that "...[a]lthough there continue to be disagreements among specialists over some of the issues related to river hydrology, and the treatment of any particular river reach will always require the application of professional judgment, expert opinion is converging around one central theme: establishing long term stability will provide both protection from flood damage and a healthy riverine environment. This means that, with a comprehensive approach to river and stream management, we will seldom have to choose between protection of human investments and protection of our state's natural resources. The right answer in most situations will work for both, and the wrong answer will work for neither...The greatest challenge in managing river morphology comes down to striking that balance between accommodating, to the greatest extent possible, the river's natural tendencies, while at the same time applying an adequate level of physical constraint to the system as necessary to provide protection of property and infrastructure."

Key to Vermont's river policy is the observation that "...[e]xperience from the1970's and early 80's...has demonstrated unequivocally the destabilization of river systems and excessive damages to private property and municipal roads and bridges resulting from gravel mining. Damage occurs from stream channel dredging where such practice is not accompanied by restoration of channel dimensions (width and depth), pattern (curvature and sinuosity) and profile (channel slope along the valley) appropriate to the location and other attributes of the stream and it's valley." Vermont then provides case study after case study of circumstances where the removal of gravel, either for strictly commercial purposes, or for flood control, ended up causing a destabilization of the river channel, often leading to more damage to the surrounding property than the value of the gravel.

In 1995, the US Department of Transportation issued a notice to state transportation agencies indicating that federal funds will no longer be available to repair bridges damaged by gravel mining. In recognition of the problems that sediment removal causes with respect to flooding, Vermont reduced its activities in the amount of material it would remove from alluvial environments. Vermont still occasionally does remove gravel for flood protection, but the amount is now very modest, equaling only 120,000 cubic metres for 100 stream-channel dredging projects over a two-year period (Vermont Agency of Natural Resources 1999).

8.2.3 State of Arkansas

In-stream gravel has been historically used as source material for the aggregate industry in Arkansas. Due to increasing demand for this material, the effects on aquatic ecosystems were studied by the Arkansas Game and Fish Commission (Filipek 1999). As a result of this assessment work, significant damage was shown to occur in aquatic environments due to gravel removal. A bill was subsequently submitted to the Arkansas legislature to ban commercial in-stream gravel mining on Extraordinary Resource Waterbodies (ERW) which include 24 streams and lakes designated as being unique in biological, physical or recreational terms.

The bill banning gravel mining on ERWs was signed into law in 1993, but the Arkansas Department of Pollution Control and Ecology was forced to place a moratorium on the enforcement of the law for two years to give miners enough time to find new sources of gravel. In 1995, it was proposed by gravel miners and some politicians that the 1993 law be repealed; however, a second bill was passed, prohibiting mining in these ERWs (Filipek 1999).

9. Protection and Restoration of Sediment-Influenced Habitat Attributes

The restoration of natural sediments to streams, and alluvial processes that contribute to the sediment-based in-stream habitats, can include a variety of different actions. In order to initiate restoration activity, Kern (1998) suggests that true river restoration must occur at the reach level. It is Kern's (1998) view that reversing disturbance of a river reach means re-establishing equilibrium conditions without restricting the morpho-dynamic development of the reach.

At its very simplest, the activities to restore alluvial processes and sediments may include not physically interfering with the structure of the river and removing any human activity as far from the floodplain as possible. The river is left to "heal itself" over time. At its most complex, the restoration of sediment processes can involve sophisticated computer modeling exercises to determine specifically-timed flow releases from a dam to restore natural sediment flushes and erosion and deposition. For example, BC Hydro recently embarked on a water use planning exercise with government agencies and the public stakeholders to determine the best use for water at dams. Part of the exercise includes consideration of flushing flows, sediment movements downstream of dams, and gravel replacement in areas of lost productivity. In order to minimize losses of water for power revenues, but maximize positive effects on the aquatic ecosystem, computer modeling is employed to determine optimum release discharges.

Restoration of sediment processes can also involve the removal of bank armoring and development of flow passageways through dikes, berms and railway grades. Some of this has occurred in the Vedder River, a tributary of the Fraser River in the lower mainland, and there is a move afoot to expand this sort of restoration.

Regardless of the activity, there are almost always social and economic costs associated with restoration or protection of fish habitats. Often, however, an accounting of these costs do not take into consideration the negative externalities in terms of damage to the environment if the restoration activity is not done. Thus, proposals to rectify aquatic ecosystems are often unconvincing at the political level, and do not get funded.

Below, we provide a short list of some of the attempts to restore in-stream sediment character and habitat quality and abundance.

9.1 ADDING SEDIMENT TO A STREAM

Where sediments of particular size classes have been lost from a stream due to human activity, and this material is deemed to perform an important ecological function, material is sometimes added to a waterway to replace that which is missing. At Barrage Iffezheim, a downstream dam on the Rhine River, 170,000 tonnes of gravel were added to the stream annually to prevent streambed incision (Kondolf 1995). At this location, incision of the river bottom had occurred over the years due to various human interventions. Apparently, this option was less expensive and environmentally damaging than construction of in-stream berms to reduce the downstream mobilization of sediments (Kondolf 1995).

Gravel can also be added to salmon rivers to replace spawning sediments that have been lost due the trapping of these materials by dams. Kondolf (1997) reported that there were at least 13 streams in California where gravel was being artificially supplied downstream of dams, as of 1992. As an example, from 1979 to 2000, sediments were being added downstream of Shasta dam on the Sacramento River to provide spawning habitat for salmon, and this was costing about $22 million. The ironic component of this enhancement is that the source of this material is from other alluvial sources. Finally, because of the continuing flow regimes in the Sacramento watershed and the dams, this gravel has to be continually replaced because it is routinely washed downstream of the placement areas.

In British Columbia, BC Hydro and the fisheries agencies have been engaged in replacing gravel in a number of streams that have been dammed and where the downstream spawning sediments have been washed away over time. This includes the Campbell River on Vancouver

Island downstream of John Hart Dam. Here, damming and changes in flow regimes due to system operations of the power generating station resulted in the loss of much of the spawning habitat for the chinook salmon. While historic records suggest the stream had an average run of about 5,000 fish, the capacity of the spawning habitat had declined a level where it could accommodate only 200 females (Sheng et al. 1998). In 1997, Fisheries and Oceans Canada, the BC government, BC Hydro, and other stakeholder groups and volunteers provided the effort and money to place washed and screened gravel of an appropriate diameter to develop 1,900 square metres of spawning habitat using a helicopter. Initial assessments suggest that spawning salmon are using these sediments. Recently negotiated changes to the flow regimes downstream of the John Hart generating station are also expected to allow the gravel to be retained longer in the river, compared to historic post-damming discharges. Furthermore, while 1,900 square metres of spawning gravel is a small fraction of the target of 20,000 square metres, there may be further efforts to expand the project, if assessment shows that the project is continuing to work successfully (Sheng et al. 1998).

Another location where sediments have been placed downstream of a dam is in the Alouette River, a tributary of the Fraser River in the lower mainland of BC. This stream was dammed in the first half of the 20th century and, with the exception of major flood events, virtually all of the discharge was diverted into another watershed for the production of power. Furthermore, the area immediately downstream of the dam became devoid of spawning-sized sediments. Investigations indicated that fish numbers were substantially lower in the reach of the river immediately downstream of the reservoir dam than in the adjacent reach further downstream which still retained reasonable gravel resources. The lack of spawnable sized sediments was considered to be the reason. In 1999 a trial placement of 230 cubic metres of spawning gravel showed almost immediate use of the habitat by salmon (Alouette River Management Society, pers. comm.).

As a cautionary note, often despite the best intentions of fishery managers, projects attempting to replace spawning sediments in streams are poorly conceived and designed. For example, Kondolf et al. (1996) evaluated chinook salmon spawning gravel that had been placed in the stream over a number of years in the Merced River in California. Firstly, they found that there was no evidence to suggest that the spawning habitat was, in fact, limiting. Secondly, the gravel was placed in areas, and in configurations, that were inappropriate for chinook spawning. Finally, the material was mobilized from the spawning sites after a number of modest floods. Kondolf (1998b) suggests that restoration projects should be planned and designed on the basis of an understanding of geomorphological and ecological processes rather than mimicry of a particular habitat form. Furthermore, he strongly recommends that post-construction assessment and evaluation be required.

9.2 CHANGING OPERATIONS AT A DAM TO ALLOW THROUGHPUT OF SEDIMENTS

One option to restore sediment sources downstream of a dam is to allow material to pass through the structure. Historically, this has been used as a method to restore the storage in a reservoir that is filling up with material including efforts at the old Aswan dam on the River Nile and the Bhatgurk Reservoir in India (Kondolf 1997). Sluicing of deposited reservoir sediments is also now being viewed as a potential method of restoring stream processes downstream of dams (Kondolf 1997). There are, however, some logistical constraints to this activity. For the most part, the reservoir has to be small and narrow and the discharge has to be large enough to carry bedload downstream. For larger reservoirs, the sediments that accumulate near the outlet at the dam tend to be fine and are potentially more destructive to downstream aquatic life than they are beneficial. Furthermore, there has to be a low-level outlet built into the dam infrastructure at the elevation of the old streambed in the reservoir.

In British Columbia, this option is currently limited to smaller reservoirs and small diversion dams and, for the most part, retrofitting is required. However, there are opportunities at new sites where the configuration of low-elevation diversion dams can be engineered so that they are retracted during high-water events. This allows sediments to pass over the structure into downstream areas.

9.3 CHANGING OPERATIONS AT A DAM TO REMOBILIZE SEDIMENTS DOWNSTREAM

An option that can be used to re-vitalize fish habitat and the channel morphology downstream of a dam is to provide artificial floods in order to remobilize sediments. For example, Wilcock (1998) stated that: "...[r]eservoir releases may be specified to improve or maintain bed sediment in gravel-bed rivers for spawning, rearing and habitat purposes. Objectives for such releases may be to (1) maximize removal of fine-grained sediments, (2) minimize the amount of water used, and (3) minimize transport of coarser sediments, subject to the constraint that sufficient gravel transport occurs to entrain the bed surface, thereby allowing subsurface flushing and loosening of the bed surface layer."

Controlled releases, or flushing flows, may replace part of the lost sediment-transport capacity of the downstream river when sufficient reservoir water volumes are available. Done properly, this can restore some of the impacts of reservoir operation with regard to the quality and quantity of the sediments in the lower reaches of the river. Kondolf and Wilcock (1996) reviewed the concept of providing flushing flows in streams below dams, and they took the position that a meaningful estimate of flushing flows requires a clear statement of objectives so that the flow necessary to achieve those targets is first determined. Depending what needs to be achieved, flows can either be specific to the preferential transport and removal of fine-grained sediments deposited on and within the bed, or to maintenance of larger scale channel features, such as bars and floodplains (Reiser et al. 1989, Wilcock 1998). Care must be taken when choosing a flow as the end-point achieved under a particular discharge regime (sand removal) may cause damage to another component of the habitat (erosion and mobilization of spawning gravel).

Objectives that can be reached using flushing flows include:

1. estoring or enhancing riffle habitat;

2. removing fine-sediment deposits from the surface;

3. removing fine sediments from gravels;

4. maintaining gravel looseness;

5. restoring/enhancing pool habitat;

6. maintaining active channel width and topographic diversity;

7. maintaining floodplain habitats; and

8. creating diverse multi-age riparian habitat.

Each of these objectives will require stream-specific flows in order to be reached.

One of the more celebrated releases of water from a dam to create flushing flows has been that on the Colorado River at the Glen Canyon Dam, Lake Powell. In March 1996, flows up to 45,000 cubic feet per second were released in an attempt to restore some of the natural physical attributes of the stream below the dam and re-create the habitat conditions for many of the native species which were declining in abundance. The primary objective was to scour out fine sediments that had accumulated in the main channel and re-organize them into beaches, a condition that was similar to pre-dam conditions. Post-flow-release inventory and assessments suggest that this objective appears to have been achieved by the flushing-flow water release (American River Management Society 1996).

Another location where both flushing flows and re-introduction of base flows were initiated after many years of damming occurred at Owens River Gorge in California. A considerable measure of success transpired in reviving an aquatic ecosystem in this stream. In a five-year period, aquatic and riparian communities made a striking come-back in abundance, and good quality micro-habitat features were formed (Hill and Platts 1998).

In British Columbia, flushing flows are now specified for a number of rivers that have been dammed. This includes the Alouette and Coquitlam rivers in the lower mainland. However, of the two, only for the Alouette River has there been any attempt to monitor the effectiveness of the flushing action.

10. Summary

1. The health of alluvial aquatic ecosystems is a function of the way that sediments move and are distributed throughout a watershed. The term "sediment" includes clay, sand, gravel, cobble and boulders.

2. Salmon and steelhead habitat quality and abundance is directly a function of how well river processes work and the parent materials that the stream has to work with.

3. The way that sediments are distributed throughout a stream defines the quality and abundance of micro- and macro-habitats and the habitat capability.

4. The sediment configuration in a stream influences periphyton growth, invertebrate habitat, salmon and steelhead spawning and incubation substrates, and juvenile rearing habitats.

5. Substantial declines in salmon and steelhead populations have occurred in British Columbia over the last century.

6. Disruption of sediment processes in streams around the world, and in British Columbia, have caused unassessed and untold losses in aquatic ecosystems. Some of the losses of salmon and steelhead populations in British Columbia have been a result of interruptions or destruction to sediment processes.

7. Disruption of sediment processes by means of human intervention has occurred in British Columbia through a variety of means including: gravel and metal mining, diking and armoring of stream banks, damming, and dredging for navigation and flood control. These activities have impacted on salmon and steelhead in most of our streams where human settlement has occurred.

8. In-stream mining or dredging are the most immediately destructive of the activities listed to in-stream aquatic ecosystems. These cause many impacts to streams including channel degradation and destabilization, removal of important spawning gravel, entrainment of fine sediments, physical impacts on periphyton (algae), insects and fish, and changes to the macro- and micro-habitat features.

9. Mining outside the low-water wetted perimeter of a stream, but within the floodplain, also causes most of the impacts listed in the above point, but the timescale for the impacts is often longer.

10. Construction of a dam on a stream interrupts the stream-sediment processes by trapping sediments behind dams and changing the downstream flow regime that is important in creating habitat and removing unwanted fine sediments from spawning and rearing areas.

11. Diking and the hardening of stream banks for the protection of property causes some of the most insidious and long-term effects on sediment processes in salmon and steelhead streams. The narrowing and hardening of banks results in less diverse stream environments, locks up sediments in banks which would otherwise be available for recruitment into riverine habitats, and increases local scour which may result in the loss of important spawning sediments.

12. Salmon and steelhead habitat features are legislated and regulated through a number of *Acts*. Two of the most important are the *Water Act* and the *Canada Fisheries Act*.

13. The *Water Act* provides the authority to work in and about a stream, as well as change flow regimes. Both activities ultimately influence how the distribution and abundance of sediments will be affected in the stream.

14. The *Canada Fisheries Act* regulates sediment and stream processes primarily through Section 35(1) (harmful alteration, disruption or destruction of fish habitat), and Section 36(3) (deposit of a deleterious substance).

15. Options for protecting and restoring sediment processes include applying existing legislation, regulation and various governmental and non-governmental initiatives. One such initiative, currently being undertaken in British Columbia, is water use planning.

16. Other jurisdictions across North America, like British Columbia, have found that there are similar impacts to aquatic ecosystems occurring as a result of the development on floodplains or due to gravel mining in alluvial environments.

17. The restoration of alluvial sediments includes release of sediments from behind dams to downstream areas, removal of rip-rap, addition of spawning gravel downstream of dams, and release of flushing flows from reservoirs.

GRAVEL REACH OF THE FRASER RIVER FROM HOPE TO SUMAS RIVER

1. The gravel reach of the Fraser River is one of the richest freshwater ecosystems in British Columbia, comprising over two-dozen species of fish that spawn, rear or migrate through this part of the watershed.

2. The floodplain of the Fraser River in the gravel reach has been significantly narrowed due to the closing of side-channel entrances and exits. Over 100 kilometres of side channels have had one or both ends cut off from the normal discharge regime of the Fraser River.

3. Although the extent of the impact of side-channel isolation to fish habitat remains unquantified, this will have implications with regards to sediment deposition due to the narrowing of the river. As a result, this action will have had significant effects on the aquatic ecosystems of this area of the river.

4. Over 50% of the channel perimeter from Sumas River to Laidlaw has been armored using rip-rap rock for the protection of the channel banks. This has changed the erosion and deposition processes of the river, with impacts to fish habitat.

5. Rip-rapping of the Fraser River banks constitutes a harmful alteration, disruption and destruction of fish habitat.

6. Sediment removal from the gravel reach of the Fraser River, for aggregate or flood-protection purposes, harmfully alters, disrupts or destroys fish habitat. Industrial removals of gravel affect these fish habitats in ways that can take years, decades or centuries to restore.

7. Gravel removal and protection of fish habitat in the Fraser River are incompatible activities.

SAND REACH OF THE FRASER RIVER FROM SUMAS RIVER TO GEORGIA STRAIT

1. Substantial removals of sand from the Fraser River between the Sumas River confluence and Georgia Strait over the last three decades have significantly changed the form and elevation of the streambed. This is particularly evident in the navigation reach of the river between New Westminster and the Georgia Strait.

2. While the number of species of fish in this part of the Fraser River is extraordinary, little is known about the effect on the fish of sand dredging from the river due to a lack of inventory and assessment of the impacts.

3. Sediment removal from the sand reach of the Fraser River harmfully alters, disrupts and destroys fish habitat.

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