SPAWNING GRAVEL QUALITY WITHIN THE COQUITLAM RIVER: POTENTIAL IMPACTS FROM GRAVEL PIT MINING

By

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ABSTRACT

Potential spawning sites within the Coquitlam River were evaluated for their ability to support embryos through to the late stages of incubation. Freeze core samples were collected from four sites beginning on December 18, 1997 through to April 14, 1998. Dissolved oxygen and relative permeability data was collected from March 28, 1998 through to April 14, 1998. Sediment traps were also placed at the four sampling locations on March 20, 1998 and removed May 4, 1998 (45 days). Two of the four sites had descriptive measures (%<0.85 mm, dissolved oxygen, and Fredle index values) that classified them as 'good' quality spawning habitat. The other two sites had descriptive measures reflective of 'poor' quality spawning habitat. Of the two 'poor' quality habitats, one was exposed to episodic upstream slides that were believed to be depositing fines within potential spawning gravel. The other site was directly downstream of discharge effluent from gravel mining. The impact from the gravel mining appeared to be localized. A site approximately 1.5 km downstream had 'good' quality spawning habitat whereas a sample site 0.3 km downstream had 'poor' spawning habitat. In addition, sediment trap data showed a significantly finer distribution of deposited material immediately downstream of the gravel mining outfall. Approximately 1.5 km downstream the deposited material had a significantly coarser distribution. Although it appeared that the gravel effluent was affecting gravel quality locally, attempts to trace the deposited material to the source was not successful.

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1 INTRODUCTION

1.1 General Impacts of Fine Sediment

The intrusion of fine sediment has been historically, and is still, considered the most detrimental form of pollution to river (lotic) ecosystems worldwide. For this reason the impacts of suspended material on rivers and streams are well researched (Chapman 1988; Ryan 1991; and Wood & Armitage 1997). The present definition of fine sediment includes all material less than 2 mm in diameter. Fines are further broken down into sand (<2000 to >63 μm), silt (<63 to >4 μm), and clay (<4 μm) (Church et al. 1987). The addition of fine sediment to a lotic ecosystem firstly causes a change in the chemical / physical conditions; these changes are often associated with detrimental impacts on the entire food chain. Moreover, addition of fines increases turbidity, limits light penetration, and can reduce the degree of primary productivity. This in turn jeopardises higher order organisms (Langer 1971). The deposition of fines changes the physical conditions on the substrate surface, thereby altering niche conditions for benthic invertebrates and aquatic flora. Subsequent penetration to depth in the riverbed increases the amount of fines and can lead to the clogging of the interstices between substrate clasts (Ryan 1991). Excessive increases in fines over an extended period of time have been shown to cause changes in channel morphology. In addition, aquatic flora diversity and density have been found to decline and in some cases they are eliminated altogether (Wood & Armitage 1997).

1.2 Salmonids and Fine Sediment

In order to maintain a successful salmonid breeding population in a river that has been subjected to human disturbances which elevate the level of fine material in suspension, a firm understanding of deposition, clogging, and intra-gravel flow needs to be obtained. Salmonids deposit their eggs within the gravel bed. The depth to which eggs are deposited depends on the species vary between 10 and 40 cm (Bjornn and Reiser 1991, and Peterson and Quinn 1996a). Once fertilized the eggs are covered with gravel and left to incubate for 2 to 6 months. The clast size of gravel chosen to cover the eggs also depends on the species. The incubating eggs require oxygen and intra-gravel flow to remove metabolic by-products. Flow through the interstitial space (void space) of the gravel matrix allows for the delivery of oxygen and the removal of metabolic by-products. However, deposition of fine material can clog interstitial space thereby reducing oxygen delivery and exchange of the metabolic by-products. In addition, fine sediment can form an impenetrable seal above the egg pocket; this prevents fry from emerging into the water column (Diplas and Parker 1987; and Crisp 1993).

1.3 The Coquitlam River

The Coquitlam River is a salmonid bearing stream that was at one time considered the best steelhead river in the world (Rosenau 1993b). Gravel mining activity within its watershed has lead to concerns about the addition of fine sediment and the quality of salmonid habitat. Gravel mining activity can potentially add fine material to the river via runoff and discharge of effluent. Proper sedimentation measures should successfully remove sand sized material before it enters the river. The majority of silt / clay that enters the river via mining effluent should remain in suspension and be transported beyond salmonid spawning grounds, thus causing little if any decline in salmonid spawning habitat. However, inefficient and inadequate sedimentation measures that allow sand to enter the river can cause clogging of spawning gravel. In addition, a small portion of the silt / clay material will settle within the interstitial pores of spawning gravel once intra-gravel flow has transported the suspended fines below the gravel surface or in proximity to the zero velocity plane. Excessive quantities of silt / clay over time may clog spawning habitat to an extent that spawning success declines (if flushing flows do not occur).

1.4 The Problem

Historical data, both published and anecdotal, indicate that the Coquitlam River once supported breeding salmonids that numbered in the thousands (Rosenau 1993b). Changes that have occurred within the Coquitlam River Watershed – gravel pit mining, forestry, and urbanization – can potentially contribute elevated levels of fine sediment. The potential addition of excessive amounts of fine material to salmonid spawning habitat has, in general, been shown to be devastating in terms of salmonid spawning habitat quality (Chapman 1988).

Sand sized effluent is assumed by the gravel pit operators to be removed by sedimentation measures before it enters the river. Testing this hypothesis was a goal of this research. In addition, the gravel pit operators have suggested that silt / clay sized material being discharged into the Coquitlam River does not actually settle out in the potential spawning reaches of the river. More likely, the silt / clay fraction travels in suspension right to the Fraser River; after which it continues through to the ocean out of harms way. It was the further intention of this research to determine if the silt / clay material originating from the gravel pits is being deposited within the interstitial spawning gravel of the Coquitlam River and thus altering salmonid spawning habitat. In order to either prevent the addition of fines to the Coquitlam River, or successfully prosecute those that discharge their effluent to the Coquitlam River, definitive scientific evidence linking the impact from the gravel pits to potential salmonid redd sites is required.

1.5 Objectives & Hypothesis

1.5.1 Objectives

1. Determine the quality of spawning gravel within the Coquitlam River as it pertains to its ability to support salmonid eggs during incubation and through to emergence. In order to reach this objective, a number of sub-objectives needed to be tested:

a) Determine the particle size distribution of the interstitial gravel within the Coquitlam River.

b) Determine the dissolved oxygen level of the interstitial gravel within the Coquitlam River.

c) Determine the relative permeability of the interstitial gravel within the Coquitlam River.

2. Determine the impact gravel pit mining effluent has on the quality of spawning gravel – especially as it pertains to its ability to support salmonid eggs during incubation through to emergence – by comparing reference sites to impacted sites.

3. Further, precisely determine if effluent is being deposited within the interstitial gravel of the Coquitlam River. If the scientific parameters (particle size distribution, dissolved oxygen, and relative permeability) revealed that the interstitial gravel downstream of the gravel pit effluent has been degraded, an attempt would be made to trace the 'degrading material' to source.

1.5.2 Hypothesis

1. Null Hypothesis:

Potential spawning sites upstream and downstream of gravel pit effluent will have interstitial gravel compositions that are of equal quality to sustain salmonid eggs during incubation through to emergence.

Alternative Hypothesis:

Potential spawning sites downstream of gravel pit effluent will not have an interstitial gravel composition that can sustain salmonid eggs during incubation through to emergence at a rate seen upstream of the gravel pits.

2. Null Hypothesis:

Gravel pit effluent will remain in suspension as it travels past potential spawning sites within the study areas of the Coquitlam River and thus will not be deposited in the interstitial gravel.

Alternative Hypothesis:

Gravel pit effluent will be deposited within the interstitial gravel of downstream sites thus reducing its ability to sustain salmonid eggs during incubation through to emergence.

1.6 History of The Coquitlam River

The Coquitlam River begins at the Coquitlam Dam and runs through the City of Coquitlam until it drains into the Fraser River (Figure 1.2-1). The name Coquitlam is derived from the Coast Salish word Kwikitlam meaning 'little red fish'. The river was modified in 1903 when British Columbia Electric Railway Company Limited, presently BC Hydro, built a small dam to supply Vancouver with electric power. Water from Coquitlam Lake was shunted to Buntzen Lake then into Indian Arm; along the way electricity was generated. The dam was enlarged and upgraded in 1914 to ensure that no 'leakage' occurred, essentially stopping the flow of water into the Coquitlam River, a flow of only 10 cfs remained (Rosenau 1993a). At the time no regulations existed which stated a minimum flow had to be maintained.

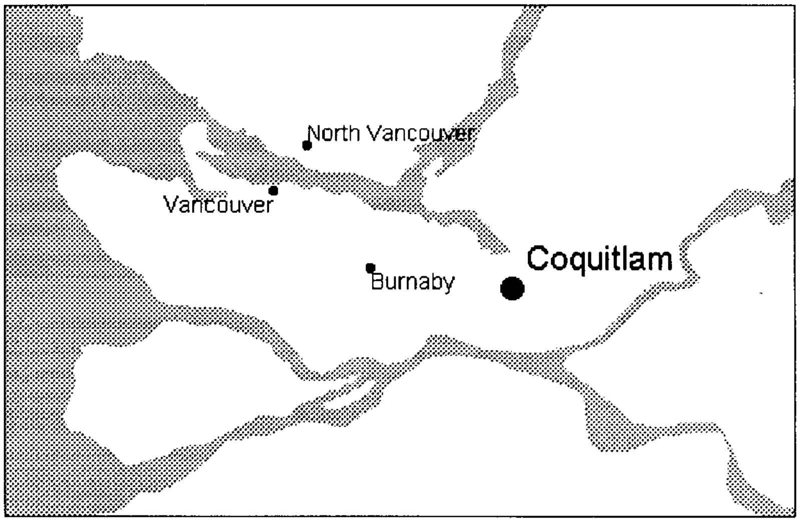

Figure 1.6-1 Map of South-western BC including Coquitlam BC.

The extraction of gravel from the riverbed had a tremendous impact on the salmon population. Gravel mining from the riverbed began in 1950 and continued till the 1960's. Pre-1950 fish populations were estimated at 2500 to 3700 chum and 1800 to 3000 pink salmon. Between 1955 and 1970, a mere 40 to 100 chum were recorded, and in 1957 (just seven years after gravel operations began) the pink salmon population was extinct (Langer 1971). The causes of the reduction in fish were threefold: gravel extraction, reduced flow from the dam, and overfishing. The main concern being gravel extraction. In 1965, the provincial court of British Columbia stopped the removal of gravel from the riverbed by means of a BC Gravel Removal Order (McLaren Hydrotechnical Inc. 1994).

Once gravel extraction was prohibited from the riverbed, gravel companies moved to the riverbanks. By 1972, suspended sediment (SS) samples as high as 200 000 mg/l were taken from the Coquitlam River just downstream of the gravel pits (Rosenau

1993b). Upstream of the gravel pits SS was between 50 - 500 mg/l during the same period. The Pollution Control Objectives for the Mining, Smelting and Related Industries of British Columbia set acceptable SS levels for the Coquitlam River in 1979. The standard of discharge was set between 25 - 75 mg/l total SS (Sigma Engineering Ltd. 1987). However, discharges above this standard were allowed during periods of 'excess runoff'. These periods are generally defined as a ten-year return event. After the implementation of this regulation settling ponds and other measures for controlling SS were devised. Minimum daily flows (1.7 m^3/s) were established after negotiations between The Department of Fisheries & Oceans (DFO) and The Greater Vancouver Regional District (Rosenau 1993a). Presently, these methods have not resolved the situation, and as a result, on going legal battles between DFO and the gravel pit operators (Jack Cewe Ltd., Allard Contractors, and Coquitlam Sand and Gravel) continue.

2 LITERATURE REVIEW

2.1 Sources of Sediment and Their Impacts

Notwithstanding the impact that human development has had on the sources of fine material to riverine habitats, two main natural pathways for fine material flow exist: (1) an instream channel source that originates from the bank and bed material, and from surrounding tributaries; and (2) non-channel sources within the catchment (Grimshaw and Lewin 1980). For in-channel sources, the supply will often be correlated with the stream discharge and the degree of bank and bed stability. However, for non-channel sources the supply varies dramatically depending on the pathway the sediment takes to the stream. Channel sources can be further broken down into: (1) river banks that are subject to erosion due to high shear and long exposure to the watercourse; (2) bar material located in erodible sections; (3) fine bed material stored within gravel interstices or from surficial deposits; (4) back water areas where flow velocities favour sediment deposition; (5) material released from macrophytic flora during their growth and decay; and (6) invertebrates like phytoplankton and zooplankton (Richards et al. 1993).

Although in-channel sources are important, in most cases, the bulk of material comes from non-channel sources. Specifically, non-channel sources include: (1) soil material within the catchment that can potentially be eroded – the pathway for this material is through gullies, rills, and other features associated with runoff erosion; (2) failure of banks or landslides and soil creep; (3) urban areas where the permeability has been altered as well as the amount of material and the time of release of that material; (4) anthropogenic sources; (5) allochthonous carbon, referring mainly to leaf litter; and (6) atmospheric deposition (Wood & Armitage 1997). Since non-channel sources must first find their way into the system before a problem can occur it is important to outline the pathway that the material will take. Basically, there are two types of pathway; one based on natural conditions and the other is based on human activities. Natural pathways contribute highly variable loads depending on the time of year and spacial considerations. For example, high loads will occur during winter storms. Because these loads occur naturally the river has adjusted over time to accommodate them. However, human induced loads are most often high when compared to natural levels and they do not coincide with the timing of natural peak loads (Wood & Armitage 1997). Davies-Colley et al. (1992) examined the suspended sediment loads entering a river after placer gold mining operations began and compared this data to undisturbed loads. They found elevated levels of SS during peak storm events, which are usually a time of fine sediment flushing.

Human activities that affect the amount of fine material entering a river include: agriculture (Walling 1990), mining (Davies-Colley et al. 1992), forestry operations (Scrivener and Brownlee 1989), urbanization including road construction (Extence 1978) and housing, and reservoir construction and flow regulation (Boon 1988). By one method or another, all of these human activities affect the hydrological, geomorphological, and ecological conditions by changing the physical conditions in such a way that runoff erosion increases and the timing of sediment delivery to the stream is altered.

Regardless of the degree of forest harvesting, an increase in the delivery of fine sediment will occur for sometime after logging. This is due to the soils reduced ability to hold water once the vegetation has been removed and the roots decay (Scrivener and Brownlee 1989). Freshly exposed soils are vulnerable to erosion and the path to the river becomes unabated. Often, forest practices include the logging of steep slopes along the banks of waterways. Once the root systems begin to decay landslides follow. Surface scour from logging roads continuously contributes sediment until the deactivated roads eventually fail. As a result, there is accelerated bank erosion due to the increased runoff and reduced infiltration (Murphy and Milner 1996). The runoff from a freshly logged forest contains a high organic content. Once this organic matter settles it is, in some instances, broken-down anaerobically. During low flow periods an oxygen shortage may occur, leading to fish kills (Mahoney and Erman 1984).

The degree of the impact timber harvesting has on a lotic ecosystem has been shown to be related to the width of the buffer zone between the logged area and the river. Davies and Nelson (1994) sampled over 45 sites, each site containing an impacted location downstream of the logging and an undisturbed location upstream of the logging. They observed a significant increase in the amount of fine material deposited in riffle / run habitats. The amount of deposition was correlated with losses in macroinvertebrate density and diversity. The degree to which a site was disturbed depended on the width of the buffer stripe left intact. Buffer strips at least 30 m wide minimized the amount of deposition and thus the impact on the aquatic community.

Agricultural activity within a watershed poses the most severe threat to an aquatic ecosystem, in comparison to any other anthropogenic disturbance. This is true for two reasons: (1) the input of suspended material occurs for an extended period of time; and (2) the particle size distribution of agricultural runoff is extremely biased toward very fine material (Walling 1990). Another important consideration with agricultural runoff is determination of the 'effective' particle size. Most fine agricultural runoff is transported as aggregate. Therefore, fine clay that normally would not settle out of suspension based on its settling velocity, deposits within the watercourse. Analysis of agricultural runoff thus requires the knowledge of aggregate size and its hydraulic dynamics (Walling 1990).. Studies show that on average only 25% of the primary clay (<4 μm) is actually reported as primary clay and the rest forms aggregates (Foster et al. 1985, from Walling 1990). The degree of aggregation and clay association with aggregates depends on the different soil types, the percentage of organic matter, and the timing of the runoff. For example, the type and size of aggregate eroded immediately following harvesting varies dramatically from the aggregates found through the growing season. Aggregation of agricultural runoff occurs more frequently than other types of runoff due to its high percentage of organic matter (Walling 1990).

Once in the water system, the problem of aggregation and deposition magnifies. An aggregate an order of magnitude larger than the individual clay particles it contains results in fall velocities of at least two orders of magnitude larger than if no aggregation occurred (Walling 1990). Therefore, a greater amount of deposition will occur than what would be predicted based on individual particle size. Determining the 'effective' particle size in the field is problematic and contains a significant margin of error. Presently, an *in situ* technique that uses a bottom withdrawal sedimentation tube technique gives a reasonable estimate (Richards et al. 1993). It is important to accurately determine the 'effective' particle size for agricultural runoff in order to assess the potential impacts and method of treatment.

The construction of a river regulating impoundment alters sediment delivery in different ways depending on the purpose of the dam. A hydroelectric dam has highly variable flows associated with its use. The high / low flows from the impoundment are not based on the hydrological conditions of the area; they are based on optimizing the amount of power generation. Flows from a dam used for water storage show moderate variations over time, thus no extreme peaks of flow events occur (Donnely 1993). In general, dams release reduced pre-regulated peak discharges and increased low flows. A large percentage of the sediment transported upstream of the impoundment will deposit within the reservoir which can lead to main channel degradation and armouring of substrate where a river retains its erosive power (Sear 1993). Reduction in peak flow eliminates the rivers natural ability to flush out deposited sediment within the armour and subsurface layers (Listle 1989). Sear (1993) examined a river with naturally high levels of SS infiltrating from tributaries and the surrounding watershed. The construction of an upstream dam made it impossible for the river to generate a large enough flow to resuspend the fine material.

2.2 Deposition of Fines

2.2.1 Intra-Gravel Flow

Flow of water beneath a riverbed provides dissolved oxygen to incubating eggs and allows for the exchange of metabolic by-products that would otherwise accumulate within the egg (Chapman 1988). The essence of intra-gravel flow is based on Darcy's Law (Freeze & Cherry 1979); the law states that the flow through a porous medium will depend on the hydraulic gradient and a constant of proportionality (hydraulic conductivity):

$$q = -K^*(dh/dl)$$

Where:

q = apparent flow

h = hydraulic head

K = hydraulic conductivity

l = distance

dh/dl = hydraulic gradient

The hydraulic gradient is the change in the hydraulic head divided by the distance the fluid has to travel through the porous medium. The greater the hydraulic gradient the greater the flow. The hydraulic conductivity is relatively high for gravel and low for clay. K is a function of both the soil medium and the fluid; by separating the individual impact each variable has on K one can further isolate the driving force behind intra-gravel flow (i.e. isolate the conductive properties of the medium from that of the fluid) (Freeze & Cherry 1979). Through experimentation, it has been found that:

$$K = C^*d^{2*}\rho^*g / \mu$$

Where: μ = dynamic viscosity

g = acceleration due to gravity

d = diameter of the grain

ρ = density of the fluid

C = constant of proportionality

The constant of proportionality (C) considers the grain size distribution, sphericity and roughness of the grains, and the nature of their packing (Freeze & Cherry 1979). Since C and d are properties of the porous medium we can simplify:

$$K = k*\rho*g / \mu$$

Where k is known as the intrinsic permeability, or simply the permeability. Therefore, when considering river water at a given temperature and density, K generally represents the permeability of the soil medium.

The process of water flowing through a porous medium is a physical one that therefore requires a potential gradient. In the case of intra-gravel flow it is the hydraulic head that determines the potential gradient and thus controls the rate of flow (Freeze & Cherry 1979). The energy (head) required for flow through a given medium is comprised of three components: a pressure, an elevation, and a kinetic component. Since the velocity through a porous medium is relatively slow, the velocity component can be disregarded, leaving:

$$h = P/\gamma + z$$

where:

h = hydraulic head

P = pressure

$\gamma = \rho*g$

z = elevation

This equation states that the amount of head available to move water through a porous medium depends on the pressure gradient and the elevation (or potential energy).

Stuart (1953) set up a tilted flume with riffle-pool sequences to determine the point where the maximum intra-gravel flow occurred and thus the maximum head loss existed. Several monometers were placed at various locations from the base of the pool to the riffle-crest. The currents measured were dependent entirely on the hydraulic conductivity, and not the velocity of the stream. The strongest current through the porous medium occurred at the riffle-crest. Riffle-pool sequences are typical of natural gravelbed rivers and it is at the riffle-crest where many salmonid species construct redds (Montgomery et al. 1995). Within a pool-riffle structure there is a downwelling current at the pool tail and an upwelling current at the riffle. The upwelling flow inhibits the deposition of fine material while still maintaining dissolved oxygen levels and aiding in the removal of metabolic by-products (McNeil 1962; Vaux 1962; and Vaux 1968).

2.2.2 Process of Fine Sediment Deposition

In order to understand the process of interstitial clogging some terminology must be made clear. Within a typical gravel-bed river there exists depth stratification. Diplas and Parker (1987) confirmed a surface bed layer known as a pavement or mobile armour, which has a coarser grain size distribution than the layers below. Under conditions that favour deposition of fines, such as low flow and backwater areas, the pavement functions as a 'sink' for fine sediment. During periods of high flows the pavement is a 'source' of fines as they are entrained into the water column by turbulence. The pavement is often referred to as the 'silt reservoir'. For complete re-suspension of settled fines the pavement must experience high energy flows which set the entire pavement in motion. The subpavement is simply the layer below the pavement; it is distinguished from the pavement by its depth in the riverbed and its smaller mean grain size. Below the subpavement is the bottom layer, which is undisturbed by spawning salmonids (Diplas and Parker 1987).

The process of fine sediment infiltration has three distinct phases that need to be acknowledged: (1) a mobile (starting) phase, where the entire gravel-bed is theoretically set in motion and all the fine material is washed from the interstitial gravel; (2) the second phase occurs during periods of low to medium flows where very fine sand and silt deposit within and below the subpavement; (3) during the third phase the pavement fills with sand and granules – essentially forming a seal over the subpavement (Schalchli 1992). The cycle is repeated once a discharge with enough energy to set the entire bed in motion can flush out the penetrated material. The amount and depth of penetration of the fine material results from the interaction between the turbulence within the river, the settling properties of the fines in suspension and the interstitial velocity, and the grain size distribution of the sediment load and gravel-bed (Lisle & Lewis 1992; Lisle 1989). Once clogging is initiated, the pore or void space within the gravel-bed begins to fill. This results in a dense packing and a compact texture (low porosity), an increased resistance to discharges, and a reduced hydraulic conductivity (i.e. permeability). Schalchli (1995) investigated how the hydraulic conductivity changed after exposing a gravel-bed to fine material. Two types of test were run using a flume and gravel from a near-by river. Test 1 observed the reduction in hydraulic conductivity with time for a given discharge, suspended load and hydraulic gradient. Test 2 observed the changes in hydraulic conductivity for an initially clogged riverbed with increasing discharges. The hydraulic conductivity was calculated using Darcy's Law.

The results from the first test showed the hydraulic conductivity only decreased in the top 15 cm (within the subpavement) but remained fairly constant below this point; this indicates a maximum depth of penetration. The maximum depth of penetration was believed to be a function of the grain size distribution of the bed load and the gravel-bed. Complete filling would occur when the grain sizes of the gravel bed is large compared to that of the bed load. Conversely, if the grain size distributions were similar, bridging between similar sized material would impede further penetration and a seal would form (Lisle 1989; and Schalchli 1992).

Test 2 results gave specific transition zones for the hydraulic conductivity, and thus the deposition of fines. The critical variable that controlled the hydraulic conductivity was again the dimensionless shear stress (Θ). Four phases were observed: (1) the clogging Phase ($\Theta < 0.056$), where the K slowly decreases from a maximum value as the result of siltation. The maximum K will occur when the gravel is free of fine material; (2) The transitional Phase ($0.06 < \Theta < 0.072$), when fines from the top layer are resuspended due to the increased energy associated with these shear stress values; (3) the flushing Phase ($0.072 < \Theta < 0.078$), where the armour layer, or pavement, breaks up and all the fines are removed from the gravel bed – the K then regains its maximum value; and (4) the mobile Bed Phase ($\Theta > 0.078$), when the entire river bed is mobilized. This phase only occurs during extremely high discharges.

The maximum depth of the subpavement depends on the grain size distribution of the riverbed and not so much on the grain size distribution of the suspended particles. The suspended material is often not in direct proximity to the riverbed and thus does not contribute significantly to the grain size distribution of the riverbed (Lisle 1989). Experiments found the depth of the subpavement to be three times the mean grain diameter of the gravel bed (Diplas & Parker 1987).

Diplas (1994) used a tilting flume to examine the process of fine sediment deposition and resuspension. An important feature of this flume study was the width of the experimental channel (0.91 m). This width allows for the natural formation of alternate bars. In a natural channel, gravel bars form on opposite sides of the channel in succession. A gravel bar has three distinct sections; each section is distinguished by its grain size distributions. The 'bar head' is located furthest upstream and contains the coarsest material. This is followed by the 'bar middle' that contains slightly finer bed material. Finally, the 'bar tail' is the furthest downstream and contains the finest bed material. After exposing the gravel bars to various concentrations of suspended loads, samples indicated that the 'bar middle' and 'bar tail' contained a much greater percentage of fine material. The disproportionate deposition of fine material that occurs as flow crosses a pool-and-riffle structure results from topographical and flow differences. The downstream end of a pool experiences downwelling currents into the gravel-bed induced by the topography. These downwelling currents favour the infiltration and deposition of suspended material. The less turbulent flow that arises downstream of a 'bar head' promotes settling of fine material. Furthermore, the streamlines at the base of a pool structure have a curvature that enhances depositional conditions (Diplas 1994).

Under medium flows the riverbed was purged of all fine material in the pavement, including fine material from the 'bar tail'. However, fines in the subpavement remained intact throughout the channel bed. As the flow increased the pavement became mobile and fines from both the subpavement and the pavement were removed. The mobilization of the armour layer can only be accomplished under flood type conditions. The large amount of energy required to mobilize the armour layer is due not only to its grain size but to the stabilizing effect of deposition of sand sized material within the pavement crevices. The infiltration and settling of fines embeds the grains of the armour layer that elevates the energy required for mobilization (Lisle 1989; and Schalchli 1995).

2.2.3 Fine Sediment Deposition Relationships

Lisle and Lewis (1992) devised a model based on a single reach of Jacoby Creek in California that links water discharge to the percent of salmonid embryo survival. Many important relationships were developed which support this link, including the role infiltration of fine sediment has on embryo survival. Water discharge values were obtained from a gauging station during a six year period. Discharges during the rainy season ranged from 0.4 to 62 m^3/s. The corresponding sediment transport rates were recorded in order to develop a predictive relationship. Sediment between 0.25 and 4.0 mm in diameter is the typical size range that infiltrate spawning gravels and this range is often transported in direct contact with the river bed. A Helley-Smith bed load sampler that had a mesh size of 0.2 mm determined the transport rates of this material. The resultant power function was:

$$q_b = (2.19 * 10^{-5}) * Q^{2.72} \qquad r^2 = 0.71 \qquad (1)$$

Where:

q_b = mean bedload transport rate per unit channel width

Q = flow

The infiltration of fine sediment within salmonid spawning gravels was then linked to the flux of fine bedload. Lislė (1989) found a power relationship existed between the volume of fine sediment that accumulates in redds of salmonids and the flux of fine bedload:

$$I = 2.03 * (q_b)_T^{0.412} \tag{2}$$

Where:

I = mean fine sediment infiltration within spawning gravel

$(q_b)_T$ = fine bedload flux per unit width

The infiltration rate of fine sediment was determined by placing sediment traps in the riverbed. The power function in equation 2 indicates that the infiltration rate decreases as the bedload transport rate increases. This is due to the progressive filling of the surficial interstices as bedload transport continues. Initially, these interstices are free of fine material and the infiltration rate is high; as bedload transport continues the rate of infiltration slowly decreases and the gravel fills with fines. The depth of infiltration is dictated by the grain size distribution of both the riverbed and the bedload material (Lisle and Lewis 1992; and Einstein 1968).

The changes in spawning gravel conditions were analyzed by two different approaches: (1) the change in the proportion of fine sediment in the gravel; and (2) a reduction in permeability (i.e. hydraulic conductivity) of the gravel. Both parameters, fraction of fines and permeability, affect the intra-gravel flow and thus the delivery of oxygenated water, and the fry's ability to penetrate the armour layer (Chapman 1988).

The particle size distribution and porosity of the spawning gravel was obtained from freeze core samples. Freeze core samples obtain gravel to a depth of approximately 0.3 m, which is the typical redd depth for steelhead trout and coho salmon (Bjornn and Reiser 1991; and Lisle and Lewis 1992). The porosity of spawning gravel was determined by the infiltration rate of fine sediment:

$$E = 0.35 - 5.0*I$$

where:

E = porosity

The permeability was calculated by Karman-Cozeny equation:

$$K = g*f(E)*D_e^2 / 36\kappa\upsilon$$

Where:

K = permeability

g = acceleration due to gravity

$f(E) = E^3/(1-E)^2$

D_e = effective grain size diameter

υ = dynamic viscosity

κ = empirically derived permeability constant, 6.4 from Johnson (1980) for spawning gravel

The apparent intra-gravel flow velocity was determined by Darcy's Law:

$$U_a = K*(dh/dl) \qquad \text{(as defined earlier)}$$

The head loss in their model was calculated for a typical riffle crest where salmonids tend to spawn, dh/dl = 0.005. From the above relationships three different embryo survival equations were determined:

$$1)\ S_1 = 167 + 46.3*\log(U_a)$$

$$2)\ S_2 = 56.8 - 0.918*I$$

$$3)\ S_3 = 56.8 - 1.964*(q_b)_T^{0.412}$$

Although these predictive equations successfully link the driving variables (water discharge and sediment transport) to the response variables (infiltration rate, porosity, percent fine sediment, and finally embryo survival), there is a large degree of variability and uncertainty associated with these linkages. For example, sediment transport is known to vary longitudinally and laterally. Moreover, using one estimate of sediment transport to obtain infiltration rates for the entire reach generates variability. Also, the infiltration rate of fine sediment and the depth to which it penetrates depends on both the grain size of the redd material and the riverbed. Einstein (1968) showed that in the absence of sand, silt and clay could successfully penetrate to the bottom layer of the riverbed. Using apparent intra-gravel flow to predict embryo survival neglects the influence of an impenetrable seal at the redd surface. This seal can prevent fry from reaching the water column (Crisp 1993). These equations are not designed to be used as a management tool but they do help in the understanding of fine sediment addition and embryo survival.

Carling (1984) observed the deposition of fine material in a flume and found the primary variable controlling deposition was the concentration of suspended sediment close to the sediment-water interface. And, of less importance, were hydraulic controls – in particular bed shear stress. The log-velocity model does not accurately predict conditions close to the sediment-water interface thus, establishing a relationship between the settling of suspended sediment and a velocity profile is not possible. Carling (1984) concluded that within the flume the deposition rates were controlled by the gross suspended sediment concentration and the exchange velocity across the 'zero' velocity plane. The 'zero' velocity plane is often situated approximately one grain diameter below the gravel surface. Other researchers (Lisle 1989, and Beschta & Jackson 1979) also found the conditions in direct proximity to the riverbed to have a direct influence on the deposition of fine material. In particular, they found that most of the infiltrating fine material (70-78%) originated from the bedload material and not from the suspended load, despite the suspended load comprising most (75-94%) of the clastic load. Bedload is defined as material >0.25 mm and suspended load as material <0.25 mm (Bagnold 1973).

2.3 Effects on the Biota

The aquatic food chain essentially consists of a three-tier pyramid with the aquatic flora at the base. Benthic macroinvertebrates use these primary producers and detritus as their food source and the resident fish population consumes them in turn.

2.3.1 Impacts on the Aquatic Flora

An increase in the concentration of suspended material inevitably reduces the amount of light penetration, and thus decreases the amount of photosynthetic activity. The degree to which reduced instream primary production impacts a river depends on its energy source, which can be either allochthonous or autochthonous. Streams enclosed by a forest canopy receive a limited amount of sunlight – this forces them to obtain their carbon source from the surrounding forest (allochthonous energy), mainly in the form of leaf litter. Larger streams have reduced riparian vegetation over head and thus receive less organic matter from their surroundings. To compensate, the aquatic flora use sunlight to generate a carbon energy source. When considering just the amount of carbon available for consumption in a given river, a well covered, allochthonous input dominated river would be less affected by increased suspended material than a river dependent on instream primary production for its energy source (Wood and Armitage 1997).

In addition to the reduced light penetration, increased suspended sediment affects primary producers in three other ways: (1) the percentage of organic matter within a periphytic cell decreases; (2) leaves and stems on macrophytic flora are stressed via abrasive damage; (3) reduced ability of algal cells to attach to substrate, and to blanket an established periphytic community (Davies-Colley et al. 1992).

The reduction in macrophytic growth with increasing levels of suspended sediment can change the hydraulic conditions in a way that further compounds the problem of increased sediment delivery. Macrophytes create areas of slow and fast moving water which increases channel roughness (Manning's n) and water depth, and increases habitat diversity (Hearne and Armitage 1993). Therefore, aquatic plant stands favour deposition in certain areas by acting as sieves thus limiting deposition of fines in other areas. Massive inputs of fines exhaust aquatic flora's ability to survive, thus eliminating this natural sieving process. In some cases only a limited increase above background levels are sufficient to reduce the amount of aquatic flora (Davies-Colley et al. 1992). The impact of alluvial mining in Alaska was investigated by Van Nieuwenhuyse and LaPerriere (1986) and they found a suspended sediment level of 200 mg/l above background caused a 50% reduction in primary production. This decline in primary production occurred despite the fact that the macrophytic community adjusted its community composition and the amount of chlorophyll *a* in each photosynthetically active cell.

2.3.2 Impacts on the Benthic Macroinvertebrates.

Throughout the course of a year fluctuations in flow cause changes to the microhabitat of benthic macroinvertebrates. The resident benthic community has adapted to these natural fluctuations over time. Along with fluctuations in flow comes fluctuations in suspended sediment load, thus the benthic community is able to accommodate increased levels of suspended material for a short duration (Graham 1990). However, long term exposure, as a result of agriculture or mining activity can change density, species richness, and community composition within the benthic environment.

The deposition and suspension of fine sediment negatively impacts benthic macroinvertebrates in four ways: (1) deposition on substrate alters its composition and suitability for benthic habitat, changing species composition and in some cases excluding all or some taxa from the area (Richards and Bacon 1994); (2) the deposition and subsequent instability associated with additional fines increases drift among the benthos (Extence 1978); (3) respiration is affected by deposition on the substrate or low oxygen levels that accompany silt deposition; and (4) suspended sediment limits the foraging behaviour of filter feeders, reducing efficiency and reducing the organic content of the available food (Graham 1990).

In general, different taxa respond in different ways to increases in suspended sediment. Some taxa can clearly survive quite well, while others are eliminated altogether. Chironomidae use deposited sediment in the construction of cases and tubes that they use for shelter; Oligochaete and Sphaeriidae prefer high suspended sediment conditions (Armitage 1995). Other taxa like mayflies and stoneflies either show reduced numbers or are absent altogether (Graham 1990). Predicting the exact direction and degree of change within a benthic community after an increase in SS is very difficult, as the change is influenced by numerous independent variables. However, a decrease in density and diversity after the addition of fine sediment is the norm. What has been referred to, as replacement faunas are taxa that either appear or increase in number after SS addition. These taxa, Chironomid larvas and oligochaete worms, prefer burrowing in soft, deposited substrates, as long as the deposited material contains some organic matter (Hellawell 1988). The identification of sensitive taxa or an indicator taxa can be useful in assessing the impact of SS on a particular river. Wagener and LaPerriere (1985) identified Acarina as an indicator organism of placer mining in Alaskan streams. They found all streams affected by placer mining to be missing Acarina from the diversity index.

A feature of survival an individual stream insect has over periphytic flora is the ability to move away from an area of poor quality; this is true for most benthic macroinvertebrate taxa. The ability of benthos to move is known as drift. The degree of movement depends on many factors including flow velocity and the specific species involved (Richards et al. 1993). Deposition of sand limits the amount of upstream drift due to the unstable conditions that follow its settling. Downstream drift, however, increases as the rate of deposition increases and the benthos search for better quality habitat (Graham 1990). An increase in rate of drift was found to occur at turbidity levels below harmful criteria thus, even though a healthy macroinvertebrate population could survive, reduction in diversity and density results.

The clogging of interstices within the gravel bed is one method of density and diversity reduction. At some time in the life cycle of most aquatic macroinvertebrates time is spent within the subsurface. The subsurface is used for shelter and protection from predators. Pugsley and Hynes (1983) found that 70% of stream insects live in the top 10 cm of the subsurface during the day and come to the surface at night. Deposition of fine material reduces flow throw the interstitial gravel and thus reduces the oxygen concentration. Invertebrates either die from the lack of oxygen or because there is a build up of metabolic by-products that can no longer are released.

Reduction in the quality of food available and the efficiency at which this food is collected are other implications of increased deposition and suspension of fines. Graham (1990) found that at even low levels of suspended sediment, the quality of periphyton available for algal grazers drops considerably. After silt was introduced the periphytic organic content fell from 52% to 22%. Also, high SS levels can clog the feeding apparatus of filter feeder's further compounding the problem (Ryan 1991).

2.3.3 Impact on fish

Any form of pollution that directly results in the decline of fish, especially salmonids, is well researched and documented. The extent of research focused on fish ecology is a direct reflection of its economical, aesthetic, and recreational value for any community and culture. From a community perspective, and in general to the scientific world, a healthy salmonid population translates into a healthy ecosystem. Ryan (1991) recognized that all anthropogenic activity directly or indirectly affects the fish population either by direct loss of habitat or via food-chain processes.

Extensive levels of suspended sediment can adversely affect the fish population in at least four different ways: (1) habitat availability is limited thereby increasing stress, making fish more susceptible to disease – one form of stress involves the clogging of gill rakers and gill filaments; (2) the deposition of SS in both surface habitat and subsurface habitat decreases the chance of egg, larvae, and juvenile survival (Chapman 1988); (3) a change the historic migratory pattern of salmonid fish; and (4) a decline in food availability in terms of reduced primary production and loss of prey habitat (Ryan 1991).

A high quality river habitat consists of many riffle, run, and pool sections. These microhabitats increase the overall habitat complexity that is necessary for a healthy fish population. Deposition of fine substrate slowly fills in these distinctive subsections; this on its own can lead to a reduction in fish diversity (Wood & Armitage 1997). Different life stages of salmonids require or prefer certain depths and flows for foraging and shelter. The high turbidity associated with increased sediment delivery results in avoidance of certain areas. Even small increases in turbidity have been known to change the swimming behaviour of salmonids. Juvenile coho salmon (Oncorhynchus kisutch) will avoid any area with suspended sediment levels greater than 70 NTU. Experimental studies that exposed coho to 100-300 NTU found the coho left altogether or died. Turbidity levels around 25-50 NTU did not elicit an avoidance response but the growth rate did decline (Boubee et al. 1997). Avoidance of highly turbid areas reduces the quality of habitat and the quantity as well, thus reducing the carrying capacity of a given reach of river. For sight feeders, the problem is compounded by a decline in the fish's ability to respond to potential food; this is known as reactive distance to prey (Ryan 1991). Further stress arises with the inevitable decline in the overall numbers of prey as the increased suspended sediment begins to impact the benthos.

2.4 Ecology of Coquitlam River Salmonids

Both anadromous and nonanadromous salmonids spend a portion of their lives within the Coquitlam River. They include coho salmon (*Oncorhynchus kisutch*), chum salmon (*O. keta*), cutthroat (*O. clarki*), pink salmon (*O. gorbuscha*), and steelhead (*O. mykiss*). The majority of the Coquitlam River salmonid stocks are maintained through the assistance of DFO Hatchery programs and local stewardship groups.

2.4.1 Timing of the Run

The timing of spawning runs varies with salmonid species and with the river system. Timing of the run is believed to be initiated by photic period; once in the river system, the initiation of spawning depends mainly on water temperature, and to a lesser extent on water level (Bjornn and Reiser 1991).

Pink salmon spawn from July to October and then die soon after. Chum salmon mostly spawn in the fall after spending 3 to 5 years at sea. There is a distinct early and late summer run of chum. Early summer chum salmon spawn from August to September; late summer chum salmon spawn from October to January. Coho salmon begin spawning in the fall and continue through to late winter. There are two runs of steelhead – one in summer and the other in winter. Summer runners spawn in June through to September whereas winter runners spawn at the end of the winter till early spring. Although presently, only a winter run of steelhead has been reported in the Coquitlam River. The only nonanadromous salmonid reported in the Coquitlam River – cutthroat trout – begins spawning in early spring and into the summer. However, cutthroats prefer smaller rivers for spawning and thus are more likely to utilize existing side-channels or suitable tributaries.

2.4.2 Spawning Requirements

All salmonids require species specific substrate, cover, water quality, water quantity, depth, velocity, and temperature range for successful spawning. Often, it is not the number of fish that limits the number of emerging fry but the quantity of quality spawning habitat (Chapman 1988); assuming the system is not perturbed by man.

The size of substrate suitable for spawning varies directly with the size of the spawning fish. A general range of material size used for most salmonids is between 1.3 and 10.2 cm. However, 80 % of this material is within a smaller size range (1.3 to 3.8 cm).

2.4.3 Redd Construction

Female salmonids excavate a pit within the riverbed by turning on their side and repeatedly beating their tail in direct proximity to the riverbed. These powerful beats generate suction within the depression causing bed material to rise into the current. The excavated material forms a mound downstream of the pit. This mound is called the tailspill (Kondolf et al. 1993). The fine substrate from the pit is carried downstream with the current. Eggs are then released into the bottom of the pit and promptly fertilized by the selected male. The female then covers the eggs by excavating another pit just upstream of the first pit. The resultant topography created by the spawning female enhances intra-gravel flow and thus helps ensure successful incubation. A single pit has four distinct strata. Firstly, there is an undisturbed layer which lies below the eggs. This layer contains the highest percentage of fines. The next layer is the egg pocket, which contains the eggs. The egg pocket is made up of one or two large stones and many smaller sized substrate. Above the egg pocket is a bridging layer; this layer is made up of material deposited by initial covering actions of the female (Peterson and Quinn 1996a). The rest of the covered material comprises a range of larger substrate.

The depth of the redd depends on the size of the salmonid and the size of the riverbed material. Generally, the larger the female the deeper the redd. Larger salmonids can move larger material (Bjornn and Reiser 1991). Table 2.4-1 lists the typical observed depth of redds for Coquitlam River salmonids.

The size of material chosen to cover the fertilized eggs also depends on the size of the spawning salmonid. Again, the larger the female the larger the material chosen for incubation (Bjornn and Reiser 1991). Table 2.4-1 lists the typical size range of material selected for incubation. Although the general size range is between 1.3 and 10.2 cm, the majority (80%) of material is between 1.3 and 3.8 cm. The larger 20% of material are found within the egg pocket to help ensure crevices exist for the incubating eggs.

Table 2.4-1 Reported redd depth and substrate size for Coquitlam River salmonids (modified from Bjornn and Reiser 1991).

Species	*Depth (cm)*	*Substrate size (cm)*	*Source*
Chum salmon	≥ 18	1.3 – 10.2	Smith (1973)
Coho salmon	≥ 18	1.3 – 10.2	Thompson (1972)
Pink salmon	≥ 15	1.3 – 10.2	Collings (1974)
Steelhead	≥ 24	0.6 – 10.2	Smith (1973)
Cutthroat trout	≥ 6	0.6 – 10.2	Hunter (1973)

2.4.4 Incubation

Survival from the initial fertilization of the egg to emergence of the fry depends on the incubation conditions experienced. Incubation conditions that influence the survival rate include dissolved oxygen levels, temperature, biological oxygen demand

(BOD) of material within the red, substrate composition, percentage of deposited fines, channel slope, channel configuration, water depth above the redd, surface water discharge and velocity, permeability and porosity of gravel in the redd and surrounding streambed, and the apparent velocity of water through the redd (Bjornn and Reiser 1991). Chapmann (1988) believes it is the availability of suitable spawning habitat during incubation that limits fry numbers and not the number of adult spawners. However, too many spawners can lead to superimposition of redds which displaces previously deposited eggs.

At the beginning of the incubation period the female can successfully purge at least 75% of the fine material from the redd (Kondolf et al. 1993). Throughout the incubation period fine material is deposited within the redd. This material alters the rate of water exchange, the concentration of dissolved oxygen available to the embryo, the exchange of metabolic by-products between egg and surrounding water, and the alevin's ability to penetrate to the surface (Chapman 1988; and Bradley and Reiser 1991). The penetration depth of the fine material as well as the amount of fine material depends on the size of the redd material, the size and quantity of the fine material, and stream flow conditions (Beschta and Jackson 1979, and Cooper 1965). Generally, the depth of intrusion of fine sediment increases as the size of the fine sediment decreases. The crevices formed between the redd material must be small enough to impede penetration to the incubating eggs. A pavement, also called armour, layer – a stratum made up of a range of matrix material that allows for tight packing of substrate – can impede fine penetration to the egg. However, a pavement layer which is too thick can make it difficult for the fry to emerge to the water column (Crisp 1993). There is a delicate balance that arises between the beneficial and detrimental impacts of an armour layer.

2.5 Criteria for High Quality Habitat

The development of a set of standards that suggest 'good' quality spawning habitat for salmonids that are applicable to different river systems and different species is a difficult task. Each river system offers slightly different conditions that influence survival to emergence. Furthermore, each genetic stock of a single species can require subtleties that greatly influence survival to emergence (McNeil and Ahnell 1964). If the assumption is made that a criterion can be applied to all river systems then the next difficulty is establishing a criterion from literature where different sampling protocols were used. Freeze core samples have been shown to be statistically unique from excavated core samples and shovel samples (Grost and Hubert 1991). However, all three sampling devices are widely used for research.

Next, the definition of material size detrimental to incubating eggs is debatable. A literature search revealed detrimental material ("fines") as being material that is <6.4 mm (Bjornn 1969; McCuddin 1977), <4.6 mm (Platts et al. 1979), <3.3 mm (Koski 1966), <2.0 mm (Hausle and Coble 1976), and <0.84 mm (McNeil and Ahnell 1964; Hall and Lantz 1969; Cloern 1976; Tagart 1976). The definition of fine material chosen for this study was <0.85 mm, based on communication with DFO, other fishery biologists, and other similar research (Tappel and Bjornn 1983; Cederholm and Salo 1979; and Cederholm et al. 1981). To be able to compare percent fines collected from salmonid spawning habitat in the Coquitlam River to other studies, not only does the sampling technique need to be similar but also, the point of truncation of the samples must be similar. The truncation point for this study was 25.4 mm. Past research that used a truncation point of 50 mm would have percent fines significantly lower than samples from Coquitlam River. The laboratory work of Tappel and Bjornn (1983) used a truncation point of 25.4 mm for research on salmonid embryo survival. Their laboratory gravel mixtures differed from natural gravel in that the experimental mixtures used contained more material in the 12.7 to 25.4 mm range than found in the field. They reasoned that the deviations from natural conditions would yield different results if the 12.7 to 25.4 mm material had negative impacts on embryo survival. At the time of the study they found no evidence that suggested this size range negatively impacted survival success. A recent review of the literature also found no evidence of detrimental effects of 12.7 to 25.4 mm material on survival to emergence. The truncation point of 25.4 mm used by Tappel and Bjornn (1983) allows for direct comparisons with samples collected from the Coquitlam River. Caution should be taken however, when applying laboratory research to field conditions.

The generally accepted maximum level of fines (<0.85 mm) above which spawning success is severely impacted is approximately 15% (Hobbs 1937; Iwamota et al. 1978; Reiser and White 1988; Bradley and Reiser 1991; Tappel and Bjornn 1983; Bjornn and Reiser 1991; and Magee and McMahon 1996). This value of 15% fines should be used with caution since these and other researchers have suggested levels as low as 4% severely lower survival to emergence. Contrary to these findings, researchers have found some species of salmonids to survive well with 14% sand within the redd (Rukhlov 1969).

Setting a geometric mean (d_g), below which spawning success is 'poor', is complicated by similar variables as those discussed for percent finer criteria. Accepting the above mentioned conditions (river system, sampling, and genetic variability), a further drawback to using geometric mean as an indicator of 'good' quality spawning habitat was shown by Lotspeich and Everest (1981). They assembled three gravel mixtures with a common geometric mean but extremely different particle size distributions. All samples had $d_g = 12.00$ mm and percent material finer then 1 mm of 0%, 15%, and 30%. Thus using d_g to assess a gravel sample's ability to support embryos from incubation through to emergence will not yield clear results. Keeping in mind the limitations of d_g as an indicator of salmonid spawning quality, research from Tappel and Bjornn (1983) suggested a d_g below 10 mm as being detrimental for survival to emergence. Whereas, Shirazi and Seim (1979) suggest a $d_g = 15$ mm was the lower limit of 'good' quality spawning habitat. Tappel and Bjornn's (1983) recommendation of $d_g =$ 10 mm for 'good' quality spawning habitat was accepted for this study due to the similar points of truncation used for determining d_g.

The Fredle Index, presented by Lotspeich and Everest (1981), is generally accepted as a better indicator of spawning quality then geometric mean. Fredle numbers represent both pore size and relative permeability, two important parameters of spawning quality. Samples collected from Phillips et al. (1975) were used to establish a relationship between survival and the Fredle index. For coho salmon, Fredle values below 3 resulted in survival to emergence near 40% whereas a Fredle value of 10 resulted in survival to emergence near 90%. For this study, Fredle values below 3 are considered detrimental to survival to emergence based on Phillips et al. (1975) and Beard and Carline (1991).

Dissolved oxygen levels believed to be sufficient for survival to emergence depend on the temperature of the water. The best possible condition is saturation. Dissolved oxygen below saturation negatively impacts embryo development (Bjornn and Reiser 1991). Embryos require different concentrations of dissolved oxygen through the various stages of incubation. Oxygen supply is critical during the early stages of incubation because the respiratory system is not fully developed, and thus not as efficient. Moreover, each species requires slightly different levels of dissolved oxygen for proper development (Bjornn and Reiser 1991). Many laboratory studies and field research have been performed to determine critical dissolved oxygen levels at various stages of development. Below 5 mg/l, fatality of most embryos is predicted to occur (Bjornn and Reiser 1991). Dissolved oxygen levels below 8 mg/l cause negative impacts to development of embryos. Improper development during incubation often translates into poor fry to adult survival (Chapman 1988). A critical dissolved oxygen level of 8 mg/l was chosen for this study. This level of dissolved oxygen during development is necessary for fry to survive to adult.

The method chosen for this study to assess relative permeability of potential spawning sites does not allow for comparison with published permeability data. The Mark VI standpipe is the generally accepted technique used to estimate spawning gravel permeability in the field. The technique used in this study to determine relative permeability could be transformed into permeability values but the differences and error associated with both techniques would not allow for reasonable comparisons.

The critical values for habitat quality, below which survival is significantly impacted are percent material finer than 0.85 mm = 15%, geometric mean = 10 mm, Fredle Index = 3.0, and dissolved oxygen = 8 mg/l.

2.6 Methods of Sampling

2.6.1 Sampling Riverbed Gravel

Many studies have been conducted which analyze subsurface riverbed material typically used by spawning salmonids. Unfortunately, no standard technique for sample collection has been used. Comparisons between field studies are only valid if all techniques used yield similar results. Presently, there are three sampling techniques commonly used for subsurface river gravel sampling. These techniques include an excavated core sampler, a freeze core sampler, and a shovel (Grost et al. 1991).

A shovel is used to collect subsurface material by forcing the blade down into the substrate to the desired depth. The shovel is then levered till parallel to the gravel bed. The sample is lifted up and out of the water for analysis. This technique is by far the least cumbersome and inexpensive way to sample subsurface material. However, during the excavation process the current potentially disturbs the sample washing fine material downstream. No vertical subsampling is plausible with this technique.

The excavated core sampler functions in the same way as an auger. A metal cylinder is worked into the subsurface to the desired depth. The cylindrical shape stops intra-gravel flow that would wash fine material downstream. Material contained within the cylinder is then scooped into a bucket and taken to the lab for analysis. Most excavated core samplers are based on the design of McNeil and Ahnell (1964). The excavated core sampler is slightly more cumbersome then using a shovel. There is potential for better representing the fine material. However, vertical subsampling of the streambed is not possible; as well, water velocity and depth (Everest et al. 1982) limit the use of an excavated corer. Extra care and experience are required to avoid under representing the actual amount of fines during extreme conditions (>60 cm) (Rood and Church 1994). Difficulty can arise with the excavated corer when spawning gravel (matrix material) is supported by large (>8 cm) clast material. Numerous attempts are often required to work the cylinder to the desired depth for a clast supported riverbed.

The initial design of the freeze corer was put forward by Walkotten (1976) and modified by Everest et al. (1980). The basic design has a single hollow steel probe with a solid steel point at the tip. The probe is hammered into the subsurface to the desired depth. The cooling medium is poured within to freeze the gravel to the probe. The cooling medium can vary between acetone-dry ice, liquid carbon dioxide, or liquid nitrogen. A freeze corer that uses acetone-dry ice requires a recirculating device that transports acetone from the dry-ice chamber down to the bottom of the probe and back to the dry-ice chamber for recooling. A less complex system is required for freeze corers that use liquid carbon dioxide or liquid nitrogen since these two cooling mediums evaporate rapidly once exposed to outside air. If numerous samples are required from remote locations it is desirable to transport the liquid CO_2 or N_2 within a pressurized cylinder. A hose and manifold assembly is then used to pump the medium down the freeze corer probe (Walkotten 1976). A tri-tube freeze corer was developed by Everest

(1980) which produces larger samples of a somewhat defined volume. The tri-tube freeze corer has three probes, all attached to each other, that form a triangle.

A major drawback of freeze corers is that they do not collect a determinate sample volume (Rood and Church 1994). Large material adhering to the probe can lead to an under representation of fine material (NCASI 1986, Klingeman 1987). Furthermore, driving the probe into the subsurface is made difficult when clast size is large. Many attempts are often required to achieve the desired depth; even greater difficulties arise when using the tri-tube freeze corer. The maximum velocity of functional operation is reported as 1 m/s. An advantage of this technqique is the ability to subsample vertically and to better repreent the fine material (Lotspeich and Everest 1981).

Grost et al. (1991) compared the three devices (shovel, excavated corer sampler, and a single probe freeze corer sampler) and found no difference between shovel and excavated corer samples. However, the freeze core samplers better represented the fine material and was distinct from samples collected with the excavated corer and the shovel.

2.6.2 Permeability and Dissolved Oxygen

Permeability, as it pertains to salmonid redd quality, is the ability of particles in the redd to transmit water per unit of time (Terhune 1958). Permeability is determined in the field by standpipes. Standpipes are metal pipes inserted into the subsurface to a desired depth. The section of pipe within the gravel is perforated. The pipe can be inserted and left for an extended period of time to allow relatively undisturbed access to the intra-gravel water. Horizontal grooves between the perforations are added to help avoid blocking by small pebbles.

The permeability of potential spawning material can be roughly estimated by relating the rate of water removal from a standpipe via pumping to predetermined relationships. Water is pumped from the standpipe into a cylinder for a given period of time to determine the amount of water collected per unit of time. Terhume (1958) determined relationships between water removal and permeability for river gravel. Another approach is to pump water out of the pipe and record the time taken for water to renter the pipe (Coble 1961). Relationships exist for both techniques to determine permeability. Although the relationships are well established caution should be taken when comparing permeabilities determined by different techniques (Moring 1982).

Standpipes, or variations of them, can also be used to determine dissolved oxygen. Once in place access to the intra-gravel water is easily obtained. The advantage of having the pipes in place over an extended period of time is having undisturbed access to the interstitial environment. Variations of the standpipes use PVC pipe, or plastic tubing attached to a peg inserted into the substrate (Jeric et al. 1995, and Peterson and Quinn 1996b). Sufficient quantity of water is withdrawn from the pipe to ensure complete flushing. A sample can then be collected from the subsurface. Slow withdraw of the sample is important in order to not disturb the intra-gravel flow. Peterson and Quinn (1996b) suggest taking at least five minutes to obtain a 125 ml sample. The sample is then sealed in a bottle and chemically fixed (American Public Health Association et al. 1989). Dissolved oxygen levels can then be determined by idiometric titration.

2.6.3 Sediment Traps

Deposition of suspended material within the interstitial river environment depends on flow conditions, river gravel size and sorting, and on the quality and size of material moving in suspension. Determining the size distribution and quantity of suspended sediment on its own, does not reveal the amount or size distribution of deposited material. Often the true suspended load does not constitute a large portion of deposited material because it is often not in direct proximity to the riverbed (Lisle 1989). The actual quantity of material deposited within the interstitial environment depends on the concentration of sediment just above the riverbed (Alonso and Mendoza 1992).

Sediment traps are used to determine the depositional processes under quasi-natural conditions. Sediment traps are containers filled with selected gravel that are buried within the riverbed. The top of the sediment trap is flush with the surrounding riverbed once properly in place. Variations in the size of gravel used within a sediment trap can be found within the scientific literature (Bartsch et al. 1996, Larkin and Slaney 1996, Larkin et al. 1998, and Davies and Nelson 1993). The size of the gravel chosen for sediment traps depends on the goal of the research. Davies and Nelson (1993) investigated the impact logging has on 1st order streams. Specifically, they were concerned with increases in material <1 mm. The gravel chosen for their study was all 2.5 cm. Larken and Slaney (1996) wanted to mimic ideal spawning gravel to determine the depositional processes that occur in a salmonid redd. Their ideal gravel was made up of 19.95 mm (50%), 9.53 mm (30%), and 4.76 mm (20%). This mixture is reflective of ideal spawning gravel (Clay 1961).

Intra-gravel flow has been shown to be a source of fine material (Lisle 1989). Sediment traps with solid walls do not allow for intra-gravel flow into the trap and thus exclude intra-gravel flow as a source of fine sediment. The influence intra-gravel flow has on accumulation within a sediment trap is not well understood. Non-permeable traps have been found to reduce the fine sediment trapping efficiency by up to 62% (Carling 1984). Material collected by solid wall sediment traps should be considered as minimum values of actual conditions (Lisle 1989). However, other researchers have found that non-permeable sediment traps collect more material over a given time period because sediment loss upon retrieval is negligible (Sear 1993).

3 METHODS & MATERIALS

3.1 The Coquitlam River

The Coquitlam River is a forth order tributary of the Fraser River; the watershed is 269.6 km^2. The reach under investigation has one main tributary, Or Creek, that joins the main stem just upstream of a small hatchery operated by DFO (Figure 3.1-1). Peak flows are dominated by winter storms with snowmelt having some influence. Minimum daily flows (1.7 m^3/s) were established after negotiations between The Department of Fisheries & Oceans and The Greater Vancouver Regional District (Rosenau 1993a).

Water contained in the Coquitlam reservoir is used for drinking and the production of hydroelectricity. Upstream of the study area industrial activity is minimal – dam maintenance and a small RCMP shooting range. Below the confluence at Or Creek a number of disturbances persist: gravel pit mining, urbanization, and concrete production. Second growth cedar and hemlock forests dominate the vegetation upstream of the study area. Alders make up a large percentage of the riparian vegetation both up and downstream of the gravel pits.

Or Creek is a third order tributary of the Coquitlam River consisting of steep slopes and large cobble/boulder substrate. This area is generally void of spawning habitat. Past logging activity within its riparian zone, along with poor logging road construction has recently and historically caused many landslides (Matt Foy, personal communication 1998). These slides deliver excessive amounts of fine material for extended periods of time.

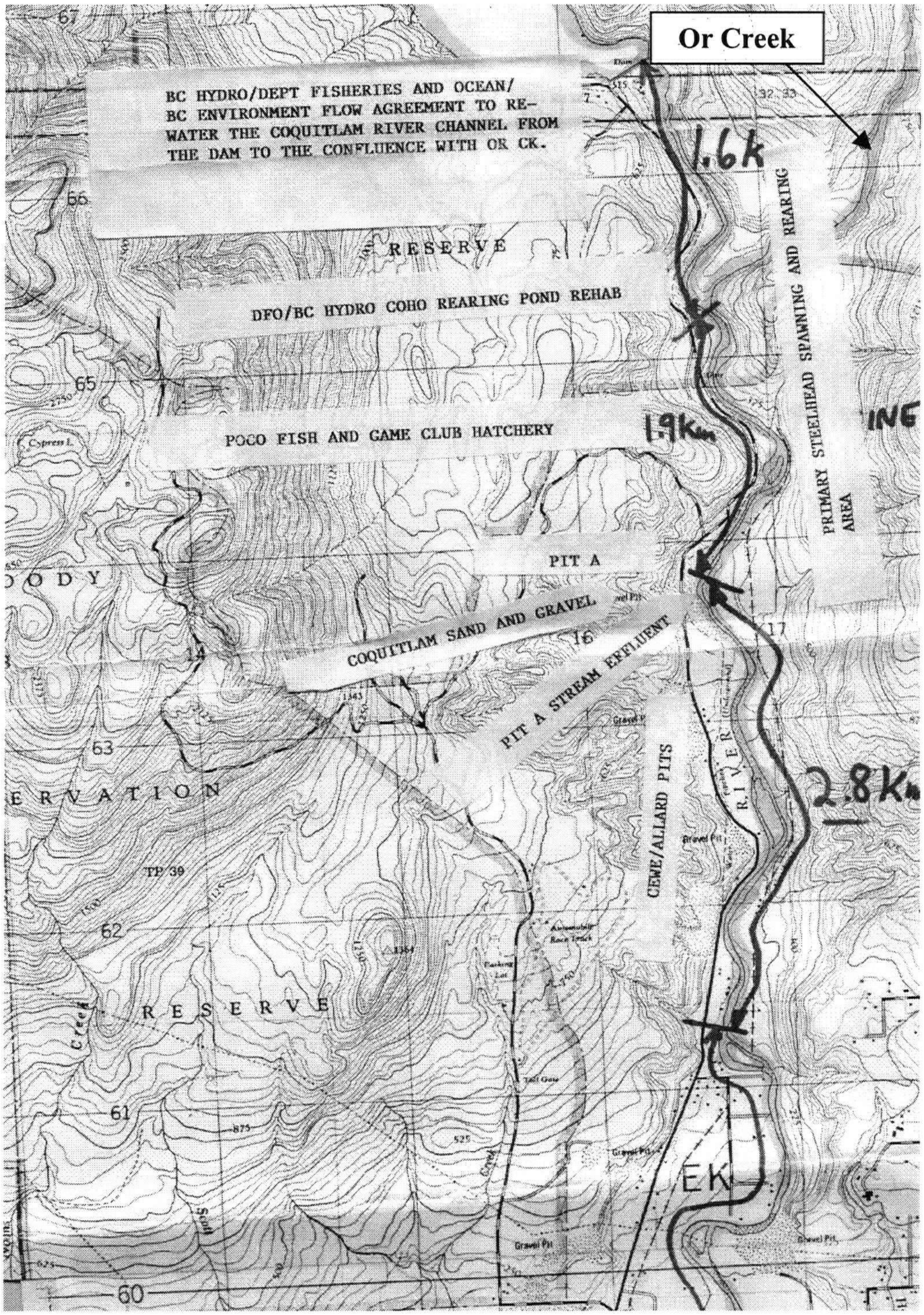

Figure 3.1-1 Map of Coquitlam River and its watershed features.

3.1.1 Coquitlam River Salmonids

A recent stock assessment of Coquitlam River salmonids by Riley et al. (1997) provides information regarding resident and returning salmonids. Currently, coho salmon (*Oncorhynchus kisutch*), chum salmon (*O. keta*), cutthroat (*O. clarki*), and steelhead (*O. mykiss*) have been observed spawning in the river. DFO has attempted to re-establish pink salmon (*O. gorbuscha*), and chinook salmon (*O. tshawytscha*) to the river. They have been only mildly successful with the pinks.

Among the six species of salmonids present in the Coquitlam River egg burial depth varies between 15 and 30 cm (Bjornn & Reiser 1991). The size of material used for redd construction varies between 13 and 102 mm; substrate in the upper end of this range is generally represented by only one or two individual rocks placed in the egg pocked. The majority of the material is made up of the lower end of this range (Peterson & Quinn 1996).

3.2 Site Selection

The consideration of river processes – such as sediment transport, deposition, and siltation – requires recognition of the different hydrological conditions within a given reach. Hydrological conditions are generally set for a particular river feature – such as pools, riffles, steps, glides, etc. A pool typically has low velocity, greater depth, and reduced sloped when compared to riffles. These hydrologic conditions favour deposition of suspended material as well as material moving as bedload. Therefore, the rate of sediment transport, degree of deposition and siltation, and the material size deposited will vary from feature to feature. Comparisons of river processes longitudinally are only valid when similar river features are considered. For this study the transitional zone between pools and riffles, also known as riffle-crests, were chosen (Figure 3.2-1).

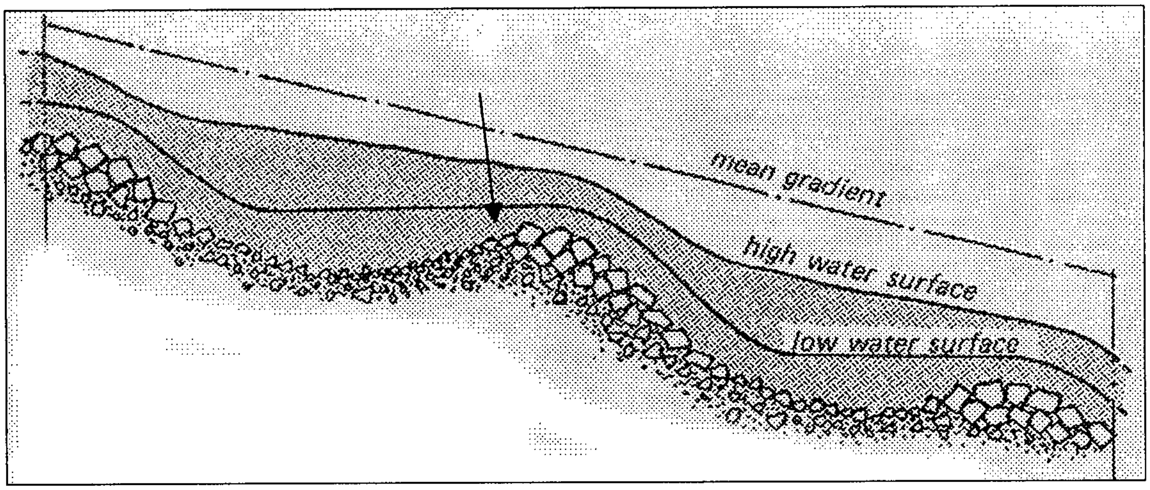

Figure 3.2-1 Cross sectional view of pool and riffle structures. Riffle-crest is indicated with an arrow (Leopold et al. 1964).

These pool-riffle transition zones have hydraulic conditions that favour the interchange of surface and subsurface water. Vaux (1962, 1968) has shown through dye studies that a concave streambed surface promotes upwelling of water currents, and a convex streambed surface promotes downwelling of water currents (Figure 3.2-2). The strongest downwelling current occurs just upstream of the riffle apex. Also, these transition zones are generally free from silt, and are loose and easily excavated (McNeil 1962).

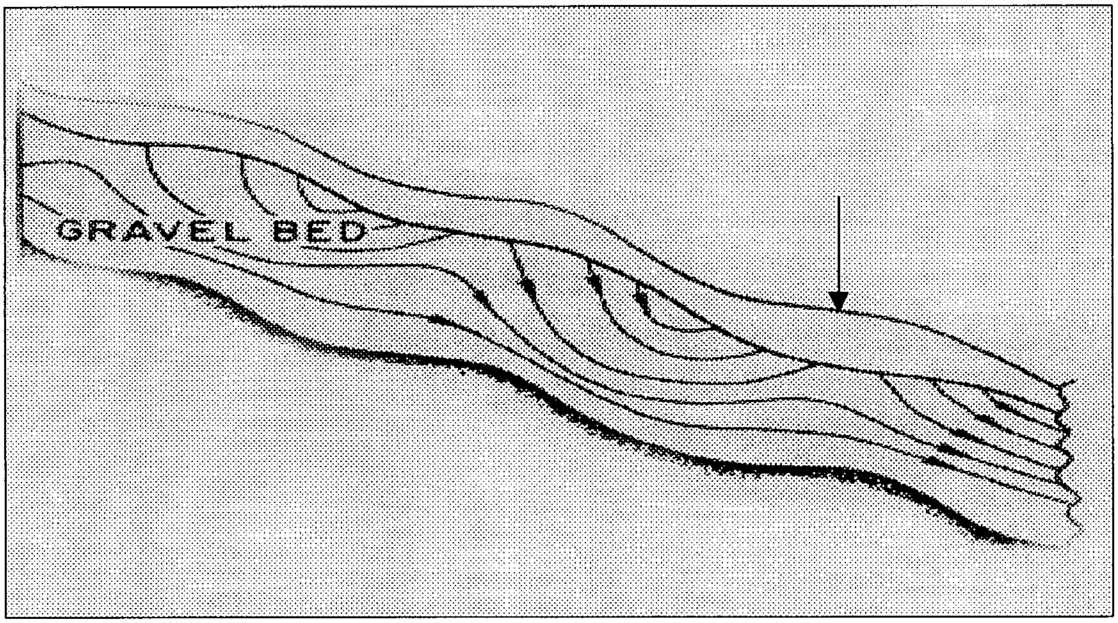

Figure 3.2-2 Pool-riffle sequence with lines showing intra-gravel movement (Vaux 1968). Arrow indicates water surface.

The downwelling currents at the riffle-crest entice salmonid redd construction (Stuart 1953). These downwelling currents ensure oxygenated water and sufficient flow for metabolic exchange reaches the incubating eggs. These zones are often void of fines that can clog subsurface gravel cutting off the supply of oxygen to ova (Vaux 1968).

3.3 Site Descriptions

Five pool-riffle transition zones along the Coquitlam River were chosen in order to represent all the various conditions – in terms of water quality. The most upstream site, designated 'GRVD', is located within the Greater Vancouver Region District restricted public access zone (Figure 3.3-1). The site is upstream of the gravel mining activity and just upstream of the confluence at Or Creek. Flows at 'GRVD' originate from Coquitlam Dam releases. These flows are no smaller than 1.7 m^3/s and do not generally exceed 3.0 m^3/s. Any flow in excess of the dam release is the result of precipitation and runoff. The distance from site 'GRVD' to the dam is approximately 1500 m. Water released from the dam is generally void of fine material due to settling within the reservoir. Peak flows, or intensive scouring flows do not occur at this site due to the dampening affect of the dam. As a result, little change in substrate size distribution, both surfically and within the subsurface, occurs throughout the year. Since this site is generally free of fine material velocities associated with the transport of fine material are not vital for flushing of spawning gravel. A large area of spawning sized gravel exists at this site. Throughout the sampling period salmon redds were observed and on occasion these redds were sampled (sampling was done at random). Typical depths and widths during sampling were 50 cm and 15 m, respectively. Fine material is generally absent from this site.

The next site in the downstream direction is just below the confluence at Or Creek and upstream of a small hatchery operated by the Department of Fisheries and Oceans (DFO); this site is designated 'U/S' (Figure 3.3-2). Both the 'GRVD' and the 'U/S' sites are upstream of all gravel mining activity. 'U/S' site flows originate from both Coquitlam Dam releases and Or Creek. The flow coming from Or Creek is approximately four times that of Coquitlam Dam releases. Thus, water quality from Or Creek dictates conditions at 'U/S'. Cobble and large gravel dominate the substrate in this area. With the exception of material close to the river's edge, spawning gravel is flushed through this riffle-crest due to the high shear stress associated with 'U/S' velocities. 'U/S' is subjected to episodic events that deliver fine material via slides along the banks of Or Creek. These slides occurred throughout the winter and were most severe during high rainfall periods. Turbid flows at 'U/S' were frequently observed throughout the sampling period. The location of the slide along Or Creek was approximately 400 m from 'U/S'. Deposition of most of the fine material at 'U/S' was assumed not to occur due to the high velocities. That is to say, velocities were such that material <0.25 mm would not settle based on gravitational processes (Bagnold 1973). An island reduced the flow at the sampling location to about 25% of the total flow. Typical water depths and widths observed during sampling were 50 cm and 10 m, respectively.

The next site in the downstream direction, designated 'S/C', is subjected to gravel pit effluent from both Allard Contractors and Coquitlam Sand & Gravel (Figure 3.3-3). This site was constructed a number of years prior by DFO in an attempt to increase spawning and rearing habitat, and is located just off the main stem of the Coquitlam River. The width at this site is considerably less than widths at all other sites (5 m). Depth of flow was also less than the other sites (30 cm). Sample location was at the riffle-crest that was downstream of three large boulders. These boulders were placed by DFO to add cover for rearing salmonids. Sample location was approximately 50 and 200 m from the gravel pit outfalls. Velocities observed at 'S/C' were the lowest of all sites.

The next site in the downstream direction, designated 'Gall', is downstream of all gravel mining activity and upstream of urbanization (Figure 3.3-4). In direct proximity to 'Gall' is a small public park utilized by many sport fishermen. The approximate distance from the nearest gravel outfall is 1000 m. The outfalls just upstream of 'S/C' are approximately 2500 m from 'Gall'. 'Gall' has the greatest width of all sites (25 m). Also, spawning sized gravel is abundant and on occasion salmonid redds were sampled through random placement of the freeze core sampler. Typical depths were 60 cm.

The site furthest downstream is designated 'Hock'; this site is below all gravel mining activity and is subjected to a limited amount of urbanization. A large island at 'Hock' was situated roughly in the middle of the river, effectively dividing the flow equally between the two channels. The width at the sample location was approximately 10 m and typical depths were 50 cm. Velocities were such that true suspended load (<0.25 mm) would remain in suspension through the sampling area.

Figure 3.3-1 Sampling site 'GVRD' looking upstream.

Figure 3.3-2 Sampling site 'U/S' looking downstream.

Figure 3.3-3 Sampling site 'S/C' looking downstream.

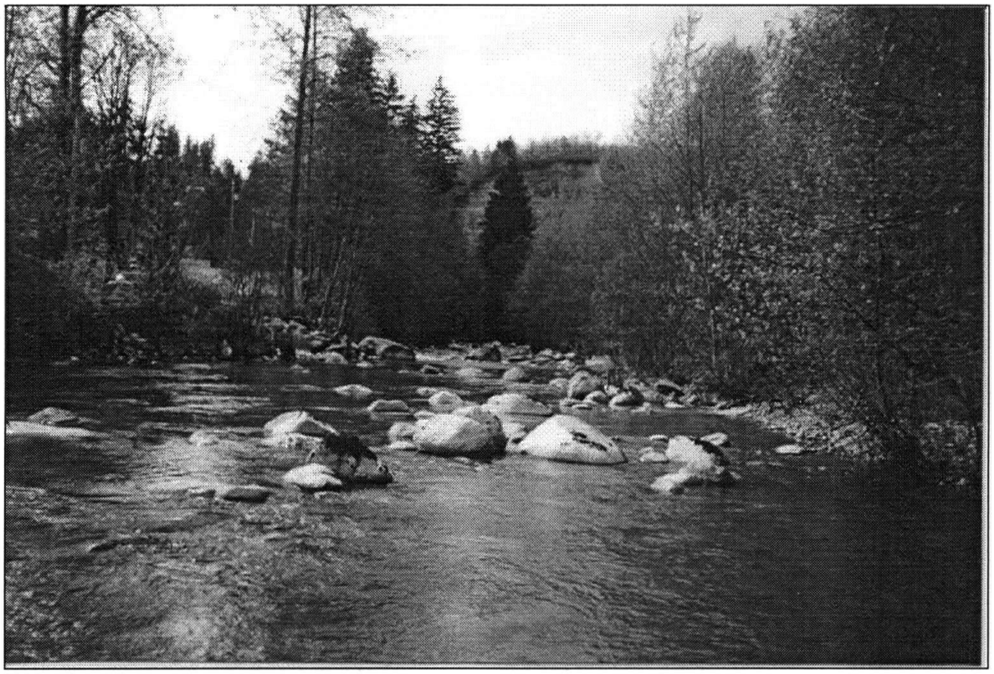

Figure 3.3-4 Sampling site 'Gall' looking upstream.

3.4 Sampling Techniques

3.4.1 Freeze Core Sampling

A freeze core sampler is basically a hollow metal probe with a solid pointed tip at the one end. The probe is hammered into the subsurface with a sledgehammer. Once the probe is in place, a cooling medium is poured within (Figure 3.4-1). The cooling medium can vary (acetone-dry ice, liquid carbon dioxide, or liquid nitrogen) depending on availability of the medium, logistics, the sample size desired, and cost (Rood &

Church 1994). Once the cooling medium has been given time to volatilize (i.e. gas can no longer be seen exiting from the opening in the probe), the freeze corer is removed from the ground with the gravel sample frozen to it (Figure 3.4-2).

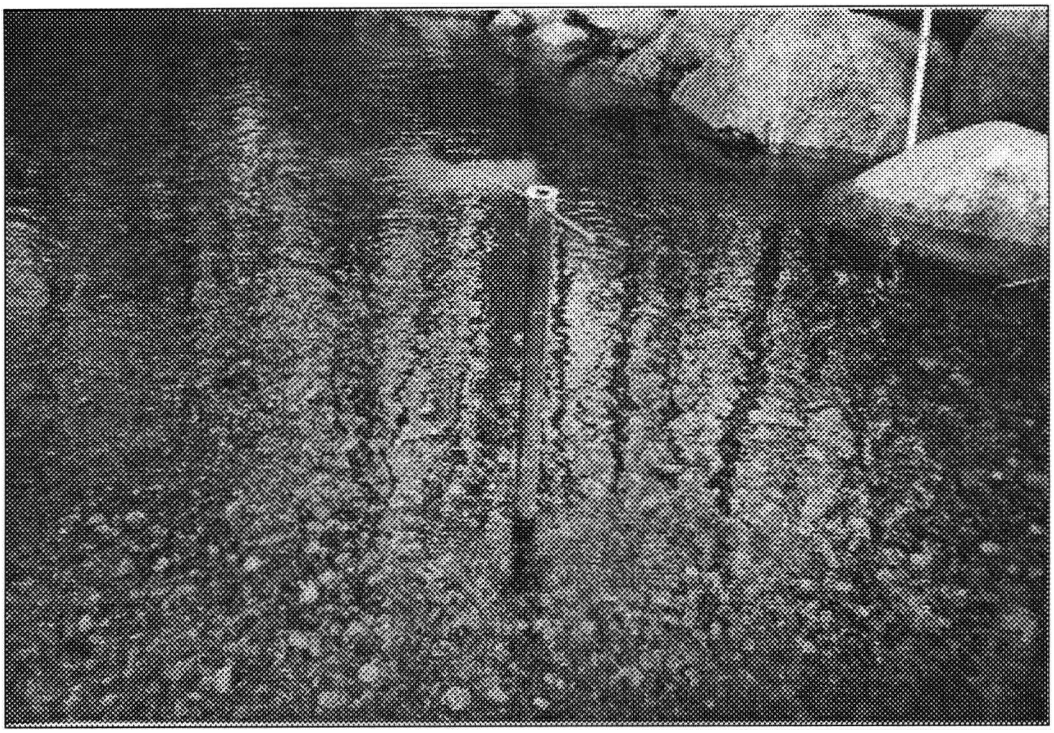

Figure 3.4-1 Freeze core probe inserted 30 cm into the riverbed at 'GVRD'. Cooling medium (liquid nitrogen) can be seen volatilising from the opening.

Figure 3.4-2 Typical sample frozen to the freeze corer after cooling medium has been added.

The design of the freeze corer used in this study was based on the modified freeze corer presented by Rood & Church (1994). The freeze corer used was 130 cm from opening to the start of the solid tip. The tip was 8 cm long; the inner and outer diameters of the shaft were 4 cm and 5 cm, respectively. Two holes, approximately 2 cm in diameter, were drilled into the sidewalls of the probe, approximately 5 cm from the opening at the top. A metal bar was then inserted to provide leverage to aid in the removal of the freeze corer with the gravel sample. Liquid nitrogen was used to freeze the subsurface gravel. Liquid nitrogen is the coolest medium available and thus provides the largest sample size. Liquid nitrogen was transported on site in a dewar flask. Initially, one 8 litre flask was used. The liquid nitrogen was poured into a metal cup (Figure 3.4-3) – approximately 2 litres per sample were used – then slowly poured into the opening of the freeze corer through a plastic funnel. The frozen gravel was dislodged from the probe with a sledgehammer and taken to the lab for analysis (Figure 3.4-4).

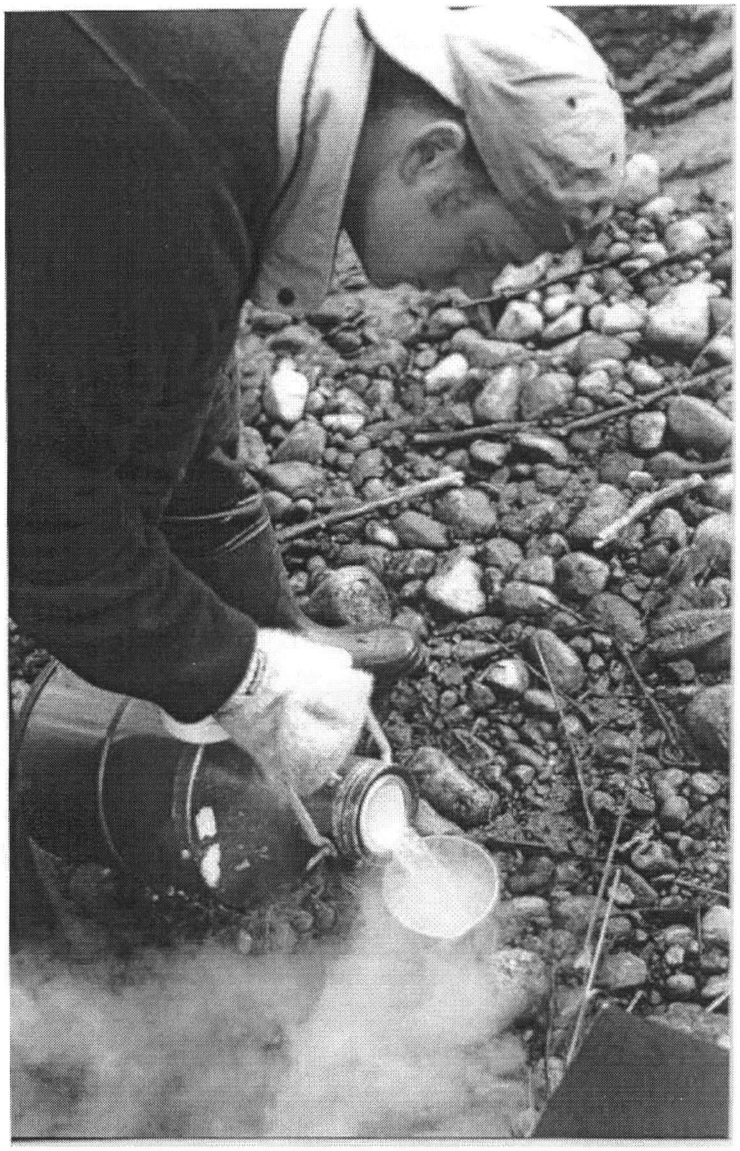

Figure 3.4-3 Liquid nitrogen being poured into a metal cup for transfer to the freeze corer.

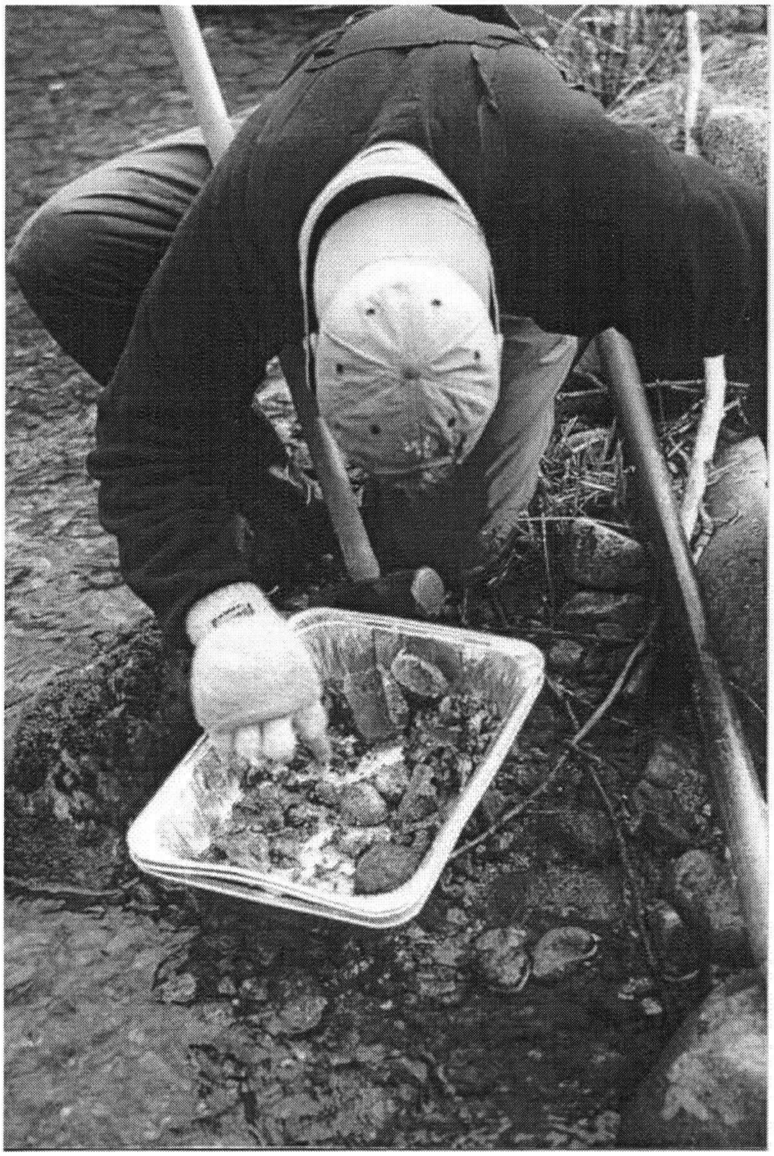

Figure 3.4-4 Freeze core sample with freeze corer to the right. Sample collected from 'GVRD'.

Once at a site (riffle-crest) the exact location of the sample was chosen based on the material surface size, i.e. if the material was usable for spawning. The total area available for sampling at a site (i.e. at one riffle-crest) varied but was around 16 m^2 for all sites. ('U/S' site had the least available sampling material). At times river water was very turbid and thus choosing a sample location within spawning sized material was done by simple trial and error. That is to say, if the freeze corer could be driven down 30 cm into the riverbed then the site was used for sampling.

A few technical problems were encountered throughout the sampling period. Firstly, as mentioned previously gravel mining from the riverbed itself removed a large portion of spawning sized gravel. The resulting situation has large cobble sized gravel being over represented. When hammering the probe into the subsurface, numerous attempts were made before the desired depth of penetration could be obtained, due to the large clast size. Secondly, often cobble-sized material would adhere to the probe. Removal of the probe from the subsurface with cobble attached made the task difficult. The probe was pushed and pulled back and forth until dislodged. The rocking motion, on occasion, resulted in lose of a sample before the probe could be removed. Loss of a sample lead to rationing of liquid nitrogen on site (due to the limited volume the dewar flask could hold). As a result, smaller then desired gravel samples were obtained. (The desired sample size will be discussed later). Lastly, winter sampling was made difficult by the high flows. A regular sampling schedule could not be maintained due to the high flows.

Sampling began on December 18/97 and was completed on April 19/98. Initially one sample from each of 'U/S', 'S/C', 'Gall', and 'Hock' was to be collected, approximately once every week. However, high winter flows either made some sites completely inaccessible or made sample logistics impossible. 'Hock' was not sampled on Dec 18/98 due to lack of liquid nitrogen on site. One sample from each site was deemed sufficient to represent the riffle-crest since the area was relatively small. Such a small area should not experience unique water quality conditions (i.e. slope, sediment size, shear stress, and velocity should be similar). Furthermore, the amount of liquid nitrogen available on site allowed for just one sample from the four sites and one extra sample if a sample was lost.

Preliminary analysis revealed a large amount of natural variation with no specific trends. At this time, approximately mid-way through the sampling period, the sampling protocol was modified from single freeze core samples at each site to three freeze core samples from each site. This change in protocol was initiated in order to perform statistical analysis with replication on the results. River processes were found to be highly variable in space, thus to truly represent the natural variation within a riffle-crest multiple samples were required.

A second change to the sampling protocol was initiated just prior to the change in number of samples collected. The reference site, designated 'U/S', was exposed to a slide that was occurring along Or Creek. This slide is believed to be the result of poor past logging practices, and thus not indicative of natural background SS levels. A new reference site was added just upstream of the confluence at Or Creek; the site was designated 'GRVD'. The limited volume of liquid nitrogen available in the field resulted in the exclusion of the 'Hock' site (furthest downstream). From March 28/98 till April 19/98, the sites sampled were 'GRVD', 'U/S', 'S/C', and 'Gall'; all sites had 3 replications per sampling date. Multiple freeze core samples were not collected from 'Gall' on April 9/98 due to equipment failure. Repeated hammering at the opening of the freeze corer confined the opening to such a degree that liquid nitrogen could not be poured within.

3.4.2 Relative Permeability

Permeability of stream interstitial gravel is related to porosity, and the size, shape, depth, and arrangement of the gravel particles (Moring 1982). As the percentage of fine material within a gravel sample increases permeability declines. In addition to using permeability as an indicator of percentage of fines, it also gives the relative level of difficulty salmonid alevins experience when attempting to penetrate through the gravel to the water column (Crisp 1993). Permeability also gives a general representation of the particle size distribution of the gravel because it is also a function of the sizes of gravel and cobble present (Moring 1982).

The true permeabilities of the sampling sites were not determined during this study. A technique was developed that offered a measure of relative permeability for site comparison purposes. To determine relative permeability a hollow metal probe 120 cm long, with an inner and outer diameter of 3.0 cm and 4.5 cm, respectively, was used. The probe was attached to a hollow, perforated pipe 25 cm long, with an inner and outer diameter of 1.2 cm and 1.5 cm, respectively. The pipe was perforated from the start of the sealed tip up 10 cm along the pipe (Figure 3.4-5). With the two pieces attached the probe was driven into the substrate with a sledgehammer until the perforated pipe was buried. This depth, approximately 30 cm, relates to the depth of salmonid redd egg pocket depth (Bjornn & Reiser 1991). Once in place an electronic depth meter (also called a water level tape) was inserted 80 cm down the probe and secured in place (Figure

3.4-6). This instrument signals with a 'beeping' sound when it is inundated. River water was scooped into a bucket and poured until the probe was just filled with water. At this time no more water was added to the probe and a stopwatch recorded the time taken for the water to be flushed out of the perforated section below the streambed. The flushing of water through the perforated section caused a drop in the water level in the column above the river water. The added water was assumed flushed to a depth of 80 cm from the pipe when the 'beeping' sound stopped. Time taken for the water level to fall 80 cm was recorded as relative permeability.

Although the change in head was held constant at 80 cm, the total head varied from site to site. The total head was considered the distance from the river water surface to the top of the probe. The maximum difference between any two sites was approximately 30 cm. A controlled test was run with a bucket of water and the probe. Two tests, one with a total height above the water level in the bucket as 110 cm, and another with 90 cm. These two tests were performed to determine the impact varying the total head had on the results. Tests with total head of 110 cm took less then 2 seconds to flush water 80 cm down the pipe. Tests with a total head of 90 cm took just over 2 seconds. Thus, it was concluded that the range of total head experienced in the field did not significantly impact the results.

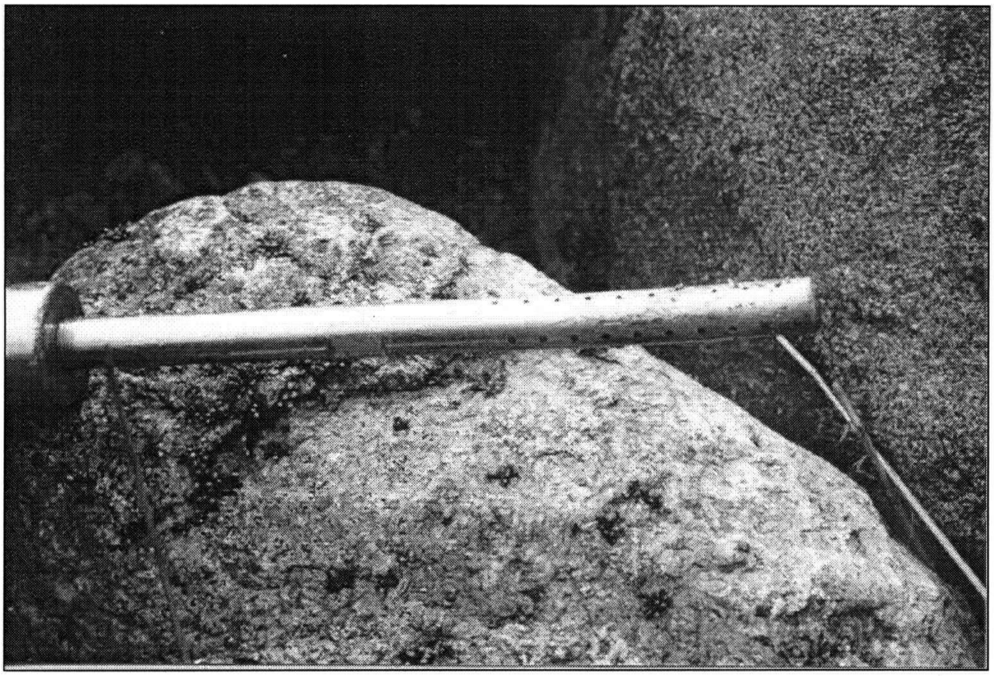

Figure 3.4-5 Probe used to determine relative permeability of interstitial gravel.

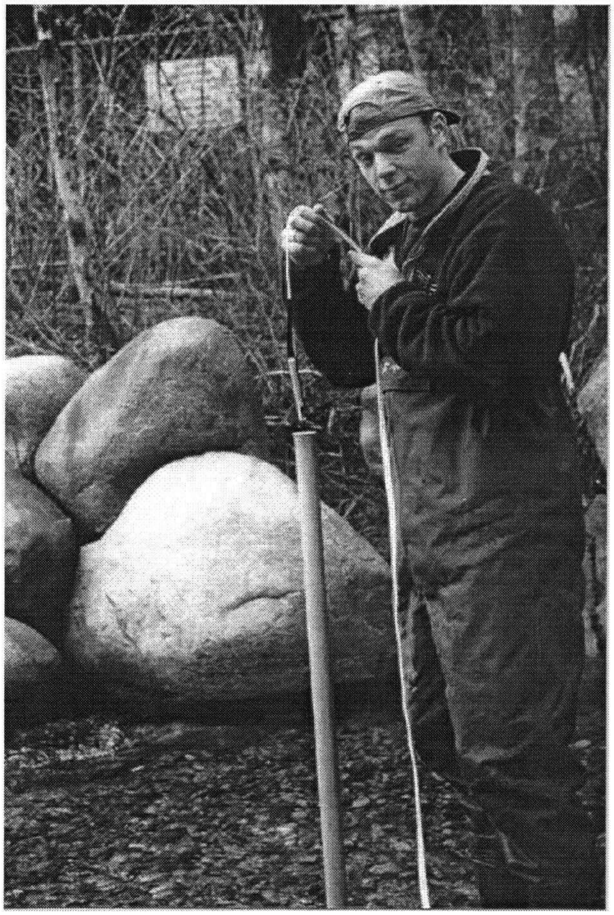

Figure 3.4-6 Relative permeability probe inserted 30 cm into the interstitial gravel. An electronic depth meter was inserted 80 cm within the probe.

At each site 5 relative permeability tests were conducted. The five locations within a riffle-crest were chosen at random. Relative permeability testing began on March 28/98 and was completed on April 19/98. Samples were collected approximately once a week. Sites used for permeability testing included 'GRVD', 'U/S', 'S/C', and 'Gall'.

The relative permeability technique developed in this study was easy to perform with two people. However, at times the perforations seemed to be clogged with fines; the replicate was still considered for analysis. This problem occurred at all sites, except

'GRVD'. Further, attempts at hammering the probe in place were often not successful the first time due to the large clast size at some sites.

3.4.3 Dissolved Oxygen

The dissolved oxygen level within the interstitial gravel provides an indication of intra-gravel flow and thus salmonid spawning success (Stuart 1953). Interstitial dissolved oxygen was measured by inserting a hollow metal probe 120 cm long, with an inner and outer diameter of 3.0 cm and 4.5 cm, respectively. The probe was attached to a hollow, perforated pipe 25 cm long, with an inner and outer diameter of 1.2 cm and 1.5 cm, respectively. The pipe was perforated from the start of the sealed tip up 10 cm along the pipe. With the two pieces attached the probe was driven into the substrate with a sledgehammer until the perforated pipe was buried. This depth, approximately 30 cm, relates to the depth of salmonid redd egg pocket depth (Bjornn & Reiser 1991). Once in place the probe filled with interstitial water to a level equal to that of the water column. A dissolved oxygen probe was then inserted within the pipe. Once the dissolved oxygen reading stabilized a recording was made. During the procedure care was taken to ensure that no surface column water entered the probe. The mixing of the subsurface and surface water would result in inaccurate interstitial dissolved oxygen readings.

At each site, 5 dissolved oxygen tests were conducted. The five locations within a riffle-crest were chosen at random. Dissolved oxygen testing began on March 28/98 and was completed on April 14/98. Dissolved oxygen samples were not recorded on April 19/98 due to equipment failure. Repeated hammering on the probe closed the opening to such an extent that the dissolved oxygen probe could no longer be inserted.

Samples were collected approximately once a week. Sites used for dissolved oxygen testing included 'GRVD', 'U/S', 'S/C', and 'Gall'.

3.4.4 Sediment Traps

A sediment trap is a bucket filled with a predetermined amount and size distribution of gravel. The bucket is placed in the riverbed for a determined period of time and later removed from the riverbed and analyzed for its additional contents.

In this study, each sediment trap consisted of a plastic bucket 17.2 cm deep with an inner brim of 21.5 cm. Each bucket was filled with a mix of three sizes of washed gravel: 19.05 cm, 9.53 cm, and 4.76 cm. The proportions used were 50%, 30%, and 20% by weight respectively. The sizes of washed gravel used as well as their proportions were taken from Larken & Slaney (1996). They chose these sizes and their respective proportions to reflect 'ideal' spawning gravel composition. Larken & Slaney (1996) used these proportions from previous work on ideal spawning gravel from Clay (1961). These proportions resulted in porosity of 0.525; determined as volume of water/volume of water and gravel.

Three traps were placed at each site ('GRVD', 'U/S', 'S/C', and 'Gall') by excavating a pit from the streambed with a shovel. Once the pit was deep enough so that the sediment traps would be flush with the streambed, gravel was placed around the sediment traps to secure them in place as a quasi-natural feature (Figure 3.4-7). The traps were placed in the river on March 20/98 and removed May 4/98 (45 days). All traps placed in the river were successfully retrieved. Removing the buckets from the river was achieved by placing a lid on the trap and then removing it from the riverbed. The lid was used to ensure no deposited material was lost (Larken & Slaney 1996).

Figure 3.4-7 Sediment traps in place at 'GVRD'.

These non-perforated sediment traps only collect materials from the surface, and exclude material transported via intra-gravel water movement. Lisle (1989) suggests that solid walled sediment traps should be regarded as minimum measures of true values.

3.4.5 Inductively Coupled Plasma

Inductively coupled plasma (ICP) is an emission spectroscopy technique developed to analyze wastewater, water, and fine sediment. ICP provides concentration of numerous metals within a sample.

Gravel pit effluent ICP samples were collected from a waste creek just upstream of the Coquitlam River confluence. Waste creeks are simply drainage ditches created and used by gravel pit operators to release effluent to the Coquitlam River. The suspended sediment samples from the waste creeks were collected with a 1 litre bottle on March 20/98. The sample was allowed to settle for one week then the remaining liquid was decanted and the sediment sample was placed in an oven at 105°C for a 24-hour period. Site ICP samples ('U/S', 'S/C', and 'Gall') were collected by sub-sampling the less than 104 μm material from March 20/98 freeze core samples. Both site and gravel effluent samples were sent to the University of British Columbia Soils laboratory for ICP analysis.

3.5 Laboratory Analysis

3.5.1 Freeze Core Sieving

Once the freeze core samples were brought to the lab they were dried in an oven at 105°C for a 24-hour period. Typical dry weight samples were 1-2 kg. Once dried the samples were placed in a series of sieves and shaken for 20 minutes to ensure proper sorting. The sieve sizes included: 25.4 mm, 19.05 mm, 9.53 mm, 4.70 mm, 2.00 mm, 1.41 mm, 0.500 mm, 0.297 mm, 0.149 mm, 0.104 mm, 0.063 mm. The remaining material was collected in a pan and re-mixed with material from the 0.063 mm sieve for further analysis (see Sedigraph Analysis). These results were used to generate particle size distribution graphs and other descriptive measures.

The freeze core samples were truncated at 25.4 mm in order to reduce the problem of non-discriminate volume samples (Rood & Church 1994). A limitation of the freeze core probe is the lack of a discriminate volume sampled. The presence of one or two large cobble/gravel size stones can lead to an under representation of the fines within the subsurface. In order to avoid this, the truncation was made. Special attention is then required to avoid collecting non-representative samples. Truncating at 25.4 mm requires a dry weight sample of approximately 1.2 kg at the 2% level for it to be representative (Church et al. 1987). The 2% level implies that one stone represents no more than 2% of the total weight of the sample. Furthermore, the truncation point of 25.4 mm is approximately the upper size range of the majority of material found in redds of Coquitlam River salmonid species (Bjornn & Reiser 1991).

3.5.2 Sedigraph Analysis

The Sedigraph 5100 particle size analysis system was used to obtain a particle size distribution for material from freeze core samples finer then 104 μm; the lower limit of detection was 1 μm. The Sedigraph 5100 analyses particle sizes based on the sedimentation method. The rate at which a particle settles can be determined by Stokes Law (Henderson 1966). Because the particle sizes are inconsistently shaped the determined size is 'equivalent spherical diameter'. Sedimentation is accomplished in the Sedigraph 5100 using a finely collimated beam of low energy X-rays and a detector to determine the distribution of particle sizes. The distributions of particle mass at various points in the cell affect the number of X-ray pulses reaching the detector. This X-ray pulse count is used to derive the particle diameter distribution (Sedigraph 5100 Micromeritics 1991). Particle size analysis as determined by the Sedigraph 5100 is considered much more accurate then laser or photoextinction devices (Church 1998, personal communication).

The Sedigraph requires 3 grams of sediment per sample. Freeze core material less than 104 μm was sub-sampled for Sedigraph analysis. The results from the Sedigraph were used to determine links between gravel effluent and the five study sites ('GRVD', 'U/S', 'S/C', 'Gall', and 'Hock'). A mixed sample from Allard Contractors and Coquitlam Sand & Gravel was taken on January 15/98. Sample was collected in a 1 litre bottle and set for one week to allow material to settle. The results showed a large percentage of the effluent sample constituted a very small size range. If deposition of gravel pit effluent were occurring within sample locations then it would be predicted that gravel effluent sized material would be over represented in the freeze core samples. A river water sample upstream of the gravel pits was also taken to determine if background material was distinct from gravel pit effluent. The river water sample was collected with three 20 litre containers. Both effluent and river water samples were allowed to sit for 1 week to permit sedimentation of suspended material. The large volume collected for the river water sample was required in order to obtain 3 grams of material for Sedigraph analysis.

3.5.3 Sediment Traps

Once the sediment traps were brought to the lab their contents were dumped into a metal tray (water included) then placed in an oven for a 48-hour period at 105°C. The extended drying period was to ensure complete evaporation of the water. Once dried a sample was placed in through a series of sieves: 4.70 mm, 2.00 mm, 1.41 mm, 0.500 mm, 0.297 mm, 0.149 mm, 0.104 mm, 0.063 mm. The remaining material was collected in a pan and re-mixed with material from the 0.063 mm sieve for further analysis (see Sedigraph Analysis). Material larger than 4.70 mm originated either from the initial mixture or from bedload movement. Bedload material was not considered for the development of particle size distributions because it does not negatively influence salmonid habitat. The weights of material collected on the sieves were used to generate particle size distribution graphs.

3.6 Descriptive Measures

3.6.1 Freeze Core Samples

Four descriptive measures were used to interpret the findings of the freeze core samples. Firstly, simple percent finer graphs were used to show the entire distribution of the sample. These graphs are commonly used to display gravel samples. Secondly, the geometric mean was determined from:

$$d_g = (d_{84} * d_{16})^{0.5} \qquad \text{(from Tappel and Bjornn 1983)}$$

Where: d_g = geometric mean particle size

d_{84} = a particle size of which 84% of the substrate is smaller

d_{16} = a particle size of which 16% of the substrate is smaller

Thirdly, the 'Fredle Index' (f_i) was determined by $f_i = d_g / S_o$

Where S_o = sorting coefficient = (d_{75}/d_{25})^0.5 (Lotspeich & Everest 1981)

The sorting coefficient utilizes d_{75} and d_{25}, which are the 75^{th} and 25^{th} percentile of the particle size distribution. f_i gives an indication of the quality of spawning gravel since d_g is directly proportional to pore size and permeability, and S_o is inversely proportional to permeability.

Finally, the percent material finer than 0.85 mm is used as one of many standard measures for comparing spawning gravel quality. The greater the percent material finer than 0.85 mm the less intra-gravel flow available to provide oxygen to incubating eggs (Tappel and Bjornn 1983; and Bradley and Reiser 1991).

3.6.2 Sedigraph

Analysis of gravel effluent and river water revealed two distinct distributions. The gravel effluent being dominated by material less then 5 μm while the river water had a more or less even distribution. Comparisons of percent finer than 5 μm between sites were made. Also, the D_{50} (size of material where 50% is finer) obtained from the Sedigraph results were used for comparative purposes.

3.6.3 Sediment Traps

Sediment collected from the sediment traps was analyzed by particle size distribution graphs, total weight of material deposited, geometric mean, and percent material less than 0.85 mm. Geometric mean (d_g) was calculated in the same manner as calculated for freeze core samples.

The Sedigraph was used to analyses material less than 104 μm. Again the descriptive measures, D_{50} and percent finer than 5 μm, were used for comparative purposes. The less than 5 μm size range was chosen because it represents a large fraction of material released from the gravel pits.

3.7 Statistical Analysis

3.7.1 Freeze Core Samples

The initial sampling protocol had one freeze core sample collected at each site. Approximately half way through the sampling period two changes were made: (1) site 'Hock' was no longer sampled and instead a new site furthest upstream ('GRVD') was sampled; and (2) sample collection was changed to three freeze core samples from each site on one sample date. A total of 12 freeze core samples were collected in one day. Statistically, this dichotomous data reduce the power of a statistical test and further complicate the statistical technique used for analysis (Zar 1974). Thus, the single sample dates and the multiple sample dates were analyzed separately.

The main approach taken for analysis was to simply compare data from each site to determine where similarity and/or differences existed. A powerful and simple parametric test available to compare means is an ANOVA. The P-value used for all tests was 0.05. The application of ANOVA requires that the error be normally and independently distributed with common variance. The assumption of normality and independence can be checked diagnostically. However, there is no way to confirm the assumption of equal variances for single sample dates (Zar 1974).

Single sample results were analyzed by a two-way-ANOVA without replication. The factors considered were site and time. Because only one sample was collected the only method of analysis was via a two-way-ANOVA. The two-way-ANOVA examines relations between sites, times, and interactions between the two. Non-rejection of the null hypothesis (all means are equal) means that the sites (times) are equivalent in terms of the variable considered (i.e. d_g, f_i, %<0.85 mm), but not necessarily at each time (site). If interactions do not exist, the conclusions can also be applied time-wise (site-wise).

Multiple sample results were analyzed by a two-way-ANOVA with replication. The factors considered were site and time. A two-way-ANOVA was used, as opposed to a one-way-ANOVA that considered each sample date separately, to increase the confidence of the analysis. Rejection of the null hypothesis indicates that the four means considered were not the same at the 95% confidence level. Rejection of the null hypothesis, however, does not suggest that all means are different from one another nor can it indicate where the differences are located. To further determine which means differed from each other multiple comparison tests were performed. Specifically, a Tukey Test was used when significant ANOVA results were found (Zar 1974). The Tukey Test tests if 'GRVD' = 'U/S', 'GRVD' = 'S/C', 'GRVD' = 'Gall', 'U/S' ='S/C', 'U/S' = 'Gall', and if 'S/C' = 'Gall'. Firstly, the means are arranged from lowest to greatest value. Pairwise differences can then be calculated for each mean pair, (i.e. $\xi_A - \xi_B$). q statistics for each comparison are then calculated by dividing the difference between means by $(s^2/n)^\wedge 0.5$, where s^2 is the error mean square from the ANOVA results and n is the number of replicates used to determine the mean.

$$q = (\xi_A - \xi_B) / (s^2/n)^\wedge 0.5$$

The calculated q is then compared to a critical value (from the F table). If the calculated q is greater than the critical value then the two means being compared are statistically different from each other. The significant level for the Tukey Test was 95%. Findings of the Tukey Test are best expressed as assigning letters to each mean. Means followed by the same letter are not significantly different at $P < 0.05$ according to the Tukey Multiple Comparison Test. Means followed by two letters (eg. 24.23 ± 2.5ab) indicates that 25.23 ± 2.5 is significantly similar to mean 'b' and 'a' but 'b' and 'a' are not significantly similar to each other.

3.7.2 Sedigraph Samples

As stated above, Sedigraph analysis uses the material less than 104 μm from separate freeze core samples. Thus, analytical techniques used for the Sedigraph results were identical to that used for freeze core analysis – single sample dates were analyzed with a two-way-ANOVA without replication, and multiple sample dates were analyzed with a two-way-ANOVA with replication. All tests were conducted at the 95% confidence interval. Significant ANOVA results for multiple freeze core sampling dates were further analyzed by the Tukey Test.

3.7.3 Relative Permeability

Relative permeability values were analyzed with a two-way-ANOVA with replication. All tests were conducted at the 95% confidence interval. Significant ANOVA results for relative permeability values were further analyzed by the Tukey Test.

3.7.4 Dissolved Oxygen

Dissolved oxygen values were analyzed with a two-way-ANOVA with replication. All tests were conducted at the 95% confidence interval. Significant ANOVA results for dissolved oxygen values were further analyzed by Tukey Test.

3.7.5 ICP

A total of eight samples were analyzed – four sites with 2 replicates. Results from each element were analyzed with a one-way-ANOVA. Elements that yielded significant results were further analyzed by the Tukey Test. Both ANOVA and the Tukey Test were performed at the 95% confidence interval.

3.7.6 Sediment Traps

The 12 traps collected – 4 sites with 3 replications – were analyzed with a one-way-ANOVA. Significant results were further analyzed by the Tukey Test. Both ANOVA and the Tukey Test were performed at the 95% confidence interval.

4 RESULTS

4.1 Freeze Cores

4.1.1 Single Sample Dates

Particle size distributions for each site ('U/S', 'S/C', 'Gall', and 'Hock') were generated by averaging freeze core results throughout the single sample sampling period (Dec. 14/97 to Mar. 14/98). Segregation of 'S/C' from all other sites occurs around the 1.41 mm grain size (Figure 4.1-1). This segregation persists through to 0.149 mm grain size. The largest difference between 'S/C' and the other sites occurred around the 0.297 mm grain size. No clear distinction can be seen between 'U/S', 'Gall', and 'Hock'. The distinction indicates that 'S/C' had more fine material than all other sites. The elevated levels of fine material renders 'S/C' 'poorer' spawning habitat when compared to all other sites.

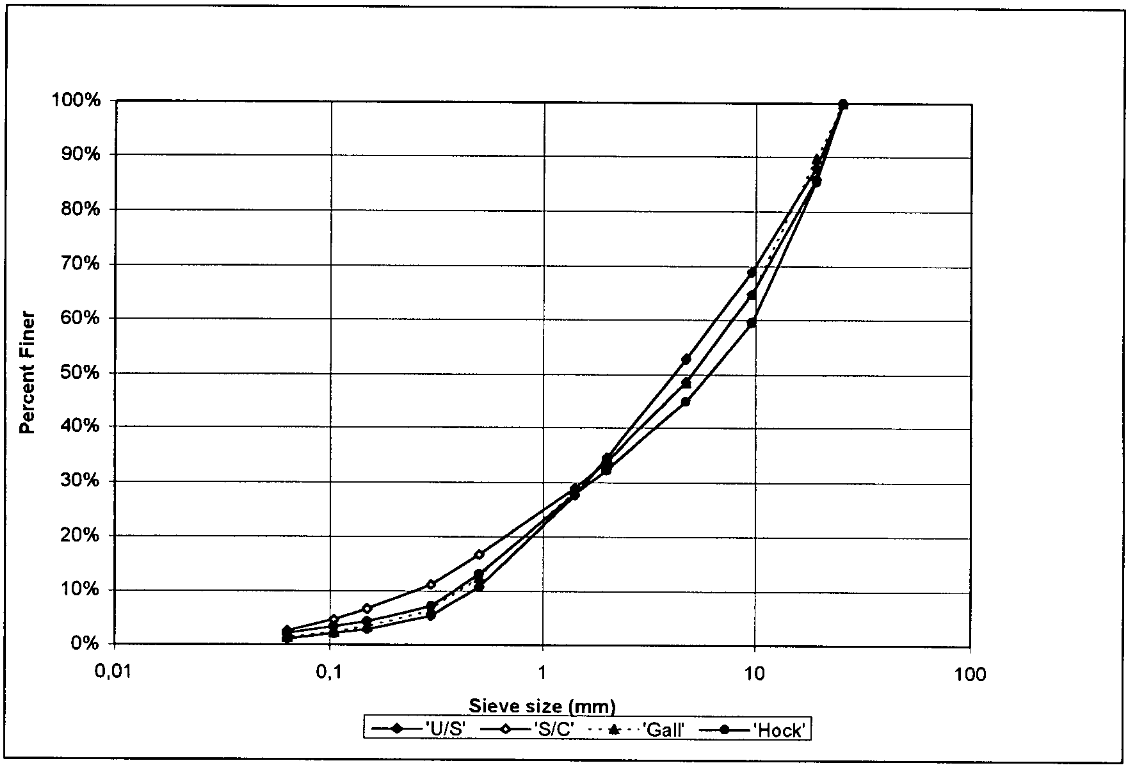

Figure 4.1-1 Average particle size distributions of single freeze core samples from all single sampling sites.

Geometric means for single sample dates did not show any consistent segregation throughout the sampling period (Figure 4.1-2). However, 'Hock' did have the largest d_g on three of the five sample dates that 'Hock' samples were collected. Statistical analysis did not support this trend nor any significant difference between sites temporally ($P_{3,15} = 0.33$). For single freeze core sampling dates 'GRVD' was only sampled once, on March 14/98. 'GRVD' had the greatest d_g (9.5 mm) when it was sampled. All d_g's calculated were below the critical level for 'good' spawning habitat.

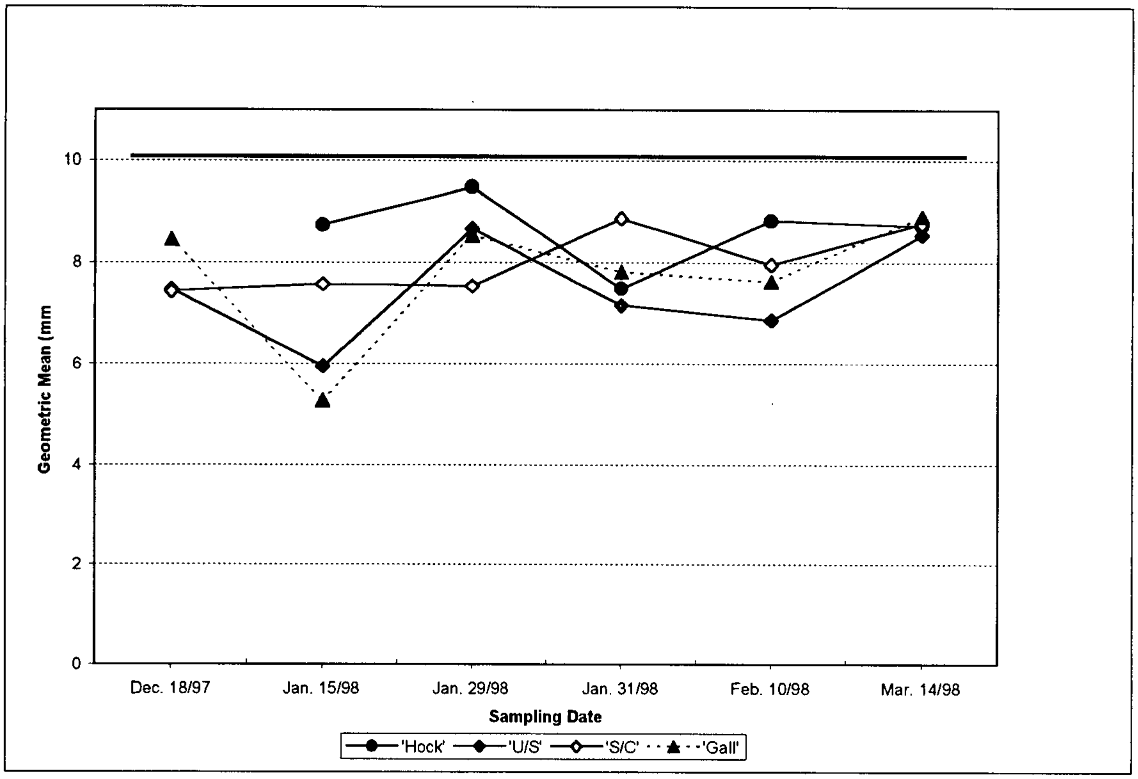

Figure 4.1-2 Geometric means as calculated from single freeze core samples plotted for six sampling dates. Bold line indicates critical level.

The Fredle index for single sample dates did not show any consistent segregation throughout the sampling period (Figure 4.1-3). Changes in f_i throughout the sampling period were not statistically significant ($P_{3,15} = 0.58$). The one 'GRVD' sample had a greater f_i value (3.8) than all other sites. 'Gall', 'U/S', and 'GRVD' each had one Fredle value that exceeded the critical level for 'good' spawning habitat.

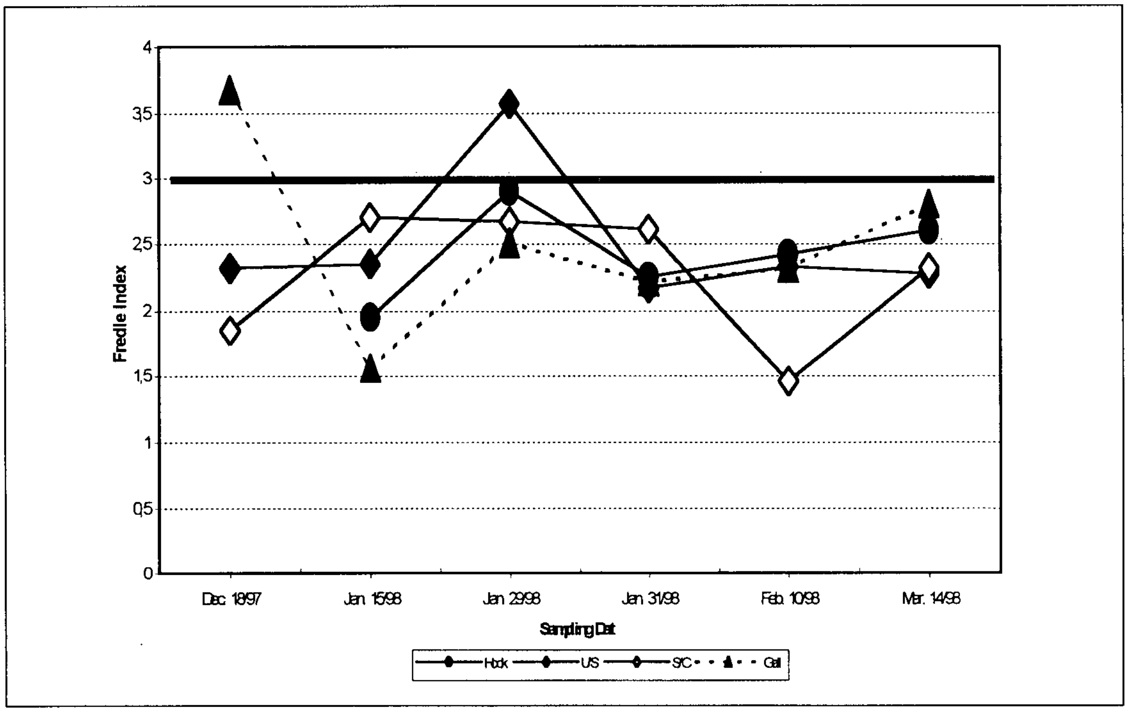

Figure 4.1-3 Fredle index as calculated from single freeze core samples plotted for six sampling dates. Bold line indicates critical level.

Although a consistent trend is hard to detect for the percent finer than 0.85 mm values obtained from single sample dates the greatest values occurred at 'S/C' on four of the six sampling dates (Figure 4.1-4). This trend was not supported statistically ($P_{3,15}$ = 0.18). 'U/S' had the least amount of 0.85 mm material on four of six sampling dates. 'Gall' and 'Hock' were generally between 'S/C' and 'U/S' in terms of the amount of 0.85 mm material. The one 'GRVD' sample had the least amount of fines (8%) for the entire single freeze core sampling period. The large values associated with 'S/C' samples indicate poorer salmonid spawning habitat compared to other sites. 'U/S' often showed the least amount of fines and thus ranked the highest in terms of salmonid spawning quality. The one 'GRVD' sample suggested high quality spawning habitat compared to the other sites. Compared to the criterion (20%), 'GRVD' and 'U/S' were consistently 'good' quality spawning habitat while 'Gall' had values below 20% on all but one sample date.

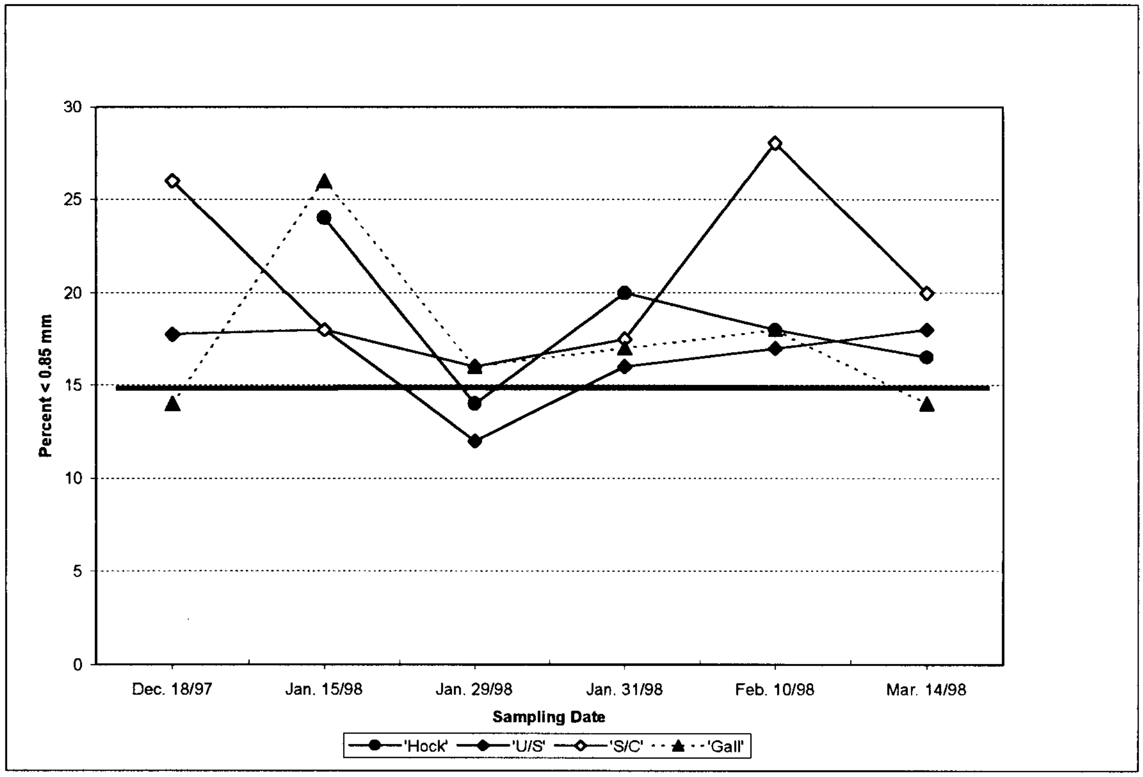

Figure 4.1-4 Percent material finer than 0.85 mm as determined from single freeze core sampling dates. Bold line indicates critical level.

Of the descriptive measures used for single sample dates only, particle size distribution graphs and percent finer than 0.85 mm suggest that 'U/S' and 'S/C' are distinct from each other. 'Hock' and 'Gall' were in between 'U/S' and 'S/C'. In order for d_g and f_i to detect significant differences between sites a greater amount of distinction is required. The overall distinction between 'U/S' and 'S/C' is such that 'U/S' contains higher quality spawning gravel then that collected at 'S/C'. The one sample collected from 'GRVD' consistently ranked it the best site for all descriptive measures considered. 'GRVD' compares well with 'good' quality spawning habitat as well (Tappel and Bjornn 1983; and Chapman 1988). No consistent trend resulted from single samples collected from all other sites. However, 'S/C' consistently had descriptive measures that rendered it as 'poor' quality spawning gravel. Percent material finer than 0.85 mm averaged 21% for 'S/C' which is beyond the critical level for 'poor' survival. Tappel and Bjornn (1983) found that material finer than 0.85 mm in excess of 20% translates into 'poor' survival to emergence.

4.1.2 Multiple Sample Dates

The particle size distributions obtained from March 20/98 showed that 'GRVD' was distinct from all other sites (Figure 4.1-5). The largest gap between 'GRVD' and all other sites occurs at the 2 mm grain size; the gap at the 1.41 mm grain size is comparable to the 2 mm gap. At grain size smaller than about 2 mm another distinction can be seen, 'S/C' plots distinctly from 'Gall' and 'U/S'. However, this separation is not as defined as the one seen between 'GRVD' and 'S/C'. The particle size distributions indicate that 'S/C' samples are of a lower quality in terms of spawning habitat; on the other hand, 'GVRD' samples had markedly higher quality spawning gravel then all other sites. Research has shown that any increase in fine material can cause severe declines in survival to emergence (Chapman 1988; and Bjornn and Rieser 1991). The critical levels chosen for this study mark the point where survival is not likely to occur; elevated levels of fines from one site to another directly translate into reduced survival to emergence.

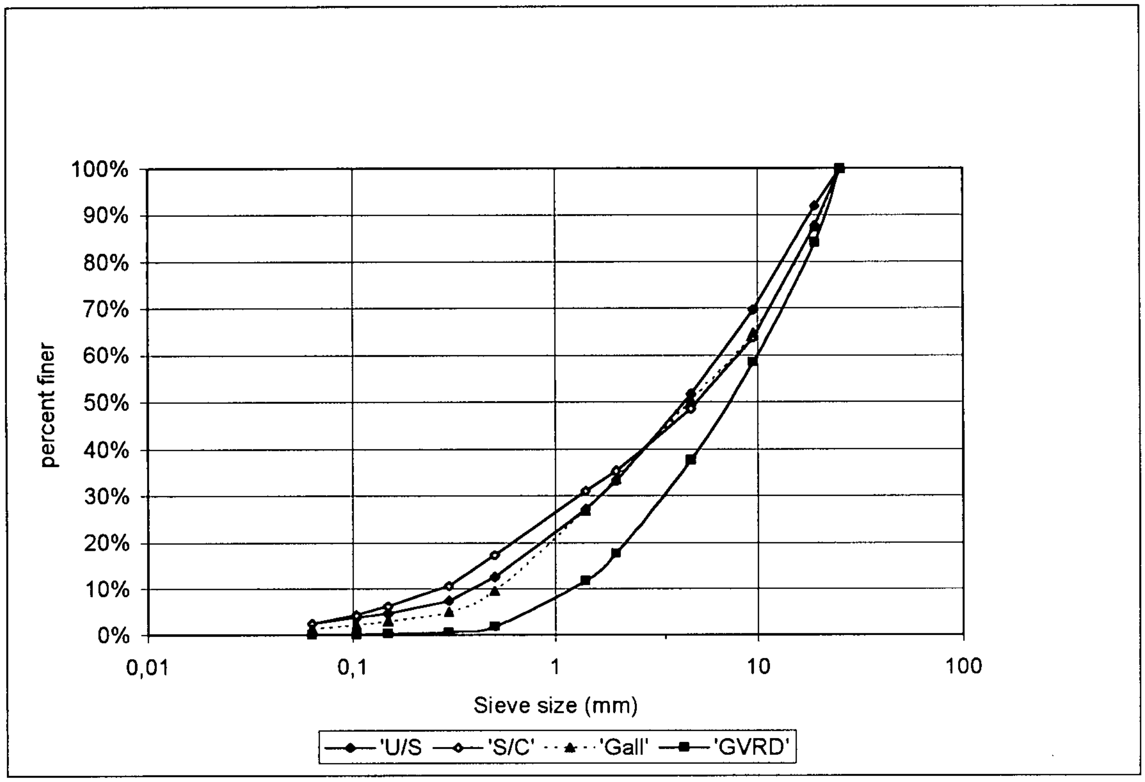

Figure 4.1-5 Average particle size distributions of interstitial material for all rifle-crest sampling locations on March 20/98.

The particle size distributions obtained on April 2/98 do not show a smooth transition throughout the distributions (Figure 4.1-6). The irregular shape of the particle size distributions from 2 mm to 1.41 mm indicates a large amount of material present in this range. The drop is most pronounced for 'Gall' and 'GRVD', but it can be seen for all sites. From grain size less than 1.41 mm a distinct segregation in particle size distribution between 'S/C' and 'Gall'/'GRVD'. 'U/S' also shows a different distribution from that seen at 'S/C' below 1.41 mm but it is not as pronounced as that seen with 'Gall' and 'GRVD'. Overall, spawning gravel quality is higher at 'GRVD' and 'Gall' (and at 'U/S' to a lesser extent) than the samples collected at 'S/C'.

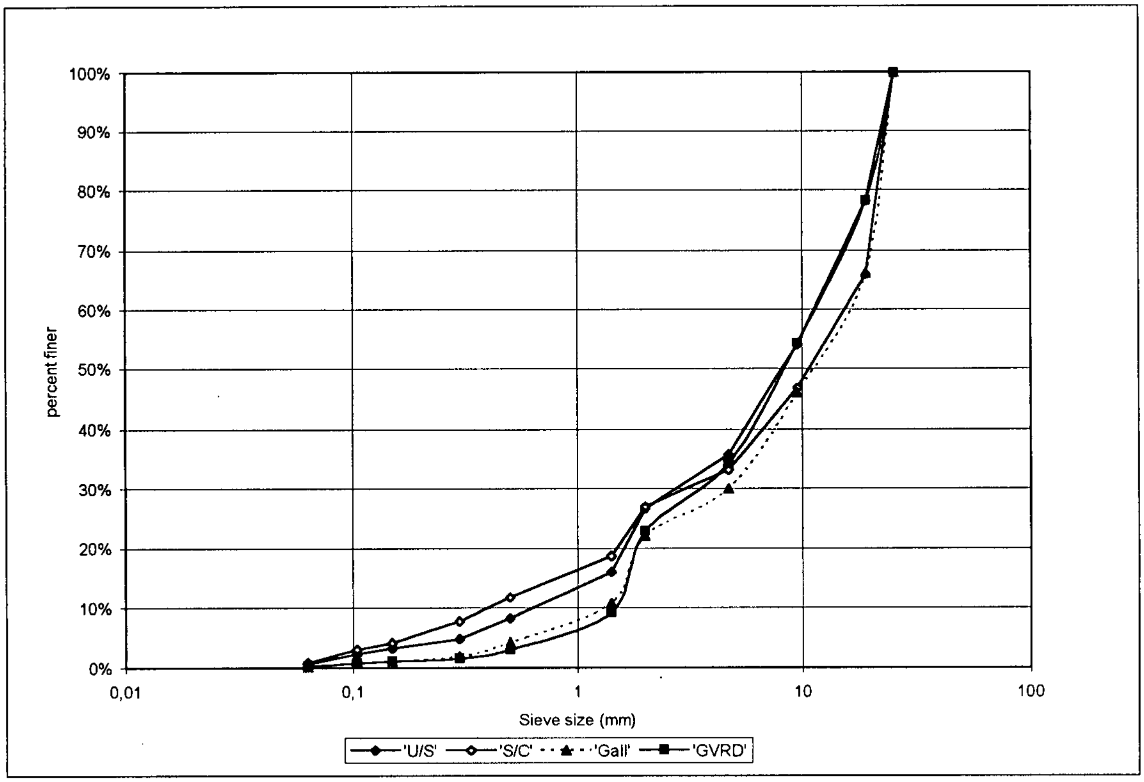

Figure 4.1-6 Average particle size distributions of interstitial material for all rifle-crest sampling locations on April 2/98.

The particle size distributions obtained on April 9/98 do not show a smooth transition throughout the grain size (Figure 4.1-7). The irregular shape of the particle size distributions from 2 mm to 1.41 mm indicates a large amount of material present in this range. The drop is most pronounced for 'GRVD', but it can be seen for all sites. Separation occurs between 'S/C' and the other sites beginning at the 9.5 mm grain size and persisting until 0.104 mm grain size. From 1.41 mm till 0.104 mm grain size 'U/S' plots distinctly from 'GRVD'. The difference between 'GRVD' and 'U/S' is not as pronounced as that seen between 'S/C' and all other sites. Overall, 'S/C' again had the poorest quality spawning gravel when compared to the other sites. 'GRVD' and 'U/S' appeared similar for most of their distributions but were both distinct from 'S/C'.

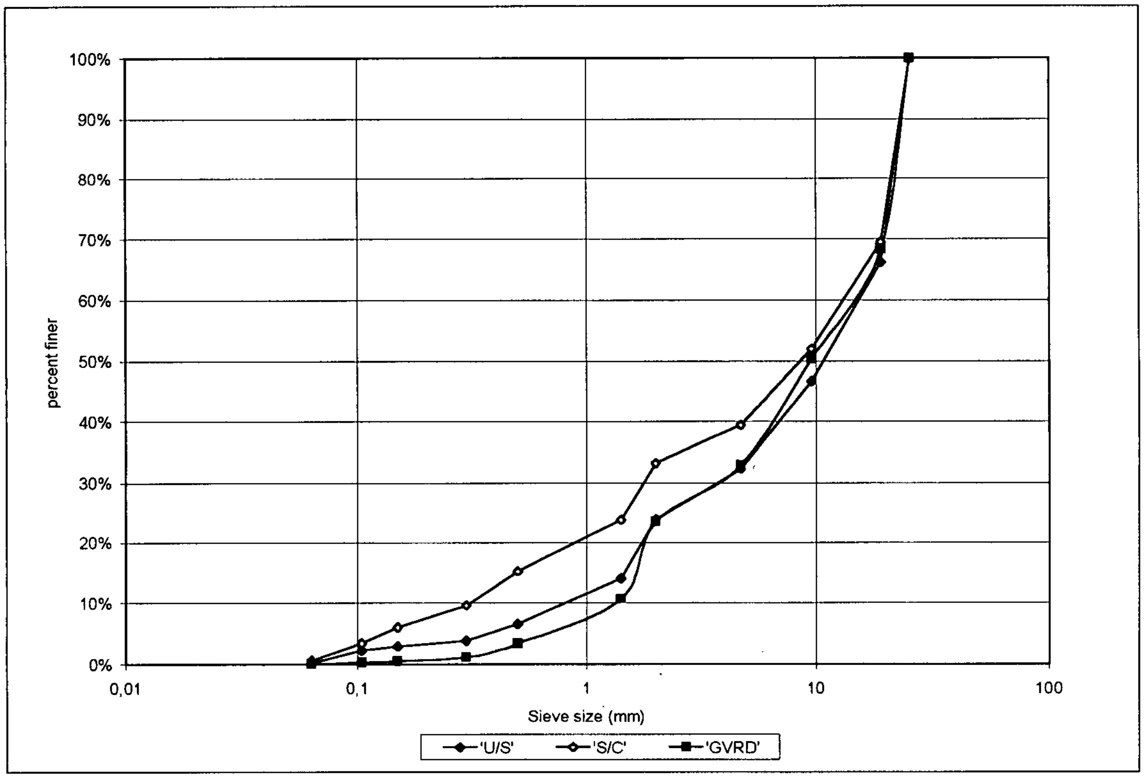

Figure 4.1-7 Average particle size distributions of interstitial material for all riffle-crest sampling locations on April 9/98.

The particle size distributions obtained on April 14/98 do not show a smooth transition throughout the grain sizes (Figure 4.1-8). The irregular shape of the particle size distributions from 2 mm to 1.41 mm indicates a large amount of material present in this range. The percentage drop appears similar for all sites. 'GRVD' and 'U/S' plot distinctly from 'S/C' beginning at 1.4 mm grain size and continuing through to 0.104 mm grain size. There is virtually no separation in particle size distribution from 25.4 mm down to 9.5 mm grain sizes for all sites. The poorest site in terms of spawning habitat was 'S/C', where as the best sites are 'U/S' and 'GRVD'.

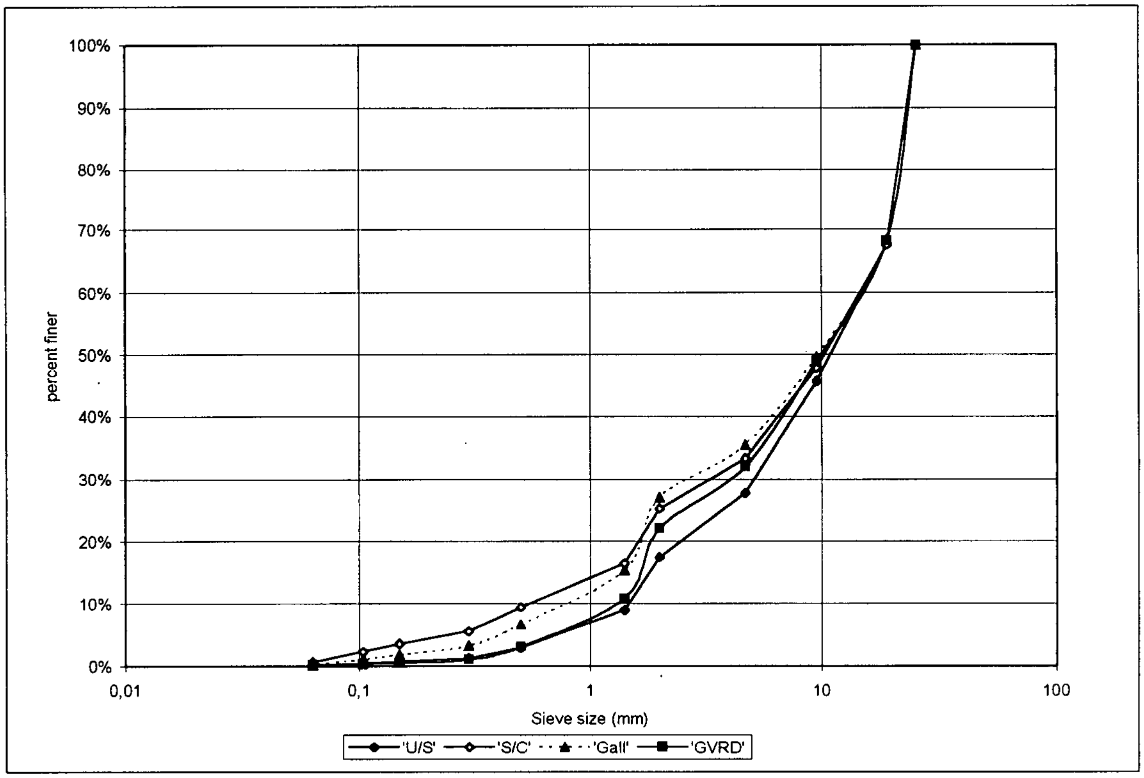

Figure 4.1-8 Average particle size distributions of interstitial material for all riffle-crest sampling locations on April 14/98.

The particle size distributions obtained on April 19/98 do not show a smooth transition throughout the grain sizes (Figure 4.1-9). The irregular shape of the particle size distributions from 2 mm to 1.41 mm indicates a large amount of material present in this range. The percentage drop appears similar for all sites. 'GRVD' begins to plot distinctly from all other sites at 19.0 mm down to 0.104 mm grain size. The largest gap between the two sets of particle size distributions occurs at 2 mm grain size. The gap present between 'GRVD' and the other sites at 1.41 mm is less, but comparable to that observed at the 2 mm grain size. 'U/S', 'S/C', and 'Gall' are virtually identical throughout their entire particle size distributions. All three are of substantially lower quality then 'GRVD' in terms of spawning habitat.

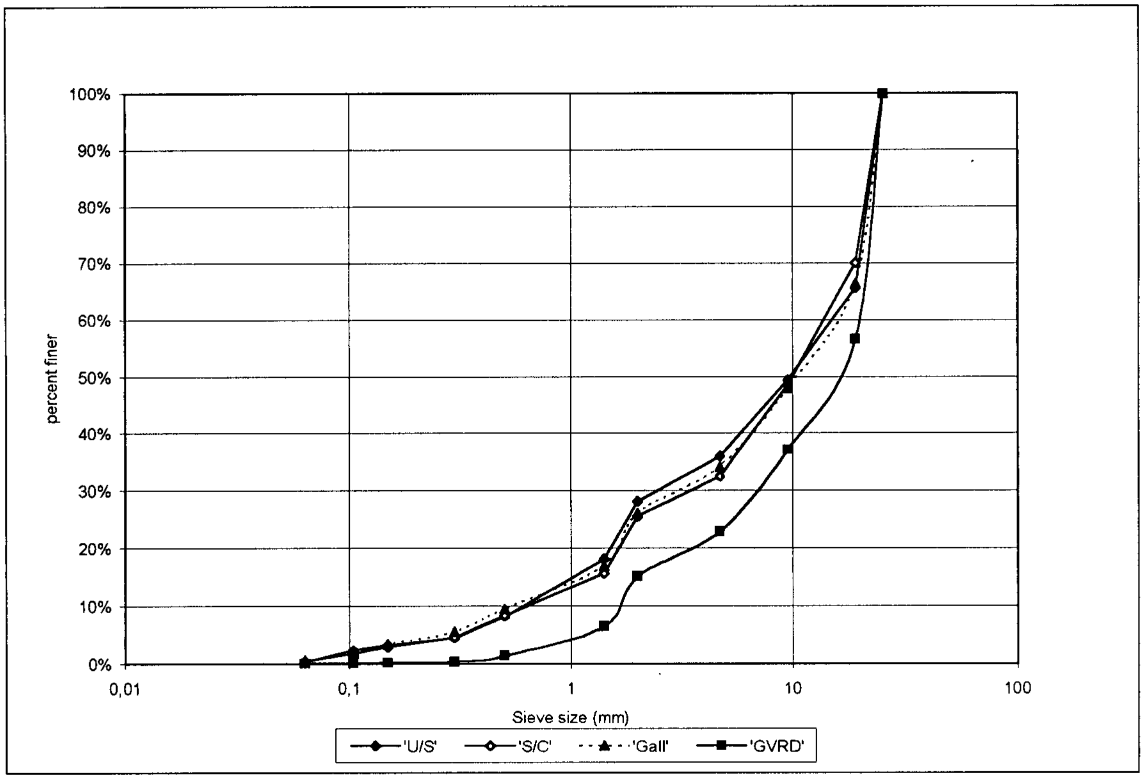

Figure 4.1-9 Average particle size distributions of interstitial material for all riffle-crest locations on April 19/98.

Geometric means for multiple freeze core samples plotted temporally did not consistently show the trend of 'S/C' being unique in terms of grain size (Figure 4.1-10). However, 'S/C' never had a d_g markedly larger than the other sites. For all sample dates, with the exception of April 2/98, either 'GRVD' or 'U/S' had the largest d_g. This is consistent with the particle size distribution plots in that 'GRVD' and 'U/S' showed distinct differences in terms of grain size distributions. The overall inconsistency observed with d_g values for various sites resulted in no statistical significant difference between sites through time ($P_{3,32} = 0.19$). That is to say, differences between sites on a given sample date were not maintained statistically. Most sites were associated with small standard deviations suggesting that d_g may not be a good descriptive measure for comparing gravel sample distributions.

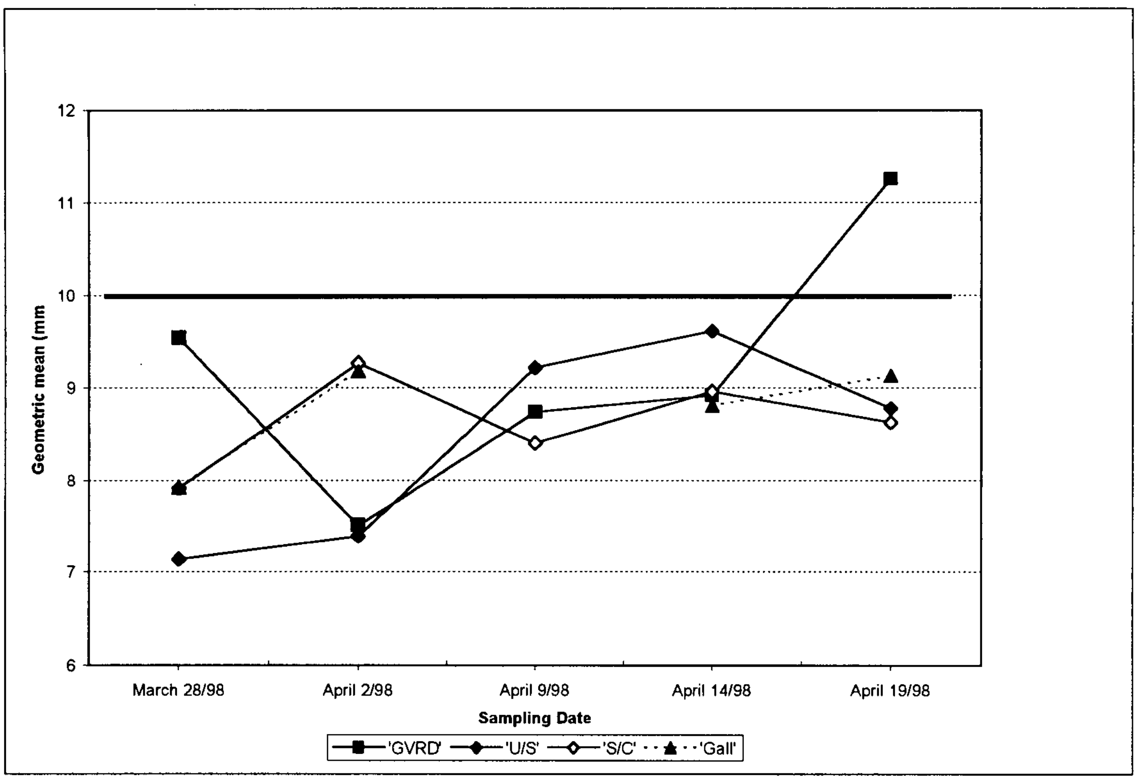

Figure 4.1-10 Geometric mean as calculated from multiple freeze core sampling dates. Sampling sites include 'GVRD', 'U/S', 'S/C', and 'Gall'.

The Fredle index for multiple freeze core samples plotted temporally did show the trend of distinction between 'GRVD' and 'S/C' (Figure 4.1-11). Statistical analysis also verified this distinction on four of the six sampling dates (Table 4.1-1). 'GRVD' most often had the largest f_i throughout the sampling period. 'S/C' was consistently associated with lower f_i as compared to other sites. A dichotomous set of distributions, 'S/C' and the others sites, was not as pronounced as observed from most of the particle size distribution graphs. Only on April 9/98 was site 'S/C' distinct from all other sites. The f_i gives an indication of spawning quality, i.e. the larger the value the higher the quality gravel. The f_i values obtained reinforce the trend of 'GRVD' and 'U/S' as being superior to 'S/C' in terms of quality spawning habitat. 'GRVD' consistently had f_i values above or close to the critical value. 'S/C' had only one sample date above the critical level.

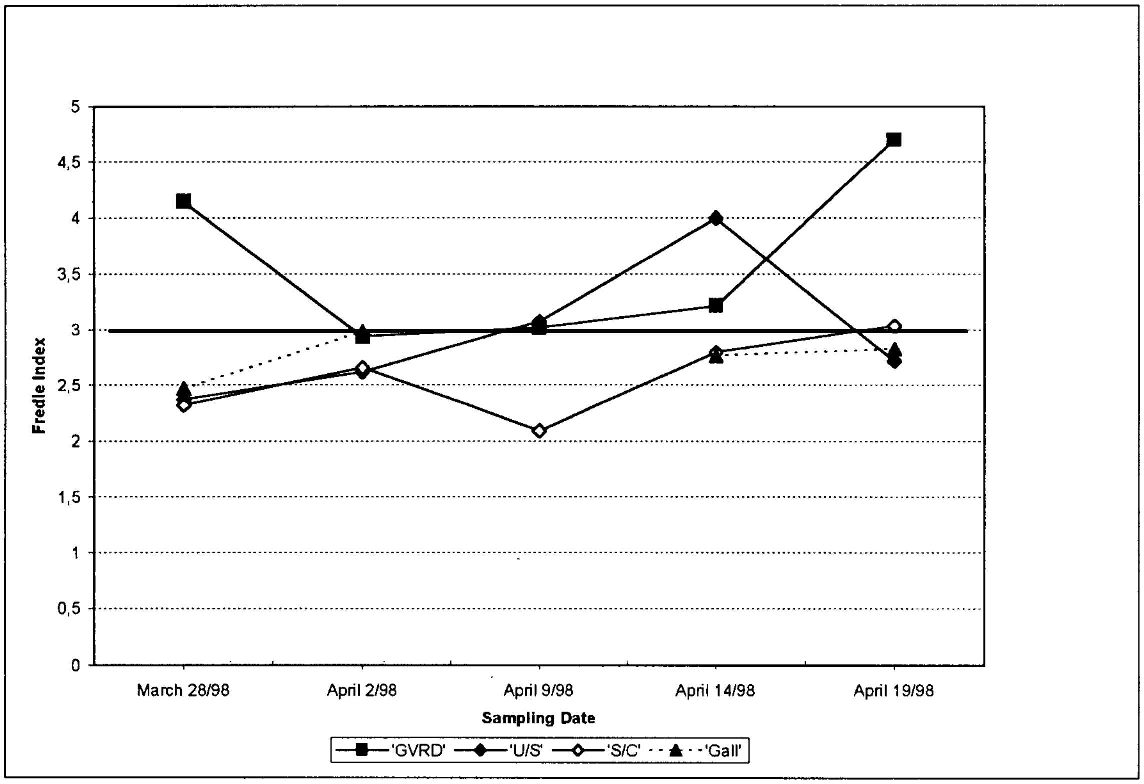

Figure 4.1-11 Fredle index values as calculated for multiple freeze core sampling dates. Sampling sites include 'GVRD', 'U/S', 'S/C', and 'Gall'. Bold line indicates critical level.

Table 4.1-1 Fredle index values as calculated for multiple freeze core sampling dates.

	Sampling Date				
Sites	**28-Mar**	**2-Apr**	**9-Apr**	**14-Apr**	**19-Apr**
'GVRD'	4.14 +/- 0.26a	2.94 +/- 0.66a	3.02 +/- 0.54a	3.22 +/- 0.87a	4.70 +/- 0.20a
'U/S'	2.37 +/- 0.35b	2.62 +/- 0.42a	3.08 +/- 0.49a	4.00 +/- 1.08b	2.72 +/- 0.45b
'S/C'	2.32 +/- 0.36b	2.66 +/- 0.37a	2.09 +/- 0.45b	2.80 +/- 0.27a	3.04 +/- 1.06b
'Gall'	2.47 +/- 0.21b	2.99 +/- 0.21a	N/A	2.77 +/- 0.38a	2.83 +/- 0.39b

Note: Means in each column followed by the same letter are not significantly different at P < 0.05 according to Tukey Multiple Comparison Test.

The percentage of material finer than 0.85 mm plotted temporally does show trends similar to those seen with particle size distribution graphs and f_i values. 'S/C' often had the largest amount of fine material where as 'GRVD' often had the least amount of fine material (Figure 4.1-12). On average 'S/C' had approximately 11% more fine material than did 'GRVD'. 'U/S' amount of fines was often less then 'S/C' values (4 of 5); 'Gall' also had typically lower amounts of fines then 'S/C'. Statistically, 'GRVD' was always different from 'S/C' (Table 4.1-2). 'U/S' was statistically different from 'S/C' on two of six sampling dates. 'Gall' statistical results did not show any strong association with any of the other sites. Again, 'S/C' was shown to be of significantly lower quality in terms of spawning habitat as compared to critical values, i.e. 4 of 5 sample dates were above or near the critical limit.

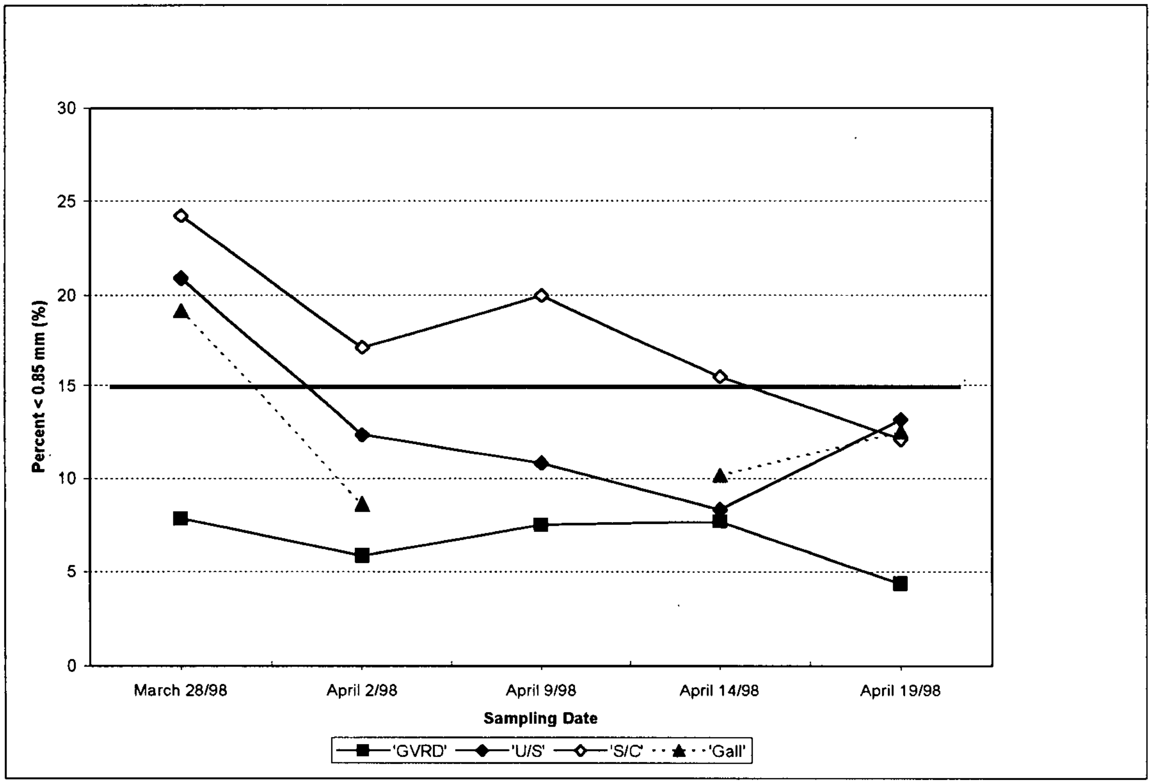

Figure 4.1-12 Percent material finer than 0.85 mm as determined for multiple freeze core sampling dates. Sampling sites include 'GVRD', 'U/S', 'S/C', and 'Gall'. Bold line indicates critical level.

Table 4.1-2 Percent material finer than 0.85 mm as determined for multiple freeze core sampling dates.

			Sampling Date		
Sites	**28-Mar**	**2-Apr**	**9-Apr**	**14-Apr**	**19-Apr**
'GVRD'	7.83 +/- 1.44a	5.84 +/- 2.89a	7.50 +/- 3.77a	7.67 +/- 3.18ab	4.33 +/- 0.29a
'U/S'	20.90 +/- 2.29bc	12.33 +/- 3.21b	10.83 +/- 3.21a	8.33 +/- 1.53a	13.17 +/- 3.21b
'S/C'	24.23 +/- 2.52ba	17.17 +/- 2.89b	20.00 +/- 4.00b	15.50 +/- 2.60c	12.10 +/- 6.06b
'Gall'	19.17 +/- 1.26c	8.60 +/- 5.02ab	N/A	10.16 +/- 2.25bc	12.50 +/- 1.80b

Note: Means in each column followed by the same letter are not significantly different at $P < 0.05$ according to Tukey Multiple Comparison Test.

These three descriptive measures (d_g, f_i, and %<0.85 mm) generally reinforce the results found from comparing entire particle size distributions. That is, 'GRVD' samples were significantly unique from those samples collected at 'S/C'. Another trend, though not as consistent, has 'S/C' samples being unique from all other sites. The uniqueness of the 'S/C' samples was always directed toward 'poor' quality spawning habitat. On the other hand, 'GRVD' showed markedly larger f_i values, lower %<0.85 mm values, and the particle size distributions were comprised of more gravel sized material. Although general appearance is such that 'GRVD' and 'U/S' are significantly similar, statistical techniques did not consistently group them together. Also, a larger amount of material was found between 2 mm and 1.41 mm sieve sizes. This observation was present on four of five multiple sampling dates.

4.2 Sedigraph Results

Sedigraph samples were obtained from sub-sampling freeze core material less than 104 μm. D_{50} and percent material finer than 5 μm were used as a measure of skewness. Significant differences between sites would suggest a skewed distribution of the samples.

4.2.1 Single Freeze Core Samples

Sedigraph determined D_{50} for single freeze core sampling dates plotted temporally did not reveal any consistent trends (Figure 4.2-1). 'U/S' had among the lowest D_{50} on four of the six sampling dates, and on the other two dates 'U/S' had the highest D_{50}. Statistical tests did not reveal significant differences between sites through time ($P_{3,15} = 0.77$). Although only one sample for each of the gravel effluent and river water was taken a large difference between their respective suspended sediment material was found (Table 4.2-1).

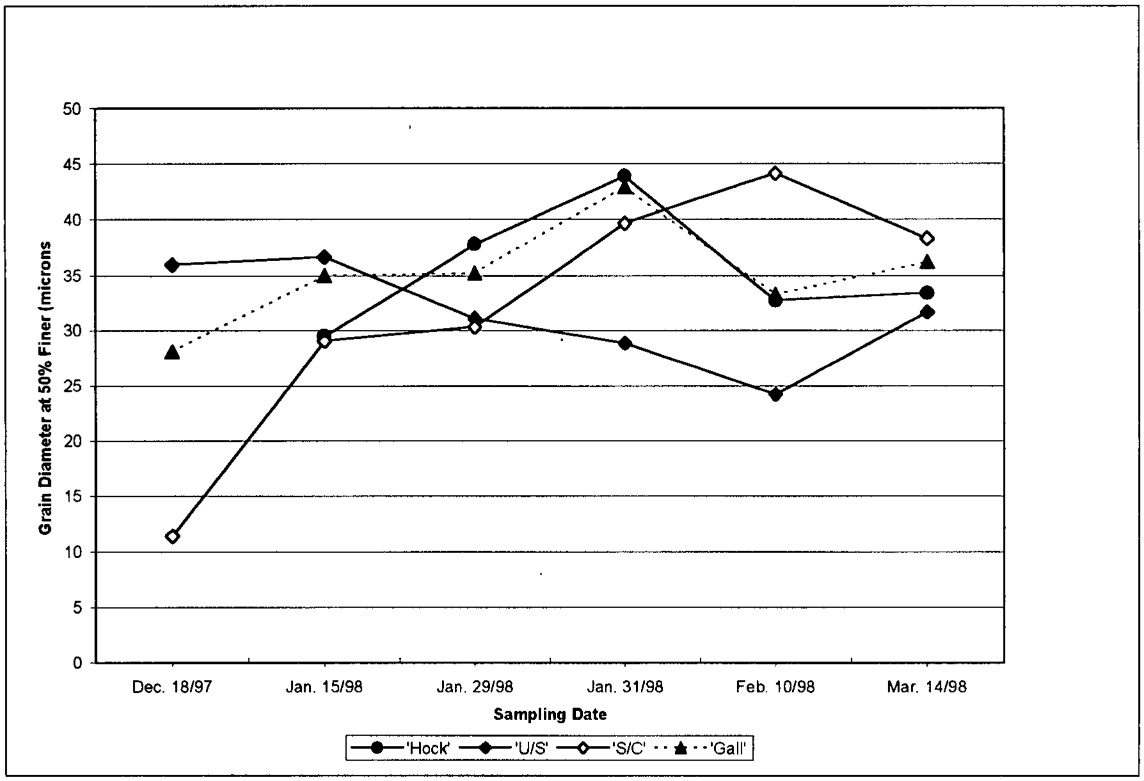

Figure 4.2-1 Sedigraph determined D_{50} (μm) for single freeze core sampling dates. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

Table 4.2-1 Sedigraph determined D_{50} for single freeze core sampling dates. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

			Sampling	*Date*		
Site	**18-Dec**	**15-Jan**	**29-Jan**	**31-Jan**	**10-Feb**	**14-Mar**
'U/S'	36.0	36.7	31.1	28.8	24.2	31.7
'S/C'	11.4	29.0	30.3	39.7	44.1	38.3
'Gall'	28.1	35.0	35.2	42.9	33.3	36.2
'Hock'		29.5	37.8	43.9	32.7	33.4
'GVRD'						27.5
Pit Outfall	2.8					
River Water	20.8					

Sedigraph determined percent material finer than 5 μm for single freeze core sampling dates plotted temporally did not reveal any consistent trends (Figure 4.2-2). Statistical analysis supported these observations ($P_{3,15} = 0.66$). Again, large differences between gravel pit effluent and river water samples were found (Table 4.2-2). No statistical testing can be done however, because only one sample for each was collected.

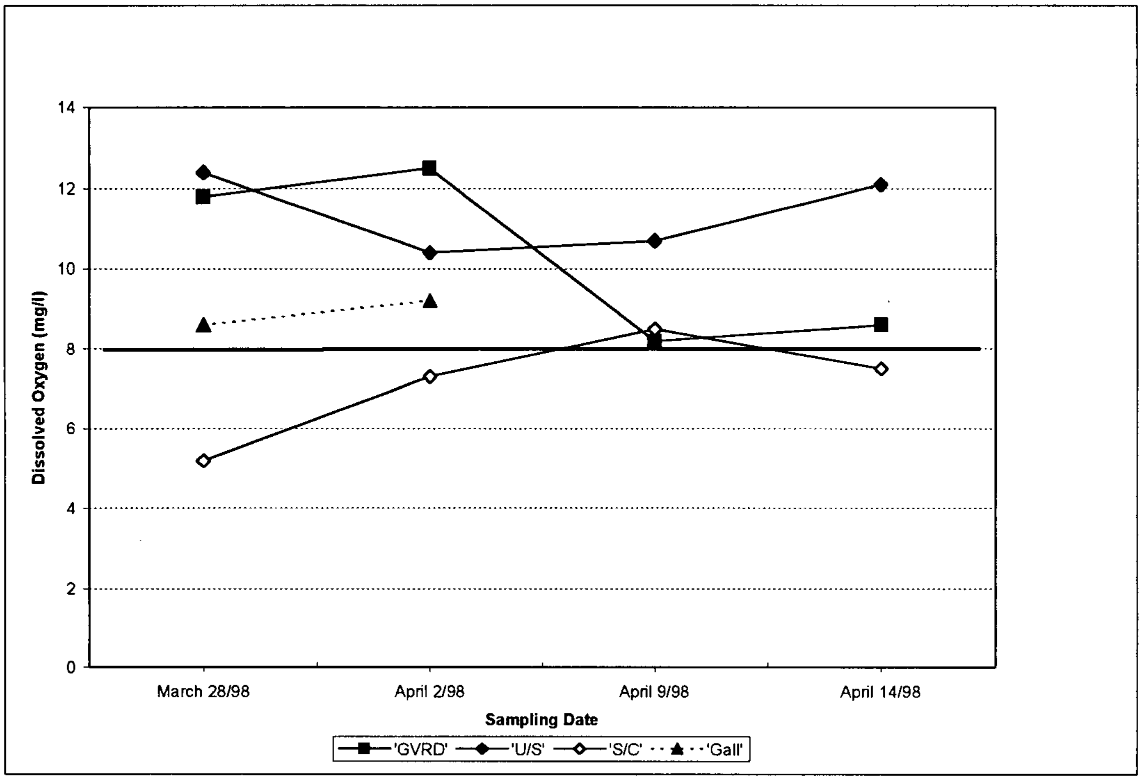

Figure 4.2-2 Sedigraph determined percent finer than 5 μm for single freeze core sampling dates. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

Table 4.2-2 Sedigraph determined percent finer than 5 μm for single freeze core sampling dates. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

	Sampling Date					
Site	**18-Dec**	**15-Jan**	**29-Jan**	**31-Jan**	**10-Feb**	**14-Mar**
'U/S'	10.4	6.1	7.5	13.8	10.9	10.1
'S/C'	39.7	14.6	13.1	8.4	4.6	5.8
'Gall'	20.3	8.2	10.1	6	11.4	11.1
'Hock'		17.1	10.4	4.3	10.9	11.9
'GVRD'						11.2
Pit Outfall	66.8					
River Water	14.5					

4.2.2 Multiple Freeze Core Samples

Sedigraph determined D_{50} for multiple freeze core sampling dates plotted temporally did not reveal any consistent trends (Figure 4.2-3). Furthermore, statistical analysis did not find significant differences between sites through time ($P_{3,32} = 0.22$). Statistical analysis in this case suggests that no consistently skewed samples existed.

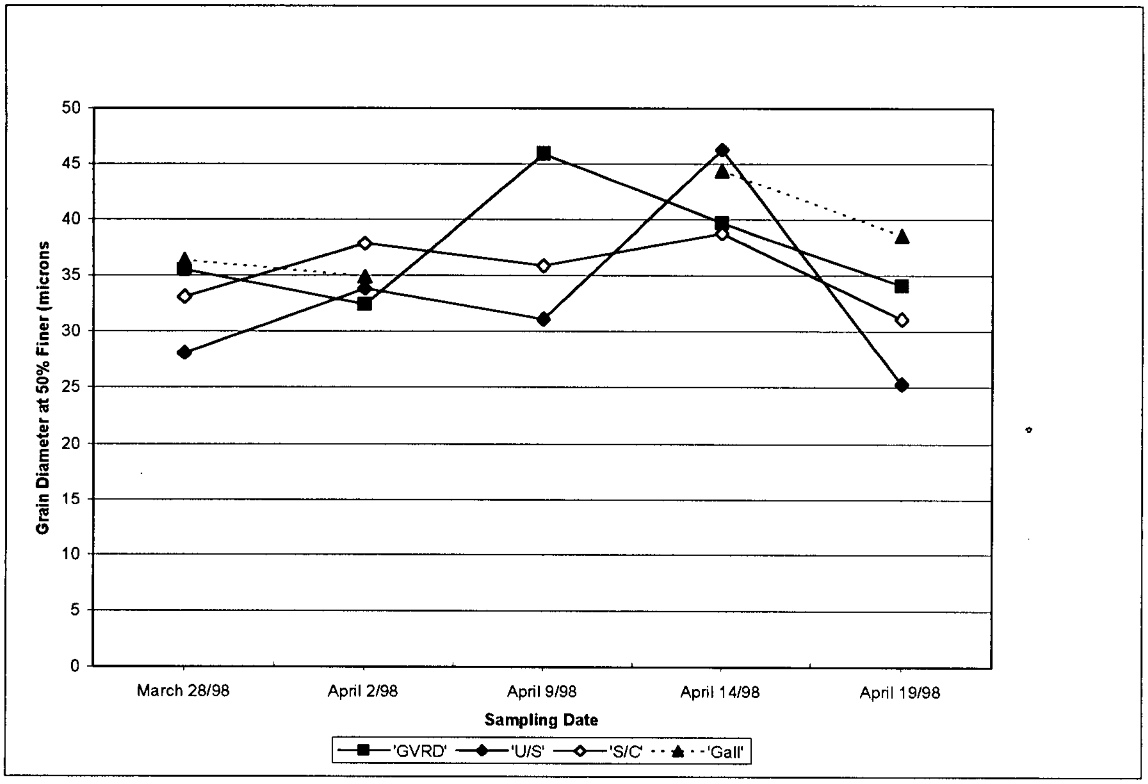

Figure 4.2-3 Sedigraph determined D_{50} for multiple freeze core sampling dates. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

Sedigraph determined percent material finer than 5 μm for multiple freeze core sampling dates plotted temporally did not reveal any consistent trends (Figure 4.2-4). Statistical analysis found significant differences between sites through time ($P_{3,32} = 0.02$).

However, the pattern of difference was not consistent enough for the Tukey Test to find specific differences between sites (Table 4.2-3). On April 19/98, 'S/C' showed elevated levels of less than 5 μm sized material, but this trend was not consistent with other sampling dates.

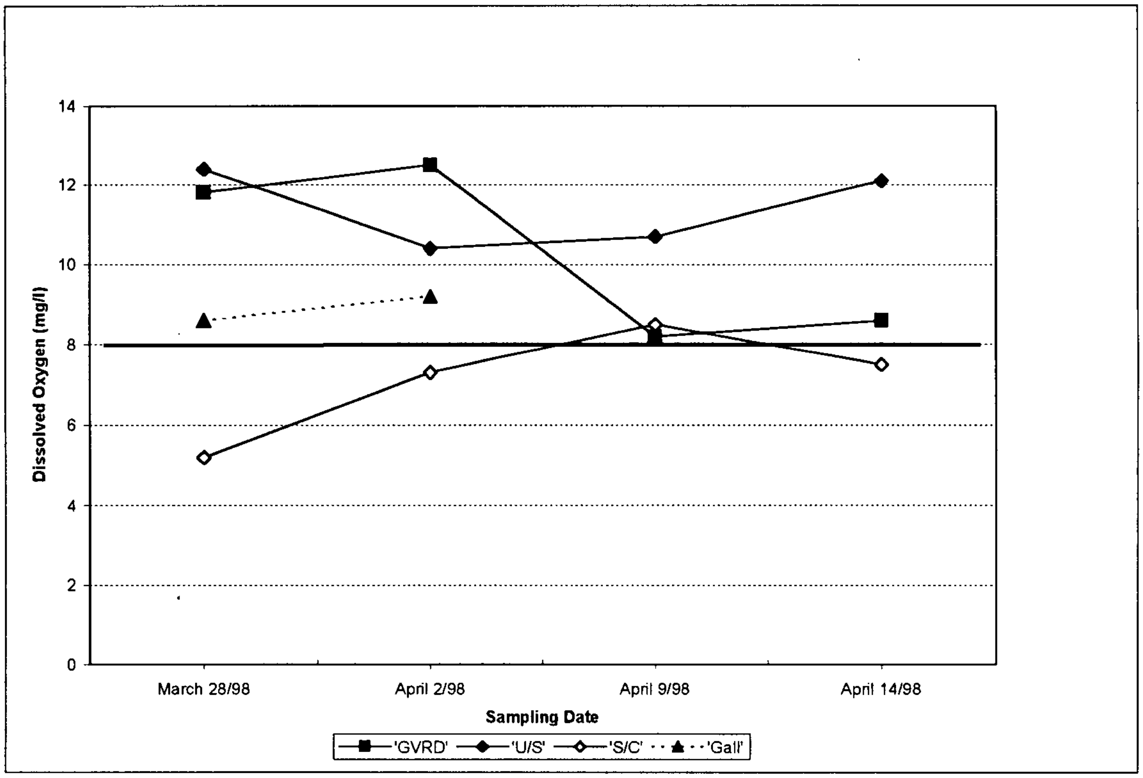

Figure 4.2-4 Sedigraph determined percent finer than 5 μm for multiple freeze core sampling dates. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

Table 4.2-3 Sedigraph determined percent finer than 5 μm for multiple freeze core sampling dates. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

	Sampling Date				
Sites	**28-Mar**	**2-Apr**	**9-Apr**	**14-Apr**	**19-Apr**
'GVRD'	8.63 +/- 5.35a	6.67 +/- 0.91a	4.33 +/- 0.97a	4.50 +/- 0.44a	5.90 +/- 1.87a
'U/S'	9.73 +/- 5.74a	6.93 +/- 0.25a	8.27 +/- 2.56a	2.63 +/- 0.59a	8.30 +/- 1.68a
'S/C'	6.90 +/- 1.18a	4.07 +/- 1.07a	6.00 +/- 0.50a	5.27 +/- 1.27a	15.40 +/- 2.76a
'Gall'	7.83 +/- 3.66a	4.90 +/- 1.44a	N/A	3.80 +/- 1.37a	10.40 +/- 2.04a

Note: Means in each column followed by the same letter are not significantly different at $P < 0.05$ according to Tukey Multiple Comparison Test.

4.3 Relative Permeability

Relative permeability levels plotted temporally showed a clear distinction between 'S/C' and all other sites. Most often, the relative permeability for 'S/C' samples were an order of magnitude lower than the other sites (Figure 4.3-1). More specifically, 'GRVD' had consistent and high relative permeability through the sample period. 'U/S' relative permeability was very similar to 'GRVD' on all but one sampling date. The elimination of the one very low relative permeability replicate recorded on this date changes the value considerably. 'Gall' plotted some where between 'S/C' and 'GRVD' values. Statistically, 'S/C' was distinct from 'GRVD' and 'U/S' on all but one sampling date (Table 4.3-1). 'GRVD' and 'U/S' were significantly similar on all but one sampling date (April 2/98) (where one outlier appeared to be present). 'Gall' was statistically related to 'GRVD' and 'U/S' on three of five occasions.

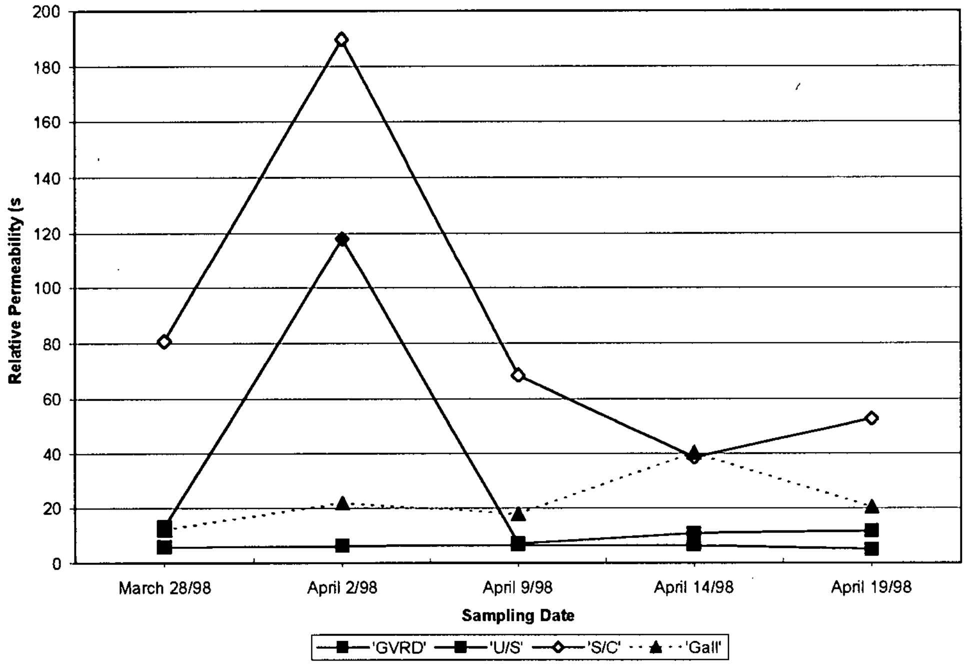

Figure 4.3-1 Relative permeability (1/s) for all sampling sites plotted temporally.

Table 4.3-1 Relative permeability (s) for all sampling sites and dates.

	Sampling Date				
Sites	**28-Mar**	**2-Apr**	**9-Apr**	**14-Apr**	**19-Apr**
'GVRD'	5.8 +/- 1.7a	6.3 +/- 1.7a	6.7 +/- 1.8a	6.5 +/- 1.9a	5.0 +/- 0.9a
'U/S'	13.0 +/- 2.8a	118 +/- 2.8b	7.1 +/- 1.8a	10.8 +/- 3.6a	11.7 +/- 2.1a
'S/C'	81.1 +/- 90b	190 +/- 91c	68.5 +/- 18b	38.6 +/- 19a	52.9 +/- 9.9b
'Gall'	12.2 +/- 3.4a	21.8 +/- 3.4a	17.7 +/- 1.7b	40.4 +/- 27a	20.4 +/- 6.8c

Note: Means in each column followed by the same letter are not significantly different at P < 0.05 according to Tukey Multiple Comparison Test.

The high degree of variability associated with this sampling technique often leads to unexpected, non-significant, statistical results, even though a trend is evident. The overall trend had 'S/C' having the lowest relative permeability and 'U/S' and

'GRVD' having comparable as well significantly greater relative permeability. 'Gall' was closely associated with 'U/S' and 'GRVD' for most of the sampling period. The lower relative permeability associated with 'S/C' suggests poorer spawning habitat quality as compared to all other sites.

4.4 Dissolved Oxygen

Dissolved oxygen levels plotted temporally show consistent segregation between 'U/S' and 'S/C' (Figure 4.4-1). 'U/S' samples plot around 11.5 mg/l where as 'S/C' samples plot around 7 mg/l. This trend is supported statistically on three of four sampling dates (Table 4.4-1). 'Gall' appears between 'S/C' and 'U/S'; however, 'Gall' recordings were only available for two sampling dates. Statistically, 'Gall' was distinct from 'S/C'. Analysis between 'Gall' and 'U/S' were not definite. 'GRVD' dropped from a dissolved oxygen level of 12 mg/l for the first two sampling dates to around 8 mg/l. Statistically, the drop in dissolved oxygen associated 'GRVD' with 'S/C' more often then with 'U/S'. The change in dissolved oxygen during the sampling period was likely due to varying water quality from the upstream dam.

A clear dichotomy between 'U/S' and 'S/C' dissolved oxygen levels associates 'U/S' with superior spawning habitat as compared to 'S/C' dissolved oxygen levels. Any dissolved oxygen levels below saturation affect development of the embryo (Chapman 1988). Although most samples were below saturation, 'S/C' often had values below the critical standard.

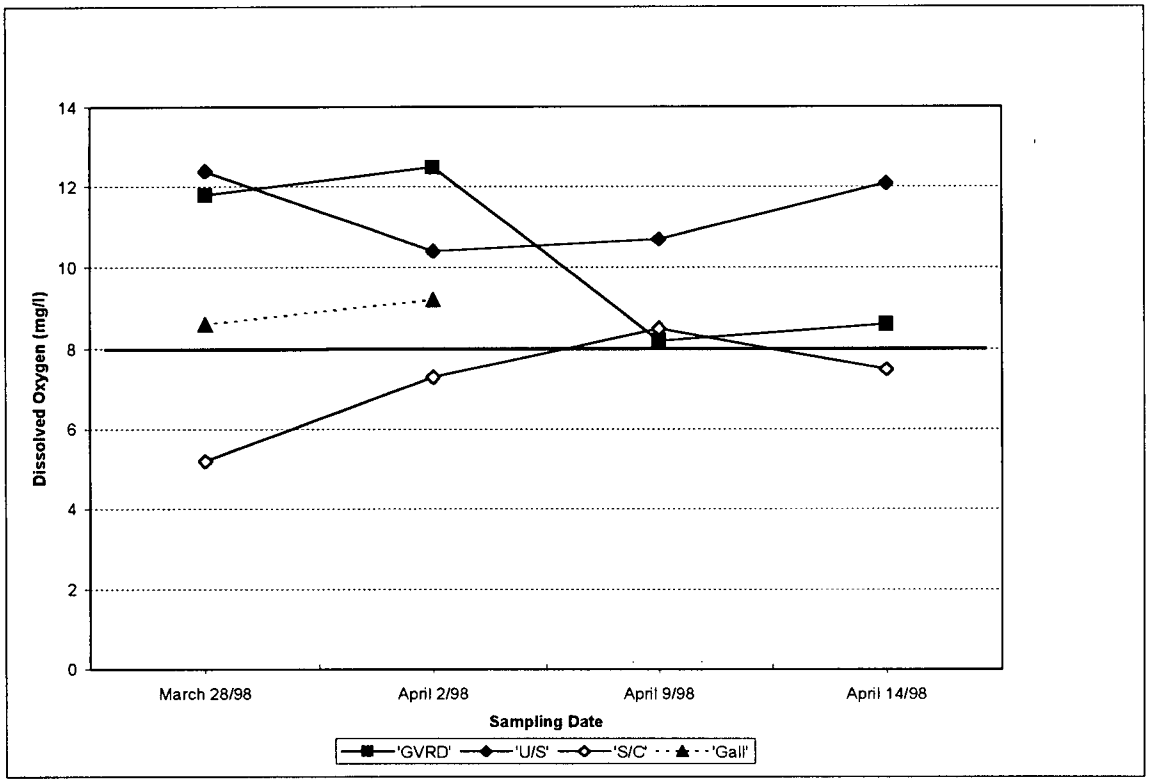

Figure 4.4-1 Dissolved oxygen (mg/l) for all sampling sites plotted temporally. Bold line indicates critical level.

Table 4.4-1 Dissolved oxygen (mg/l) for all sampling sites and dates.

	Sampling Date			
Sites	**28-Mar**	**2-Apr**	**9-Apr**	**14-Apr**
'GVRD'	11.8 +/- 0.3a	12.5 +/- 0.1a	8.2 +/- 2.2a	8.6 +/- 1.4a
'U/S'	12.4 +/- 0.5a	10.4 +/- 2.2b	10.7 +/- 2.3b	12.1 +/- 0.1b
'S/C'	5.2 +/- 2.8b	7.3 +/- 0.7c	8.5 +/- 1.4b	7.5 +/- 0.9a
'Gall'	8.6 +/- 1.3c	9.2 +/- 1.4b	N/A	N/A

Note: Means in each column followed by the same letter are not significantly different at $P < 0.05$ according to Tukey Multiple Comparison Test.

4.5 Inductively Coupled Plasma

Of the ten elements analyzed from each sample location ('U/S', 'Gall', 'S/C', and gravel pit effluent) six were not statistically different between sample locations (Table 4.5-1). The elements that were statistically different were calcium, iron, magnesium, and aluminum. 'S/C' had statistically lower values than all other sample locations for the significantly different elements. Effluent samples were only similar to 'U/S' samples. Iron had effluent samples being statistically similar to 'Gall' but not 'S/C' and 'U/S'. Magnesium samples from the effluent site were statistically similar to 'Gall' samples but unique from the others. Aluminum effluent samples were unique from all other samples. Low iron levels were found at 'S/C', where as effluent and 'U/S' samples had significantly higher iron levels. 'Gall' iron levels were statistically similar to effluent samples. Calcium levels dropped from 'U/S' to 'S/C' and then increased at 'Gall'.

Table 4.5-1 ICP results (ppm) for ten elements from four sampling sites.

	Element Analyzed				
Sample	**Ca**	**Mg**	**Mn**	**Fe**	**Cu**
Effluent	112.7 +/- 0.40b	105.3 +/- 0.09b	6.46 +/- 0.04a	336.8 +/- 1.38a	0.34 +/- 0.00a
'S/C'	100.2 +/- 0.65c	87.0 +/- 0.40c	4.79 +/- .001a	291.5 +/- 0.69b	2.76 +/- 0.02a
'Gall'	106.3 +/- 0.73a	110.6 +/- 0.01ab	6.37 +/- 0.03a	340.1 +/- 1.10a	3.86 +/- 0.01a
'U/S'	110.6 +/- 2.00ab	113.7 +/- 0.71a	6.28 +/- 0.09a	418.0 +/- 5.42c	3.68 +/- 0.07a

	Element Analyzed				
Sample	**Zn**	**Si**	**Al**	**Cr**	**Pb**
Effluent	0.81 +/- 0.00a	2.11 +/- 0.03a	299.0 +/- 0.06a	0.23 +/- 0.004a	0.726 +/- 0.04a
'S/C'	1.19 +/- 0.00a	1.17 +/- 0.01a	239.1 +/- 1.28b	0.21 +/- 0.008a	0.710 +/- 0.01a
'Gall'	1.63 +/- 0.01a	2.25 +/- 0.08a	280.6 +/- 0.29c	0.25 +/- 0.010a	0.865 +/- .001a
'U/S'	1.71 +/- 0.01a	1.45 +/- 0.01a	280.8 +/- 3.22c	0.27 +/- 0.003a	0.844 +/- 0.02a

Note: Means in each column followed by the same letter are not significantly different at $P < 0.05$ according to Tukey Multiple Comparison Test.

The four elements that were found to have statistically unique results at the various sites all showed high levels at 'U/S' followed by a decline at 'S/C', and then an increase at 'Gall' (Figure 4.5-1). These results suggest that element levels are diluted after 'U/S', and between 'S/C' and 'Gall' there is either inconsistent mixing, a new source of these elements or a combination of both.

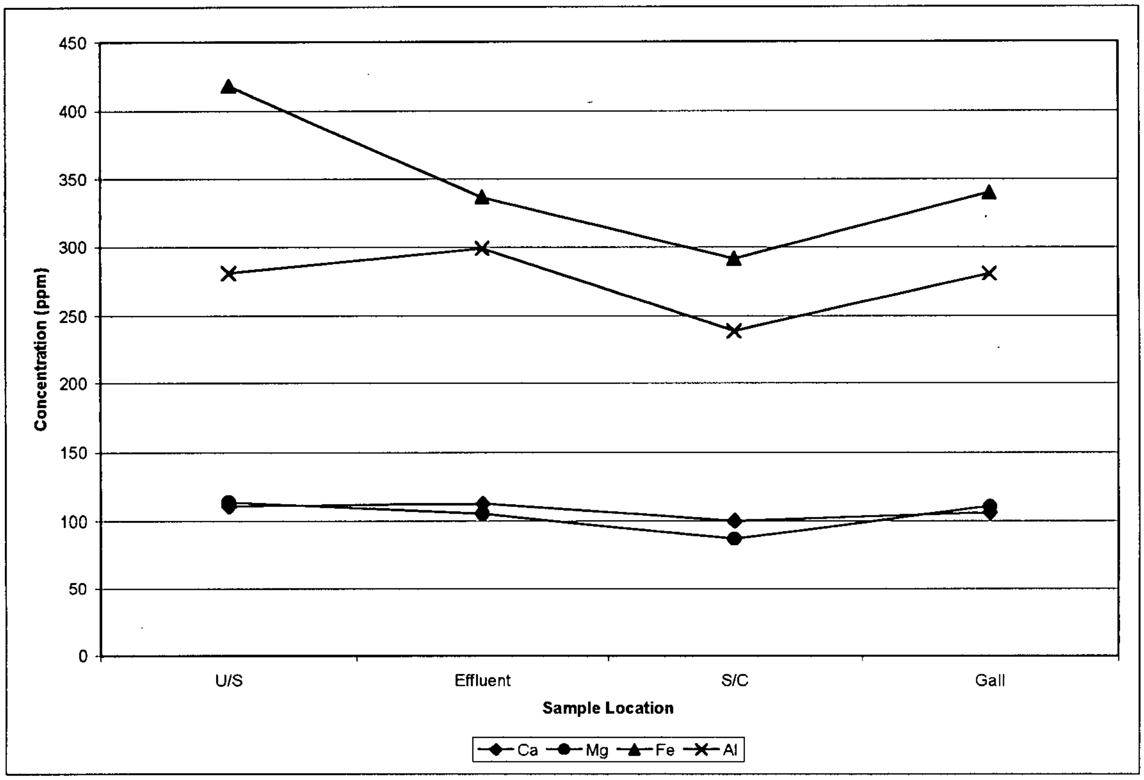

Figure 4.5-1 Statistically significant ICP element levels plotted for all sites.

4.6 Sediment Traps

4.6.1 Descriptive Measures

The particle size distributions generated for the four sites show four distinct distributions (Figure 4.6-1). 'S/C' traps had 40% of its material less than 0.063 mm. The next closest in this size range was 'U/S' with around 15%. The greatest difference between sites was seen with 'S/C' and 'GRVD'.

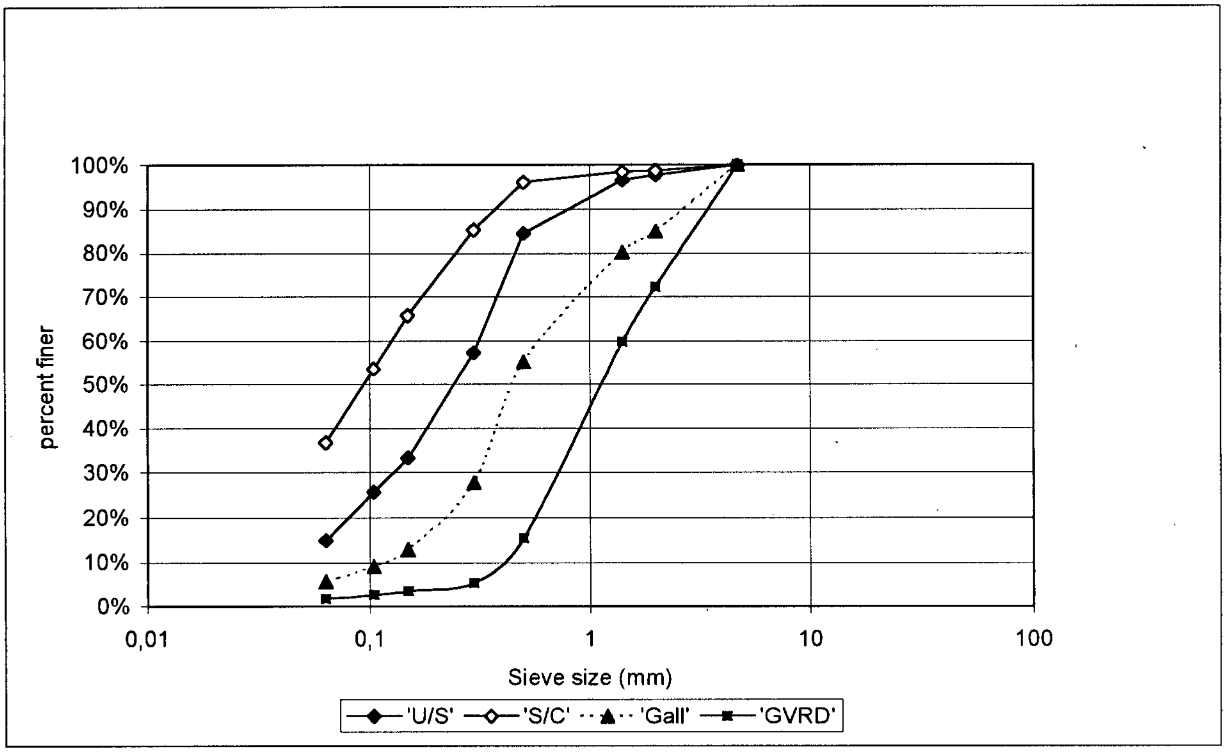

Figure 4.6-1 Average particle size distributions of material collected in sediment traps over a 45 day period for all sites.

The total weight of material collected was greatest for 'U/S' and lowest for 'GRVD' (Table 4.6-1). The differences in total weight collected were significant for all sites except between 'U/S' and 'Gall'.

Table 4.6-1 Descriptive measures applied to sediment trap material after a 45 day period for all sites.

	Variable Tested		
Sites	**Total Weight (g)**	**Geometric Mean (mm)**	**Material < 0.85 mm (%)**
'GVRD'	204.3 +/- 96.2a	1.61 +/- 0.11a	32.7 +/- 4.2a
'U/S'	1631.3 +/- 69.7b	0.40 +/- 0.05b	89.3 +/- 3.1b
'S/C'	1128.3 +/- 77.0c	0.20 +/- 0.03c	96.8 +/- 1.0c
'Gall'	1567.4 +/- 201.8b	0.97 +/- 0.10d	64.7 +/- 1.5d

Note: Means in each column followed by the same letter are not significantly different at P < 0.05 according to Tukey Multiple Comparison Test.

Geometric means calculated for all sites were statistically different. 'GRVD' had the greatest d_g and 'S/C' had the lowest d_g (Table 4.6-1).

The percentage of material finer than 0.85 mm collected in the traps was also statistically significant (Table 4.6-1). Values for all sites were statistically unique. 'S/C' had the most material finer than 0.85 mm and 'GRVD' had the least.

All four descriptive measures had statistically significant results that showed 'GRVD' to be superior from all other sites in terms of salmonid spawning habitat. Further, all four descriptive measures statistically revealed that 'S/C' had the poorest quality salmonid spawning habitat.

4.6.2 Sedigraph Results

Sedigraph analysis on sediment trap material did not find any significant trends between sites (Table 4.6-2). This analysis with sediment trap material is consistent with the analysis with freeze core material.

Table 4.6-2 Sedigraph determined D_{50} and percent finer than 5 μm for sediment trap material collected from all sites. Sedigraph samples are from freeze core sub-samples (>104 μm fraction).

	Variable Tested	
Sites	**D50 (microns)**	**% < 5 microns**
'GVRD'	25.4 +/- 4.2	6.4 +/- 1.4
'U/S'	27.4 +/- 5.2	5.3 +/- 2.4
'S/C'	25.0 +/- 4.2	5.4 +/- 2.0
'Gall'	26.0 +/- 4.2	5.4 +/- 2.5

5 DISCUSSION

The previous results were obtained to address three objectives: 1) is the gravel within the sampling areas of sufficient quality to support salmonid eggs during incubation through to emergence; 2) is there a difference in the quality of gravel samples up and downstream of the gravel pits; and 3) is gravel washing or extraction effluent being deposited within the potential spawning sites of the Coquitlam River.

5.1 Site Evaluation

In order to determine if the samples collected from the Coquitlam River are of sufficient quality to achieve moderate levels of survival to emergence, a standard of comparison must be developed. Chapman (1988), Bjornn and Reiser (1991) suggested five descriptive measures that indicate a gravel sample's ability to support incubating salmonids: 1) percent 'fines'; 2) permeability; 3) Fredle index; 4) dissolved oxygen; 5) and thickness of the sand seal. (Note that geometric mean is not included due to its inability to reveal unique differences between gravel samples). The sand seal thickness dictates the ease to which fry can penetrate to the water column. Researchers have placed fry in laboratory gravel with varying thickness of sand above the egg pocket (Crisp 1993). Reduced survival to emergence was observed as a direct result of the sand seal. Sand seal thickness can only be determined in the field by dissecting gravel samples vertically (Peterson and Quinn 1996a). Samples from the Coquitlam River were not dissected vertically thus the impact of the sand seal could not be determined.

Permeability is another important factor influencing survival to emergence. The relative permeability data collected from the Coquitlam River can not be compared to published permeability data due to the different sampling procedures. Thus, the descriptive measures used to analyze sites along the Coquitlam River as potential spawning habitat were percent fines, the Fredle index, and dissolved oxygen. Although great attempts were made to sample similar types of habitat along the Coquitlam River (for comparative purposes), each site is slightly unique in terms of its depositional processes and supply water quality.

5.1.1 'GRVD'

'GRVD' had percent fines, Fredle values, and dissolved oxygen levels that would classify it as 'good' quality spawning habitat. 'GRVD' receives its water from reservoir releases with little input from runoff due to its proximity to the dam. Reservoir water is often completely void of fine material (Sear 1993). The lack of fine sediment delivery to 'GRVD' is observed in the consistently low levels of fines within the subsurface, and from sediment trap data. The riparian zone between 'GRVD' and the dam (consisting of many shrubs, alder, and some conifers) contributed the limited amount of fines found within the gravel (from general observation). Large quantities of organic material have been found to reduce dissolved oxygen levels of spawning gravel (Chapman 1988; and Bjornn and Reiser 1991). Dissolved oxygen levels at 'GRVD' did not drop to below critical levels. Average dissolved oxygen levels of around 10 mg/l were found, though the range was between 12 and 8 mg/l. Fluctuations of results could be due to BOD of organics or from dam water releases having varies levels of dissolved oxygen. Depending on the depth of the release from the reservoir the dissolved oxygen concentration can vary (Sear 1993).

Another influence of the dam is a dampening of peak flows. Winter storm floods have two opposing influences on salmonid spawning. Competent floods that just mobilize the pavement layer can flush fine material to depths of around 10 cm (Beschta and Jackson 1979; Schalchli 1992; and Montgomery et al. 1995). Flood flows that completely mobilize the pavement layer can scour the gravel bed to depth that dislodges the incubating eggs. A large percentage of embryo mortality is believed to result from scouring flows (Montgomery et al. 1995). During the incubation stage of salmonids a dam can help improve survival to emergence by providing fine free water, if flows are sufficient that dewatering of the redd does not occur. Salmonid redds have been shown to tolerate dewatering for short periods of time if the humidity within the redd is maintained near saturation (Bjornn and Reiser 1991). Numerous redds were sampled at 'GRVD' through random placement of the freeze core probe with live alevins. The high quality of gravel, as indicated by the descriptive measures, appeared to result in survival to the late incubation stage.

Research has shown that the particle size distribution of redds differs significantly from the surrounding gravel composition immediately after redd construction. Throughout the incubation period fines are deposited. At the end of incubation redd particle size distribution resembles that of the surrounding riffle (Peterson and Quinn 1996a). For the multiple sample dates at 'GRVD' a larger standard deviation was expected when sampling one redd and two non-redd sites and computing an average. However, a large standard deviation was not found. This suggests that redd sites did not greatly differ from non-redd sites. There are two possible explanations: 1) the time between redd construction and sampling was sufficient for the fining of redds to background levels; and 2) 'GRVD' is generally a clean site with little to no fine storage. The latter is more plausible due to the 'clean' flows and hydraulic conditions that generally maintain material in suspension.

5.1.2 'U/S'

Conditions at 'U/S' varied between 'good' and 'poor' spawning habitat throughout the sampling period. These results were expected due to the episodic delivery of fine sediment from upstream slides that occurred along Or Creek. The flow velocity at 'U/S' appeared greater than all other sites. Samples were taken just downstream of the confluence at Or Creek such that the 'clean' water from the dam did not influence conditions at 'U/S'. Also, samples were collected between the river edge and a large island; this structure confined the flow and increased velocity. Flow velocity at 'U/S' appeared sufficient to keep suspended sediment from being deposited. A velocity of only 0.24 m/s is required to suspend 1.0 mm material as computed by Hjulstrom curve (Vanoni 1975). However, research has shown that regardless of the turbulent conditions in the river a portion the fine sediment in suspension will be deposited within the bed (Lisle 1989; and Schalchli 1992, and 1995).

A zone of zero velocity exists above the bed to a height approximately the size of the largest pavement grain diameter (Diplas and Parker 1987). Once fine material is in direct proximity to the bed gravitational processes apply (Einstein 1968). Also, turbulent pulses can send suspended sediment to depths where quiescent conditions prevail, and deposition occurs (Peterson and Quinn 1996a). The episodic nature of the slides was believed to produce flows with very high suspended sediment concentrations during periods of erosion. Once the slide was exhausted flows were believed to once again run clean. The clean flows would flush the gravel of pre-deposited fines (Carling 1984) to a depth that depends on Froude number (Beschta and Jackson 1979). Flows that do not set the pavement in motion can flush the gravel to a depth of around 10 cm (Beschta and Jackson 1979). Also, due to the limited available spawning gravel at 'U/S', samples were collected near the river edge. Sear (1993) found samples closest to the channel margins to have higher deposition rates compared to samples collected in the middle of a cross section. Samples collected further from the edge of the channel at 'U/S' may have resulted in better quality samples. During the sampling period one redd was sampled (via random placement of the freeze core probe), indicating that at least one salmonid considered this site for spawning. Approximately seven eggs were found and all had died before reaching alevin stage. The descriptive measures, along with the low survival observed from one redd, suggest 'U/S' is of marginal quality for spawning habitat.

5.1.3 'S/C'

'S/C' samples were collected from the head of a side-channel built by DFO some years ago to increase spawning and rearing habitat. At the branch point lie three large boulders placed to provide cover and to dissipate flow energy. The low velocity of flow and proximity to effluent outfalls together rendered it 'poor' in terms of spawning quality. Furthermore, the close proximity to source does not allow for complete mixing of effluent that would help improve 'S/C' conditions. Only once did dissolved oxygen and Fredle values achieve levels required for 'good' habitat. 'S/C' did not appear to receive flows of the magnitude required for flushing the pavement or subpavemment layer. If these flows were to occur so that scour and fill could take place to depth, then the percent of fines would likely increase. The continuous supply of effluent, and thus fine material, could then obtain access to the deeper zones (Carling 1984). Lisle (1989) observed filling to a depth of 30 cm below the surface when flows that mobilize the subpavement contain high amounts of sediment. As flow increases fines in the pavement are suspended, this action loosens the pavement making it more susceptible to transport. A further increase in flow sets the pavement in motion; the subpavement (defined by its finer grain size distribution than the pavement) is now exposed to competent flows. The zero velocity plain now reaches depth within the gravel, where fines can completely in-fill the subsurface (Peterson and Quinn 1996a). Flood flows that do not mobilize the pavement clean the upper layer of fines. However, once peak flows decline filling of recently cleaned pores occurs (Carling 1984). The maximum depth of cleaning depends on the degree of overlap between the grain size distribution of the gravel bed and the sediment load (Diplas and Parker 1987). If no overlap occurs between the two distributions then the interstitial voids will be large enough to allow for complete filling of the gravel framework with matrix material (Einstein 1968). If some overlap exists, grains will be caught up in the voids and a seal will form. This seal prevents further penetration of fine material. A sand seal is frequently observed above the egg pocket of redds (Peterson and Quinn 1996a). The seal can prevent fines from filling voids in the egg pocket. However, too thick of a seal can prevent penetration to the water column when the fry are ready to emerge (Chapman 1988). The large supply of fines continuously exiting gravel outfalls, along with pre-deposited fines in the area, suggest that flushing flows would not improve the conditions at 'S/C' to an extent where sufficient survival to emergence could occur. Insufficient mixing of gravel effluent and river water due to proximity to source, along with hydraulic conditions that appear to favour deposition, rendered 'S/C' samples as 'poor' quality spawning habitat.

5.1.4 'Gall'

Samples from 'Gall' identify the gravel as 'good' quality in most cases. Fredle values averaged below critical, but dissolved oxygen and percent fines were within the acceptable range. The inconsistency found from the descriptive measures suggest that 'Gall' samples are subject to temporal variability. A large percentage of the transported material at 'Gall', both washload and bedload, has a particle size distribution considerably smaller than the pavement. This is believed because of two possible contributing factors: 1) the particle size distribution of the gravel effluent being extremely biased toward fine material; and 2) the dampened peak flows from the dam have reduced sediment transporting capabilities that limit the maximum size of transported material. The two different particle size distributions between the gravel bed and the transported material allow for deep ingress into the gravel bed of the sediment being transported (Alonso et al. 1988). Removal of this material is only possible if 'clean' competent flows are present. Competent flows are flows that have sufficient energy to initiate sediment transport. During the sampling period the large flows that did occur from storm events appeared to contain extremely high SS loads. The high SS loads are believed to be the result of precipitation that falls within the gravel pits and drains into the river, and from flushing of fines that have built up over years of gravel mining activity (Rosenau 1993b). (The ditches dug by the gravel pit operators to carry effluent to the river contain an inexhaustible supply of sand, silt, and clay). Despite these conditions 'Gall' still had percent fines and dissolved oxygen levels sufficient for 'good' quality spawning. This is likely due to the relatively large distance from source of the fines; Carling (1984) found a downstream decrease in siltation rate from a point source was a negative exponential function of distance from that source. Mixing between effluent and river water from source to 'Gall' would reduce the quantity of fines in direct proximity to the gravel bed and thus the deposition rate. 'Good' conditions could also be attributed to the hydraulic conditions that do not favour deposition of very fine material. Velocities in the sampling area were much greater than at 'S/C' and 'GRVD'. Furthermore, the riffle-crest had fairly uniform depth from bank to bank; this allowed for sampling far from the channel edge.

Redds at 'Gall' were sampled on occasion with live alevins within. Because salmonids can purge up to 75% of fines from a redd during construction, redd sites should have less percent fines when sampled (Peterson and Quinn 1996a). However, the loose structure of a redd aids deep penetration of fine material. Although sampling one redd and two non-redd sites to obtain an average probably influenced the quality of the gravel to some degree, it did not produce samples with significantly higher variability than found at the other sample locations. The live alevins, low percent fines, and sufficient dissolved oxygen levels suggest 'Gall' gravel can maintain adequate levels of survival to emergence.

5.2 *Effluent Impact on Spawning Gravel*

The impact that gravel pit mining has on the quality of spawning gravel within the Coquitlam River can only be isolated if similar sampling sites up and downstream are selected. Traditionally, evaluating an input of a potential pollutant involved using upstream sites as reference and downstream sites as potentially impacted. However, sample sites from the Coquitlam River are such that unique conditions persist that complicate up / downstream comparisons. Ideally, sample sites immediately up and downstream of the effluent discharge would be chosen. However, the lack of similar hydrological environments immediately up and downstream of the effluent discharge did not permit it. Different hydrological environments cause different depositional processes that alter gravel composition. The constant and large effluent input from the gravel pits does allow, however, for up / downstream gross comparisons. The spawning sites used with similar hydrological environments were located some distance apart; the largest distance was about 1000 m. A potential source between the sites was runoff from the undisturbed sections of the watershed; this was believed to be minimal.

'S/C' samples differed significantly from 'GRVD' samples. A 'significant' difference implies a difference that leads to reduced survival to emergence. Research has found any increase in fines, reduction in permeability or dissolved oxygen cause additional stress to incubation embryos (Chapman 1988). Stress can translate into reduced survival to emergence, or reduced rearing success. Conditions at 'GRVD' are not truly representative of conditions between 'GRVD' and 'S/C'. 'U/S' is a better comparative site because it receives quasi-natural flows. Furthermore, 'U/S' is exposed to episodic periods of high SS. Conditions at 'U/S' should translate into 'poorer' gravel samples since research shows that a portion of SS will undoubtedly be deposited even if turbulent conditions are present. 'S/C' is also exposed to upstream slides but at such a distance downstream that SS could be deposited prior to reaching 'S/C'. As well, mixing of slide material with water released from the dam further dampens the impact of the slides. Relative permeability, dissolved oxygen, and percent fines all have 'U/S' as being higher quality spawning habitat than 'S/C'. Thus, gravel pit effluent appears to have a stronger impact on spawning gravel quality than upstream slides.

'Gall' is exposed to two sources of gravel effluent and runoff from an upstream concrete operation, but still had higher quality spawning gravel than 'S/C'. Keeping in mind the different hydraulic conditions, proximity to source appears to be an important factor in determining gravel conditions. The proximity to source influences the depositional rate and the degree of dilution through transverse mixing. Conditions at 'Gall' were predicted to have finer material than 'S/C' but considerably less quantity of deposited fines. Once the effluent source reaches the river the larger grains would settle out first, due to gravitational processes and their proximity to the gravel bed – despite the SS constituting a large percentage of the total load (Lisle 1989). Further downstream, a suspended load biased toward finer material would flow through 'Gall' thus producing fine gravel samples. However, a larger quantity of material was deposited at 'Gall' and the deposited material was significantly larger than material deposited at 'S/C'. The different discharges between the two sites could account for the difference in quantity deposited but not for the difference in grain size distribution. Larger discharges can carry more material through a site as compared to smaller discharges. The larger than expected grain size distribution at 'Gall' as compared to 'U/S' could be the result of transverse mixing of effluent. The highly concentrated effluent that passes through 'S/C' does not properly mix across the river. At 'Gall' the very fine material is well mixed vertically in the water column, as well as transversely. The diluting effect of mixing reduces the quantity of very fine material in direct proximity to the gravel bed. Thus, courser fines may be deposited at 'Gall' as compared to 'S/C'.

Gravel mining activity undoubtedly affects gravel quality within the Coquitlam River. The impact appears significantly greater than the impact from upstream slides — though no samples are available that indicate 'S/C' and 'U/S' samples did not vary before gravel mining and slides began. Sediment trap results provide the best possible insight into the fate of a newly constructed redd. The sediment traps used did not allow for intra-gravel flow but they do represent similar initial conditions. All descriptive measures considered (total weight, D_{50}, and %<0.85 mm) found 'S/C' to have unique conditions. The smaller D_{50} and higher %<0.85 mm reduced 'S/C' gravel's ability to support embryos during incubation. The smaller D_{50} at 'S/C' compared to 'U/S' suggests that gravel mining effluent has significantly finer grain size distribution than material transported by upstream slides. One SS sample taken during a storm event reinforced this finding. However, more material was deposited at 'U/S' from slides than deposited at 'S/C' from gravel mining and slides. This is likely due to the difference in discharge between the two sites. The same can be speculated for the large quantity of material deposited at 'Gall'. Almost all the material deposited at 'S/C' was less than 0.85 mm (97%). Further downstream at 'Gall' only 65% of material was finer than 0.85 mm. The difference in grain size distribution of deposited material could be due to the different hydraulic conditions – the greater turbulence at 'Gall' causes selective deposition of coarser material – or due to the proximity to longitudinal mixing and subsequent dilution. The dominant variable could only be determined if hydraulic conditions were similar or if a similar effluent source was stationed directly upstream of 'Gall'.

Sediment trap data alone would have 'U/S' being poorer quality habitat than 'Gall'. Both had a statistically similar total quantity of material deposited but the material deposited at 'U/S' was statistically finer than 'Gall' material. Although hydraulic conditions are from observation in the field and not from scientific analysis, flows at 'U/S' appeared more turbulent and of a greater velocity. However, the grain size distribution at 'U/S' was smaller than 'Gall'. It was expected that the fine material from gravel pit outfalls would cause fining of the deposited material at 'Gall'. The predicted outcome did not occur. More likely, the material from the slides was finer than material transported through 'Gall'. This suggests that very fine material is being deposited quickly, i.e. within a kilometer.

5.3 Tracing Source Material

Sedigraph information was collected to analyze sub-distributions from the various samples located. A sub-sample of material finer than 0.104 mm was analyzed for its distribution. The inspiration behind the sedigraph work was this: if gravel mining effluent had a unique distribution from that of the Coquitlam River, and this material is believed to be depositing at sample locations, then these sites subjected to gravel mining effluent would have a grain distribution that resembled that of gravel effluent (to some extent). SS samples from both the river and gravel mining effluent showed two very distinct SS distributions. Gravel mining effluent had a D_{50} seven times smaller than that of the Coquitlam River. However, no significant or consistent trend was found between up and downstream sites. Material from the gravel pits may not have been deposited to an extent that affected the truncated grain distributions. Most material from the outfall is 'true' washload material (<0.29 mm) (Bagnold 1973). Lisle (1989) examined flows with washloads comprising 90 – 95% of the total load; however, most material deposited (85%) was made up of bedload sized grains (>0.29 mm). Freeze core samples collected, that analyzed the distribution from 25.4 mm and finer, showed 'S/C' to have the highest percentage of fines on most occasions, presumably due to gravel mining outfalls. The two methods of analysis do not yield complementary results. The likely explanation is that both river and gravel material deposited within the interstitial environment. The added fines from the outfall was sufficient to show differences at a large scale but not sufficient to skew the sub-distribution.

ICP analysis was preformed to aid sedigraph results. It was predicted that effluent samples would be statistically more similar to 'S/C' samples if effluent was being deposited at 'S/C'. The ICP results did not show any explainable trends. Elemental fingerprinting is a highly variable technique. Fletcher (1995) used ICP analysis to show material from an upstream slide deposited within the riverbed 1-2 km downstream. Low levels of gold found at the slide allowed for such fingerprinting. Slide material diluted gravel bed material. Furthermore, the slide material was from a unique geological origin that aided the highly sensitive analysis. Samples from the Coquitlam River were within the same reach; also similar glacial processes deposited all the material. The inconclusive ICP results does not prove gravel effluent is not depositing in the Coquitlam River but it does provide some insight to the complexity of depositional processes.

5.4 Single Sample Variability

A large spacial and temporal variability was observed during single sample dates. For single samples collected temporally, no consistent trend was maintained throughout the sampling period. Chapman (1988) noted that sampling with a single freeze core probe often yields highly variable results. Tri-tube samplers collect gravel from a larger area and thus can better represent a sample site. A single freeze core sampler had to be used for Coquitlam River sampling due to the large clast size generally encountered at a site. Furthermore, Adams and Beschta (1980) found the percentage of fines to vary considerably within a riffle-crest. They reasoned that the variation stemmed from the different hydraulic conditions, supply of fines, and size of gravel substrate and fines (Adams and Beschta 1980). Although efforts were made to sample from similar hydraulical environments, gravel patchiness and subsequent hydraulic variability can not be avoided in the field (Peterson and Quinn 1996a). The temporal variability observed from single sample dates can be the result of the above mentioned spacial variability within a riffle-crest, and the degree to which flushing of fines from the gravel occurred through the sampling period. Compensatory flows, flows sufficient for bed mobility, help remove deposited fine material from the pavement layer. Flows that set the pavement layer in motion flush fines from the subpavement (10 – 30 cm below the surface). The patchiness of the gravel bed within a riffle-crest causes selective flushing of fines. These two processes, patchiness and fine flushing, together lead to highly variable results. The variation observed with single sample results initiated the change in sampling protocol to multiple freeze core samples.

5.5 Methodology Critique

5.5.1 Freeze Core Sampling

Although multiple samples are required to reduce natural variability, freeze core sampling is the best method of sampling spawning habitat to date. The technical problems encountered during this study (numerous attempts at achieving the desired depth of sampling and large cobble sized gravel adhering to the probe) cannot be avoided, but can be overcome with persistence. Making a smaller diameter probe would help limit these problems, but it would reduce the size of the sample.

Although a tri-tube freeze core sampler provides a larger volume, and thus could potentially reduce spacial variability, the use of it in a river dominated by large cobble is not possible. For these conditions, the single probe with a slightly wider diameter should obtain sufficient samples with minimal difficulty.

5.5.2 Sedigraph

Sedigraph analysis was performed in an attempt to trace the fine material to source; it was not successful. This was likely due to upstream slides. Sedigraph analysis could have been successful in determining differences between sites if two conditions were met. Firstly, the slides need to be controlled. Secondly, flushing flows would be required to remove pre-deposited fines. If pre-deposited fines were not removed, no significant distinction between 'U/S' and 'S/C' could be made. If flushing flows were not available, I would suggest using sediment traps and performing sedigraph analysis on the collected contents.

5.5.3 Dissolved Oxygen and Permeability

Determining dissolved oxygen and permeability throughout the winter with the techniques used in this study yielded highly variable results. Spacial variability was believed to contribute to the variable results. Taking multiple samples from one specific location was attempted, but the permeability test caused flushing of fines in the subsurface. Decreasing values were obtained when this procedure was attempted. Spacial variability can be avoided by installing standpipes at the beginning of the spawning season, i.e. during low flow. Standpipes, as discussed in Section 2.6.2, are hollow pipes buried vertically in the riverbed. These pipes make it possible for repeated sampling from one location, thereby reducing natural spacial variability.

The advantage of using the technique presented in this research is ease of sampling during 'high' flows. Standpipes must extend above the water throughout the sampling period in order to avoid mixing surface water with subsurface water. The relative permeability technique used for this study could obtain samples when water levels were greater than 1 m. However, the drawback is that the relative permeability data can not be compared to other published data. One method to overcome this is to sample 'good' quality spawning gravel (preferably in the same river system) as determined by other common descriptive measures, and use the relative permeability results as a standard of comparison. Further laboratory tests could be done to calibrate relative permeability data with actual permeability data.

5.5.4 *Sediment Traps*

The sediment traps were highly successful in terms of their ability to show differences in quantity and particle size distribution of gravel being deposited. Other research has also found them to be very effective. The traps used for this study were not placed in the river during times of peak flow and SS loads. If traps are in place during peak periods there is a possibility that the traps at the various sites could fill in with fines, and thus differences could be masked. To avoid this, many traps should be used and their removal should be staggered. For example, removing three traps after 30 days and removing the other three after 45 days.

Sediment traps are ideal for low budget and time constrained research. The freeze core data, which costs more money in terms of both labour and materials, basically mirrored the data from the sediment traps. Sediment traps are easily installed and removed by researchers with little experience. The only stipulation is that they can only be safely installed during low flows, as this researcher experienced first hand.

6 SUMMARY

The results of this study showed that 'GRVD' and 'Gall' can successfully support salmonids during incubation. Both had descriptive measures (%<0.85 mm, dissolved oxygen, and Fredle index values) that classified them as 'good' spawning habitat. 'U/S' samples were of marginal to 'poor' quality; and all descriptive measures from 'S/C' indicated that it could not support salmonids during incubation. The varying degrees of habitat quality were related to the site's proximity to gravel pit outfalls and riverbank slides. Although 'U/S' was upstream of all gravel mining activity, riverbank slides appeared to add significant amounts of fine material. 'S/C' was in direct proximity to the gravel pit outfalls (approximately 30 m) and thus sufficient mixing of gravel pit effluent with river water could not occur. Further downstream at 'Gall' the mixing of gravel effluent with river water, along with its location (approximately 1.5 km downstream), resulted in significantly higher quality spawning habitat. Although gravel pit effluent is the major source of fines, attempts to trace deposited fines to the gravel pits were not successful. It is believed, that riverbank slides upstream of gravel mining activity contributed to this studies' inability to trace the fines to source.

7 CONCLUSIONS

• Freeze core samples taken from various locations along the Coquitlam River indicate that 'GRVD' can support salmonids to the late stages of incubation.

• The 'poor' quality spawning habitat at 'S/C' is likely due to gravel mining effluent. The proximity to source lowered spawning gravel by eliminating a buffer zone where the effluent could mix with river water.

• Sediment traps collected large quantities of fines at 'S/C', as compared to the other sites.

•The impact gravel mining effluent had on gravel quality was significantly reduced further downstream at 'Gall'. The impact of the gravel mining effluent appears to be localized (within 500 m).

• Attempts to trace the source of the fine material at 'S/C' were not successful. The different hydraulic conditions together with episodic upstream slides were believed to complicate the investigation.

8 IMPLICATIONS

The inspiration behind this study was to determine if gravel mining activity negatively impacts spawning habitat. I believe both freeze core samples and sediment traps placed up and downstream of gravel outfalls provided significant evidence for the deterioration of spawning habitat. It is well understood by the scientific community that a portion of fines will deposit within the subsurface, regardless of hydraulic conditions. This being true, the large quantity of fines discharged into the Coquitlam River will inevitably reduce spawning habitat quality even if the proportion of material that settles out is low. If the Coquitlam River experienced flushing flows then perhaps the small portion that settles out could be flushed away. The present conditions at 'S/C' are such that flushing flows do not occur. The gravel pit operators should take responsibility for the loss of habitat via legal prosecutions. Sufficient legislation exists to prosecute polluters but the situation with the Coquitlam River is complicated. BC Hydro has effectively eliminated flushing flows for years that would have undoubtedly improved the conditions downstream of gravel mining activity and perhaps negated the negative impact of gravel mining altogether. After examining the results of this study I would suggest gravel mining operators should provide the necessary funds to replace the lost spawning habitat, as well, BC Hydro should work together with fishery biologist from DFO to establish timing and quantity of flushing flow releases.

Eliminating the upstream slides would provide government officials with just slightly less than ideal conditions for an up / downstream comparative study, due to the varying hydrological environments. Given that the law states that any loss of salmonid spawning habitat is unlawful, it can easily be proven in the future just as it has been in this study, that the gravel operators are reducing quality salmonid habitat.

9 RECOMMENDATIONS

Rehabilitating spawning gravel impacted by gravel mining activity would require 'clean' flushing flows that could mobilize the subpavement to a depth of 30 cm. Elimination of the source material is required for flushing flows to improve the gravel's ability to support incubating embryos to emergence. The large quantity of stored fines would require flushing flows for an extended period of time. However, since the impacts appear localized, the cost of eliminating the source and releasing additional water from the dam may not be justified. Adding spawning gravel upstream or some distance downstream to compensate for the loss of spawning habitat may be more cost effective.

Further studies that can determine the total area impacted by gravel effluent should be undertaken prior to any rehabilitation measures. Suspended sediment, bedload, and freeze cores samples at numerous locations up and downstream from the source, together with sediment traps could provide insight into how the conditions change longitudinally. The range of sampling techniques suggested is required due to the high degree of variability associated with depositional processes and the complex nature of the phenomenon. Controlling the activity of upstream slides would further aid in the isolation of gravel mining impacts.

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