SEASONAL VARIABILITY OF FINE-GRAINED SEDIMENT MORPHOLOGY IN A SALMON-BEARING STREAM

by

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Seasonal variability of fine-grained sediment morphology in a salmon-bearing stream

Abstract

This study incorporates an event-based sampling approach to characterize the suspended sediment structure and settling properties within O'Ne-eil Creek, British Columbia, Canada during the 2001 open water season. The factors investigated, which regulate flocculation of fine-grained sediment, were shear stress, conductivity, pH, suspended sediment concentration, bacterial content, and organic matter source and supply. Effective particle sizes are largest during active spawning, with much lower particle densities and settling rates than those of equivalent sized inorganic particles. This period exhibits increased suspended material for the given hydrologic conditions, and an abrupt change in isotopic signal (carbon and nitrogen). The isotopic variation is due to marine nutrients from anadromous sockeye (*Oncorhynchus nerka*) salmon that die shortly after spawning. These results indicate that the presence of spawning salmon changes particle structure due to a combination of biotic resuspension of settled material and incorporation of organic matter from post-reproductive carcasses into floc matrices.

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Chapter 1—Introduction

A recent review of Canadian research on fluvial systems (Ashmore et al., 2000) expresses the concern that, although the Canadian landscape has been formed largely due to glaciation, fluvial processes share a considerable, if often overlooked, role in shaping the land surface. In terms of relative contemporary impact on the earth's surface, fluvial processes likely exceed those of glaciation. Ashmore et al. (2000) detail the major mechanisms by which material is eroded and moved through watersheds from headwaters to outlets, and describe the impact of these riverine processes on aquatic habitat and the effects of anthropogenic disturbances.

Material of a range of sources and sizes is transported differently depending on hydrologic regime, local climate, and physical and chemical nature of the particles. Hydrologic theory indicates that higher flow rates result in suspension of larger substrates (Hjulström, 1939). As well, discharge and precipitation dictate the provenance of material transported to and within rivers and streams. Hydrology also regulates storage of material in transit along waterways. While it was previously assumed that all eroded material in fluvial systems was transported inevitably out to sea, relatively recent research has identified conveyance losses form upstream inputs to overall sediment yields (e.g., Meade, 1982; Walling, 1983). Transported material is apparently retained due to deposition on floodplains during overbank flows and accumulation on streambeds in low energy discharge (Nicholas and Walling, 1996; Owens et al., 1999). While storage depends mainly on hydrologic conditions, several studies have focused on the role of in-stream modifications to particle structure (e.g., Droppo and Ongley, 1994; Droppo and Stone, 1994; Petticrew, 1996, 1998).

These alterations are attributed to flocculation of smaller particles to form large aggregates, more prone to settle out of the water column.

Flocculation is a complex process involving cohesive or fine-grained sediments (< 63 μm diameter) where primary inorganic grains are bound together (Tsai and Hwang, 1995; Liss et al., 1996) by some combination of physical, chemical, and biological mechanisms (Droppo et al., 1997). Numerous studies (e.g., Kranck, 1979; Droppo and Ongley, 1992, 1994; deBoer, 1997; Petticrew and Biickert, 1998; Petticrew and Droppo, 2000) provide extensive proof for the existence of composite particles (also called flocs or aggregates) resulting from flocculation. However, the relative contribution of factors causing flocculation is still uncertain. Petticrew and Biickert (1998) identified six major factors influencing flocculation, (1) sediment mineralogy; (2) ionic concentration; (3) bacterial concentration; (4) shear stress and velocity; (5) suspended sediment concentration; and (6) organic matter source and supply. Considerable attention has focussed on most of these, the last point being the exception, under either laboratory conditions (e.g., Milligan and Hill, 1998), and naturally in both marine (Kilps et al., 1994) and freshwater (Droppo and Ongley, 1994) environments. Regardless of the nature of flocculation, the potential implications for aquatic habitat are problematic.

Fine-grained sediment is a known pollutant affecting the habitat and survival of biological organisms (Newcombe and MacDonald, 1991). Sediment influences fish survival by altering food organism supply, channel morphology, and bed composition. Highly turbid waters result in a reduced ability of brook trout to identify prey and food sources (Sweka and Hartman, 2001). A related phenomenon is that increased fine-sediment loading reduces invertebrate density (Hartman et al., 1996). Van Steeter and Pitlick (1998) note that significant changes in channel morphology, specifically narrowing, cause loss of potentially important fish habitat. Changing channel morphology redistributes the types of stream habitat available, and narrowing simply reduces habitat altogether. As well, fine sediment can degrade the quality of spawning habitat by filling interstitial spaces in gravels. Low flow periods after the annual snowmelt facilitate build up of fine sediment on and in the bed (Pitlick and Van Steeter, 1998). In fact, flushing of sediment that has infiltrated the bed gravels to appreciable depths requires movement of the gravels themselves. Considerable flow rates are necessary to do this, and so the fine sediment may be stored in the gravels for long periods of time. Sediment storage could reduce oxygen levels in spawning gravels by decreasing permeability and through oxidation of sediment-associated organic matter (Soulsby et al., 2001). Anthropogenic disturbances to watersheds have the potential to alter sediment dynamics, which could cause detrimental impacts to aquatic habitat and organisms.

Many studies have investigated the impacts of timber removal and associated activities (e.g., road and bridge building) on aquatic processes. Martin et al. (1984) found that stream water temperature tends to increase, as reduction of forest canopy enables greater infiltration of solar radiation. In addition, these authors found that pH decreases and concentration of exchangeable cations increases. Deforestation typically increases the potential for mass movement (Lowrance et al., 1984; Singh, 1998), and thus increases sediment supplies to streams. Road building and culvert installation associated with logging practices leads to extensive erosion and sediment inputs to streams (Ziegler and Giambelluca, 1997; Gunn and Sein, 2000). A greater quantity of sediments can translate to alterations of stream channel morphology, position, and slope, as well as increased turbidity, all of which can act to modify in-stream habitats.

Concern for aquatic habitat quality has led to the development of sediment transport models in order to predict potential impacts of watershed disturbances. Spatial and temporal analysis is an integral part of determining potential impacts on spawning and rearing habitat. Transport of suspended fine-grained sediment is regulated by a number of variables, most of which are described above. Flocculation is the major process acting to change sediment structure and regulate the hydrodynamic behaviour of sediment (Droppo et al., 1997) and thus has the potential to control sediment retention in waterways. Predictive models typically do not account for flocculation of fine sediment. Thus, models that do not consider flocculation may provide inaccurate information by underestimating the amount of material deposited in transit (Nicholas and Walling, 1996; Droppo et al., 1998).

The purpose of this thesis is to assess temporal changes in suspended sediment structure in a single stream, O'Ne-eil Creek. This stream is located in the northern headwaters of the Fraser River in the Stuart-Takla region of northern British Columbia (BC), which is the setting for the first interior BC fish/forestry interaction project. It was chosen as such due to the well-documented annual migration of spawning Pacific sockeye (*Oncorhynchus nerka*) salmon. Earlier work by Petticrew (1996, 1998) has indicated that fine sediment is being deposited and stored as aggregates in the gravels during the spawning periods in this area. With future harvesting planned, further study with respect to the relative importance of the particular factors influencing flocculation is important in order to evaluate the potential impacts of timing of disturbances on this problem. The objectives of this study are (1) to characterize suspended sediment structure (i.e., size, shape, and settling characteristics) temporally, and (2) to determine the relative importance of the various factors (e.g., shear stress and suspended sediment, organic matter, and bacterial concentrations) that influence flocculation within this system. In order to evaluate the seasonal changes in fine sediment structure and morphology, samples were collected over a range of hydrologic and biologic watershed events. These were partitioned into five discrete response types, which are: (1) rising water levels of springmelt; (2) summer low flow conditions; (3) rain events; (4) active salmon spawning; and (5) post-spawn. These periods were chosen as they exhibit different sources of organic material, as well as a range of flow and shear rates.

Figure 1.1 presents the hypothesized seasonal trends for important flocculation factors, and the expected influence of these factors in terms of floc-building. Springmelt is a period characterized by high discharge, and this is when the first flushed material stored in-channel and on the floodplain occurs. Less suspended load is moved during the baseflow levels of the low flow period, where the source material is predominantly in-stream. Rain events are characterized by higher than baseflow discharge, where suspended sediment concentrations are expected to increase, and comprise a combination of in-stream and terrestrial inputs. Rain events occur during baseflow, salmon spawn, and post-spawn, so they reflect the combined effects of resuspension of gravel-stored material that occurs during storms and the predominant source of organic matter for the particular sampling date. The period of active salmon spawn combines the introduction of anadromous organics and biological disturbance of gravels. This organic matter is expected to remain within the system post-spawn, but, because live fish are no longer present, disturbance of gravels is minimal. Note that shear stress and discharge are both derived from velocity measurements, which means that they exhibit similar seasonal trends. Also, bacterial activity increases with temperature (Phillips and Walling, 1995), and depends on organic matter quality (Webster et al., 1999). Sediment mineralogy and ionic concentration are presumed to have little effect on flocculation in O'Ne-eil Creek due to insignificant seasonal variation. Seasonal patterns of fine-sediment concentration, size, density, and settling rate were identified using this approach.

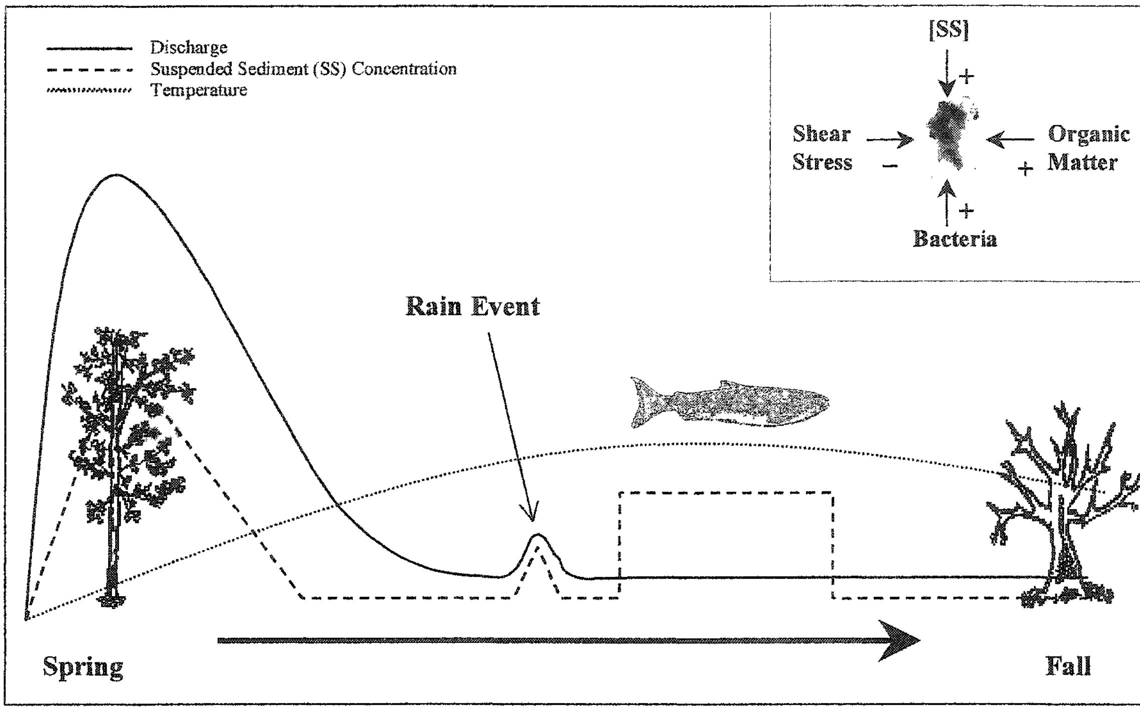

Figure 1.1 A hypothetical depiction of seasonal patterns of suspended sediment concentration ([SS]), discharge, and temperature. Inset relates four important factors to flocculation, where +/- symbols indicate whether flocculation is enhanced or inhibited. While only one rain event is shown, several typically occur during the season. Relative and absolute relationships between the variables depicted here are approximate.

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Chapter 2—Literature Review

2.1 Basin Scale Erosion

There are several factors that regulate the magnitude of sediment introduced to streams, including climate (e.g., precipitation, temperature), catchment characteristics (e.g., basin size, geology, topography, vegetation, soils), and human activities (Beschta, 1996). These factors collectively influence the amount and timing of sediment delivery. Precipitation produces the driving force for sediment movement, where there is a direct relationship between stream discharge and precipitation (Dunne and Leopold, 1978). The process of runoff is dictated by the ability for soils to store water. Basically, water enters the soil and whatever is not lost through evaporation or used for biological processes (e.g., uptake by vegetation) runs off on the surface or recharges the soil supply. Sediment can be eroded in both instances, where surface water will entrain and transport fine-grained sediment to streams, or saturation of soils can lead to mass movement. A secondary factor regulating both of these is soil texture (or hydraulic conductivity), where the propensity for water infiltration increases with the grain size of soils (Brady and Weil, 1996). These variables, in addition to vegetation cover, affect slope stability (Ritter et al., 1995). Mass movement of material does not occur unless a threshold is reached, where resisting strength is overcome by some driving force. Vegetation effectively enhances soil stability, as does cohesivity of soil particles, whereas precipitation, combined with topography (i.e., slope), creates the force to potentially trigger slope failure.

Basin size is an influential variable with respect to sediment delivery. First, small basins tend to exhibit steeper slopes, implying that mass movement is an important delivery process within these catchments. Second, floodplain area increases with basin size, resulting in a greater opportunity for storage of sediment. While there is more soil in larger basins to potentially lead to higher amount of sediment transported, it has been found that sediment yield (quantity of sediment transferred from catchment to the mouth per unit area) decreases with increasing basin size (Ritter et al., 1995). The reasons for this are that sediment is stored in the floodplains and channels. As well, sediment source areas can differ within actual basin area. This means that the probability that sediment will be delivered to a stream decreases with increased distance from the channels. Further, Pearce et al. (1986) state that area contributing to sediment delivery expands and contracts seasonally, depending on antecedent soil moisture, soil physical properties, water table elevations, and storm events. It appears that soil moisture is of utmost importance with respect to sediment erosion processes.

The anthropogenic influence on sediment erosion processes manifests itself in the form of land use practices. Whether it is for agricultural, urbanization, mining, or timber harvesting purposes, removal of vegetation and associated changes to the landscape surface results in changes in sediment erosion and transport. Trees and other vegetation perform a number of significant functions related to sediment supply and delivery to surface waters. Interception of precipitation by the forest canopy decreases both direct erosion of soil by rain impact and the amount of water reaching the ground that will entrain sediment and transport it to surface waters (Dunne and Leopold, 1978). Vegetation, via roots, increases the strength of the soil structure, resulting in an increased erosion threshold. Evapotranspiration by vegetation balances soil infiltration of precipitated water so that soil moisture remains at a level below the threshold for mass wasting under normal precipitation conditions (e.g., mudslides). Vegetation removal can thus disrupt the hydrological cycle of drainage basins by altering the balance between rainfall and evaporation, as well as changing the runoff response (Sahin and Hall, 1996). In addition, clearcutting can upset nutrient cycles and water chemistry. For example, Martin et al. (1984) state that increased exposure of the forest floor to solar radiation and direct precipitation causes increased temperature and water content, higher rates of decomposition of organic matter, and decreased pH in forest soils, which displaces exchangeable cations that can then be transferred to surface waters.

Deforestation can increase water runoff through soil compaction via heavy machinery and generate a greater amount of exposed sediment through road building, digging of roadside ditches, and introduction of culverts. Compaction is dependent on the type of machinery in use as well as the soil characteristics (Carling et al., 2001). How much harvesting directly leads to soil loss is subject to considerable disagreement; however, most researchers concur that roads and road construction cause a significant amount of soil loss. A special issue of the journal *Earth Surface Processes and Landforms* (2001) focused on the importance of forest roads as a source of sediment. The addition of forest roads can increase the drainage density of a basin, depending on the types of roads constructed (Croke and Mockler, 2001). Increasing the drainage density should, theoretically, increase sediment delivery as the source area of sediment becomes larger. Wemple et al. (2001) note that overall road-related erosion processes contribute significantly to sediment production in forested basins. However, they stated that road location, in terms of slope position, probably dictates how much sediment will be eroded. In a review of studies, Fransen et al. (2001) observe that the majority of the erosion is derived from unprotected cutbanks rather than directly from road surfaces. Bank stability is an important consideration, and thus riparian leave strips can reduce the possibility of mass wasting and bank erosion (Lowrance et al., 1984), where large quantities of sediment can be added to streams instantaneously. As well, riparian forests are important buffers for filtering nutrient and sediment transport from adjacent disturbed areas (Perry et al., 1999).

A significant problem induced by increased sediment loads in streams, other than water quality, is changes in erosional processes, as more sediment means more material being transported, which acts to scour streambeds and banks. This, in turn, can result in alteration of channel shape, position, and/or slope. Disturbance of any type (man-made e.g., logging or natural e.g., fires) can alter the natural conditions for maintaining the most efficient stream functioning by altering the rates of erosion and sediment yield (Beschta, 1996). The magnitude and significance of transported sediment is highly variable both spatially and temporally. Thus, it is important to examine sediment dynamics on both scales in order to determine the impact of planned or potential disturbances.

2.2 Sediment Transport

Stream channels are composed of a wide range of substrates varying in size and composition. Depending on the range of energy the system exhibits, mineral material is eroded and transported from areas of high elevation, or headwater streams, toward lower elevations where deposition occurs. In streams of high elevation and slope, much energy is dissipated in the form of turbulence, but the remainder is spent on moving substrates downstream (Ritter et al., 1995). The size of the substrates that will be moved is reliant on the amount of energy available, and this depends on factors such as topography and hydrology (e.g., velocity, discharge, and water temperature). Conversely, deposition of suspended material occurs when velocity/turbulence decreases to the point that transport is impossible (size dependent). This can occur in deltaic environments, on the upstream side of flow blockages (e.g., large woody debris), in backwater areas, and/or during low flow after the freshet and climatically dry periods (Dunne and Leopold, 1978). Given the dependence of sediment transport on flow velocities, a quantitative relationship between water and sediment discharge exists (Wolman and Miller, 1960).

There are two different categories of downstream transport, which also depend on the substrate size and available energy. Coarse material (sand to boulders) is often moved as bedload, meaning it remains close to the channel bed and slides, rolls, or bounces along with the slope gradient. Fine-grained sediment, composed of particles < 63μm in diameter (silts and clays), is transported as suspended load. Importantly, Petticrew (1998) suggests that hydrodynamic models predict little prolonged (> day) in-channel storage for particles of this size. The amount of sediment entrained (brought into suspension) depends on the type and amount of sediment available in/near the stream, as well as the size and shape of the specific sediment particles and the water velocity. These factors, in addition to water density, fluid viscosity, and sediment density, also dictate the settling rate or deposition of the suspended sediments in question.

An important property of fine-grained particles that differs from larger grains is cohesivity. This attribute expresses itself in two different ways. First, once these particles settle, a greater critical shear stress is required to resuspend them than their size indicates (Hjulström, 1939; Ritter et al., 1995). Second, these particles have a tendency to aggregate or flocculate. The phenomenon of flocculation alters sediment transport behaviour (Droppo et al., 1997), where fines, not typically believed to be stored in-channel, deposit. This has implications for biological organisms (Petticrew, 1998) and transport of particle-bound contaminants (Liss et al., 1996).

2.3 Flocculation

Flocculation is a complex process involving the binding together of fine-grained, cohesive sediments by a combination of physical, chemical, and biological mechanisms (Tsai and Hwang, 1995; Liss et al., 1996; Droppo et al., 1997). Flocs or aggregates are the products of this occurrence. A review of the available literature (e.g., Kranck, 1979; Droppo and Ongley, 1992, 1994; Petticrew, 1996; deBoer, 1997; Petticrew and Biickert, 1998; Petticrew and Droppo, 2000) provides extensive proof that fine-grained sediment is transported as aggregated or flocculated structures in both marine and freshwater systems, however there is much debate about the relative contribution of the factors that influence flocculation. In fact, the complexity of the process makes it difficult to isolate any one particular factor in natural environments. Petticrew and Biickert (1998) suggested six major factors influencing flocculation: (1) sediment mineralogy; (2) ionic concentration; (3) bacterial concentration; (4) shear stress and velocity; (5) suspended sediment concentration; and (6) organic matter source and supply. All of these except that last have been studied extensively in laboratory experiments (e.g., Milligan and Hill, 1998), and naturally in both marine (Kilps et al., 1994) and freshwater (Droppo and Ongley, 1994) environments. These factors either enhance or inhibit flocculation in the sense that they affect particle collision frequency or efficiency.

2.3.1 Sediment Mineralogy

Inorganic particles, like soil colloids, exhibit surface charges, which depend on sediment mineralogy and pH of the water. In near neutral or high pH waters, there is a net negative charge, which induces an electric double layer that creates repulsive forces between particles and enhances dispersion (Stumm and Morgan, 1981; Evangelou, 1998). The extent of this electrostatic layer depends on: (1) the type of mineral; and (2) the size of the mineral. Information from soil science literature (e.g., Brady and Weil, 1996) indicates that minerals of the fine-grained fraction (silt and clay) exhibit different types and amounts of charge. Aluminosilicates commonly exhibit permanent charge due to isomorphous substitution, and the intensity of the charge is greater for 2:1 clays (e.g., smectite) versus 1:1 (e.g., kaolinite) and 2:2 (e.g., chlorite) clays (Evangelou, 1998). On the other hand, metal-oxides are observed to have pH-dependent charges due to (de)protonation of hydroxyl groups associated with the metal (Evangelou, 1998). Silicate clays also exhibit pH-dependent charges at sites called broken edges, where hydroxyl groups are exposed. Since this phenomenon inhibits flocculation, but flocculation does occur, there must be conditions where this electrostatic double layer is overcome. Kretzschmar et al. (1997) found that this was the case in conditions of decreased pH or increased ionic strength.

2.3.2 Ionic Concentration

Arora and Coleman (1979) note that flocculation occurs only beyond a minimum electrolyte concentration called the critical salt concentration (CSC). In fact, McBride and Baveye (2002) acknowledge that it was the effect of electrolyte concentration on (clay) interparticle interactions that yielded proof for diffuse double layers and attractive and repulsive forces upon colloidal particles in suspension. Aqueous cations are attracted to the negatively charged minerals, which effectively compresses the double layer, enhancing flocculation (Evangelou, 1998). Once this electrostatic layer is compressed, collisions between inorganic particles result more efficiently in cohesion, and forces such as van der Waals are able to overcome the original repulsive force (Tsai and Hwang, 1995). Further, the rate of flocculation is dependent on the number of valence electrons a cation possesses (McBride and Baveye, 2002). Divalent cations, such as Ca^{2+}, increase the rate of flocculation over monovalent cations (Zita and Hermansson, 1994). The role of salt flocculation has been studied extensively in marine systems (van Leussen, 1999); however, the relative contribution of ionic concentration versus biological components in freshwater environments is in question (Droppo and Ongley, 1994).

2.3.3 Bacterial Concentration

Microbial association with inorganic particles effectively increases the efficiency of particle collisions to produce flocs. Bacteria secrete extracellular polymeric fibrils or substances (EPS) that act to bind the primary constituents of flocs (Droppo et al., 1997). They do so in a manner similar to aqueous cations, where the electrostatic double layer is compressed assisting particle collision, while the sticky nature of the cells/fibrils 'glues' the particles together. Exopolymeric fibrils are a component of "marine snow" (Alldredge and Silver, 1988; Santschi et al., 1998) and grain-to-grain adhesion of fine sands comprising bed material in marine environments (Dade et al., 1990). This bacterial adhesion in fine sands was correlated to increased critical shear required for entrainment by Dade et al. (1990), which indicates an increase in sediment stability due to bacterial presence. The adsorption of bacteria to particles tends to depend on salinity (Bell and Albright, 1981), where free-floating bacteria are more prolific in marine environments. This relationship is probably not due directly to the salt concentration, but rather is more likely related to particle concentration

(Kirchman and Mitchell, 1982). The relative proportion of bacteria cells bound to sediment as compared to free floating is greater in turbid freshwater environments.

The macromolecular compounds produced by bacteria have been shown to vary in quantity and composition as growing conditions change. For example, Phillips and Walling (1995) state that flocculation is depressed at low water temperatures due to decelerated microbial activity. Kirchman (1983) found a seasonal pattern for the number of cells per particle, where larger bacterial numbers were associated with suspended sediment in summer compared to winter months. This pattern may indicate that more bacteria were available to colonize particles or that the quality of particles as substrates for growth was greater in the summer period. Kirchman (1983) observed that the majority of particles colonized by bacteria were largely of irregular structure, which typically suggests high organic content. Cell size was also evaluated and significantly larger cells were found attached to particles rather than free-floating, which suggests that attached bacteria are more metabolically active than free-floating cells. This idea is corroborated by Koetsier et al. (1997), who identify a spatial and temporal pattern of bacterial response to changing quantity and source type of organic matter. Greater bacterial growth occurs when the nutrient supply is more biologically available.

Concentration of attached bacteria should also vary with concentration of suspended sediment. Goulder (1976) found a significant correlation between the concentrations of sediment-attached particles and suspended sediment, where attachment was highest when suspended sediment was the highest. A similar trend was identified by Droppo and Ongley (1994), where the attached bacteria and suspended sediment concentrations were highly correlated in the spring, during high suspended sediment concentration, but this correlation was not repeated during the summer, or low suspended sediment period. Thus, the causative factor for seasonal variation in sediment-attached particles is not singular, but rather likely due to a combination of changes in temperature, supply of organic matter, and suspended sediment concentration. As well, determining the relative importance of each of these factors is dependent on obtaining valid and reliable bacterial cell counts.

The direct-count method, using fluorescence microscopy, has been commonly implemented to enumerate aquatic bacteria (Hobbie et al., 1977). A fluorescent dye is used to stain the bacterial cells so they are easily identified. Given that freshwater bacteria are found as both sediment-bound and free-floating forms (Paerl, 1975), the method enables differentiation between the populations. This is important when assessing potential versus actual contribution of bacteria to flocculation, and this directly relates to the concentration of suspended sediment (i.e., at low suspended sediment concentrations there will be relatively more free-floating bacteria assuming all other factors are constant).

There are several prerequisites for this technique, including (1) filters of appropriate pore size to retain bacteria, (2) visibility of cells on the surface, and (3) optimal contrast between the bacteria and the filter (Hobbie et al., 1977). Because the majority of aquatic bacteria fall in the size range of 0.3 to 0.7 μm, black nucleopore filters of at 1.0 μm pore size are used to examine sediment-bound bacteria as they will be retained on the filter; the filtrate is passed through 0.1 μm to determine free-floating bacteria (Droppo and Ongley, 1994). It should be noted that concentration refers to number of cells per unit volume of the filtered sample. Thus, a ratio of sediment-bound and free-floating bacteria can be obtained. This ratio may be erroneous as free floating bacteria may settle on the sediment during the first filtration, which will prevent these cells from passing through the filter, and bacteria may be attached to the underside of sediment, no longer visible for counting. Kirchman and Mitchell (1982) estimate a possible 50% (coefficient of variation) systematic error in underestimating attached-bacteria using size fractionation and standard acridine orange direct counts. They suggest a technique of rinsing the stained filter twice with 1 mL of filter-sterilized water to decrease error from retention of unattached cells. As well, Droppo and Ongley (1994) accounted for cells attached on the undersides of particles by doubling the counted number. These suggestions collaborate to decrease the systematic error, which should make comparisons of bacterial counts comparable between studies.

2.3.4 Shear Stress and Velocity

The influence of hydrodynamics on flocs is a highly contentious issue. Interparticle collisions are induced by three main fluid dynamic mechanisms (Dyer and Manning, 1999): (1) Brownian motion; (2) differential settling; and (3) turbulent shear. Brownian motion, or the random motion of water molecules, acts on particles < 0.1 μm in diameter (Tsai and Hwang, 1995), and is not significant for larger particles and flocs (Partheniades, 1993; McBride and Baveye, 2002). Differential settling occurs in low shear environments (Lick et al., 1993). The premise is that larger particles (> 50 μm) settle faster than smaller ones, enabling collisions between these two particle populations. Turbulent shear is the primary mechanism for collision of particles between 0.1 and 50 μm (Tsai and Hwang, 1995), and is predominant in highly turbulent conditions. In this last case, the high-energy environment can result in both the formation and destruction of flocs, depending on the floc strength.

Lick and Lick (1988) state that turbulent shear stresses inhibit flocculation through disaggregation processes, or increased collisions, and fluid shear itself is not important.

However, Burban et al. (1989) note that high turbulence intensities destroy flocs by stretching or breaking the bonds, whether they are biological or chemical. Further, van Leussen (1999) found that increased shear resulted in a reduction in floc size. Thus, it appears that there is an optimal range, where flocculation is enhanced at low shears, but higher shear results in disaggregation, either through increased collisions or the fluid motion itself.

2.3.5 Suspended Sediment Concentration

Similar to shear stress, there is no clear understanding of how suspended sediment concentration influences flocculation. In general, it is believed that the probability of flocs forming increases with increasing suspended sediment concentration. Work by Milligan and Hill (1998), Eisma and Li (1993), Droppo and Ongley (1994), and Berhane et al. (1997)confirm this relationship (i.e., a strong positive correlation between maximum floc size and concentration). However, laboratory studies by Tsai and Hwang (1994) and Tsai et al. (1987) have shown that collisions between flocs induced by high suspended sediment concentrations result in disaggregation. Dyer and Manning (1999) confirm this latter theory and state that the simultaneous increase of shear stress and concentration may lead to break up of flocs, but the effect of concentration appears to be of greater importance than shear for causing breakage. These experimental conditions may have been devoid of biological material. As suggested previously, sediment-attached bacteria are often found when suspended sediment concentration is high, and bacteria are typically found attached to amorphous particles (or flocs). This would indicate that suspended sediment concentration, when associated with bacteria, results in larger flocs.

2.3.6 *Organic Matter*

Although it has been identified that organic matter influences flocculation and floc structure (Petticrew and Biickert, 1998; Petticrew and Droppo, 2000), the extent of the contribution and the exact processes involved are in question. Two possible explanations include: (1) flocculation is partially facilitated by the organic matter promoting successful collisions; and (2) bacteria utilize and colonize organic particles and then promote floc building through the secretion of metabolic products. First, organic matter, whether it is dissolved or particulate, is composed of hundreds of macromolecules, such as proteins, polysaccharides, lipids, and humic and fulvic acids (Santschi et al., 1998). Polysaccharides, specifically, have been found to comprise fibrils that form the binding material within flocs (Leppard, 1997). As well, under certain conditions, organic matter (e.g., humic acid) will adsorb to inorganic particles, which affects the surface charge, and thus the diffuse double-layer, of these particles. In other words, organic matter can be composed of fibrillar material or it can alter the surface properties of particles, where both increase the likelihood of floc formation. Second, aquatic microorganisms function primarily as decomposers of organic matter, and require this material as an energy and nutrient source (Ward and Johnson, 1996). The rate at which organic material is assimilated by bacteria is dependent upon its relative quality (Koetsier et al., 1997; Webster et al., 1999). Thus, it is apparent that, if microbial activity is a significant aspect of flocculation, then organic matter quality and quantity should be considered. Importantly, these factors, as well as temperature, vary seasonally (Ward and Johnson, 1996), which has implications for temporal variation of floc formation and structure in systems.

Sources of Organic Matter

Organic material is introduced to stream ecosystems through several possible routes, from a variety of terrestrial, freshwater, marine, and atmospheric sources. The diversity with regards to both sources and routes creates spatial and temporal variation in quality and quantity of organic material. Examination of this on a longitudinal scale throughout watersheds led to the development of what is known as the River Continuum Concept (RCC) (Vannote et al., 1980), which predicts a gradual decrease in size and quality of organic matter as it is transported downstream (Minshall et al., 1983). The definition of quality used here refers to the bioavailability of the source. In other words, a source of higher quality is more easily utilized and assimilated by microorganisms than lower quality material. There are two general types of organic matter that are important to the nutrient and energy budgets of stream ecosystems. These are: (1) allochthonous, or material derived from outside the channel, such as terrestrial vegetation, soil humus, and atmospheric particulate matter; and (2) autochthonous, or organic matter that originates from sources within the aquatic system, such as periphyton and invertebrates (Merritt and Cummins, 1996; Young and Huryn, 1997). In addition, the former often influences the latter by providing essential nutrients and regulating light intensity (Minshall et al., 1985). Hynes (1975) was the first to acknowledge the importance of the interaction between aquatic and terrestrial domains of ecosystems (Minshall et al., 1985). Specifically, topography, soil properties, and climatic patterns affect the flow of organic material in stream systems, just as they do sediment delivery. Thus, spatial and temporal patterns in the terrestrial environment are intimately linked to those in the aquatic realm. This section will focus on the factors influencing organic matter source and flow patterns, and the techniques available to quantify these variables.

2.4.1 Allochthonous Sources

Allochthonous influence depends on the spatial variation of riparian species and relative contribution to streams. The specific composition of riparian vegetation depends on properties inherent in the parent geological material, climate, and topography (i.e., biogeoclimatic designation), and thus varies greatly depending on the scale of focus (e.g., watershed versus reach) (Allan et al., 1997). As well, the probability that riparian material will enter a stream depends on bank slope (France, 1995a), water level, vegetation proximity to channel, and size of material. Assuming that all material has an equal chance of introduction to streams, there is also an issue of organic matter quality. In particular, Webster et al. (1999) separated allochthonous inputs into four categories, which were large wood (logs), small wood (sticks), leaves, and fine particulate organic matter (FPOM). They found that small wood and leaves provided higher quality material than large wood and FPOM, and this was related to decomposition rates or microbial activity (i.e., higher quality with higher rates). More specifically, Koetsier et al. (1997) found that leaves from different tree species contributed organic matter of differing quality, which was also related to rate of breakdown. It is apparent that organic matter quantity and quality varies on local spatial scales depending on the type of material available to streams from adjacent riparian forests, and factors that increase the probability of introduction of these sources.

Similarly, allochthonous inputs from riparian forests exhibit a temporal dynamic in the form of seasonal fluctuations, especially in temperate regions (Minshall et al., 1992; Johnson and Covich, 1997). This is related to two major factors: (1) seasonal availability of species; and (2) seasonal fluctuations in stream discharge. First, a large proportion of allochthonous contribution to streams is in the form of leaves from riparian trees. However, there is an obvious variation in organic matter introduced to streams on a seasonal basis. The most conspicuous input comes from autumn-shed leaves, but imported leaves resulting from storms may also contribute significantly to the organic material load (Koetsier et al., 1997). Researchers (e.g., Stout et al., 1985; Irons et al., 1991; Koetsier et al., 1997) have also identified a change in quality of leaves from the same species over time, and this is a function of the level of decomposition before they reach the aquatic system. Second, seasonal fluctuations in discharge affect the proportion of influence that allochthonous sources have on the total organic matter balance within streams. This is related to coupling between floodplains and stream/river channels and the retentiveness of the channel itself. There is a lateral exchange of material between streams and associated floodplains, where, depending on flow level, organic matter, either recently deposited by riparian forests or stored from upstream inputs during floods, can be imported to streams (Tockner et al., 1999). As well, coarse detritus is easily retained within stream reaches by physical obstacles (e.g., rocks or large woody debris) within the channel (Johnson and Covich, 1997), whereas the ability of streams to retain smaller forms of organic matter depends on flow and flocculating conditions. These factors dictate the degree of local influence that riparian forests have on the organic composition of streams.

2.4.2 Autochthonous Sources

Even though up to 90% of carbon used as energy sources within streams is derived from riparian forests (Johnson and Covich, 1997), autochthonous organic matter cannot be excluded from the overall carbon budget of stream ecosystems. The quantity of primary producers, such as periphyton and macrophytes, depends, to some degree, on riparian canopy cover, which regulates light intensity (Allan, 1995; Sand-Jensen, 1998) and allochthonous inputs of nutrients. As well, the ability of these organisms to maintain the same habitat over time depends on discharge in a two-fold manner. At high flow, organisms may be uprooted or "ripped" from their habitat. As well, streambed substrates are mobilized and sorted in high discharges. This limits the habitat that autotrophs can occupy as well as their residence time. Aquatic organisms are also influenced by other properties of streams such as water temperature, and since this factor is a function of air temperature, there exists a seasonal variation in temperate regions. Thus, it is apparent that autochthonous sources of organic matter to streams also vary in space and time, and, as they are tightly linked to the riparian organic matter, are seasonally dependent for reasons similar to those given above for allochthonous sources.

2.4.3 Marine-Derived Sources

As described in the previous sections, transport of organic matter is typically conceptualized as a unidirectional process from headwaters to delta. However, the relationship between marine and freshwater systems also occurs in reverse due to mobile organisms that are able to travel against the gradient of flow (Garman and Macko, 1998). This is particularly apparent in freshwaters that are habitat for migratory fishes such as salmon (e.g., *Oncorhynchus* spp.). These salmonid fishes contribute significantly to nitrogen (Kline et al., 1990; Bilby et al., 1996) and organic matter (Garman and Macko, 1998) budgets of freshwater ecosystems; specifically in the form of marine derived nitrogen and organic matter (MDN and MDOM, respectively) from post-reproductive carcasses (Kline et al., 1994). Moreover, these nutrients are made available to terrestrial vegetation due to flooding and predator activity (Ben-David et al., 1998), where salmon carcasses are transported to riparian areas by high water or bears and other animals. Finney et al. (2000) note that the climatic change and commercial harvesting has influenced the productivity of freshwater systems, where marine derived nutrients contribute significantly to the trophic food webs. Hence, upstream migration of organic matter represents an ecologically important seasonal contribution to the annual material budgets of salmon-bearing streams that should not be ignored.

2.4.4 Bacteria

Here it is important to note that bacterial cells are also considered to be a source of organic material. Microorganisms provide a significant amount of energy to aquatic environments (Zimmermann et al., 1978). Dade et al. (1996) note the ubiquitous nature of microbes in marine sediments. Kirchman and Mitchell (1982) and Hall and Meyer (1998) emphasize the importance of bacteria in trophic food webs. The ecological significance of aquatic bacteria is mainly associated with their ability to remineralize dissolved and particulate organic matter (Kirchman and Mitchell, 1982). And, their activity results in the production of more biomass in the form of extracellular polymeric substances (EPS; see Section 2.3.3). For the purpose of this study, bacteria are considered to be a part of the autochthonous group because they utilize nutrients from other sources (Johnston et al., 1998) and their specific chemical signals depend on the available nutrient supply. However, it is important to acknowledge the significant biological contribution that bacteria provide to aquatic environments.

2.5 Identifying Source Types of Organic Matter

Organic matter is the energy source for a variety of freshwater and marine organisms, and thus it is important to identify provenance and transformations through trophic food webs in order to better understand such things as nutrient cycling, population dynamics, and interrelationships of energy pathways. Stable isotope analysis is one method of investigation that has shown great promise in this regard. Methodologies such as quantification of total organic carbon and gravimetric determination of percentage organic matter are used to assess the magnitude of organic inputs into aquatic systems, but are not suitable for identifying source materials.

2.5.1 Stable Isotope Analysis

The term isotope refers to the fact that there exist elements with two or more atomic forms, meaning they possess the same number of protons, but differ by their neutron count (Ehleringer and Rundel, 1988; Kendall and Caldwell, 1998). For example, carbon exists in two forms, ^{12}C, which is 98.89% of the total carbon abundance within the earth-atmosphere system, and ^{13}C, which comprises the other 1.11% (Ehleringer and Rundel, 1988; Boutton, 1991). Of the 1700 isotopic elements, 26 are known to be stable (not radioactive) (Sidle, 1998). Stable isotopes do not appear to decay to other isotopes on geologic time scales, and thus are useful for a number of reasons to be mentioned within this section. Coincidentally, several of these stable forms include elements that are of significant biological importance.

Elements, such as carbon, nitrogen, sulfur, hydrogen, and oxygen, comprise the building blocks of biological organisms. Isotopic composition of these elements changes predictably as they cycle in nature (Peterson and Fry, 1987). For example, the essence of the carbon cycle is that CO_2 is exchanged between the atmosphere and the bio-, hydro-, and lithospheres. Carbon is assimilated by primary producers in the process of photosynthesis; the carbon is fractionated (Smith and Epstein, 1971) leaving these organisms with isotopic signals that differ from the original carbon source (atmospheric CO_2). Further fractionation occurs proportionally to the number of transfers between trophic levels (Fry, 1988), but varies depending on the specific biochemical/metabolic pathways of the organisms within the chain (O'Leary, 1981; Cifuentes et al., 1988). In summary, fractionation is a function of variation in the physical and chemical properties of the isotopes and is proportional to differences in their masses (Broeker and Oversley, 1976; Ehleringer and Rundel, 1988). Similarly, nitrogen isotopic composition of various organisms differ from atmospheric nitrogen, but this depends on biological processes such as denitrification, fixation, and assimilation (Rennie et al., 1976; Cifuentes et al., 1988). Essentially, organisms exhibit a unique isotopic signal that reflects the concentration and isotopic composition of the sources of elements they utilize, as well as the various ways in which they metabolize these sources. The corollary is that, stable isotope information is useful for two types of analysis, which are: (1) the examination of fractionation processes; and (2) the ability to trace sources and sinks of organic material in nature.

A review of the primary literature indicates that there is great potential for the utility of stable isotope analysis (SIA). The first data on $^{13}C/^{12}C$ ratios was published by Nier and Gulbransen (1939), and with the advent of an isotope mass spectrometer (Nier, 1947) as well as improved analytical techniques (McKinney et al., 1950; Fry et al., 1992), researchers from many fields have recognized the value of SIA. The initial focus was to determine isotopic ratios of organic material to examine differences in natural abundance of elements and then relate these differences to biochemical pathways (e.g., Craig, 1953, 1954). This has led to the ability to determine the impact of environmental factors such as temperature, light intensity, and fluid dynamics on the isotopic composition of species (Cooper and DeNiro, 1989; France, 1995b, 1995c; MacLeod and Barton, 1998). Stable isotopic tracers have been used to monitor flows of organic matter (i.e., trace trophic relations) in marine (Peterson et al., 1985; Fry, 1988; Hedges et al., 1988; Cifuentes et al., 1988) and freshwater systems (Bunn et al., 1989; France, 1995d), and the introduction of marine nutrients into freshwater environments (Kline et al., 1990; Bilby et al., 1996; Ben-David et al., 1998). These studies have included identifying the various sources of organic material into surface waters, from the floodplain (Hamilton and Lewis, 1992) and riparian (McArthur and Moorhead, 1996) regions. However, the utility of SIA for identifying sources can be limiting for several reasons.

The main limitation identified by these studies is the difficulty in discerning between the various sources of organic matter. There is overlap in carbon isotope ratios among the various terrestrial plants, and even between aquatic and terrestrial vegetation. In other words, in order for isotopes to be used as indicators of source origin, the signals from the various sources must be isotopically distinct from one another (Lajtha and Michener, 1994). This has led to the development of mixing models that enable more accurate determination of sources, but the relative contribution of each source must be known. Others have suggested that analysing multiple stable isotopes simultaneously (Peterson et al., 1985; McArthur and Moorhead, 1996), or combining other tracers such as C/N ratios (Andrews et al., 1998), could prove to mitigate this problem.

Other limitations include the fact that isotopic composition of organisms changes temporally and spatially. Decomposition of detritus results in further fractionation of the isotopic ratios, food sources of organisms may vary seasonally, and environmental conditions fluctuate over a range of time periods (microscales, diurnal patterns, seasonal patterns). Isotopic ratios differ not only among species, but also within individuals of a single species. For example, Leavitt and Long (1989) identified intertree variability of the carbon isotopes in tree rings, which reflects changing environmental factors (e.g., light and nutrient levels) over time. However, given the extensive list of organic substances that have been studied, the methods' potential for tracing organics, and a well-defined methodology with high precision and accuracy, it would seem that SIA has the foundation for much further use.

The basic premise behind measuring ratios of stable isotopes is that during fractionation, the heavier isotope of each pair is either enriched or depleted relative to the lighter isotope, thus organisms, which metabolize differently should exhibit different ratios. The method of stable isotope measurement involves the comparison of a sample to a standard with a known, and unchanging, ratio. Typical standards include Pee Dee Belemnite (PDB), a marine limestone fossil used for carbon analysis (Craig, 1953), atmospheric nitrogen (Mariotti, 1983), and the triolite standard of the Canyon Diablo meteorite (CD) for sulfur (Krouse, 1988). The reason for the use of this differential approach is that absolute variations are typically very small, and thus absolute isotopic composition is not reliable (Lajtha and Michener, 1994). The differential approach allows for very small differences in isotopic composition of two samples to be accurately and reliably determined.

Methods for sample preparation vary for each isotope; for example, if the carbon isotope is sought, the samples must first be acidified (usually 1 N HCl) in order to remove carbonates, which are heavier than organic molecules and will skew the results (Lajtha and Michener, 1994). In general, all samples must be converted quantitatively to purified gases (e.g., CO_2, N_2, and SO_2 or SF_6) via combustion, the gases are cryogenically separated, and then analyzed by a stable isotope ratio mass spectrometer (Peterson and Fry, 1987). Ehleringer and Rundel (1988) summarize the mass spectroscopy process in that the converted pure gas is introduced to one end of the flight tube, ionized by an electron beam source, and then the ions are deflected in a magnetic field into circular paths. The radii of the paths are proportional to the masses of the isotopes. The ions are separated, depending on associated mass, into collectors (Faraday cups), and the ionic impacts are converted into frequencies. The critical parameter is the ratio of the signals corresponding to the different collector cups. The differences in ratios are then calculated relative to the relevant standard as per equation (1):

$$\delta\,(‰) = (R_{sa} / R_{std} - 1) \times 1000 \qquad 1.1$$

where R_{sa} is the isotopic ratio of the sample and R_{std} is the isotopic ratio of the standard.

2.5.2 Total Organic Matter and Carbon

Typically, the percentage of organic matter in sediments is determined by loss-on-ignition analysis (Nelson and Sommers, 1996). Suspended sediment samples should be filtered onto pre-ashed, pre-weighed glass fibre filters prior to the ignition process. The American Public Health Association (1995) methodology indicates that the filters are then dried and weighed, where the difference in weight, accounting for the volume filtered, provides the total suspended sediment concentration. The filters are then ashed in a muffle furnace at 550°C for at least an hour to remove the organic material, leaving only inorganic particles, which allows for the calculation of organic matter percentage by subtraction and comparison to total suspended sediment. This method is limited in that structural components of the inorganic portion of the suspended sediment may be lost along with the organic material upon combustion (Nelson and Sommers, 1996). This would mean that the weight loss would be in excess of the actual organic matter content. This is particularly a problem with high clay, low organic matter sediments (Howard and Howard, 1990).

Organic matter content can also be estimated from total organic carbon measurements because it is largely composed of carbon derived from organic (living) sources. Organic carbon is the difference between total carbon and inorganic carbon, and thus is determined directly from a measurement of total carbon after the inorganic portion is removed (Nelson and Sommers, 1996). There are two basic steps involved in the process. First, the organic carbon must be converted to a measurable form. There are several methods to accomplish this, and the most common involves oxidation of organic carbon to CO_2 by thermal combustion (Qian and Mopper, 1996). Second, the CO_2 evolved from the previous step is detected by some method (e.g., nonsuppressed ion chromatography) (Fung et al., 1996). This will yield a value for organic carbon, which can then be converted to percentage organic matter using a multiplicative factor. However, determining the appropriate factor is difficult due to the variation among and within soil samples, and thus this estimation method is not highly accurate. Nelson and Sommers (1996) suggest that the organic carbon content be identified and reported as a gauge of organic matter because the latter is typically not accurately measurable.

2.6 Characterizing Suspended Sediment Structure

The above review of literature has illustrated that there are two structural populations of particles, primary or individual grains and flocculated or composite particles. The latter tends to exhibit higher organic content and variable morphology and therefore each of the populations must be investigated by different means. Assessing the primary or constituent particles, the building blocks of flocs, results in an absolute particle size distribution (APSD). Measuring the APSD is relatively easy, in that it is not necessary to treat the samples gently when retrieving or processing them. A commonly used technique involves removal of all organic material, disaggregation of samples, and subsequent analysis in a Coulter Multisizer (Kranck and Milligan, 1983). The result is a spectrum of constituent particle size or the distribution of particles that potentially form flocs in natural environments. Studies have shown that this type of distribution can yield important information about the inorganic source material delivered as suspended sediment (e.g., Kranck et al., 1993) as well as the spatial and temporal variation of suspended sediment in a given system (e.g., Walling et al., 2000). Other research have used the APSD as a basis for comparison to determine the relative proportion and size of flocculated material to illustrate the size increase due to flocculation (e.g., Petticrew, 1996), the changes in hydrodynamic behaviour as a result of flocculation (e.g., Petticrew and Droppo, 2000), and the relative influence of environmental factors on flocculation (e.g., Droppo and Ongley, 1994). Measuring the effective particle size distribution (EPSD), or size range of flocs, is more difficult as it requires non-destructive methodology, and this is generally achieved by utilizing *in situ* techniques. A review by Wren et al. (2000) details the operating principles of the available techniques for measuring suspended sediment along with an in-depth comparison between them. For the purposes of brevity and relevance to the author's research, an examination of only three of these, being in-stream photography, settling chambers, and laser backscatter/diffraction, is provided here.

2.6.1 In-stream Photography

One non-invasive method to assess floc structure is to obtain snapshots of particles as they move in the water column. This is achieved by submerging a plankton camera as per Milligan (1996) and Petticrew (1996) parallel to the flow, where the shutter opens, a flash operates, and flocs are backlit producing a silhouetted image. This is a non-microscopic method, and therefore is suitable for systems with a large median particle size (~300 μm) and low sediment concentration (Kranck et al., 1993). The photographs are then analyzed with any image analysis system capable of measuring particle size distributions. Potential limits to this method are the difficulty in aligning the camera parallel to the flow, especially in turbulent systems, and the fact that there is a minimum resolution of 32-43 μm/pixel due to the film, digitization, and lens aperture (Milligan, 1996). Thus, this technique is not useful in systems where the measured floc size is less then the techniques' resolution (Biickert, 1999). In addition, this method is hampered by the specialized and time-consuming nature of the measurements (Phillips and Walling, 1995) and the fact that it is limited to low concentrations, where particles are less likely to overlap each other (i.e., easier to discern between individual particles). However, Wren et al. (2000) believe that this technique could be successfully applied to research seeking conclusive information about the dimensional properties of suspended sediment particles.

2.6.2 Settling Chambers

Several researchers have utilized modified Plexiglas plankton chambers (Droppo and Ongley, 1994; Droppo et al., 1996; deBoer, 1997) to assess floc structure. The sampling column is immersed parallel to the direction of the flow, capped, and inverted upright (Droppo, 2000). Particles are either allowed to settle onto a glass slide or Millipore filter for subsequent analysis with an microscope interfaced with an image analysis system. The sampling volume is varied depending on the suspended sediment concentration, as it is important to minimize overlap of particles. Droppo et al. (1996) modified the methodology by adding aragose in order to stabilize the filtered structures, enabling use of multiple microscopic techniques without disruption of flocs. Alternatively, water samples can be taken and filtered in a laboratory setting, however, the extra steps of handling, transport, and resampling increase the probability of disturbing floc structures, and thus increases the chance of error (Phillips and Walling, 1995).

2.6.3 Laser Backscatter/Diffraction

Available techniques for assessing *in situ* particle structure include laser backscatter/diffraction sizing. This involves submerging a probe connected to a portable computer, where particles flowing past an aperture are sized, resulting in particle counts in real-time (Biickert, 1999). Two types of measurements occur with this method: (1) diffraction-based; and (2) backscatter-based. A Malvern particle size analyzer is an example of a diffraction-based instrument, where a laser is passed through the water column, and the diffraction caused by particles passing through the low intensity beam (2 mW) is measured. The Fraunhofer diffraction theory is used to convert the resulting diffraction pattern to particle sizes (Krishnappen et al., 1994; Biickert, 1999). The backscatter instrument (e.g., Par-Tec 200/300) used by Phillips and Walling (1995) requires an oscillating lens that sweeps the focus point of a laser across a defined water column. The acquired signals are then translated to chord lengths of individual particles (Phillips and Walling, 1995). The use of these instruments is limited in field experiments due to the size and awkwardness of the apparatus and the financial expense of procuring this equipment (Phillips and Walling, 1995; Wren et al., 2000).

2.7 Summary

Sediment is eroded from watersheds and delivered to streams, where it is eventually transported from point of entry to the river mouth. There are biologic, climatic, hydrologic, and geomorphic factors regulating the magnitude and timing of sediment delivery, and anthropogenic impacts have been found to change the inherent balance within these systems. Sediment is transported either as bedload or suspended load depending on the nature of the particles (e.g., cohesiveness, size) and energy available in the fluid medium. Fine-grained sediment typically comprises the majority of the suspended load, which is generally not stored, over long time periods in the channel. However, it has been found that modification of the fine-grained size fraction is caused by flocculation. A floc is defined as an aggregate of two or more primary particles (inorganic and/or organic) bound together by some combination of physical, chemical, and biological factors. Researchers have tended to address the factors contributing to flocculation, including sediment mineralogy, ionic concentration, bacterial concentration, shear stress and velocity, suspended sediment concentration, and organic matter source and supply individually, in order to assess the causal linkages. However, it would seem that the complexity of the process of flocculation means that isolation of influential factors may be difficult, and perhaps a multivariate approach is preferable. In addition, the difficulty in obtaining *in situ* data concerning floc structure impedes the process of relating particle morphology to the influential factors.

Despite the difficulties, all of these factors have been studied extensively, with the exception of the influence of organic matter source and supply. Organic material in aquatic systems is derived from both autochthonous and allochthonous sources. The quality depends on the ease of assimilation by microbes (i.e., a higher quality source is one that is more easily decomposed), which is reliant on the specific source (e.g., leaves versus large woody debris). Both the quantity and quality of sources vary spatially and temporally. At the seasonal scale variability is caused by climatic factors (e.g., temperature, precipitation, insolation) and lifecycle patterns of biological organisms. In other words, biological organisms exhibit an optimal range of tolerance for temperature, water availability, and radiation, and thus species composition changes over the annual timeframe. Spatial variation in source material occurs in the form of changing inputs longitudinally from headwater to mouth, as well as due to changes in hydrologic conditions. The latter is especially important for autochthonous sources that persist in the channel and are directly influenced by water currents. An added variable is that of marine derived organic matter in the form of migrating salmon that enter freshwater streams in order to spawn.

Organic matter sources can be quantified by several different methods. Stable isotope analysis (SIA) is used to trace the origin of sources, and to examine processes that cause fractionation of isotopic composition ratios. SIA is limited because isotopic ratios must be distinguishable between sources in order to discriminate accurately. However, using multiple isotopes, and/or other tracing mechanisms in conjunction with SIA, should mitigate the problems. Loss-on-ignition analysis is employed to quantify organic matter in streams, as is the determination of total organic carbon.

There is an apparent need to characterize suspended sediment in aquatic systems because of the implications for contaminant transport and retention in fluvial systems and aquatic habitat quality. Many researchers have done so using either the absolute or effective particle size distributions, or both. In terms of examining the process of flocculation, the latter size distribution is necessary. There are several techniques used for the purpose of measuring these distributions, some of which are more limiting than others depending on the intent of the research and the resources available to the researcher.

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Chapter 3—Seasonal variation in structure and settling characteristics of fine-grained suspended sediment in a salmon-bearing stream

Abstract

Recently, researchers have found that the suspended sediment load of most fluvial systems is primarily comprised of aggregated or flocculated particles that typically exceed their constituent mineral grains in diameter by at least one order of magnitude, depending on the associated hydrologic conditions. Discrepancies in particle size of this magnitude imply that more material can be settled and stored, at least in the short-term, within freshwater systems than is indicated by conservative sediment transport models, a phenomenon that could potentially modify aquatic habitats. This study incorporates an event-based sampling approach to characterize the suspended particulate matter (SPM) concentration, absolute and effective particles size distributions (APSD and EPSD), and the settling velocity and density of the suspended sediment for O'Ne-eil Creek, British Columbia, Canada during the 2001 open water season. An increase in the average D_{99} from 68 to 1056 μm for APSD and EPSD, respectively, indicates that the suspended sediment in O'Ne-eil Creek is transported as flocs/aggregates. Analysis of inorganic spectra demonstrates coarser grains moving as suspended particles during salmon activity and a change in source material for post-spawn suspended sediments. During the spawn period, the *in situ* particle sizes exceed those from all other event types and exhibit much smaller particle densities and settling rates than those of equivalent sized inorganic particles. The results indicate that the presence of spawning sockeye (*Oncorhynchus nerka*) salmon changes particle structure due to a combination of biotic resuspension of

settled material and introduction of marine-derived organic matter to floc matrices. Further research is required to elucidate the exact nature of the relationships.

3.1 Introduction

Hydrodynamic theory predicts that riverine fine-grained sediments (< 63 μm diameter) will be effectively transported, with minimal channel storage, out to sea, based on the assumption that they are moving as individual grains characterized by very slow settling rates. This idea that efficient translation of sediment (i.e., insignificant intermittent storage) occurs through river networks has led researchers to focus on developing and using yield models to predict sediment and contaminant source, fate and effect (Droppo, 2001). However, recognition of an apparent conveyance loss from upstream inputs to downstream sediment yields (e.g., Meade, 1982; Walling, 1983) renders these models inadequate. The apparent inefficient delivery of suspended sediment has been attributed to storage on floodplains and within channel beds (Owens et al., 1999). High discharge events (e.g., freshet and storms) inundate floodplains and suspended sediment is deposited as a result of laterally declining velocity, and increasing roughness gradients due to shallow flows and terrestrial vegetation (Nicholas and Walling, 1996). Conversely, low discharge periods are conducive to sediment deposition and accumulation on streambeds (Droppo and Stone, 1993; Pitlick and Van Steeter, 1998). While the magnitude and duration of storage depends mainly on hydrologic conditions, the stored load may comprise a significant portion of a system's annual sediment budget (Walling et al., 1998; Owens et al., 1999) contrary to traditional thought. This is largely due to the misconception that particles are transported as single grains.

Studies that have examined fine-grained sediment structure have led to a relatively new understanding that suspended sediment is commonly transported in a flocculated form (e.g., Droppo and Ongley, 1992, 1994; Lick and Huang, 1993; Phillips and Walling, 1995, 1999; Petticrew, 1996, 1998; Droppo et al., 1997, 1998), rather than as individual particles. Flocculation is the process whereby single sediment grains (inorganic and/or organic) combine together to form larger units or flocs. Petticrew and Droppo (2000) identified two populations of composite particles that included compact aggregates and amorphous flocs, distinguishable by respective densities and settling rates. Woodward et al. (2002) suggest that both aggregates and flocs belong to the population of composite particles, where the source material distinguishes the respective type; they suggest aggregates enter the system as such and flocs form within the water column.

Regardless of origin, particle structure is a major factor in regulating the behaviour of suspended material in aquatic environments (Kranck, 1993; Nicholas and Walling, 1996). Flocculation alters the hydrodynamic properties of sediment (Petticrew and Biickert, 1998; Droppo, 2001) by increasing the effective size of particles, which results in corresponding changes to structural characteristics of particles within a system, including shape, density, porosity, and composition (Gibbs, 1985; Li and Ganczarczyk, 1987; Andreadakis, 1993; Nicholas and Walling, 1996; Droppo et al., 1997, 1998; Phillips and Walling, 1999; Droppo, 2000). Fluid dynamic principles dictate that these modifications will result in subsequent adjustments to transport and storage of sediment. For example, Petticrew and Biickert (1998) suggest that storage of fine-grained sediment in gravel beds should be increased compared to what is currently predicted by hydrodynamic models.

Fine-grained sediment represents a gravimetrically insignificant proportion of the total sediment load in freshwater systems due to the relatively small mass as compared to other substrate fractions. However, long-term storage of fine-grained sediment has important implications for streams that support prime salmon-spawning habitat, and the potential for increased storage is a specific concern in anthropogenically-disturbed watersheds. Turbid water and heavily silted gravels can result in suffocation of eggs and a reduction of available food organisms (Newcombe and MacDonald, 1991), and are detrimental to emerging juveniles (Soulsby et al., 2001). Gravels must be clean and well oxygenated for optimal survivorship of salmon stocks. Road building and stream modification practices associated with timber removal translate to greater inputs of sediment to streams (Ziegler and Giambelluca, 1997; Gunn and Sein, 2000). Elevated sediment loads during lower stream flow are problematic because these periods are prone to create build-up of fine sediment on streambeds (Pitlick and Van Steeter, 1998) and most salmon spawning occurs during late summer during baseflow discharge. Timing and type of forestry practices prescribed for specific watersheds should occur accordingly.

Accurate prediction of detrimental impacts to aquatic organisms due to fine-grained sediment requires adequate characterization of suspended and gravel-stored dynamics. As flocculation is regulated by many biological, chemical, and physical factors (see Droppo, 2001), which are highly dynamic in natural systems, the *in situ* process is complex. Efforts should be made to examine the variability of sediment structure on both temporal and spatial scales in natural systems prior to watershed disturbance requiring sediment modeling. The purpose of this study is to characterize the variability in fine sediment structure and settling properties over a variety of temporally different conditions in a salmon-bearing stream located in the Stuart-Takla region of northern British Columbia in order to provide a baseline for (1) a basis of comparison to future disturbances for identification of changes and (2) the ability to predict storage patterns and their implications. This was accomplished through construction of constituent and *in situ* particle populations, determination of relevant dimensions of particle structure (e.g., maximum and median diameter), quantification of settling properties (e.g., fall velocity and shape) and related densities, and subsequent comparison of these characteristics based on hydrologic and biologic events in the watershed.

3.2 Materials and Methods

3.2.1 Study Area

The study region (Figure 3.1) includes watersheds located in the Hogem Range of the Omenica Mountains in the Takla Lake region of northern British Columbia, an area under examination by partners in the Stuart-Takla Fish/Forestry Interaction Study (STFFS). This project was undertaken in the early 1990s with cooperation between government agencies (e.g., Department of Fisheries and Oceans (DFO) and the Ministries of Forest (MOF) and Water, Land, and Air Protection (MWLAP)) and academic institutions (e.g., the Universities of British Columbia (UBC) and Northern British Columbia (UNBC) and Simon Fraser University (SFU)), local First Nations communities (Tl'Azt'En Nation), and forestry companies (Canadian Forest Products (Canfor)) to obtain information regarding the relationship between forestry activities and the productivity of aquatic ecosystems in B.C.'s central interior. Considerable research on this topic has occurred in coastal systems of British Columbia; however, due to significant differences in biogeoclimatic characteristics compared to the central interior, this information is generally not transferable. This is especially true for sediment research, in that basin traits (e.g., slope), surficial geology, vegetation, and precipitation are some of the factors that play a role in regulating the magnitude and timing of sediment delivery through systems, and these differ significantly on a regional scale.

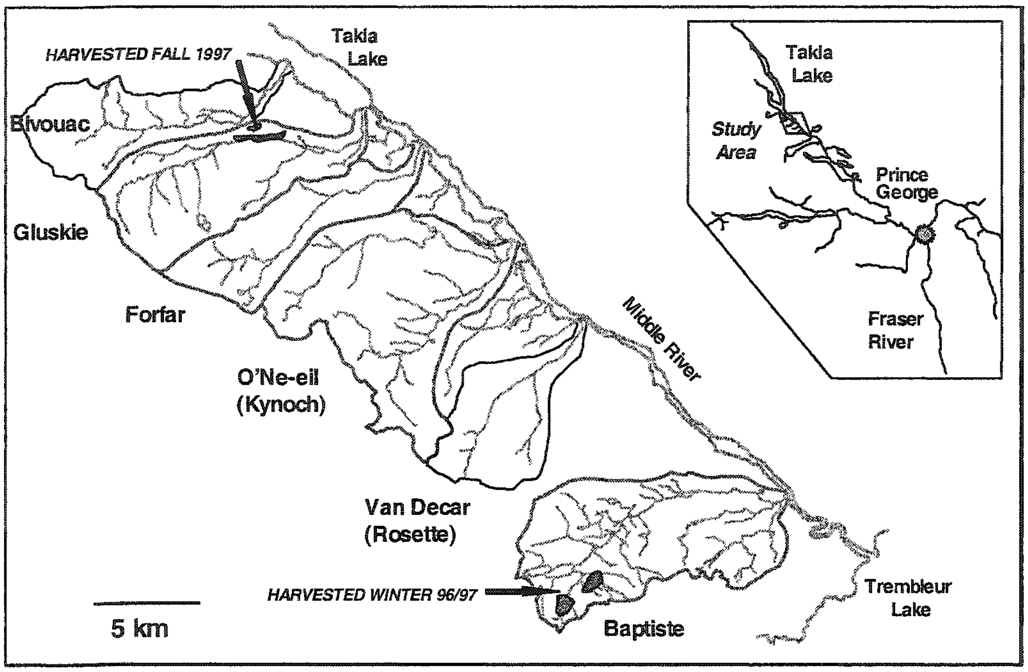

Figure 3.1. Map of the Stuart-Takla region of northern British Columbia. Note O'Ne-eil watershed in the center.

Part of the most northern extent of the Fraser River watershed (55°N, 125°50'W), O'Ne-eil (also known as Kynoch) basin features a range in relief from 700-1980 m (Petticrew, 1996). Surficial material is comprised of glacial tills and lacustrine clays at higher elevation (Macdonald et al., 1992) and fine-grained glaciolacustrine sediment in the lowland areas (Ryder, 1995). Encompassed within the Engelmann Spruce Sub-alpine Fir (ESSF) biogeoclimatic zone, the basin is relatively small (~ 75 km^2), but O'Ne-eil Creek is an important fish-bearing stream, where annual migration of salmon is well documented (Petticrew, 1996). The mainstem channel of O'Ne-eil Creek is approximately 20 km in length and 4 to 5 m wide at the mouth (Petticrew, 1996). The study reach exhibits favourable spawning habitat with appropriate substrate size distribution in low gradient (0.5 - 2 %) riffles (Petticrew, 1996). Little anthropogenic disturbance has occurred within this watershed specifically, however, a forest service road enables access to the lower reaches. One site in O'Ne-eil Creek, downstream of the forestry access bridge and approximately 1500m upstream of the mouth, was sampled during the period of May 18 to August 21, 2001

One sampling site was deemed adequate for resolving temporal patterns in suspended sediment structure, while the interpolation of spatial trends was considered beyond the scope of this study. However, the identification of temporal trends should enable translation of information to other watersheds at similar spatial scales (i.e., biogeoclimatic zones and reach position downstream from the headwaters), as well as provide baseline data for O'Ne-eil Creek watershed prior to anthropogenic disturbances to allow prediction and comparison for future conditions.

3.2.2 Study Approach

Sediment transport is driven by hydrologic factors within watersheds, and thus as discharge changes over time so does the magnitude and source of sediment (Ritter et al., 1995). High flow (discharge) provides a high-energy environment, where large substrates and obstacles that had blocked the flow and enabled deposition of fine-grained sediment are potentially entrained and moved downstream. The principle of continuity illustrates that, as discharge increases, there is a proportional increase in either the cross sectional area and/or water velocity (Vogel, 1994). In other words, the entrainment velocity and/or water level increases, enabling erosion of material from areas (e.g., floodplains, banks, and gravel storage) not ordinarily accessed at lower flows (Walling, 1983; Owens et al., 1999). Therefore, a greater amount of material, especially fine-grained sediment, could be entrained within the water column during these periods of high flow.

Flow velocities vary seasonally depending on factors such as precipitation and temperature (causing snowmelt). A concomitant variation in maximal sediment size of mineral material entrained and suspended should ensue, although some researchers indicate that maximal floc sizes could be reduced in higher flows due to breakage (Lick and Lick, 1988; Burban et al, 1989; van Leussen, 1999). This study was designed to determine what type of relationship exists for O'Ne-eil Creek. In order to evaluate the seasonal changes in fine sediment structure and morphology, it is necessary to collect samples over a range of watershed events. These were partitioned into five discrete response types, which are (Figure 3.2): (1) springmelt during the period of rising water levels; (2) summer low flow conditions, but isolated from rain events; (3) rain events; (4) the period during active spawning; and (5) post-spawn, where no actively spawning or live salmon were present. Springmelt is a period characterized by high discharge, and this is when the first flushed material stored in-channel and on the floodplain occurs. Less suspended load is moved during the baseflow levels of the low flow period, where the source material is predominantly in-stream. Rain events are characterized by higher than baseflow discharge, where suspended sediment concentrations are expected to increase, and comprise a combination of in-stream and terrestrial inputs. Rain events occur during baseflow, salmon spawn, and post-spawn, so they reflect the combined

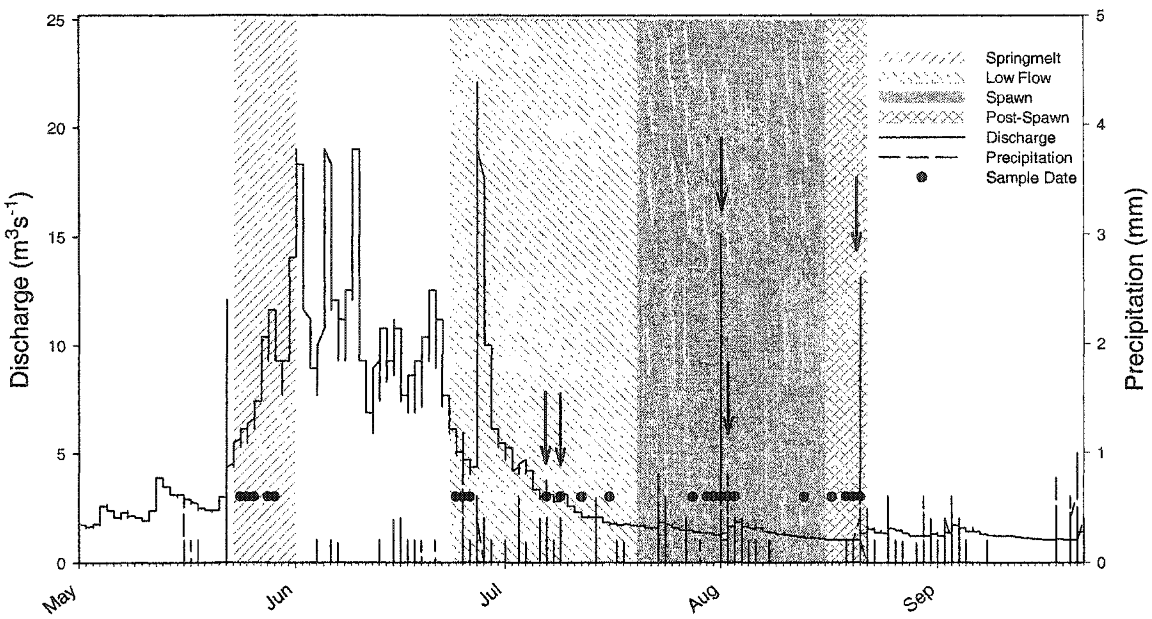

Figure 3.2 Schematic of sampling approach during the 2001 open water season. Points represent sampling times, shaded areas depict the four major event types of rising limb of springmelt, low flow after springmelt, and the active spawning period and post-spawn (i.e., no live/spawning salmon). Arrows designate sampled rain events. Note that June 25th sampling occurred prior to the onset of precipitation.

effects of resuspension of gravel-stored material that occurs during storms and the predominant source of organic matter for the particular sampling date. The period of active salmon spawn combines the introduction of anadromous organics and biological disturbance of gravels (see Figure 3.3). This organic matter is expected to remain within the system post-spawn, but, because live fish are no longer present, disturbance of gravels is minimal. Seasonal patterns of fine-sediment concentration, size, density, and settling rate were identified for each of the above stated response types using this approach.

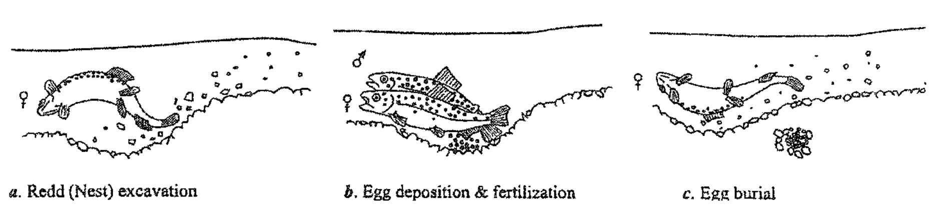

Figure 3.3 Spawning activities of salmon. a. Females dig out the area to prepare of egg deposition. b. Females deposit eggs and males subsequently fertilize. c. The fertilized eggs are buried for overwintering. From Soulsby et al. (2001).

3.2.3 Discharge Measurements

Continuous discharge data was derived from datalogged stage gauge values. The stage height was logged hourly by equipment maintained by the Department of Fisheries and Oceans (DFO). Stage height was converted to discharge using an exponential equation (3.1) obtained from a rating curve developed by DFO:

$$Q = 0.247e^{3.78S} \qquad 3.1$$

where Q is discharge (m^3s^{-1}) and S is stage height (m). The datalogging station was situated about 25 m upstream of the sampling site. Periodic cross-sectional flow measurements at the sampling site, using a Swoffer Model 2100 propeller current meter, were taken and these calculated discharges were closely related to the logged discharge values.

3.2.4 Sample Collection and Processing

3.2.4.1 Suspended Particulate and Organic Matter

Water was collected using wide-mouthed 1 L Nalgene bottles. The sampling process involved wading to the sampling point, which was designated by a length of steel bar driven into the streambed at the approximate center of the stream. The lid of the bottle was removed and placed over the opening. The bottle was then immersed parallel to the flow and the cap removed from the opening. After filling, the immersed bottle was reverted to an upright position, and the cap was secured. The bottles were transported in a Coleman brand insulated cooler to the field laboratory, which was about 10 km from the stream. Anywhere from 20 to 60 bottles were retrieved, depending on the visually observed suspended sediment concentration for the sampling date (i.e., more bottles were collected when the suspended sediment concentration was lower).

Data for suspended particulate matter (SPM) and suspended organic matter (SOM) concentrations were obtained through gravimetric determination. The bottles were mixed well to obtain representative samples and then a known volume of stream water was filtered through pre-combusted and pre-weighed 47mm diameter glass-fibre filters with a nominal pore size of 0.7 μm. Triplicate samples were filtered. The filters were then folded in half, placed in glassine envelopes, and stored in a desiccator. The filters were stored until analysis could occur at the UNBC laboratory. The filters were dried at ~60 °C and weighed to 10^{-5} grams, where the difference in weight divided by the volume filtered provides the SPM concentration. The filters were then ashed in a muffle furnace at 550°C for an hour to remove the organic material and then reweighed, allowing for calculation of SOM concentration.

3.2.4.2 Absolute Particle Size Distribution

In order to determine constituent or absolute particle size distribution for comparison with the floc or effective particle size distribution, Coulter Counter analysis of filtered inorganic sediment occurred. The method was as per Kranck and Milligan (1983), where all organics are removed with low-temperature ashing and ultrasonic dispersion, and subsequent sizing and enumeration of individual inorganic grains was attained by electroresistance particle size analysis via a Coulter Multisizer. Milligan and Kranck (1991) describe operation and calibration of this instrument. Water samples (three per sampling event) were filtered onto ashable, 8 μm SCWP Millipore mixed acetate filters as per Petticrew (1998), which were dried and then completely combusted by low-temperature ashing (~60°C) at the Bedford Institute of Oceanography (Dartmouth, NS), leaving only the inorganic component of the sample. These filters effectively retain particles > 0.5 μm (Droppo, 2000). Sizing and counting of the remaining inorganic constituent particles took place at the UNBC laboratory using a Coulter Multisizer.

3.2.4.3 Effective Particle Properties

For the settling experiments, stream water was collected in 20 L water jugs and transported to the field laboratory. Then, at the field-based laboratory, for each settling run, a large rectangular plexiglass tube (1.51 x 0.14 x 0.06 m with a capacity of 13.4 L) equipped with two removable end caps (see Petticrew and Droppo, 2000) was filled with about 12 L of the well-mixed stream water (as the bottom end of the tube was capped). The tube was then carefully placed in a tripod that held it upright facing a charge-coupled device (CCD), with a resolution of 512 by 512 pixels, interfaced with an Intel-based PC running Northern Exposure (Empix Imaging, Mississauga, ON, Canada). About 45 images, having square pixel dimensions of 55 μm ± 10 μm, were captured and timestamped after waiting for turbulence to subside, as the particle population fell naturally downward due to gravity through the water column. A slight change in procedure occurred mid-June, where the analog CCD was replaced by a Retiga 1300 digital CCD (resolution 1280 X 1024 pixels) with resulting images having 6.7 X 6.7 μm pixel dimensions. The software was also upgraded to Northern Eclipse (Empix Imaging, Mississauga, ON, Canada) with an associated specialized fastcapture program that allowed for collection of 100 images at timed intervals of three seconds. The settling tube was outfitted with a scale on the back of the tube attached using white adhesive paper to aid in image analysis.

The digital images from both techniques were analyzed using the Northern Eclipse software package in two ways. First, dimensions (e.g., diameter, area, perimeter, and shape) of 500-1500 particles for each run of 45 (for the spring samples) and 100 (for all other sample dates) images were measured by thresholding about every fourth greyscale image. This interval of four images ensured that particles were not measured more than once. The concept of thresholding is based on the fact that each pixel in a black and white image is characterized by a value between 0 for black and 255 for white. Northern Eclipse allows the user to 'highlight' objects by assigning a value to the image that best defines the object in question. This technique is limited by the choice of optics, which defines pixel size, where several pixels are required to reliably define an object (Milligan and Hill, 1998), as well as the user's detection of a particle (i.e., operationally defined). The minimal particle size detected was 42 μm. For each image, the thresholding was gradually increased until sections of the image were adequately represented, and then dimensional measurements were taken based on a pre-determined length calibration. The resulting database of dimensions enabled determination of the effective particle size spectra (EPSD).

Second, fall velocities and particle diameters were measured for as many particles as possible for each settling run (between 20 and 150). All images from a particular run were overlain in a movie format to enable detection and tracking of individual falling particles. Once a suitable particle was displayed, the two relevant images were isolated and the Boolean operator minimum was used to fuse the images together so that the particle was shown frozen in its original position versus its fallen position. A straight-line measurement was then made between the centers of both images of the particle. Settling velocity was determined from the distance traveled by the particle divided by the time interval between images. The dimensions of the particles were then measured and, if the apparent size was different between the two due to particle rotation during settling, averaged dimensions were calculated.

Direct measurement of settling velocities is necessary rather than calculation based on Stokes' law of particle settling because of the apparent divergence from model settling rates found by Namer and Ganczarczyk (1993) and Petticrew and Droppo (2000). This is due to a decrease in sphericity that flocculated particles exhibit compared to model particles. A version of Stokes' law corrected for particle shape deviating from spherical was used to determine particle density. First, particle size and settling velocity measurements collected using image analysis allowed for computation of particle Reynolds numbers as per Namer and Ganczarczyk (1993):

$$\mathrm{Re} = x_a\, u\, \rho_w \,/\, \mu \qquad 3.2$$

where Re is the Reynolds number, x_a is the diameter of the particle, ρ_w and μ are the fluid density and dynamic viscosity, respectively, and u is the settling velocity. Calculating Reynolds number was necessary in order to determine which version of Stokes' law to use for particle density derivation.

Appropriate correction factors were calculated according to the Reynolds numbers by:

$$k_s = 0.843 \log(\xi_2 \,/\, 0.065) \qquad 3.3$$

for particles in Stokes' region (Re < 0.2),

$$k_n = 5.31 - 4.88\xi_2 \qquad 3.4$$

for particles in Newton's regime ($1000 < Re < 3 \times 10^5$),

$$k \approx [k_s - (0.43 / k_n)^{1/2}]\,(1000 - Re) / (1000 - 0.2) + (0.43 / k_n)^{1/2} \qquad 3.5$$

for particles in the transition range ($0.2 < Re < 1000$), where k_s is the Stokes correction factor, k_n is the Newton correction factor, k is the transition correction factor, and ξ_2 is the two-dimensional shape factor. None of the measured particles fell within Newton's regime, so the densities were calculated for Stokes' region:

$$\rho_f - \rho_w = 18u\mu / (k_s g x_a^2) \qquad 3.6$$

where ρ_f is the floc density, g is the acceleration due to gravity, and k_s is replaced by k to calculate the density of particles falling in the transition zone.

3.2.5 Spectral Analysis

Fine-grained inorganic sediment particle size distributions are typically plotted as smoothed histograms of log concentration versus log diameter (Milligan and Kranck, 1991; Kranck, 1993; Petticrew, 1998). Usually these distributions are obtained from disaggregated, constituent particles measured using a Coulter counter, where the organic portion of the sample is removed. This study examines both constituent and flocculated material and the data for both were processed similarly and, for the most part, as per Kranck (1993). Diameter is defined by class midpoints, where the class limits correspond to the resolution of this instrument (1/3 ϕ) (Kranck, 1993). All particles for each sample were grouped into bin classes by their diameters. Then the volume was calculated for each bin class based on the formula for sphere volume and particle size spectra were presented as percentage volume (y-axis) versus bin diameter (x-axis) (log-

log transformation). Typically, volume/volume values are used for this representation. Because volume/volume is dependent on the initial concentration of the sediment in the samples, data in this report are assessed in the form of percentage volume to allow for direct comparisons between samples.

Log-log plots were used to allow for comparison between samples and to assess compliance of particle spectra to a power law relationship (Kranck and Milligan, 1983; Kranck, 1993). Kranck and Milligan (1983) state that this type of plot enables comparison between spectra because "portions of distributions with similar relative values will have similar forms independently of the overall size distribution and the power law distribution will plot as straight lines." In other words, the shapes of different spectra can be used to compare between them. The power rule mentioned above is defined by Kranck (1993), as

$$V = QD^{m}\, e^{-K\alpha DD} \qquad 3.7$$

where V is the volume concentration of sediment, Q is the y-axis intercept, which is dependent on total concentrations, K describes the fall off in grain size at the coarse end of the distribution, m is the slope, D is the particle diameter, and αDD defines the settling rate (based on Stokes' Law). Figure 3.4 illustrates the relationship between the variables.

There are two characteristics of the spectra that are of interest here for comparison between particle populations. The first is the shape of the left limb of the particle spectrum. This is also referred to as the source slope of the curve because it accentuates differences in the source of the sediment (Kranck and Milligan, 1983; Kranck et al., 1996). Kranck et al. (1996) compared sediment spectra from different environments and geographical locations and were able to differentiate the sites using the respective characteristic slope (m) values. This is because the spectrum slope gives an indication of proportion of fine versus coarse particles, which reflects the source sediment. Simply, steeper slopes indicate a smaller portion of the very fine particles being transported within the water column, whereas flatter curves suggest that very fine particles make up the larger portion of the fine sediment being moved. The spectra slope then can be used as a type of fingerprinting technique to differentiate source materials.

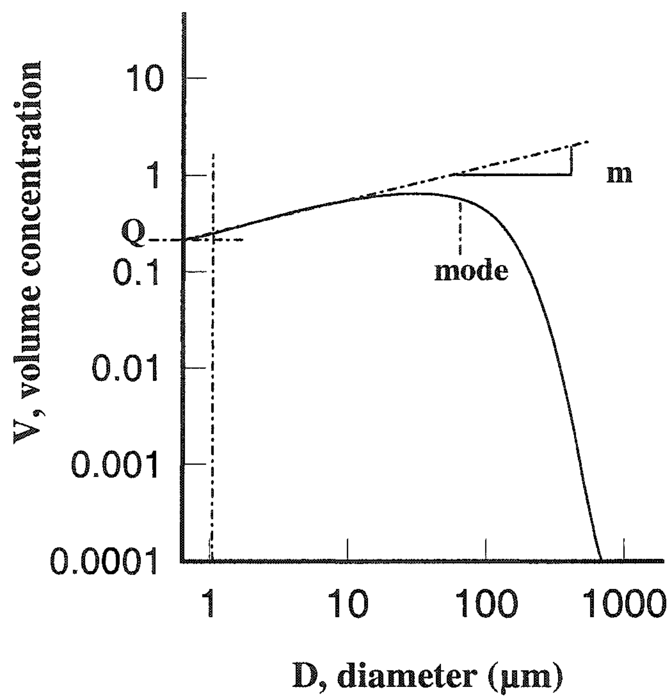

Figure 3.4 Model grain size distribution spectrum illustrating the significance of variables noted in equation 1. The dotted line refers to parent source material described by $V = QD^m$. The solid curve denotes a size distribution, which shows the effects of coarse grain fall off and settling rate. Mode is the peak of the curve corresponding to the size class with the greatest concentration of particles. Modified from Kranck (1993).

Differences can be noted visually, but the typical method for more rigorous analysis is the calculation of the slope of the regression curve for the section of the population falling between 1 and 10 µm. The 1 to 8 µm slopes were calculated for this study because findings by Petticrew (1998) indicate the spectral mode for the source sediment in O'Ne-eil Creek is 8 μm. It should be noted that this might only be reliable for absolute particle size distributions derived from Coulter analysis. Effective particle size distributions are typically limited by the lower end resolution, which often precludes that measurement of particles between 1 and 10μm in diameter (Biickert, 1999). The y-axis intercept (Q) is also part of the left limb of the curve. It reflects the volume of the finest particles and depends on total concentrations, which implies that the value of the intercept is reliant on the hydrologic conditions (i.e., higher energy environments should produce larger intercept values). However, this is only true for data plotted as volume/volume as calculating the percentage volume removes the effect of total concentrations.

The second characteristic of interest is the position of the spectrum mode, or size class exhibiting the highest concentration. Kranck et al. (1993) state that the mode is indicative of the coarsest particle size that can be kept in suspension under the flow conditions present in the system under consideration. Particles larger than the mode value settle out of suspension creating the abrupt fall off at the coarse end of the spectrum as displayed in Figure 3.4. The implications of this are that the larger the particle, the more energy it requires to become entrained or to remain entrained. Thus, if the mode is large, it is likely characteristic of a high-energy environment with higher bottom shear stress (Biickert, 1999).

Slope values and modes were extracted from the particle size spectra obtained from each APSD filter processed. The data were then coded by event type and an analysis of variance (ANOVA) was performed on the data set using Statistica® 6.0

(Statsoft, Inc, Tulsa, OK) in order to assess the ability to determine differences between each sample type compared to replicates and to characterize any variation that exists.

A similar analysis was performed on the EPSD for each sampling day. However, a limitation of the analysis for the EPSD is that the differences between population modes are not always visually straightforward. This is because there may be bin classes with similar volumes of particles, which are separated by other classes with smaller volumes (as emphasized by Figure 3.5) probably due to a smaller number of particles in the bin class (classes with less than three particles are not represented) and the exponential increase in bin class volumes (Volume α (Diameter/2)^3). This problem was addressed by calculation of the D_{50}, D_{84}, and D_{99} values for cumulative percentage volume curves

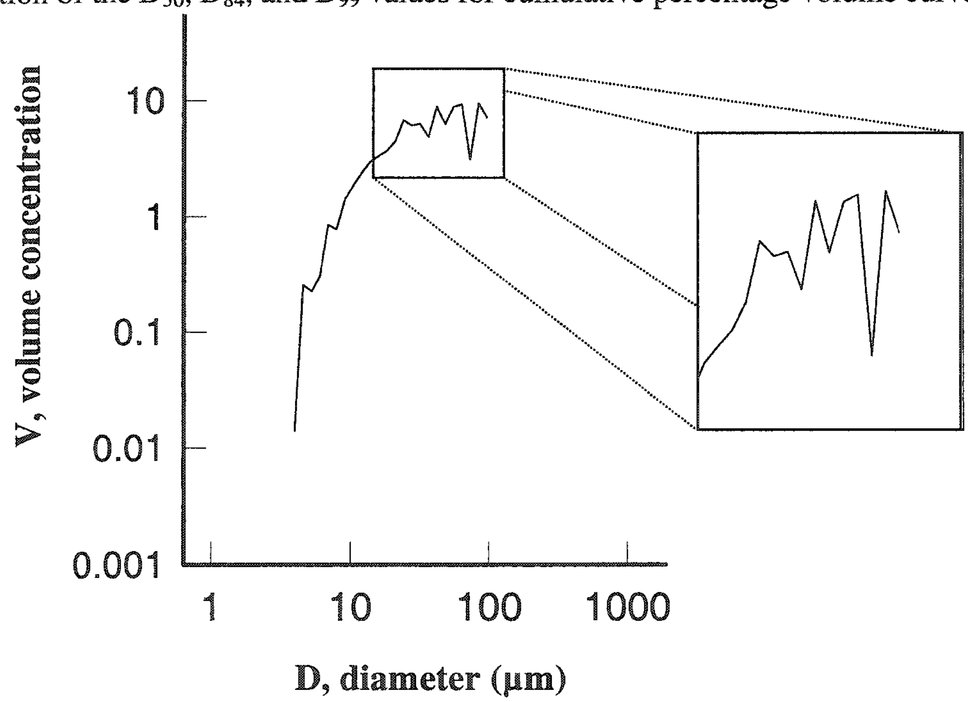

Figure 3.5 Example particle size distribution spectrum illustrating the difficulty in determining the precise value of the mode due to the erratic fluctuations at the curve peak.

instead of the mode. Linear interpolation between values was used to develop equations for deriving the particle diameter at these respective percentages of the population.

Another method was as per Biickert (1999), who circumvented this problem by using a non-parametric measure of goodness of fit, the Kolmogorov-Smirnov test. Kurashige and Fusejima (1997) also identified this non-parametric test for independent samples as a way to compare between whole populations of particles. The Kolmogorov-Smirnov test evaluates the similarity between two entire populations, where a positive result is attained when the descriptive statistics are significantly different. The one-sample test compares a cumulative relative frequency curve to a normal distribution. Biickert (1999) used the two-sample version of this test to identify differences between a base case (i.e., control) and experimental cases. In this study, SYSTAT® 9.0 (Systat Software Inc., Richmond, CA) was used to execute the Kolmogorov-Smirnov two-sample test on data from spectra selected based on the objectives stated above.

3.3 Results

3.3.1 Discharge

The measured flow rate for O'Ne-eil Creek during the 2001 open water season ranged between 1.0 and 22.1 m^3s^{-1}, the minimum being August 20th and the maximum falling on June 27th, respectively. Springmelt began on May 21st, where Figure 3.6A shows a relatively constant increase in discharge after that date. The first large peak occurred on June 1st with a flow rate of about 19 m^3s^{-1}, followed by a decrease and another peak of 19 m^3s^{-1} on June 5th. A third peak of 19 m^3s^{-1} took place on June 9th. Two more high points came on June 15th (11.2 m^3s^{-1}) and June 20th (12.5 m^3s^{-1}). This last peak was followed by a significant decline until a rain-on-snow event of about 1 mm hr^{-1} caused the highest flow of the season on June 27th (22.1 m^3s^{-1}). Precipitation values are approximate

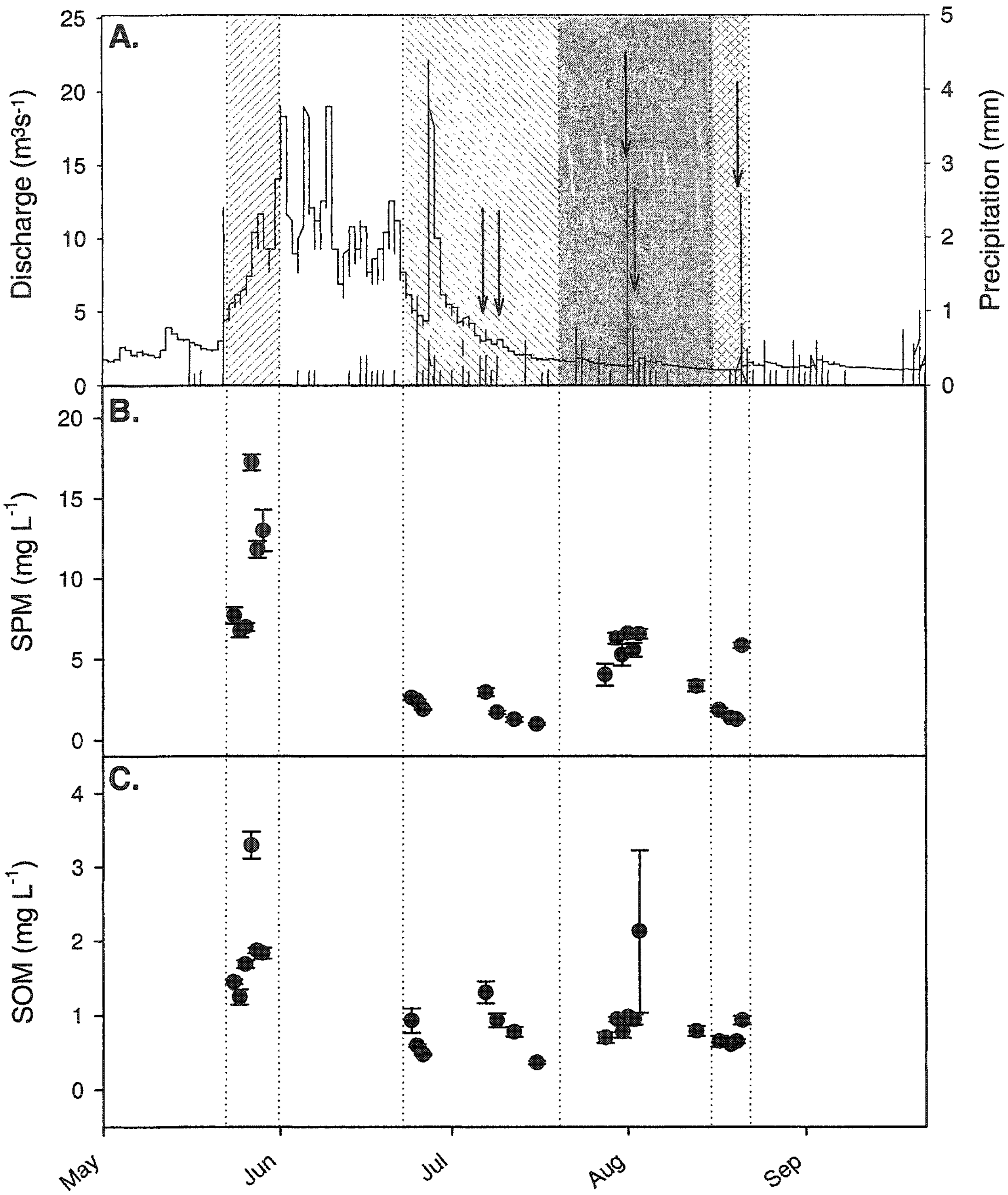

Figure 3.6 Suspended sediment variability measured in O'Ne-eil Creek over the open water season in 2001. A. Discharge was calculated from stage height logged approximately 25 m upstream from the sampling site. Legend as per Figure 3.2. Precipitation data were collected at a meteorological station about 10 km from the stream. B. SPM and C. SOM were sampled periodically over the season, where bars are ± 1 SE among triplicate samples. Dotted lines separate event types, while arrows identify rain events.

because the meteorological station was about 10 km from the O'Ne-eil Creek watershed.

Discharge values decreased from the major peak to a baseflow of about 1 m^3s^{-1}. Small fluctuations in the curve correspond to rain events. Five rain events of different intensities were sampled over the season (Table 3.1). The rain events resulted in corresponding maximum increase of between 0.2 and 0.8 m^3s^{-1} of flow through the sample site cross-section during the event. July 7 and 9 rose from 2.9 to 3.7 and 2.8 to 3.1 m^3s^{-1}, respectively, while the August events were 1.2 to 1.9, 1.5 to 1.8, and 1.0 to 1.2 m^3s^{-1}, for August 2nd, 3rd, and 21st. The highest intensity storm occurred on July 7, while the lowest was on August 21st. Note that Figures 3.2 and 3.6A indicate rain for the June 25th sampling date; however, precipitation began after sampling was already complete and stopped during the night. The water level did not increase between June 25th and 26th.

Table 3.1 Rainfall duration and intensity for five summer sampling periods in O'Ne-eil Creek for the open water season of 2001.

Date	Overlapping Event Type	Duration (hr)	Rainfall (mm)	Intensity (mm hr^{-1})	Increase in Q (m^3s^{-1})
July 7	Low Flow	7	5.8	0.83	0.8
July 9	Low Flow	6.5	2.8	0.43	0.7
August 2	Spawn	16.45	10.6	0.64	0.6
August 3	Spawn	4.5	3	0.67	0.3
August 21	Post-Spawn	11.5	5.4	0.39	0.2

3.3.2 SPM and SOM

Suspended particulate matter varied over the season with a maximal concentration of 18.1 mg L^{-1} during springmelt (May 27th) and a minimum of 0.9 mg L^{-1} for the low flow period (July 16th). The peak of the springmelt hydrograph was not sampled as flows were too fast for safe entry into the stream. Suspended organic matter concentration varied correspondingly with maximum and minimum values of 3.5 and 0.33 mg L^{-1} for those same days. For the most part, the SPM and SOM curves followed that of the hydrograph in that the general trend was higher suspended material during higher discharge (Figure 3.6). However, the data deviated from the hydrograph during the active spawning period, where the amount of suspended material was higher than what would be associated with low flows. Figure 3.7 displays the data grouped by the five event types to isolate and verify the differences.

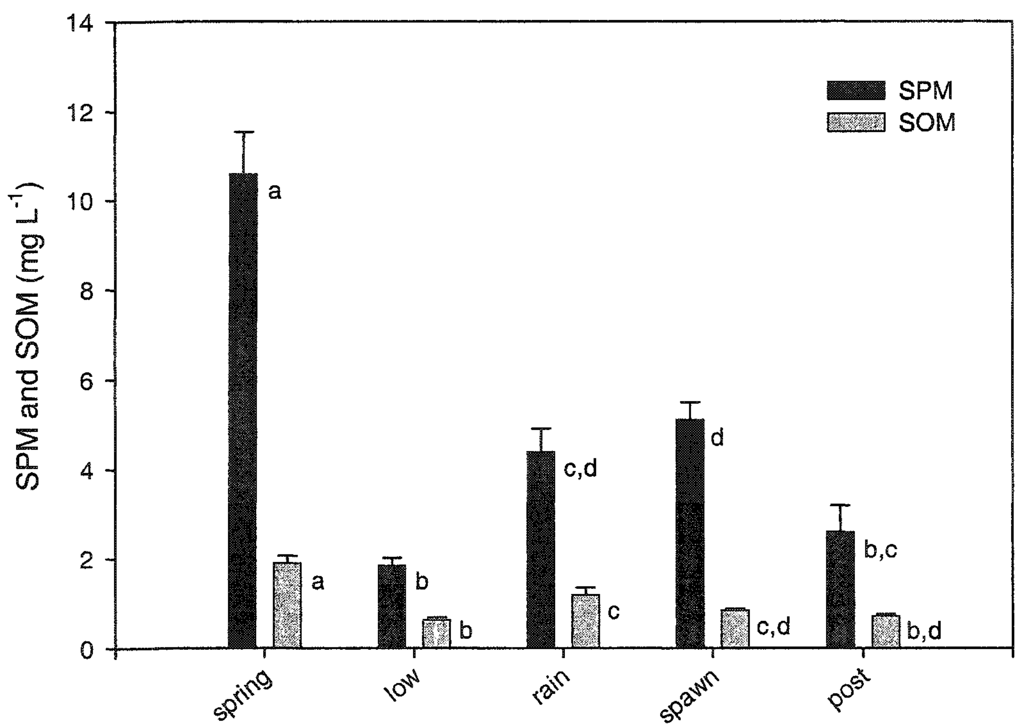

Figure 3.7 Suspended particulate and organic matter concentrations as grouped by event type. Five periods were sampled for each event type, except post-spawn (n = 4). Error bars are ± 1 SE, and means tagged by similar letter are not significantly different (α = 0.05).

Considerably more material was suspended during springmelt than any other period and differences between other events. An analysis of variance for SPM resulted in significant main effects ($F_{0.05(1), 4, 66} = 37.7$, $p < 0.001$) and post hoc pair-wise comparison (Tukey Honest Significant Difference (HSD) for unequal N (Spjotvoll/Stoline test)) indicated significant differences between springmelt SPM and all other event types ($p < 0.001$), between low flow and both the rain and spawn events ($p < 0.005$), and between spawn and post-spawn ($p < 0.001$). Similar analyses were performed for SOM data and means were also found to be significantly different ($F_{0.05(1), 4, 65} = 33.3$, $p < 0.001$). Pair-wise comparison revealed that the main effects differences are attributed to springmelt compared to all other event types ($p < 0.01$), and low flow compared with rain and spawn events, $p < 0.01$ and $p < 0.05$, respectively. The post-spawn and spawn periods were not different as they were with the SPM data, but the post-spawn and rain events were ($p < 0.005$). All SPM and SOM data were logarithmically transformed because a Shapiro-Wilks test of normality confirmed that the raw data were not normally distributed.

3.3.3 Absolute Particle Size Distribution

Absolute inorganic particle size distributions consisted of operationally defined lower and upper limits of approximately 1 and 120 μm, but the largest primary particles measured were no greater than 111 μm. Analysis of five absolute particle size distributions representing each of the different event classes over the season is shown in Figure 3.8. The spectra are graphed as log-log distributions of particle sizes within each sample by the representative percentage volume. There is very little visual difference between the APSD curves throughout the year with the exception of the post-spawn curve, which exhibits a flatter slope and peaks at a smaller particle diameter.

More stringent analysis involved two spectral properties in particular and included samples for all the dates and replicates collected. The first is the slope of the left limb, calculated using linear regression of the points from 1 to 8 μm. Figure 3.9A presents the means and standard errors for the grouped data. The average slope for the post-spawn period was 0.31, while all others events fell between 0.50 and 0.60. The post-spawn slopes were flatter than springmelt, low flow, and spawn periods. There is a visual difference between post-spawn and all other event classes, and the ANOVA states that this is statistically significant ($F_{0.05(1),4,63} = 3.71$, $p < 0.01$). Note, sample dates were removed from the group average if the coefficient of determination derived from linear regression of source slope was insignificant ($r^2 < 0.497$, $\alpha = 0.05$). Specifically, four replicates were removed in total; three of nine from the post-spawn period and one of 15 for the low flow class.

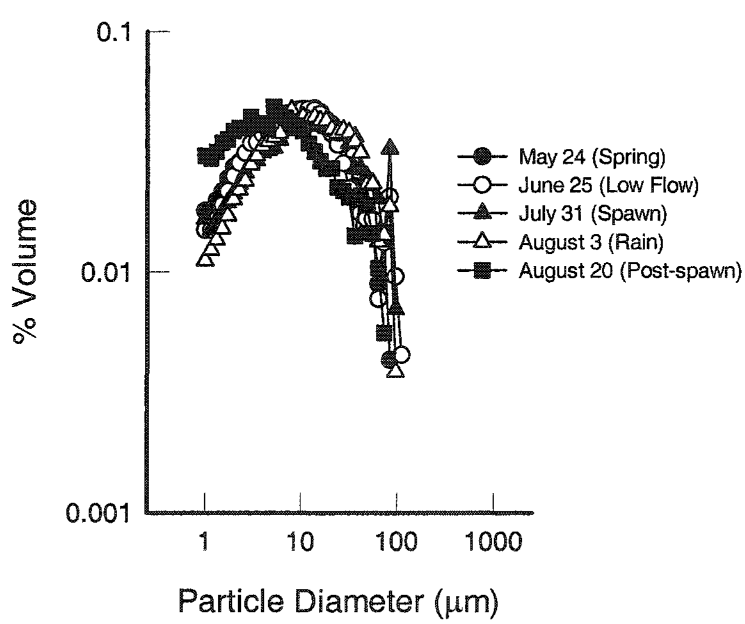

Figure 3.8 Absolute particle size spectra of % volume by particle diameter (μm) representing five event types through the 2001 season.

The second important spectral property is mode. The average mode values for each event type are presented in Figure 3.9B. Once again, spectra that were shown to

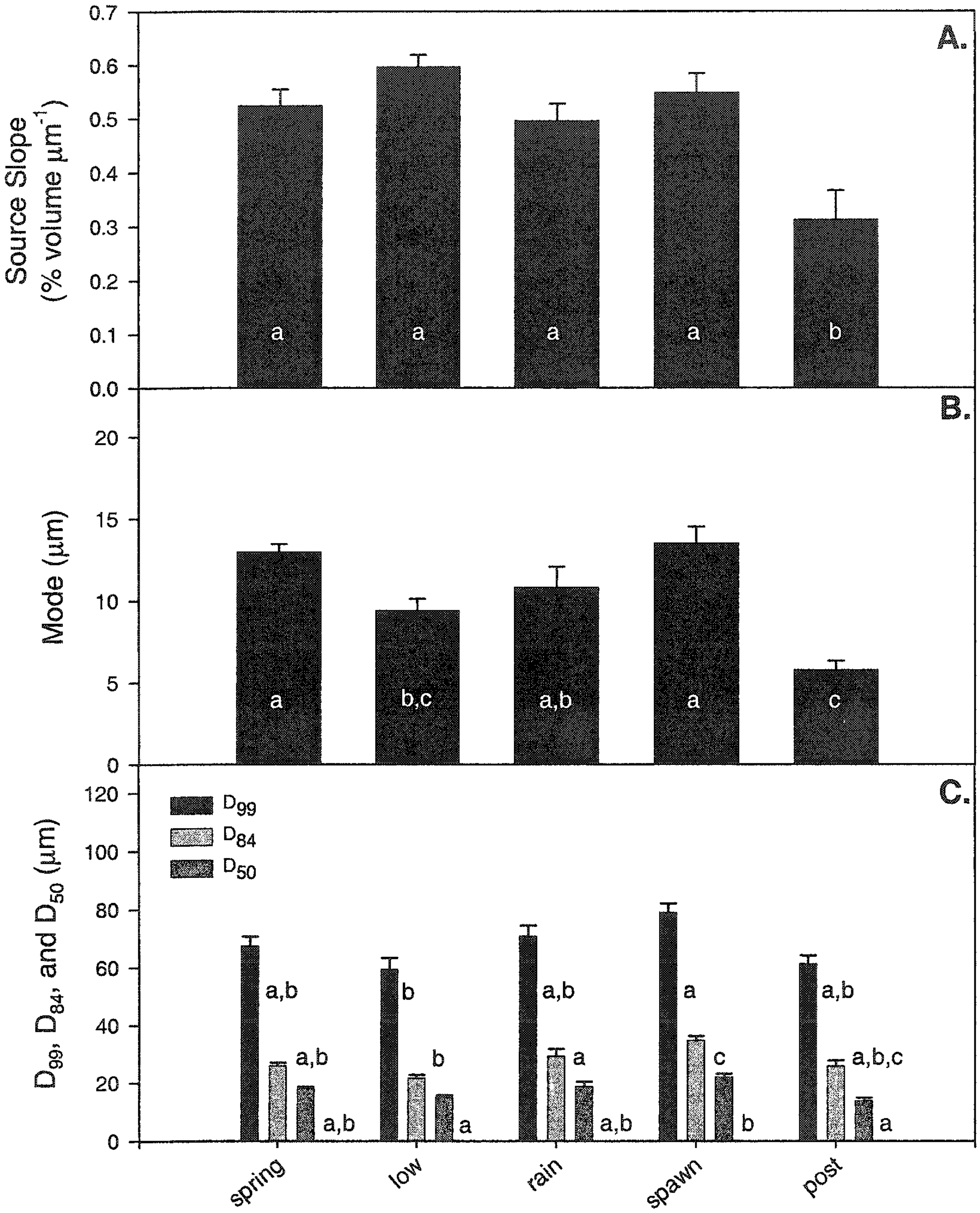

Figure 3.9 A. Source slopes, B. spectral modes, and C. particle diameter at 50, 84, and 99% of the absolute particle size distributions (APSD) grouped by event type. Error bars are ± 1SE. Springmelt, low flow, and post-spawn event labels are abbreviated. Means tagged by similar letter are not significantly different ($\alpha = 0.05$).

possess insignificant r^2 values were removed in case the anomalous spectral left limb altered the mode as well. The main effects of an ANOVA are significant ($F_{0.05(1), 4, 63}$ = 8.0, $p < 0.001$) and attributable to differences between post-spawn and springmelt ($p < 0.005$), post-spawn and rain ($p < 0.05$), post-spawn and spawn ($p < 0.001$), as well as low flow and spawn and low flow and springmelt ($p < 0.05$). Visually it appears that springmelt and spawn periods are most similar in modal values with 13 and 13.5 μm, respectively. The lowest mode of 5.3 μm occurs during post-spawn, which are also the curves that possessed the lower or flatter slopes.

Further examination of the absolute particle size distributions included transformation to cumulative percentage volume curves, so that the particle diameters at 50, 84, and 99% could be extracted. The results, averaged by event type are shown in Figure 3.9C. The spawn period demonstrates the highest values and the pattern of spawn > rain > springmelt > post-spawn > low flow holds for D_{99} and D_{84}, but the latter two categories are reversed for D_{50}. An ANOVA was used to test this pattern, and all percentile diameters had positive results. Pair-wise comparisons resulted from the Spjotvoll/Stoline test. Low flow and spawn periods were significantly different with respect to D_{99}, D_{84}, and D_{50} ($p < 0.01$). Springmelt consisted of smaller D_{84} values than spawn ($p < 0.01$) and rain events had greater D_{84} values than low flow ($p < 0.05$). D_{50} values were greater during the presence of salmon as opposed to after die-off ($p < 0.01$).

3.3.4 Effective Particle Size Distribution

The effective particle size distributions are analyzed in a similar manner to the absolute spectra. One discrepancy is that the lower resolution of the image analysis technique limits the smallest particle measured, so the left limb of the effective particle size distributions is not the source slope because no particles between 1 and 8 μm could be measured. The grain size of the 50, 84, 99th percentiles is of primary importance in this case. The modal class is situated much higher and to the right on the graphs, which indicates a greater frequency of larger particles. However, because of the difficulties determining the spectral mode indicated in section 3.2.5, the mode was not included in this analysis. Figure 3.10 shows the EPSD, where the lower resolution is between 42 and 67 μm, the upper size limit is greater than 1000μm. Note that there is considerably more variation in the curves as compared to the APSD.

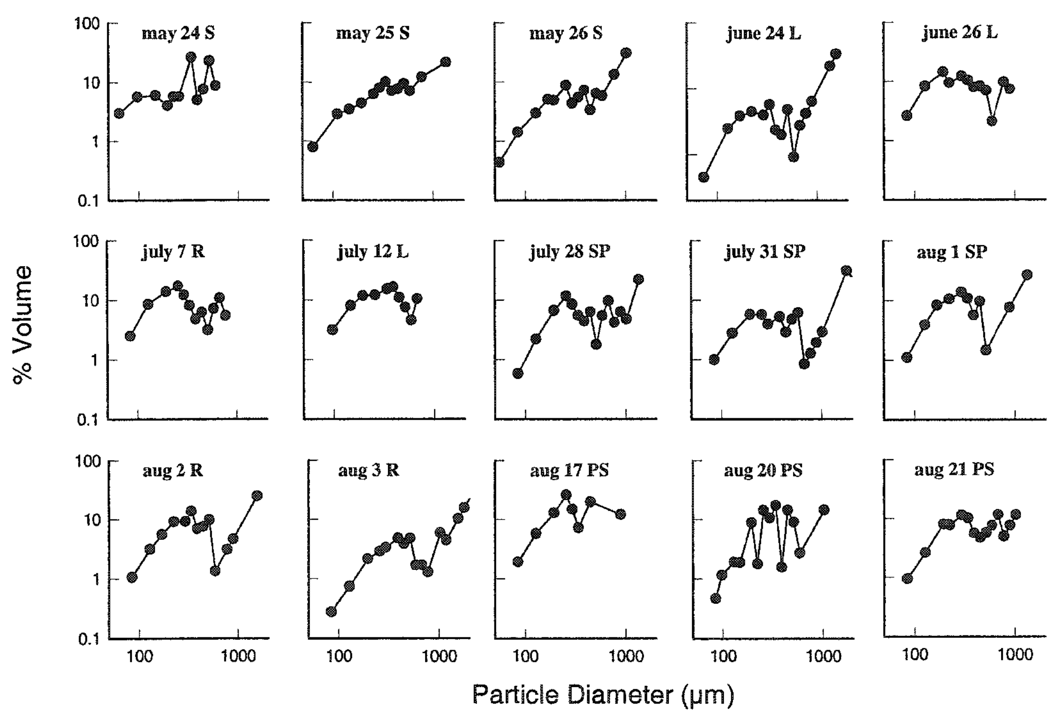

Figure 3.10 Effective particle size distributions as percentage volume by particle diameter derived from image analysis of *in situ* settling populations. The respective sampling dates and event types (S = Spring, L = Low Flow, R = Rain, SP = Spawn, and PS = Post-spawn) are displayed above each curve.

When grouped by event type in Figure 3.11, D_{99} and D_{84} grouped averages reveal a trend; spawn > rain > low flow > springmelt > post-spawn, while the D_{50} differs by transposing the spawn and rain events. The range of averaged particle sizes is 832 to 1366, 553 to 1177, and 294 to 654 μm, for D_{99}, D_{84}, and D_{50}, respectively. Although these patterns are visually apparent, an ANOVA was performed on the log-transformed data and no significant differences were detected between event types for any of the particle size variables. This lack of positive statistical results contradicts the differences that appear to exist in the ungrouped data displayed in Figure 3.12.

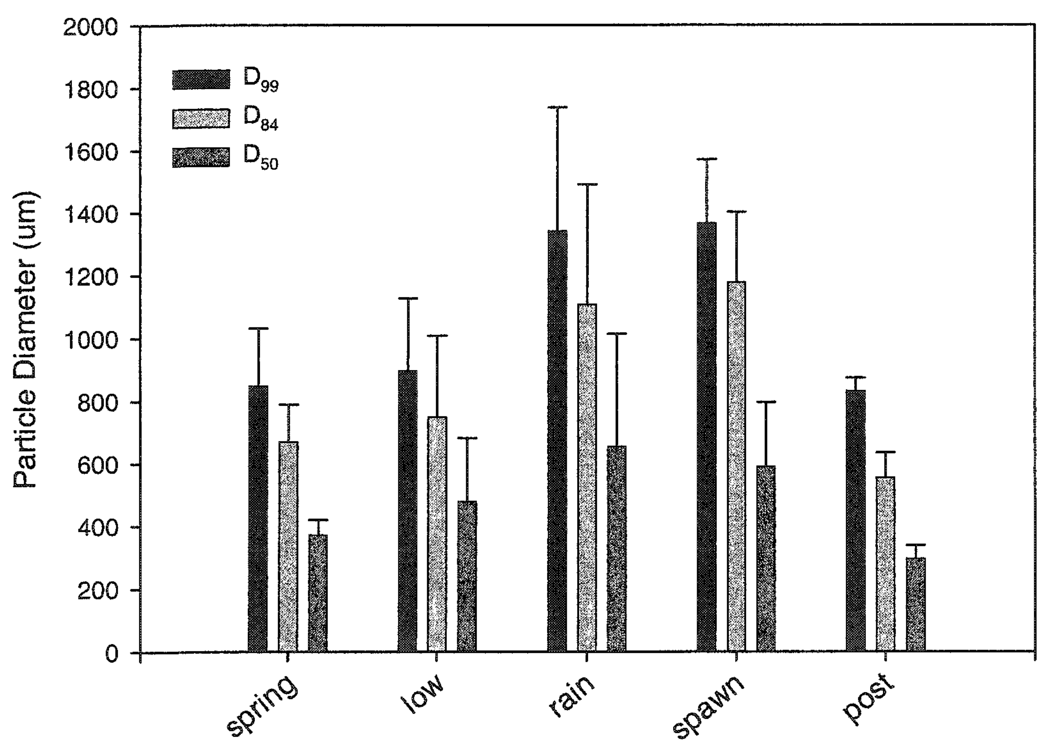

Figure 3.11 Averaged particle diameter at 50, 84, and 99% of the effective particle size distributions (EPSD) grouped by event type. Error bars are ± 1SE.

The diameters for each percentile appear to be much higher during the salmon spawn period, but the variation within the event is so large that an ANOVA cannot detect the differences between events. The rain data crossed over with other event types, and two of these sampled rain events occurred during the salmon spawning period. The August 3rd rain date exhibits the highest values of the entire data set. In order to better understand seasonal patterns, rain event data was coded into the respective crossover event type (i.e., rain events during spawning were added to the spawn sample set). The result was that the highest values for all of mode, D_{99}, D_{84}, and D_{50} occurred during active salmon spawning. An ANOVA detected no statistically significant differences between event types for D_{50}, but the D_{99} and D_{84} data were different ($F_{0.05(1), 3, 11} = 4.1$ and 4.2, $p < 0.05$) and attributed to variation between the spawn and post-spawn periods.

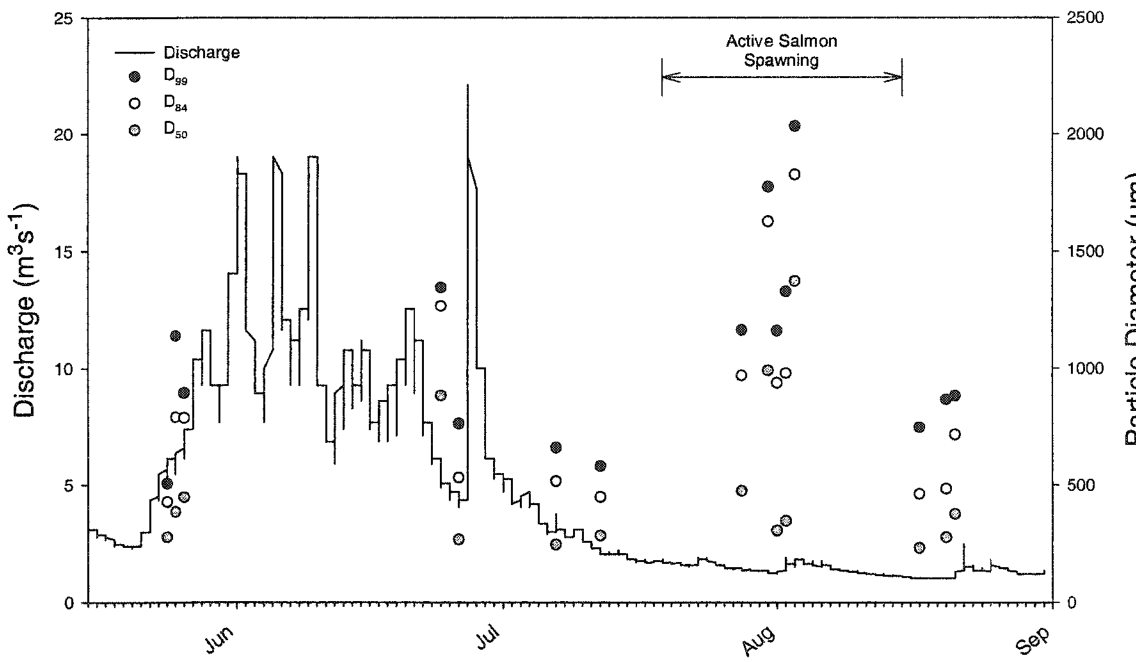

Figure 3.12 Seasonal distribution of D_{99}, D_{84}, and D_{50} values derived from effective particle size distributions. Note the highest values of all percentages generally occur during the spawn period.

To further test the pattern statistically, the Kolmogorov-Smirnov two-sample test was used to compare the general shape of the curves. All EPSD curves were compared against each other and the two-sided probabilities are detailed in Table 3.2, where significant results are bold and italicized. Differences were found between curves within and between event types. Within event differences are low flow event dates of June 24th and 26th, August 3rd and all other rain events, and August 1st and July 31st spawn dates.

Table 3.2 Two-sided probabilities from Kolmogorov-Smirnov test. Significant p values ($\alpha = 0.05$) are italicized and bold. Lines separate event types, springmelt, low flow, rain, spawn, and post-spawn, from top to bottom.

		May 24	**May 25**	**May 26**	**June 24**	**June 26**	**July 12**	**July 7**	**Aug 2**	**Aug 3**	**July 28**	**July 31**	**Aug 1**	**Aug 17**	**Aug 20**
	May 24	.													
Spring melt	**May 25**	0.33	.												
	May 26	0.74	0.99	.											
	Jun 24	0.05	0.20	0.33	.										
Low Flow	**Jun 26**	0.74	0.33	0.52	***0.03***	.									
	July 12	0.99	0.33	0.52	0.05	0.99	.								
	July 7	0.74	0.52	0.52	***0.03***	0.99	1.00	.							
Rain	**Aug 2**	0.20	0.74	0.92	0.11	0.20	0.11	0.20	.						
	Aug 3	***0.01***	0.05	0.05	0.74	***0.00***	***0.00***	***0.00***	***0.03***	.					
	July 28	0.20	0.74	0.99	0.20	0.33	0.33	0.52	0.99	0.05	.				
Spawn	**July 31**	***0.01***	0.05	0.11	0.99	***0.00***	***0.01***	***0.00***	***0.03***	0.33	0.05	.			
	Aug 1	0.33	0.92	0.92	0.05	0.20	0.20	0.20	0.92	***0.01***	0.92	***0.01***	.		
	Aug 17	0.74	0.20	0.33	***0.01***	0.92	0.99	0.99	0.11	***0.00***	0.20	***0.00***	0.20	.	
Post-spawn	**Aug 20**	0.74	0.33	0.52	0.05	0.99	0.92	0.99	0.20	***0.01***	0.33	***0.01***	0.20	0.52	.
	Aug 21	0.74	0.92	0.99	0.11	0.92	0.92	0.92	0.52	***0.03***	0.92	***0.03***	0.74	0.74	0.92

Between event differences are more numerous. For the springmelt curves, the May 24th spectrum differs the August 3rd rain event and the July 31st spawn date. Representing the low flow period, June 24th differs from the July 7th rain event and the August 17th post-spawn date, while EPSD curves from June 26th and July 12th both vary from August 3rd and July 31st. The July 7th and August 2nd rain events differ from the July 31st spawn date, and the August 3rd rain event varies from the August 1st spawn date and all post-spawn spectra. For the active spawning period, July 31st is significantly different from all post-spawn spectra. The spectra from each event were then averaged and the K-S test performed on this data. No significant differences were found. The largest differences between averaged curves were for post-spawn and spawn ($D = 0.276$), post-spawn and rain ($D = 0.276$), springmelt and rain ($D = 0.241$), and springmelt and spawn ($D = 0.241$).

3.3.5 Rain Events

Patterns derived from data with rain events could be confounded by the fact that these data overlap with other event types, as all rain events occurred during one of the other event periods. Up until this point, rain events have been treated as if they occurred during a discrete period, and the overlapping event types have been generally ignored. A closer look at these events provides a pseudo-synoptic view of seasonal patterns because rain events were sampled during the low flow, spawn, and post-spawn periods. Figure 3.13A shows the SPM and SOM concentrations for five rain events. The SPM concentrations for the low flow rain dates are lower than the spawn and post-spawn. Because the data are not normally distributed, a Kruskal-Wallis non-parametric test was used to test for differences, and resulted in significant differences.

Little variation between the three overlap event types is apparent for SOM with the exception of the spawn period. The active spawning period exhibits higher SOM values, but with greater standard error (i.e., not statistically significant). The D_{99}, D_{84}, and D_{50} values follow a pattern similar to that found with all seasonal events, however,

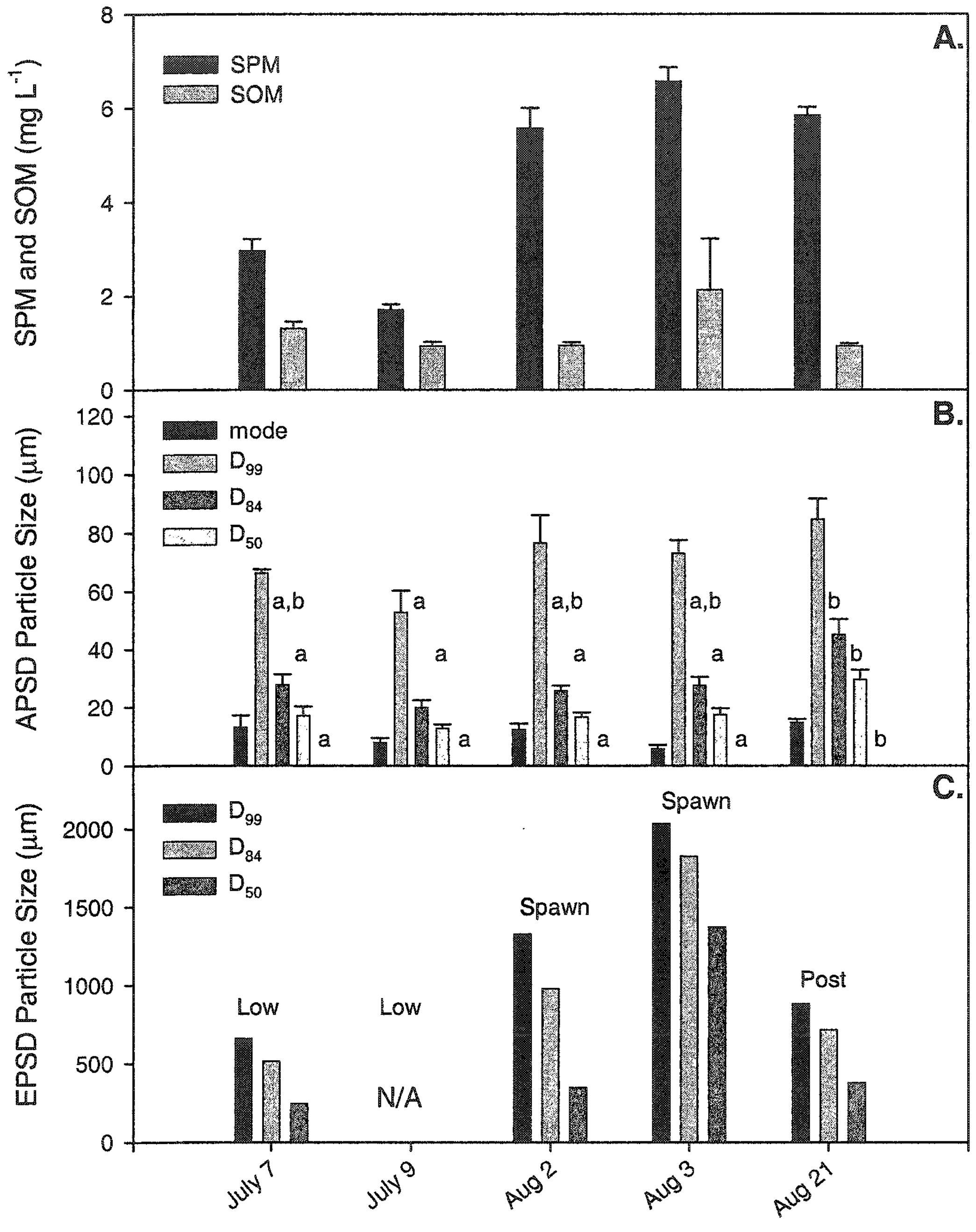

Figure 3.13 Data summary (averages) for sampled rain events. A. SPM and SOM concentrations. B. Diameters at the mode, and 99, 84, and 50% of the cumulative percentage volume curves for the absolute particle size distributions (APSD). C. Diameters at 99, 84, and 50% of the cumulative percentage volume curves for the effective particle size distributions (EPSD). Error bars ± 1SE. July 7th and 9th = Low Flow, August 2nd and 3rd = Spawn, and August 21st = Post-spawn periods.

those derived from the APSD for the post-spawn overlapping rain event (August 21st) are significantly higher than the spawn according to an ANOVA. Previously, the trend followed a decrease in constituent particle size from spawn to post-spawn. In terms of source slope (not presented in Figure 3.13 due to the large scale difference compared to the other variables), there are no differences between event types, with rain events exhibiting an average slope of 0.50 ± 0.06, 0.48 ± 0.05, and 0.52 ± 0.07 for low flow, spawn, and post-spawn, respectively. This differs from the larger dataset for the post-spawn period, as previous findings were that post-spawn spectra had significantly smaller slope values.

3.3.5 Settling Velocity and Density

The relationship between settling velocity and particle size is shown in Figure 3.14. There does not appear to be an obvious pattern between settling velocity and particle diameter for the grouped dataset. The majority of tracked flocs/aggregates fall in the range of approximately 100 to 500 μm diameter, while the maximum size of tracked flocs/aggregates exceeds 2000 μm. The majority of the smaller aggregates exhibit settling velocities of 6 mm s^{-1} or slower. However, a smaller proportion of this size class settle at velocities up to about 10 mm s^{-1}. The faster travelling composite particles (> 6 mm s^{-1}) represent ~4% of the total number of particles, and belong to the post-spawn (2.5%), spawn (0.7%), rain (0.3%), and low flow (0.5%) event types.

Similarly, a subset of the seasonal floc/aggregate population, about 3.4%, exceeds 500 μm in diameter. All event types are represented in this larger class, although the greatest number are from the rain (1.2%), spawn (0.8%), and post-spawn (0.8%) periods.

Of the rain proportion, the majority of particles were sampled on August 2nd and 3rd; both days belong to the spawn overlap period. When these days were added to the spawn period total, its proportion of particles greater than 500 μm increased to 1.7%. Particles in this size class all settle at less than 6 mm s^{-1}, with the exception of one particle from the post-spawn period that falls at more than 12 mm s^{-1} and two others (7.7 and 6.2 mm s^{-1}), two particles from the spawn period (velocities of 6.3 and 7.8 mm s^{-1}), and two flocs from rain events at 7.3 and 6.4 mm s^{-1}.

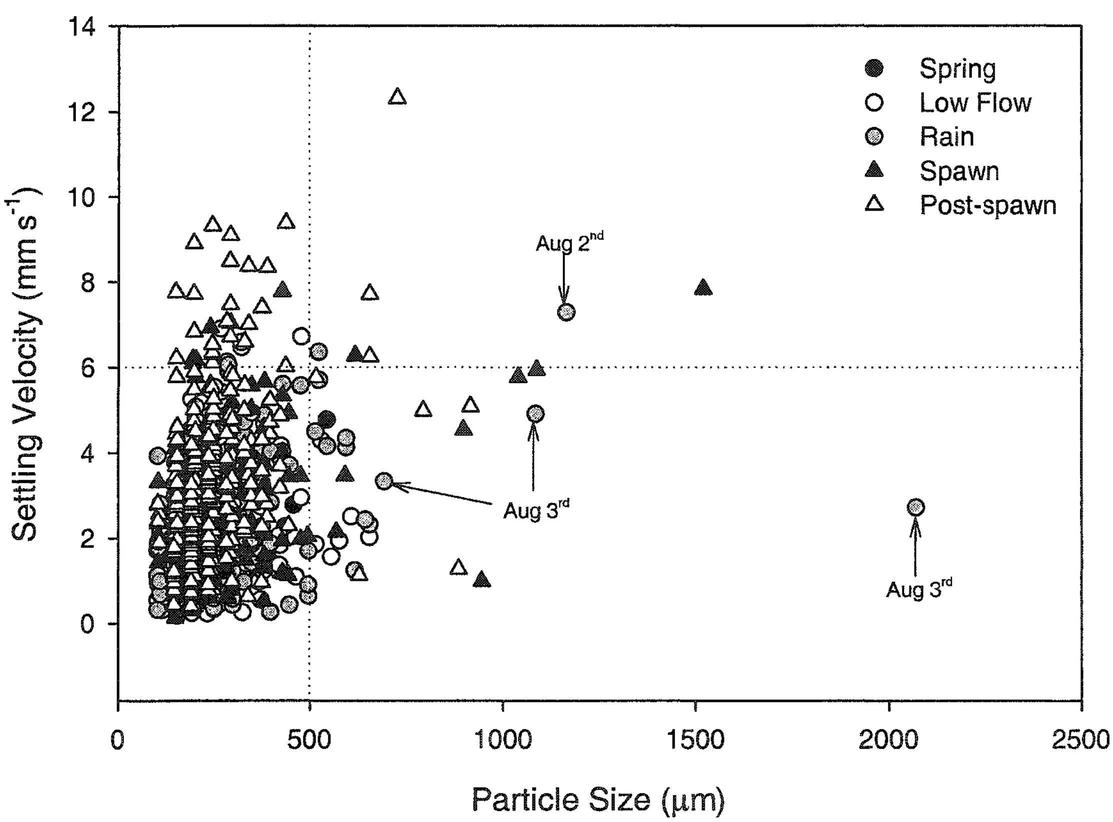

Figure 3.14 Settling velocity by particle diameter. Symbols differentiate between event types. Arrows designate rain events that belong to the spawn sub-category.

A Kruskal-Wallis non-parametric test to compare median settling velocities between event types was used to determine whether differences exist between event types. Significant differences were detected at the α-level of 0.05. It appears that the majority of the difference is due to higher settling velocities found during the post-spawn period. Similar testing for particle size revealed no significant differences.

Figure 3.15 indicates that density decreases exponentially as particle diameter increases. Visual inspection reveals no apparent differentiation between event types except that the larger, least dense particles belong to the low flow, spawn, and post-spawn periods. A similar proportion of particles from the latter two periods appear to fall in the lower diameter-higher density spectrum, but no particles sampled from the low flow period are represented. No large, low-density composite particles were observed for spring, while only three flocs > 500 mm (< 3 mm s^{-1}) were found in low flows. Significant differences were detected using the Kruskal-Wallis H test and are again attributable to the post-spawn period, although a slight trend of increasing density from spring through to post-spawn is evident.

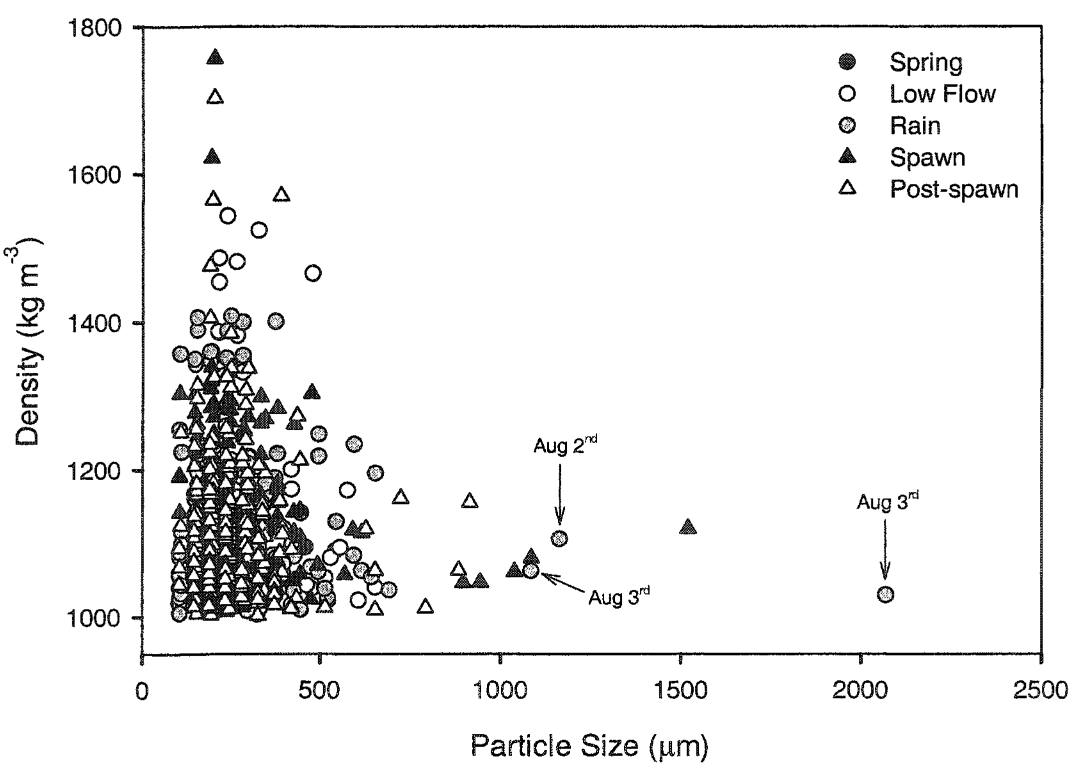

Figure 3.15 Particle density by diameter. Symbols differentiate between event types. Arrows designate rain events that belong to the spawn sub-category.

3.4 Discussion

3.4.1 Variation in SPM and SOM

Conventional hydraulic theory predicts a proportional relationship between suspended sediment concentration and flow due to increased turbulence and shear stress assuming constant sediment supply. The sources of sediments does change depending on flow conditions. Springmelt is characterized by flushing of a large pulse of stored inorganic and organic material from both the channel and the floodplain. This includes scouring of stream banks and removal of debris blockages. Rains events are presumed to draw from similar source supplies, although on a smaller scale. Sediment sources are limited to mainly in-stream for low flows. The data from this study follows the expected pattern with deviations during the active salmon spawning period. These observations indicate that the salmon presence is creating an increase in suspended inorganic material. Soulsby et al. (2001) note that female fish dig spawning redds by exerting enough force on the bed to move the gravels. After spawning, this same force is used to bury eggs. During this process, smaller material stored in the gravels is suspended and transported downstream. In a stream reach where hundreds of salmon are spawning simultaneously, a considerable amount of gravel-stored fine sediment is suspended. The data in Figure 3.6B appear to reflect this biotic resuspension of sediment. The SPM elevation (aside from the freshet peak) is restricted to the active spawning period, and concentrations return to an expected level related to discharge when live salmon are no longer present within the reach. The rain event analysis elucidates that rain events sampled during the spawn period exhibit increased SPM concentrations compared to the low flow. The significant difference between low flow and rain events is due predominantly to the high SPM levels associated with the two rain events sampled during the spawn period.

A similar relationship is expected for the SOM pattern and the data comply. Springmelt is characterized by elevated organic matter concentrations. A pulse of organic material moves with inorganic material that has been entrained after storage over the winter months. Higher salmon spawn and rain concentrations compared to the low flow period likely reflect the decomposition of salmon carcasses and release of marine-derived organic material. The rain event analysis does not aid in interpretation of relationships because it shows that the August 3rd SOM concentration is the only detectable difference, and the variation within SOM data for this date is significantly higher than any other sampling date. A technique that is more sensitive in quantifying the organic matter suspended within the water column, and determination of the sources as they change over the season, may better resolve the organic matter patterns seen here. These will be presented in the following chapter.

3.4.2 Variation in APSD

Slope values from absolute particle size distributions relate to the source materials from which the sample was derived (Kranck et al., 1996). Different sources will contain varying proportions of fine and coarse particles. Spectral slopes for spring, low flow, and spawn periods are derived from a steeper source than the post-spawn, indicating a greater proportion of larger grain sizes. Sources comprised of a wider range of size classes, such as terrestrial, stream bank, and channel bottom inputs, likely contribute during these periods. The post-spawn rain event slope increased to equal those of other events when the channel bottom, banks, or floodplain was disturbed as might be expected in higher flows. During the post-spawn period, which exhibits low flow velocities, the greater proportion of smaller particles (< 5 μm) suspended could be a result of a limited ability of the flows to entrain the larger material into the water column. The source is mainly the streambed during this period, and lower flow rates compared to other time periods means that only the finest size fraction will be mobilized.

Modal values extracted from APSD reveal the size of the largest particle that is suspended under the flow conditions in question (Kranck et al., 1993). A decrease in mode from springmelt to low flow to post-spawn tracks the relative decrease in discharge. The rain events appear to fall within a middle value compared to all other events, which is anticipated because rain events combine low flow, spawn, and post-spawn periods. The spawn period deviates from theoretical expectations with respect to flow conditions. Salmon spawn activity increases the inorganic particle size that is entrained. Petticrew and Droppo (2000) studied an anthropogenic disturbance of the gravel in O'Ne-eil Creek that was intended to simulate movement by spawning salmon. They found that the APSD were markedly altered after, compared with before, the disturbance. The concentration increased and the modal values were shifted to the right. Both findings corroborate the data presented here.

This relationship is further emphasized by significantly larger particle diameters measured when salmon were active in the stream as compared to the range of flow conditions experienced from springmelt to baseflow. Although the discharge measured during the freshet should have entrained all fines from the gravels to the same or greater depth as the salmon, the suspended fines are comprised of smaller inorganic particles.

Combining this finding with the idea that a relatively small portion of the sampled inorganic particles was larger than 20 μm, implies that the notion of association between absolute particle size and discharge is misleading. Rather, the size more accurately reflects the source material available (Kranck et al., 1996; Petticrew, 1996), glaciolacustrine deposits in this case. Walling et al. (2000) report comparable results and relate the lack of association between APSD and flow to the relative importance of different sources. A possible systematic explanation for measuring larger particles for spawn as opposed to spring (D_{99} = 80 and 67, respectively) could be that the water level was considerably lower during salmon spawn. In the spring, the water level was ~1 m as compared to < 0.5 m for low flows. This means that the probability of sampling near-bottom sands would be much greater during the salmon spawning period. Walling et al. (2000) further note that the relationship between absolute grain size composition and discharge is complicated by the fact that hydraulic regulation of suspended sediment directly influences the *in situ* or effective particle distributions, rather than the constituent inorganic grains.

3.4.3 Variation in EPSD

Comparison between absolute and effective distributions (Figures 3.8 and 3.10) indicates a large degree of flocculation occurring in O'Ne-eil Creek, with an average seasonal D_{99} increase of 68 to 1056 μm. This translates to a floc factor of ~16, which is greater than the reported 10 times for maximal diameters by Petticrew (1998) for Stuart-Takla streams. Note the sampling technique used here enabled exclusion of sands and larger mineral particles, which is evidenced by the largest APSD diameter recorded being in the range of fine sands (~111 μm). Thus, majority of larger particles are flocs/aggregates. As well, the maximum floc sizes reported here exceed those found in the Mackenzie River delta (~90 μm) (Petticrew and Droppo, 2000) and Fraser River (~ 100 μm) (Petticrew and Biickert, 1998). Petticrew (1998) found a maximum floc size of 1290 μm in 1994 after the peak of salmon spawn. Here, a maximum floc size of 2032 μm, and increased floc factor, measured during a similar time period seasonally indicates either inter-annual variation in particle structure, highly variable seasonal structure, or differences in sampling and analysis techniques. Petticrew and Arocena (in press) reported a floc factor of about 11 for gravel-stored flocs in O'Ne-eil Creek for 2001 samples in the same reach as presented here. As well, they used the same methodology. It is likely that in-gravel structures would be smaller than suspended flocs and the data reported here support a difference of ~1.5 (11x to 16x floc factor). The between system disparities in floc size are probably attributable to either differences in discharge (Biickert, 1999), mineralogy (Milligan and Hill, 1998), or organic matter content (Droppo and Ongley, 1994; Petticrew, 1996), but clearly the Stuart-Takla streams are well-flocculated.

While it is not statistically supported, there is a seasonal pattern in effective particle sizes for O'Ne-eil Creek (Figures 3.11 and 3.12). A general increase in particle size from springmelt to spawn implies that discharge is not positively related to flocculation within this stream. The largest sizes are found during active salmon spawn, a time when base levels of flow were recorded. Variation occurs within and between sampled event types (Table 3.2), although conspicuous differences occur between spawn spectra and curves from all other event types. The pattern may be solidified by improved sample size. The trend of increasing floc size (spawn > rain > low flow > spring > post-spawn; Figure 3.11) does not lend support to the collision theory of aggregation (Milligan and Hill, 1998), which indicates that the largest particles should occur during highest particle concentration, so as to enhance collision. While the highest SPM concentrations occur in springmelt (Figure 3.7), the shear stress due to high flows could act to break larger aggregates and flocs (Dyer and Manning, 1999).

Laboratory studies have dominated examination of the connection between suspended sediment concentration and flocculation, where the organic component was controlled or excluded. The relationship becomes much more complex in natural systems. Researchers studying particle structure under field conditions (e.g., Droppo and Ongley, 1994, Petticrew and Biickert, 1998, and Woodward et al., 2002) have speculated that organic matter content and biological activity may have significant influence on particle structure in freshwater systems.

The linkage between organic matter and particle structure remains relatively unexplored, however salmon carcass-derived nutrients are known to enhance the growth of microorganisms (Wold and Hershey, 1999). Bacterial adhesion is one mechanism of biological flocculation (Dade et al., 1990; Droppo et al, 1997). As well, the nature of organic molecules appears conducive to assisting floc formation through the production of extracellular polymeric fibrils. Using scanning electron microscopy, Petticrew and Arocena (in press) found visual evidence of changes to particle composition and structure of gravel-stored sediment due to salmon activity and carcass decomposition. Thus, it is possible that spawning salmon in O'Ne-eil Creek influence particle structure by some combination of increasing SPM during low flow conditions and introducing a pulse of organic matter.

3.4.4 Variation in Settling Properties

Petticrew and Droppo (2000) visually and quantitatively characterized two distinct particle populations sampled from a water column that included the suspended sediment and material resuspended from gravel-bed storage. While the majority of particles were small (< 500 μm) and settled slowly (< 6 mm s^{-1}), two sub-populations were apparent: (1) small, fast settling, compact aggregates and (2) larger, slow settling, flocs. Again, the majority of particles observed here are in the < 500 mm diameter, < 6 mm s^{-1} fall velocity category, yet a proportion of the total group fit into these sub-populations as defined by size and settling rate (Figure 3.14). The majority of the largest size fraction belongs to the spawn event type; however, the small, faster settling particles occur after this period during post-spawn.

The post-spawn period in this study is characterized as the period when no living salmon remain in the stream. The system is in low flow conditions, therefore has a limited supply of inorganic sediment, but is receiving biological breakdown products from decaying salmon carcasses. These smaller, fast-settling aggregates sampled during post-spawn were also observed by Petticrew and Droppo (2000), who sampled this same stream in the post-spawn period of 1996. The major difference was that they disturbed the gravel matrix to resuspend gravel-stored flocs. They presumed the compact aggregates they observed were resuspended from the gravels, while the larger flocs were generated and carried in the water column. Clearly some of these compact aggregates are moving in the water column during low flows. As they have high settling velocities (100 μm sands settle at ~9 mm s^{-1}), they will drop out of the water column more quickly than the larger flocs. So, possibly the aggregates are stored on the gravel surface and moved via saltation along the bottom where they were sampled in the shallow, post-spawn waters (depth < 0.5 m). Sands of 100 μm have densities of ~2650 kg m^{-3}, and would be more difficult to entrain at these flows (velocities < 0.3 m s^{-1}), while irregular shaped, 200 to 500 μm particles, with densities between 1200 and 1500 kg m^{-3} could potentially be moved in these shallow flows.

In terms of salmon influence on these same gravel beds in 2001, Petticrew and Arocena (in press) observed an increasing settling rate in gravel-stored flocs from pre-spawn to post-fish, with no appreciable increase in particle diameter. They report a mid-spawn low in mean particle size, combined with intermediate settling velocity and density. Particle break up induced by salmon activity is cited as a likely cause, which would support the argument that the suspended particle size described here is a function of flocculation processes occurring within the water column.

Important inferences can be made using the assumption that particle geometry and matrix properties regulate settling velocities. The bulk of particles > 500 μm settled < 6 mm s^{-1} and all particles fell considerably slower than predicted by Stoke's equation (Petticrew and Droppo, 2000). These particles are characterized by irregular shape with lower density, and higher porosity and organic content as compared to Stoke's spherical, dense, mineral counterparts. The spawn event exhibits the largest particles densities, which are still much smaller than the hypothetical values calculated using Stoke's equation for mineral grains of similar diameter. Organic material introduced to the stream by spawning salmon is likely incorporated into these particles to create large, light flocs. Continuous settling and subsequent resuspension due to spawn activity probably facilitates stability for these particles, enabling preservation of size (Petticrew and Droppo, 2000). A partial explanation for the observed patterns in this study are that a high degree of flocculation occurs during active salmon spawn, resulting in much larger composite particles than possible without the presence of salmon. After salmon die-off, these large flocs settle out of the water column and are stored on or within the gravels (assuming the discharge remains limited to facilitate storage). The smaller, fast-settling aggregates may be sporadically entrained from the gravel surface, thereby moving by saltation downstream, and flocculation during this period occurs from smaller constituent particles. These compact aggregates likely form from incorporation of inorganic particles into the matrices of existing flocs. Again, spawning activity seems to play a substantial role in shaping particle morphology, in terms of both physical and chemical processes. Further examination of the connection between particle morphology and organic matter source and supply should clarify the nature of the relationship.

3.5 Conclusion

Temporal analysis of suspended sediment structure in relation to important hydrodynamic events and the presence of anadromous fishes demonstrated that seasonal changes in suspended sediment concentration and structure in O'Ne-eil Creek are linked to salmon spawning activity. Increases in both particle quantity and effective diameter occur during the presence of migrating salmon due to a combined effect of physical resuspension of gravel-stored sediment and introduction of pulse of nutrients from reproductive products and post-reproductive carcasses. The increase seen in diameter coincided with low settling velocity and density relative to expected or modeled values determined from Stoke's Law. The combined existence of these results indicates that the presence of spawning salmon enables incorporation of low density organics into floc matrices as well as other physical effects such as increased porosity. Further research into the organic processes involved should better explain the association and implications. The findings presented here necessitate careful planning of any anthropogenic disturbances in watersheds that support migratory salmon stocks to ensure suitability and availability of spawning habitat.

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Chapter 4—Contributions of seasonally changing organic matter sources to suspended sediment structure in a salmon-bearing stream

Abstract

The prevalence of aggregated or flocculated particles dominating the suspended sediment load of freshwater and marine environments is well-documented. The predominant causative factor in marine systems is electrolyte concentration, however, it is more likely that flocculation in freshwater systems is due to organic binding agents such as bacterially-produced exudates. Organic matter adsorbed to particles provides favourable microhabitat for bacterial colonization, which allows for increases in metabolic activity of these organisms, in addition to being composed of macromolecules that may facilitate particle binding directly. This study investigates the hypothesis that variability in particle structure between studied systems is largely due to temporal variation of organic matter source and supply. O'Ne-eil Creek, a site for annual migration of sockeye salmon (*Oncorhynchus nerka*) in northern British Columbia, was sampled using a seasonal approach to characterize organic factors contributing to flocculation. Larger diameter particles where found in suspension during the period of salmon spawn, compared to low flow. Seasonal patterns from stable isotopes of carbon and nitrogen indicate that the change in particle size is related to salmon presence due to the introduction of microbial growth enhancing, post-reproductive carcass-derived nutrients. Enrichment of nitrogen due to the influx of marine-derived nutrients provided by post-reproductive salmon carcasses are an important factor related to increases in particle size. Future laboratory experiments directly examining the relationship will elucidate the issue more conclusively.

4.1 Introduction

Fine-grained sediment (<63μm) in suspension not only moves as individual particles, but also as particle aggregates or flocs. Flocs are comprised of both organic and inorganic material, bound together by a combination of physical, chemical, and biological forces (Droppo et al., 1997). The rate of flocculation depends on site-specific variables such as ionic and suspended sediment concentration, shear stress, pH, and organic source and supply (Droppo and Ongley, 1994; Petticrew and Biickert, 1998). This is evident in the comparison between marine and freshwater systems. Flocs are prolific in marine environments, where high concentrations have afforded them being termed "marine snow" (Alldredge and Silver, 1988). Conversely, riverine flocculation is less apparent visually, and hydrologic conditions were preliminarily thought to be too energetic to facilitate floc-building. Flocculation is now a well-documented phenomenon in freshwater lotic systems (e.g., Droppo and Ongley, 1994; Petticrew, 1996, 1998; Petticrew and Biickert, 1998; Petticrew and Droppo, 2000), although the resulting particles are typically an order of magnitude smaller than their marine counterparts (e.g., 10^2 to 10^3 μm diameter).

The main operational difference between these riverine and marine systems is ionic concentration. Flocculation in saline environments has been attributed mainly to the high electrolyte concentration (Alldredge and Silver, 1988; van Leussen, 1999), while freshwater systems are characterized by much lower salinity (> 10^3 μS cm^{-1} for marine at 25°C versus << 10^3 μS $cm^{-1}$for freshwater; Kalff, 2002). van Leussen (1999) states that the role of salt flocculation is currently in question, and that organic binding agents may play an important function in the process for both environments. Further, Droppo and

Ongley (1994) suggest that suspended sediment, organic matter and bacterial concentrations may combine to regulate freshwater/riverine flocculation, although the extent that each individual variable contributes is uncertain.

Organic material introduced to river/stream ecosystems is derived from either autochthonous or allochthonous sources. Both of these sources vary temporally. Seasonal variation of terrestrial sources is attributed to the presence of species and hydrologic regime. The composition of the riparian species changes over time, as does the proportional species contribution to streams (Johnson and Covich, 1997). Stage height and precipitation also facilitate transfer of terrestrial material to streams (Koetsier et al., 1997; Tockner et al., 1999), both laterally and longitudinally. In-stream productivity is dependent on environmental factors such as insolation and temperature (Allan, 1995; Sand-Jensen, 1998), as well as terrestrial nutrients. In addition, the hydrologic regime regulates the available substrates and refugia for aquatic organisms.

Organic substances incorporated into floc matrices are known to control floc morphology and settling behaviour (Petticrew and Droppo, 2000; Droppo, 2001). Flocs containing high concentrations of organic matter tend to appear irregular and loosely bound and exhibit low settling rates and densities, while compact aggregates (dense and fast settling) are probably comprised of a greater percentage of inorganic particles. The influence of organic material may be related to its quality in terms of utilization by bacteria, where higher quality sources should enhance microbial productivity (Petticrew and Arocena, in press). Temporal variability in floc morphology may therefore be due to changes in the sources of inorganic and organic material. Investigation of this idea requires accurate definition of organic sources. The use of stable isotope analysis for this purpose has increased dramatically in recent years (Griffiths, 1998; Phillips and Gregg, 2001). Stable isotopic tracers have been used to monitor flows of organic matter (i.e., trace trophic relations) in marine (Peterson et al., 1985; Fry, 1988; Hedges et al., 1988; Cifuentes et al., 1988) and freshwater systems (Bunn et al., 1989; France, 1995). Others (e.g., Kline et al., 1990; Bilby et al., 1996; Ben-David et al., 1998) have utilized this technique to characterize the introduction of marine nutrients into freshwater environments. The ultimate goal of this technique is to determine the proportional contributions of multiple sources to a mixture. Linear mixing models are used for this purpose to examine two source, single isotope, or three source, dual isotope signatures (Phillips, 2001; Phillips and Gregg, 2001).

The objective of this study was to evaluate the role of seasonal changes in environmental factors that influence flocculation of suspended sediment. This was accomplished by measuring the suite of environmental (e.g., temperature, pH, conductivity, shear stress) and biochemical factors (e.g., dissolved organic carbon (DOC), colour, stable isotopes, bacterial content) over the period of one open water season in a productive salmon-bearing stream. The sampling strategy was intended to capture important hydrologic and biologic events within the study system, where samples were collected (1) for springmelt and baseflow to allow for comparison between instances of minimum and maximum suspended material, (2) for summer rain events to incorporate resuspension of material from the bed gravels, and (3) for periods when different organic sources were evident (e.g., spawning salmon). Trends and correlations between the regulatory factors and the sediment population characteristics are assessed here to determine the degree of contribution each may have to the process of flocculation at different times of the year. The overall goal is to gain information to explain the potential impacts of land use changes and changing contributions of both inorganic and organic material on sediment structure and settling properties (i.e., transport, settling, and storage), which has consequences for aquatic habitat.

4.2 Materials and Methods

4.2.1 Study Area

The study region (Figure 4.1) includes watersheds located in the Hogem Range of the Omenica Mountains in the Takla Lake region of northern British Columbia, an area under examination by partners in the Stuart-Takla Fish/Forestry Interaction Study (STFFIS). This project was undertaken in the early 1990s with cooperation between government agencies (e.g., Department of Fisheries and Oceans (DFO) and the Ministries of Forest (MOF) and Water, Land, and Air Protection (MWLAP)) and academic institutions (e.g., the Universities of British Columbia (UBC) and Northern British Columbia (UNBC) and Simon Fraser University (SFU)), local First Nations communities (Tl'Azt'En Nation), and forestry companies (Canadian Forest Products (Canfor)) to obtain information regarding the relationship between forestry activities and the productivity of aquatic ecosystems in B.C.'s central interior. Considerable research on this topic has occurred in coastal systems of British Columbia; however, due to significant differences in biogeoclimatic characteristics compared to the central interior, this information is generally not transferable. This is especially true for sediment research, in that basin traits (e.g., slope), surficial geology, vegetation, and precipitation are some of the factors that play a role in regulating the magnitude and timing of sediment delivery through systems, and these differ significantly on a regional scale.

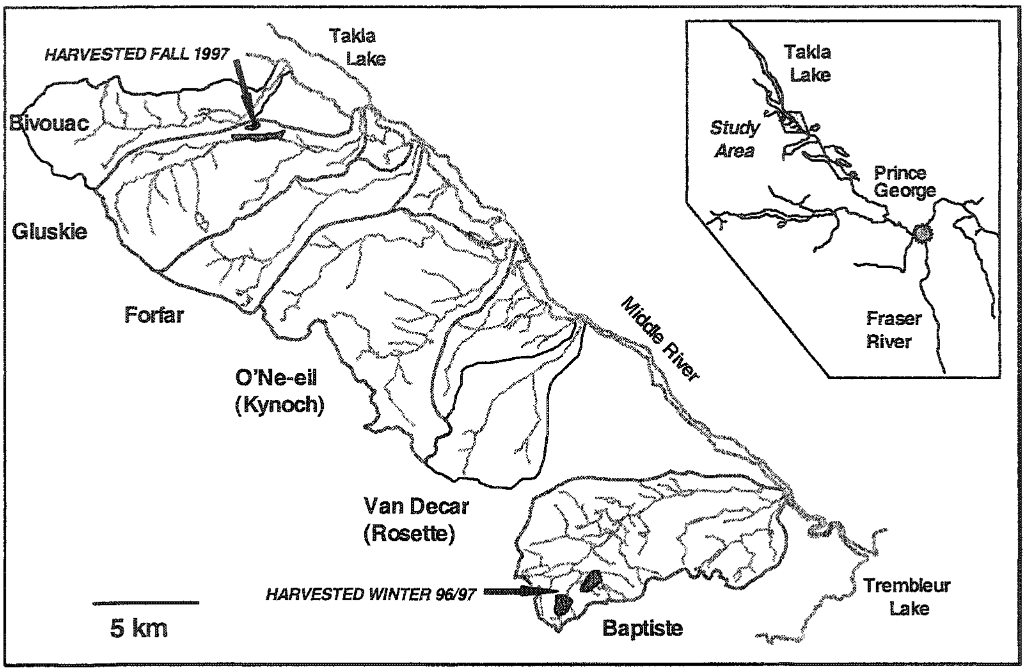

Figure 4.1. Map of the Stuart-Takla region of northern British Columbia. Note O'Ne-eil watershed in the center.

Part of the most northern extent of the Fraser River watershed (55°N, 125°50'W), O'Ne-eil (also known as Kynoch) basin features a range in relief from 700-1980 m (Petticrew, 1996). Surficial material is comprised of glacial tills and lacustrine clays at higher elevation (Macdonald et al., 1992) and fine-grained glaciolacustrine sediment in the lowland areas (Ryder, 1995). Encompassed within the Engelmann Spruce Sub-alpine Fir (ESSF) biogeoclimatic zone, the basin is relatively small (~ 75 km^2), but O'Ne-eil Creek is an important fish-bearing stream, where annual migration of salmon is well documented (Petticrew, 1996). The mainstem channel of O'Ne-eil Creek is approximately 20 km in length and 4 to 5 m wide at the mouth (Petticrew, 1996). The study reach exhibits favourable spawning habitat with appropriate substrate size distribution in low gradient (0.5 - 2 %) riffles (Petticrew, 1996). Little anthropogenic disturbance has occurred within this watershed specifically, however, a forest service road enables access to the lower reaches. One site in O'Ne-eil Creek, downstream of the forestry access bridge and approximately 1500m upstream of the mouth, was sampled during the period of May 18 to August 21, 2001

One sampling site was deemed adequate for resolving temporal patterns in suspended sediment structure, while the interpolation of spatial trends was considered beyond the scope of this study. However, the identification of temporal trends should enable translation of information to other watersheds at similar spatial scales (i.e., biogeoclimatic zones and reach position downstream from the headwaters), as well as provide baseline data for O'Ne-eil Creek watershed prior to anthropogenic disturbances to allow prediction and comparison for future conditions.

4.2.2 Study Approach

The intent of this study is to examine the seasonal interaction between environmental conditions and flocculation. More specifically, the hypothesis is that the variability in size and shape of flocs is regulated by the organic component. The assumption is that in temperate forest areas such as the study region, the quality and quantity of organic material incorporated into the stream system varies over the season depending on source types available, hydrologic regime, and conditions for biological processing. Organic matter of good quality, and/or high concentrations, may significantly increase the size of flocs, resulting in faster settling rates. This may be attributed to two factors: (1) flocculation is directly facilitated by the organic matter, or macromolecules comprising organic material; and/or (2) organic matter provides the nutrients and habitat for bacteria, which exude polymeric fibrils that bind particles together (Droppo et al., 1997). The latter is dependent on organic matter as a nutritional resource, and thus the bacterial concentration should provide an index for organic matter quality (Koetsier et al., 1997). Other factors influencing flocculation vary temporally as well, thus alternate hypotheses could be that floc size is regulated by (a) shear stress or (b) water chemistry parameters such as conductivity or pH.

Hydrological conditions regulate the presence and distribution of biological organisms (e.g., periphyton and invertebrates) (Allan, 1995), the transport and transfer of solutes (e.g., ions and nutrients) (Webster and Ehrman, 1996), and the provenance and movement of organic material (Minshall et al., 1985). Water temperature, which is intimately linked to air temperature, varies both seasonally and diurnally, as well as among locations due to regional differences in climate, elevation, extent of streamside vegetation, and relative importance of groundwater inputs (Allan, 1995). Temperature is of significant biological importance in that it regulates metabolic rates of organisms, fluid dynamics, and levels of dissolved gases (Hauer and Hill, 1996).

Of utmost importance to transport of organic sources is the seasonal variation of organic matter supply to streams. Not only do hydrological factors affect the relative proportion of various sources of organic material, but the seasonal availability of source types does as well. As floodplains are inundated during overbank flow periods, stored organic matter may enter the stream. This occurs during episodic events such as spring melt (i.e., freshet) and rain events. Rain, and associated wind, has an added impact in that allochthonous (generated from the watershed) material may get blown into the stream from riparian areas. Autochthonous (generated within the stream) sources are linked to several environmental factors, including temperature, light intensity, available nutrients, and discharge, where favourable conditions are more likely to occur during low flow periods. Allochthonous sources often follow seasonal lifecycles, where leaves and needles are shed in autumn, and new growth does not occur again until spring. A third source of organic matter exists in many watersheds that are linked to marine environments. Anadromous salmon, migrating upstream to spawn, are known to introduce important marine-derived nutrients to freshwater systems (Bilby et al., 1996). In general, organic matter contribution to streams is approximately harmonized with the seasonality of systems.

Johnston et al. (1998) present the seasonal variation in the source organic contributions to Stuart-Takla streams for 1996. Riparian litter inputs were noted for the period between July and October, varying between 10 and 300 g m^{-2} in dry weight, with the majority being of deciduous rather than coniferous origin. The magnitude of vegetation introduced to the streams decreased logarithmically with distance from stream banks, while the mean areal loadings decreased as channel width increased. In-stream productivity in the form of benthic algal biomass increased in late summer in response to introduction of salmon carcass derived nutrients.

The cycle of spawning salmon is that female fish cut spawning redds by digging up gravels, simultaneously leaving a depression for deposition of spawning products and cleaning out fine material stored in interstitial spaces that may hinder oxygen transfer for eggs (Figure 4.2; Soulsby et al., 2001). After spawning, this action is used to bury eggs. Shortly thereafter (days) both the female and male die and the remaining carcasses are left to rot in-stream. Johnston et al. (1998) report that the organic inputs from such carcasses (15 to 200 g m^{-2}), exceeded those of riparian leaf litter in Stuart-Takla streams exhibiting high densities of spawning salmon.

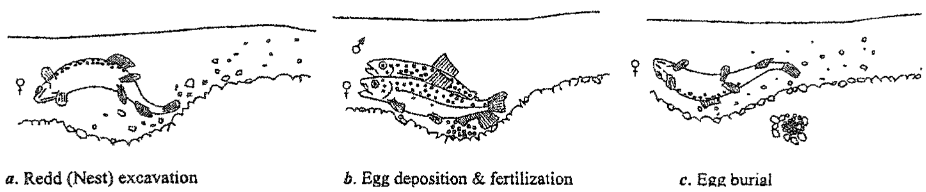

Figure 4.2 Spawning activities of salmon. a. Females dig out the area to prepare of egg deposition. b. Females deposit eggs and males subsequently fertilize. c. The fertilized eggs are buried for overwintering. From Soulsby et al. (2001).

With this in mind, it is easy to see the potential impact of seasonal variation of the various environmental factors discussed here on flocculation. If physical, chemical, and biological factors interact in the process of flocculation, and they vary temporally, then so potentially should floc structure. In fact, Petticrew and Arocena (in press) identified seasonal variation in particle structure and settling behaviour, which they speculated was due to changing organic matter contributions and composition as well as physical resuspension of gravel-stored material by spawners. On a smaller temporal scale, Petticrew and Droppo (2000) observed a difference in floc morphology between rising and falling limbs of the freshet peak on a springmelt hydrograph. Thus, because the hydrologic conditions were similar for both time periods sampled, there must be associated differences in the suite of factors that influence sediment morphology occurring between these two instances or, alternatively, the source organic material could be the differentiating factor.

In the specific system where this study took place, the premise is that the relative importance of organic material of differing quality changes with time. Of particular interest is the pulse of organic matter introduced after the salmon-spawning period, where a large amount of nutrients is made available to microbes from post-spawn carcasses. In order to evaluate the seasonal changes in the suite of factors that influence flocculation, samples were collected over a range of watershed events to incorporate seasonal hydrologic and biologic changes. These were partitioned into five discrete response types, which are (Figure 4.3): (1) springmelt during the period of rising water levels; (2) summer low flow conditions, but isolated from rain events; (3) rain events; (4) the period during active spawning, which includes live and dead fish; and (5) post-spawn, where no actively spawning or live salmon were present, but carcasses were still evident

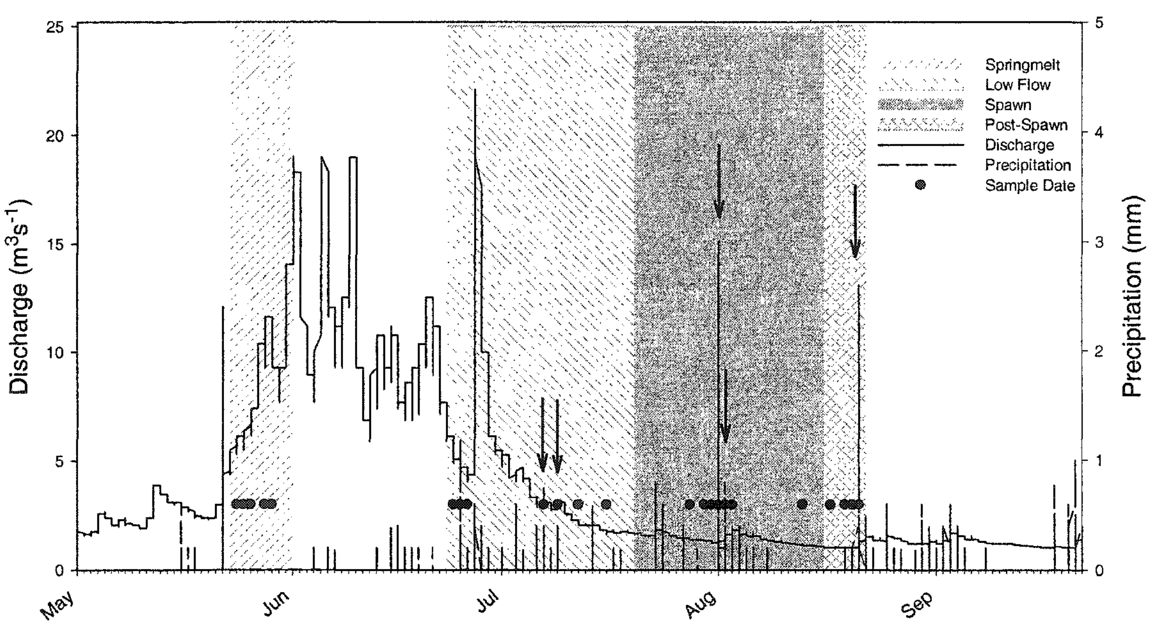

Figure 4.3 Schematic of sampling approach during the 2001 open water season. Points represent sampling times, shaded areas depict the four major event types of rising limb of springmelt, low flow after springmelt, and the active spawning period and post-spawn (i.e., no live/spawning salmon). Arrows designate sampled rain events. Note that June 25th sampling occurred prior to the onset of precipitation.

in the channel. Springmelt is a period characterized by high discharge, and this is when the first flushed material stored in-channel and on the floodplain occurs. Less suspended load is moved during the baseflow levels of the low flow period, where the source material is predominantly in-stream. Rain events are characterized by higher than baseflow discharge, where suspended sediment concentrations are expected to increase, and comprise a combination of in-stream and terrestrial inputs. Rain events occur during baseflow, salmon spawn, and post-spawn, so they reflect the combined effects of resuspension of gravel-stored material that occurs during storms and the predominant source of organic matter for the particular sampling date. The period of active salmon spawn combines the introduction of anadromous organics and biological disturbance of gravels. This organic matter is expected to remain within the system post-spawn, but, because live fish are no longer present, disturbance of gravels is minimal. Seasonal patterns of fluid properties, water chemistry, and organic matter were identified using this approach.

Chapter 3 indicates that the hydrologic regime differs greatly between these periods (i.e., maximum versus minimum discharge for springmelt and late summer, respectively), and it is presumed that other factors affecting flocculation (e.g., organic matter source and supply) do as well. The salmon-spawning period is of particular interest because marine-derived organic material is supplied to freshwater systems (Garman and Macko, 1998) from deposition of eggs and post-reproductive carcasses (Kline et al., 1994). More specifically, Kline et al. (1990) and Bilby et al. (1996) state that salmonid fishes contribute significantly to freshwater nitrogen budgets during this time. Springmelt was selected based on the premise that organic material stored within the system over the winter is introduced to streams during this time. Though it has been determined that organic matter influences flocculation (Petticrew and Biickert, 1998;

Petticrew and Droppo, 2000), the nature and extent of this effect is presently unclear. Correlational analysis was used to determine the significant factors that may cause the seasonal variation in particle structure seen in the previous chapter.

4.1.1 Sample Collection and Processing

4.1.1.1 Shear Velocity and Stress

Velocity profiles were used to estimate shear stresses acting on flocs. Velocity measurements were taken at equal intervals of 5 or 10 cm, depending on the water depth at sampling time, from bed to surface using a Swoffer current meter (Model 2100). This instrument measures depth to a precision of ±0.05m and velocity to ±0.01m s^{-1}. The graphical representation of the relationship of velocity versus water depth was derived and the horizontal axis (water depth) was logarithmically transformed. The shear velocity (V_*; m s^{-1}) along a hydraulically rough streambed was calculated from the slope (*b*) of the regression line fit to the data points as per Gordon et al. (1992), expressed as:

$$V_* = b / 5.75 \qquad 4.1$$

Bottom shear stress (τ_0; N m^{-2}) is directly proportional to the square of the shear velocity and the density of the water (ρ; kg m^{-3}), which is dependent on temperature (Nowell and Jumars, 1984):

$$\tau_0 = \rho\,(V_*)^2 \qquad 4.2$$

Only one profile per sample period was used to determine shear stresses exerted on flocs; however, due to fluid turbulence, considerable variation was encountered in the current velocity for the period(s) of data collection. For depth each interval, five velocity values were measured and the average was used to construct the velocity profiles. This technique is limited by water depth (D), where it is difficult to obtain a profile comprising greater than two velocity measurements when the propeller diameter exceeds D/3. The water level at the sampling point never fell below this critical depth.

4.1.1.2 Temperature, Conductivity, and pH

Both air and water temperature was monitored using Onset Stowaway Tidbit loggers measuring hourly intervals. Two loggers were fastened to the streambed at the sampling point (approximately the stream center), protected with steel tube shields, and one was suspended approximately three meters above the stream to provide air temperature measurements. These instruments operate in a range of –5 to 37 °C, with a resolution of 0.15 °C. Logger precision is dictated by the resolution and calibration ensured accuracy. Conductivity (i.e., ionic concentration) was measured using a Hach CO150 meter, where the probe was calibrated with a standard (1413 $\mu S\ cm^{-1}$ at 25 °C, Hanna Instruments) prior to sampling. Measurements are facilitated by immersing a probe interfaced to a hand-held monitor into the water and waiting for the digital readout to stabilize. Because conductivity depends on temperature, this instrument is equipped with a built-in temperature probe. This instrument is precise to ±0.1°C and ±1μS for temperature and conductivity, respectively. A Canlab portable pH meter, precise to ±0.01, was used to measure pH. This instrument is utilized similarly to the conductivity meter in that it must be calibrated at pH 4 and 7 to a particular temperature beforehand, and equilibration must be reached before the value is accurately determined. Only one measurement of conductivity and pH was necessary per sampling day, as large fluctuations did not occur on small time scales.

4.1.1.3 Chlorophyll *a*, Colour, and Dissolved Organic Carbon

Water was removed from a central sampling point within O'Ne-eil Creek as per Section 3.2.4.1 using 1 L wide-mouth Nalgene bottles for triplicate samples of (1) chlorophyll *a* extraction, (2) colour analysis, and (3) dissolved organic carbon (DOC). The first analysis required filtration through precombusted/weighed glass fibre filters (GF/F) with an operational pore size of 0.7 μm. Filters were retained in sterilized 50 mL centrifuge tubes covered with aluminum foil to reduce light exposure. Extraction in 30 mL of 90% buffered ($MgCO_3$) acetone occurred over a 24-hour period at 4 °C after which absorbance values were read using a spectrophotometer at 664, 665, and 750 nm, before and after acidification with 0.1 N HCl, in order to determine the amount of chlorophyll *a* and phaeophytin *a* per volume filtered. Absorbance measurements were converted to pigment values as per Eaton et al. (1995):

$$\text{Chlorophyll } a \text{ (mg m}^{-3}) = 26.7\ (664_b - 665_a) \times V_{ext} / V_{sample} \times L \qquad 4.3$$

$$\text{Phaeophytin } a \text{ (mg m}^{-3}) = 26.7\ (1.7(665_a) - 664_b) \times V_{ext} / V_{sample} \times L \qquad 4.4$$

where 664_b and 665_a are the optical densities of 90% acetone extract before and after acidification, respectively, V_{ext} is the volume of 90% acetone used (L), V_{sample} is the volume of the sample filtered (m^3), and L is the light path (cm), which is effectively the width of the cuvette.

Water filtered through Nylaflo (Gelman) nylon membrane filters of 0.45 μm pore size was dispensed into 125 mL amber Redi-pak Boston Round narrow-mouthed bottles and sealed with Teflon-lined polypropylene caps for later analysis of dissolved organic carbon (DOC) using a Total Organic Carbon Analyzer (Shimadzu TOC5000-A) at

Okanagan University College, Freshwater Laboratory located in Kelowna, British Columbia. Samples were preserved by a common method of 2N HCl at 200 μL to 40 mL of sample (Curtis, J., pers. comm.). Prior to acidification, a small aliquot of each filtered sample was scanned at the UNBC laboratory to differentiate colour using a UV/VIS spectrophotometer (Perkin Elmer). Samples were stored at 4 °C in the dark during transport. The absorption spectra for the range of 290 to 800 nm wavelengths were obtained. Green and Blough (1994) state that light absorption by organic material, in both marine and aquatic environments, decreases exponentially for near UV and visible wavelengths and fits this mathematical relationship:

$$a(\lambda) = a(r) \exp [S\ (r - \lambda)] \qquad 4.5$$

where $a(\lambda)$ and $a(r)$ are absorption coefficients at wavelength λ and reference wavelength r, and $a(\lambda)$ is found from

$$a(\lambda) = 2.303\ A(\lambda)\ /\ l \qquad 4.6$$

where $A(\lambda)$ is the measured absorbance and l is the cell pathlength (m). In general, the samples collected conformed to these functions. Those that did not were not analyzed further. Each spectrum was then plotted as $\ln(a)$ versus λ and S was determined to be the slope of the linear regression resulting from the data from 290 nm to the wavelength at which the absorbance dropped off to zero. The E_4/E_6 (absorbance values at 465 and 665 nm) ratios were extracted from these spectra. This ratio has been used to characterize the composition of acidic material in soils, where higher values indicate fulvic material and lower ratios suggest humic material (Stevenson, 1994). Separate measurements were recorded for the absorbance coefficient at 320 nm (a_{320}) as per Williamson et al. (1999).

This value indicates the boundary between UV-B and UV-A radiation and may be used as a measure of coloured dissolved organic carbon (CDOC) in natural waters.

4.2.3.4 Stable Isotopes of Carbon and Nitrogen

Stable isotope mass spectrometry (UBC, Stable Isotope Laboratory) was used to characterize seasonal sources of organic matter. The isotope ratios for both organic tissue and suspended sediment filters were measured and expressed relative to conventional standards as δ values defined as:

$$\delta X\ (‰) = (R_{sa} / R_{std} - 1) \times 1000 \qquad 4.7$$

where X is ^{13}C or ^{15}N, R_{sa} is the isotopic ratio of the sample (either $^{13}C/^{12}C$ or $^{15}N/^{14}N$), and R_{std} is the isotopic ratio of the standard (PeeDee Belemnite for carbon and air for nitrogen). The technique enables assessment of seasonal distribution of organic matter sources by comparing isotopic ratios from source material with those from suspended sediment samples. Carbon and nitrogen content was measured prior to stable isotopes and C:N ratios were calculated from the resulting values. This ratio is often used to estimate sources for organic matter because autochthonous material exhibits much lower values (< 15) than allochthonous (Owen et al., 1999).

Tissue from terrestrial vegetation (e.g., spruce needles and birch leaves), in-stream periphyton and algae, and salmon flesh was collected and stored in 1.2 mL centrifuge tubes and freeze-dried. Isotopes of carbon and nitrogen, as well as percentages of each, were determined. It should be noted that algae and periphyton are separated here even though the term *benthic algae* is typically used to characterize both. In fact, periphyton (or biofilm) is defined by Steinman and Mulholland (1996) as a complex assemblage of algae, bacteria, fungi, and meiofauna attached to substrata within a polysaccharide matrix. The algae collected for this study was visually distinguishable from periphyton. As well, it was necessary to 'scrape' periphyton from substrates, while algae was not readily attached and was much easier to collect. Then, water samples collected as in the previous section were filtered onto pre-combusted and weighed glass fibre filters, which were freeze-dried and analyzed as per the tissue samples. Seasonal trends were assessed using both carbon and nitrogen isotopes and ratios of percentage carbon and nitrogen for these filter samples.

A dual isotope (C,N), three-endmember (algae, salmon, and terrestrial vegetation) mixing model based on mass balance equations (Phillips and Gregg, 2001) was used to define these trends more quantitatively, and to examine relationships (e.g., Figure 4.4)

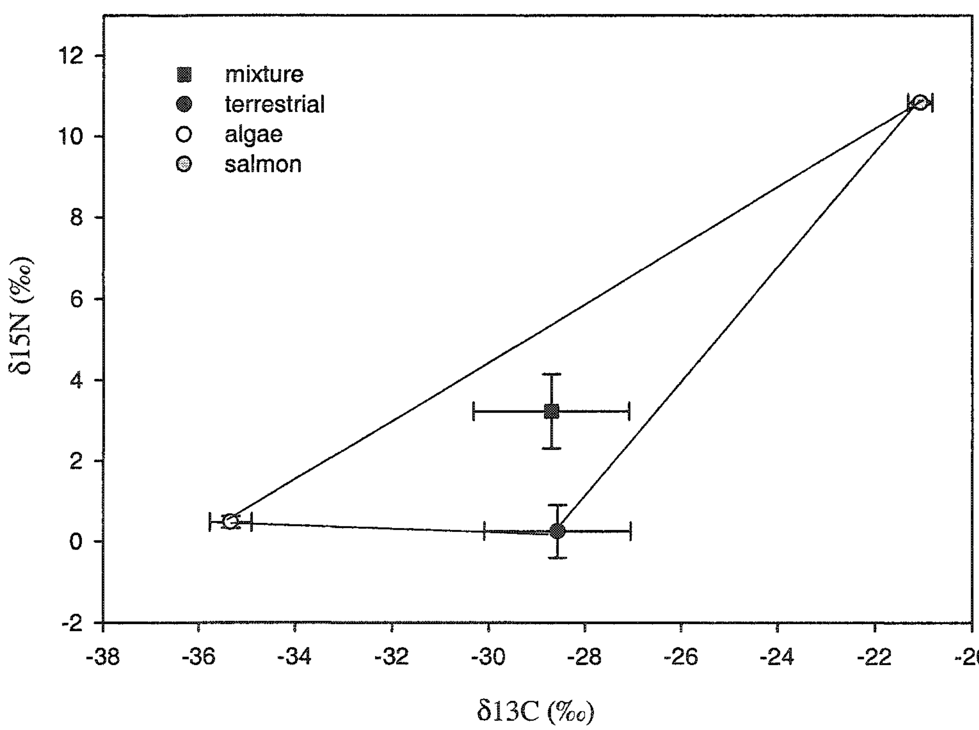

Figure 4.4 Hypothetical partitioning of source contributions (terrestrial vegetation, algae, and salmon flesh) to stable isotope mixtures derived from sediment filter data.

more conclusively. The spreadsheet used to determine source proportions, variances, standard errors, and confidence intervals can be accessed at http://www.epa.gov/wed/pages/models.htm. Figure 4.4 shows a hypothetical partitioning of the three source types used for this study, terrestrial vegetation, algae, and salmon, with the resulting mixture falling within the triangle formed from the 3 points. This mixture represents the stable isotopes of the filtered sediment, and its position within the triangle would vary seasonally due to differences in proportional source contributions.

4.2.3.5 Bacterial Content

Smaller amber (60 mL capacity) bottles were used for unfiltered water samples designated for bacterial analysis. Because it was not possible to do the actual counts in the field due to availability and expense of required equipment, the samples were fixed using a solution of 10% (w/v) phosphate buffered glutaraldehyde to a ratio of 1:9 to give a final fixative volume of 1%. All bottles were stored at 4 °C in the dark. The acridine orange direct count method was used to assess bacterial concentration in a similar manner as Droppo and Ongley (1994). In order to optimize visibility of bacterial cells, a very small amount of water (1.26 mL) was filtered onto 25 mm diameter polycarbonate filters (Millipore). The volume was determined by trial and error in order to obtain an optimal 10 to 30 bacterial cells per field of view as suggested by Kirchman et al. (1982). The filters were pre-stained with Sudan black B dissolved in 100% ethanol to a final ratio, after dilution to 50%, of 1:15,000 as per Zimmermann et al. (1978). The sample volume filtered was diluted with filter sterilized distilled water (0.2 μm pore size) to a total filtered volume of 4 mL, including acridine orange stain, and allowed to stain for 3 to 4 minutes. After staining, low pressure was applied to gently pull the stained volume through the filter without causing cell damage. The prepared filters were counted under a BX-50 (Olympus) fluorescing microscope at 1000x magnification. In order to control for contamination, the reagents were filtered through 0.2 μm filters, stained, and analyzed in the same manner as the samples. Sample concentrations were standardized by these blanks. Concentration of cells per volume was calculated as per (Kepner and Pratt, 1994):

$$\text{Bacteria (cells/mL)} = (N \times A_t) / (d \times V_f \times G \times A_g) \qquad 4.8$$

where N is the number of cells counted, A_t is the effective area of the filter (mm^2), A_g is the area of the counting field of view (mm^2), V_f is the volume of the diluted sample filtered (mL), d is the dilution factor, and G is the number of fields of view examined.

Discrimination between sediment-attached and free-floating populations followed the methods prescribed by Droppo and Ongley (1994). First, 1.0 μm pore size filters were used to capture the sediment-bound bacterial cells. The staining procedure described above was then used. Next, a second homogenous subsample was filtered without dilution and stain. The filtrate was retained, stained, and filtered through a 0.1 μm black filter. Researchers (e.g., Kirchman and Mitchell, 1982) have noted that the ratio may be erroneous as free floating bacteria may settle on the sediment during the first filtration, which will prevent these cells from passing through the filter, and bacteria may be attached to the underside of sediment, no longer visible to be counted. Filters were flushed twice with 1 mL of filter sterilized distilled water after filtration (Kirchman and Mitchell, 1982) to reduce the former error. The latter effect was minimized by doubling the counted number of bacterial cells to account for the probability of attachment to the underside of particles (Droppo and Ongley, 1994). Differentiating between the two populations should provide a measurement of the potential versus the actual bacterial influence on flocculation, where the attached portion will be evaluated with respect to floc size.

4.2 Results

4.2.1 Shear Velocity and Stress

The sample site was exposed to dramatic changes in the discharge as shown in Chapter 3. This is further expressed as considerable variation in shear velocity over the season. The highest shear velocity (0.24 m s^{-1}) occurred on May 29th during the largest flow period that was measured (~ 10.4 m^3 s^{-1}), while August 19th was characterized by the lowest shear velocity of about 0.14 m s^{-1}. Figure 4.5 shows the shear velocities for the season.

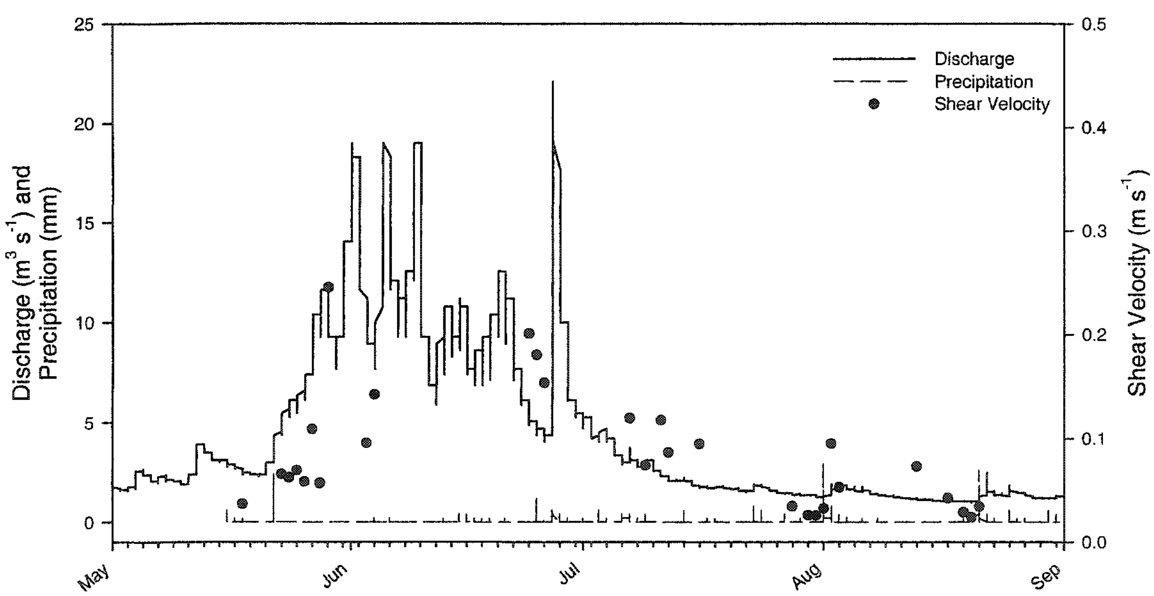

Figure 4.5 Shear velocity values derived from vertical velocity profiles. Data are shown in conjunction with discharge and precipitation curves to facilitate interpretation.

The corresponding range of shear stress was from 0.6 to 60.2 N m^{-2} with a mean of about 10.2 ± 3.0 N m^{-2}. Shear stress follows the pattern of discharge, where higher values exist during hydrograph peaks. Increases in shear stress are also apparent after rain events particularly on the August 2nd and 3rd events, which is consistent with increased discharge values. In fact, the data grouped by event type and logged for normality are significantly different in terms of means. An ANOVA indicates that the spawn and post-spawn periods, with the lowest discharge of all event types, are different than the periods with faster flows. A correlation between shear stress and discharge is appropriate due to the mutual reliance on velocity in their derivation.

4.2.2 Temperature, Conductivity, and pH

Seasonal patterns for air and water temperature are seen (Figure 4.6). Both temperature curves are presented as daily averages. Diurnal variation also exists but is not presented here because sampling occurred at similar times of day over the entire season. Spring air temperature hovered at or below 10 °C, while maximum summer temperatures (high 20s) occurred in early August. Spring water temperature was approximately 3 °C, while peak summer temperatures of about 14 °C were measured in mid-August. Patterns in water temperature reflect air temperature fluctuations as well as water sources. For example, the spring period exhibits a larger difference between air and water temperatures because of a greater supply of water derived from snow and ice combined with a lower influx of solar radiation. However, the general patterns are comparable in terms of large peaks and dips, which negates groundwater influence on water temperature.

Conductivity and pH of water followed no obvious pattern of seasonality, but they were nonetheless included in correlational analysis (Section 4.3.6). Conductivity ranged from 41 to 154 with a mean of 69.9 ± 5.2 μS. pH values varied from 7.05 to 7.58 and averaged 7.25 ± 0.04.

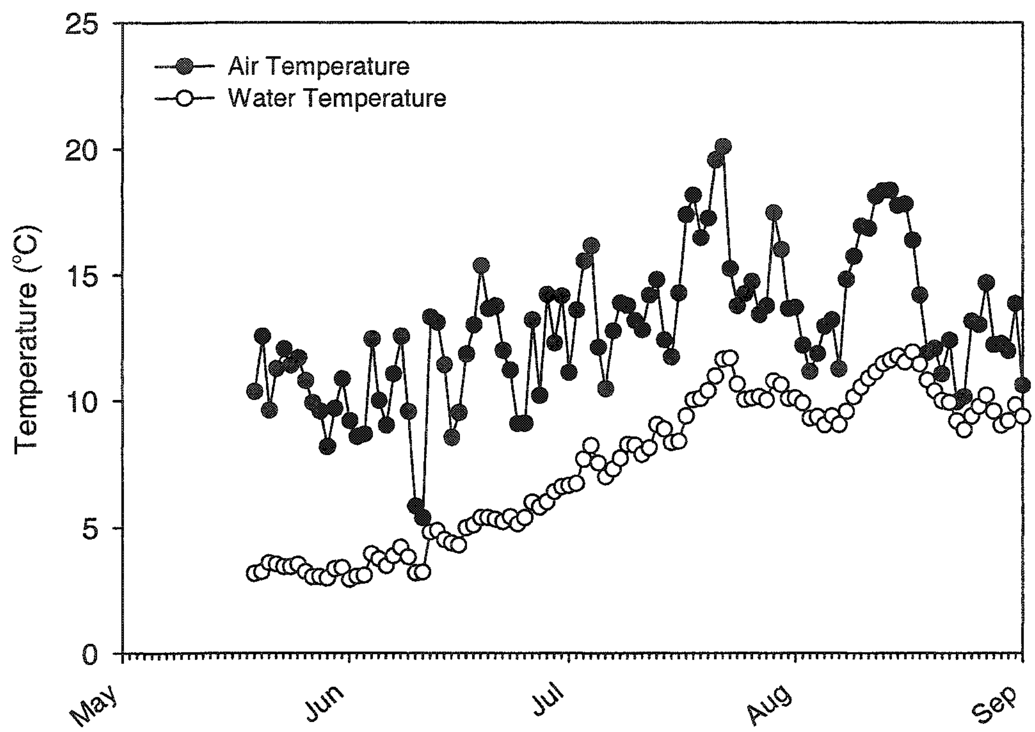

Figure 4.6 Air and water temperature displayed as daily averages.

4.2.3 Chlorophyll *a*, Colour, and Dissolved Organic Carbon

Chlorophyll *a* data show little variation between sample dates over the season; however, some trends and differences were found upon statistical analysis. A pattern is seen where slightly higher values were measured for the springmelt period as compared to all other times of the year. Table 4.1 lists chlorophyll *a* values as grouped by event type. Analysis of variance for the log-normalized transformation resulted in a positive main effects outcome with $F_{0.05,4,56} = 6.4$, $p < 0.001$. Pair-wise comparison of specific events (Tukey

Honest Significant Difference for unequal N (Spjotvoll/Stoline test)) indicated that the variation was due to the higher chlorophyll *a* values found during springmelt, as this event type differed from all others except the post-spawn at $\alpha = 0.05$. Variation between the remaining four event types was not significant aside from the low flow period being lower than the post-spawn. In general, chlorophyll *a* fluctuated with discharge aside from the apparent increase after salmon die-off. Phaeophytin *a* is not reported, but were found to be approximately zero for averages of data grouped by event type.

Table 4.1. Chlorophyll *a* and colour indices as averaged over watershed event type. Numbers in parentheses are standard errors (< 0.01 were not reported).

Event Type	Chl *a* (mg m^{-3})	a_{320} (m^{-1})	DOC (mg C L^{-1})	a_{320} : DOC	S (nm^{-1})	E_4/E_6
Springmelt	0.76 (0.10)	0.127	9.29 (0.39)	0.014	-0.014	29.7 (5.7)
Low Flow	0.33 (0.07)	0.070	4.77 (0.25)	0.015	-0.016	24.2 (2.5)
Rain	0.46 (0.09)	0.052	3.55 (0.14)	0.014	-0.017	14.7 (3.6)
Spawn	0.37 (0.09)	0.037	2.85 (0.07)	0.013	-0.016	18.0 (3.8)
Post-spawn	0.47 (0.04)	0.034	3.80 (0.72)	0.010	-0.018	12.2 (1.0)

Colour was examined using three different methods. First, the spectra were graphed as the natural log of absorbance versus wavelength and the slopes of the regression curves were recorded for comparison between spectra. The slope parameter (S, nm^{-1}) provides a measure of how rapidly the absorption decreases with increasing wavelength (Green and Blough, 1994). Figure 4.7 shows examples of spectra taken from each event type, where the slopes of the spectra are similar, while the intercepts vary considerably. Table 4.1 lists S values averaged for each event type. A trend is seen of decreasing slope over the season (-0.014 to –0.018), and a Kruskal-Wallis non-parametric ANOVA test indicates that significant differences between event types are present

($H_{0.05,4,24} = 13.4$, $p < 0.01$) and probably attributed mainly to variation between springmelt and post-spawn periods.

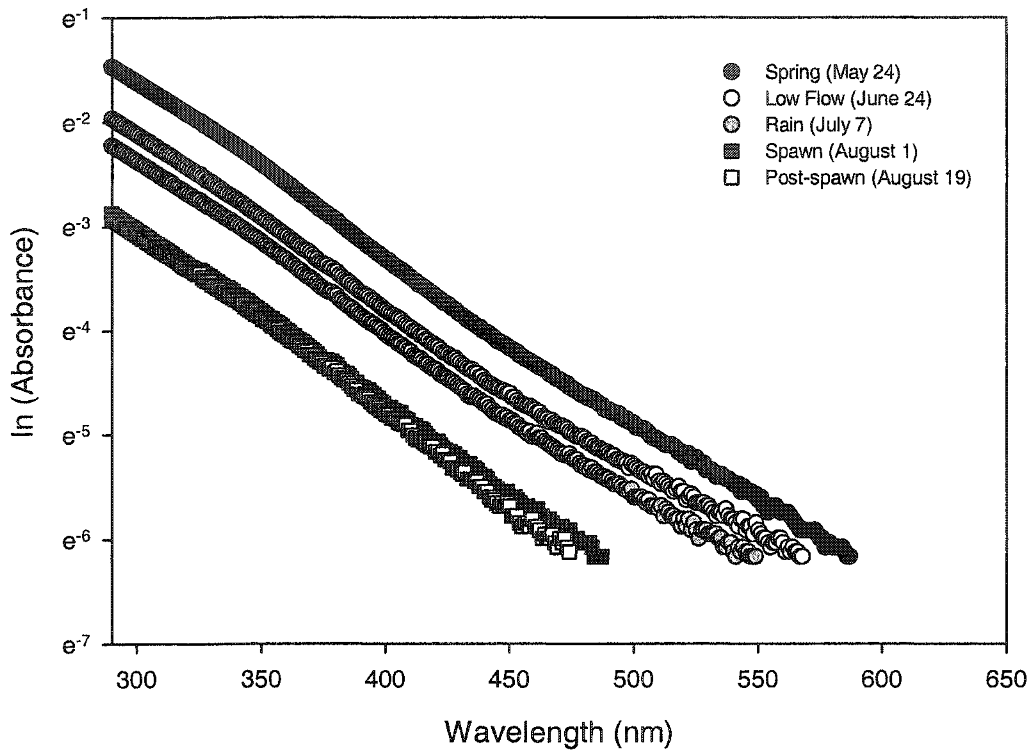

Figure 4.7 Example colour spectra for each event type in the form of ln(absorbance) for wavelengths from 290 nm to the wavelength where absorbance was measured as zero. The slopes are the same, but the intercepts vary. Specific sample dates are provided in parentheses.

Second, absorbance coefficients for the 320 wavelength (a_{320}) were measured. This index is the established boundary between UV-B and UV-A radiation, and, for that purpose, Williamson et al. (1999) use a_{320} as a metric of coloured dissolved organic carbon (CDOC) in natural waters. Table 4.1 lists the averaged a_{320} values for each event type. An apparent pattern of decreasing absorbance with discharge exists. A Kruskal-Wallis test found this trend to be significant ($H_{0.05,4,24} = 19.4$, $p < 0.001$). Williamson et al. (1999) also examined the relationship between a_{320} and DOC. While a_{320} and DOC characterize the quality and quantity, respectively, of organic carbon sources, DOC-specific absorbance (a_{320}:DOC), listed in Table 4.1, enables comparison of the two between water samples. Examination of the total effects of an ANOVA yields no significant differences.

Third, the E_4/E_6 ratio was calculated for all measured absorbance spectra. Variation between replicates was so large that seasonal patterns could not be visually determined. Grouping the data by event type revealed a general decrease over the season, where springmelt exhibited the highest averaged values (29.7 ± 5.4), the lowest were found during post-spawn (12.2 ± 1.0). This trend was not significantly distinguishable using a Kruskal-Wallis test ($p > 0.1$).

Gravimetric determination of organic matter content (i.e., SOM) is often insensitive to characterize organic content in small quantities of sediment. Nelson and Sommers (1996) suggest determination of organic carbon as a more accurate method of quantifying organic matter in soils. Thus, the combination of particulate organic carbon (POC) and DOC values should provide a good index of the quantity of organic matter in the water column. Figure 4.8 displays the average POC and DOC values of triplicate samples for each sampling day including standard error of the mean. POC concentrations were obtained from filters prior to mass spectrometry for stable isotope analysis. The seasonal POC pattern is very similar to the one between discharge and SPM, with deviation from the discharge curve during salmon spawn. DOC follows the discharge pattern more closely than POC. The seasonal DOC pattern is emphasized as averaged by event type (Table 4.1). Kruskal-Wallis ($\alpha = 0.05$) non-parametric tests indicate that seasonal patterns for POC and DOC are significant.

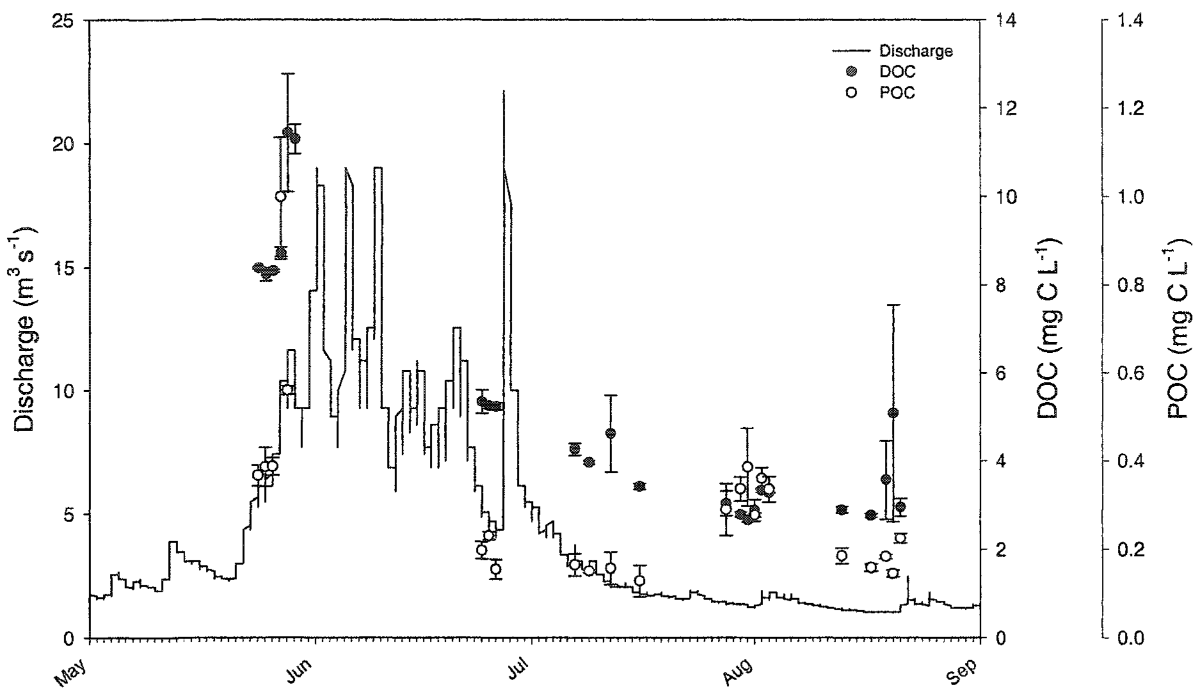

Figure 4.8 Seasonal patterns of particulate and dissolved organic carbon (POC and DOC) concentrations of the water column in relation to discharge. Error bars are ± 1 SE.

4.3.4 Stable Isotopes of Carbon and Nitrogen

While examining chlorophyll *a*, colour, and dissolved organic carbon quantitatively characterizes the organic matter, stable isotope analysis allows the identification of the specific source material. Initially, the proportion of carbon and nitrogen comprising the suspended sediment fraction was determined. Figure 4.9 shows the seasonal pattern of the ratio of carbon to nitrogen. The pattern in the C:N ratio shows high values occurring during the spring period and remaining fairly constant until the salmon are introduced to the reach. The C:N ratio decreases while the salmon spawn and carcasses are present in-stream. Figure 4.10 provides a breakdown of the C:N ratios for tissue types sampled within and adjacent to O'Ne-eil Creek over the season. Values for tissue samples taken several times over the season of allochthonous, or terrestrially-derived, vegetation

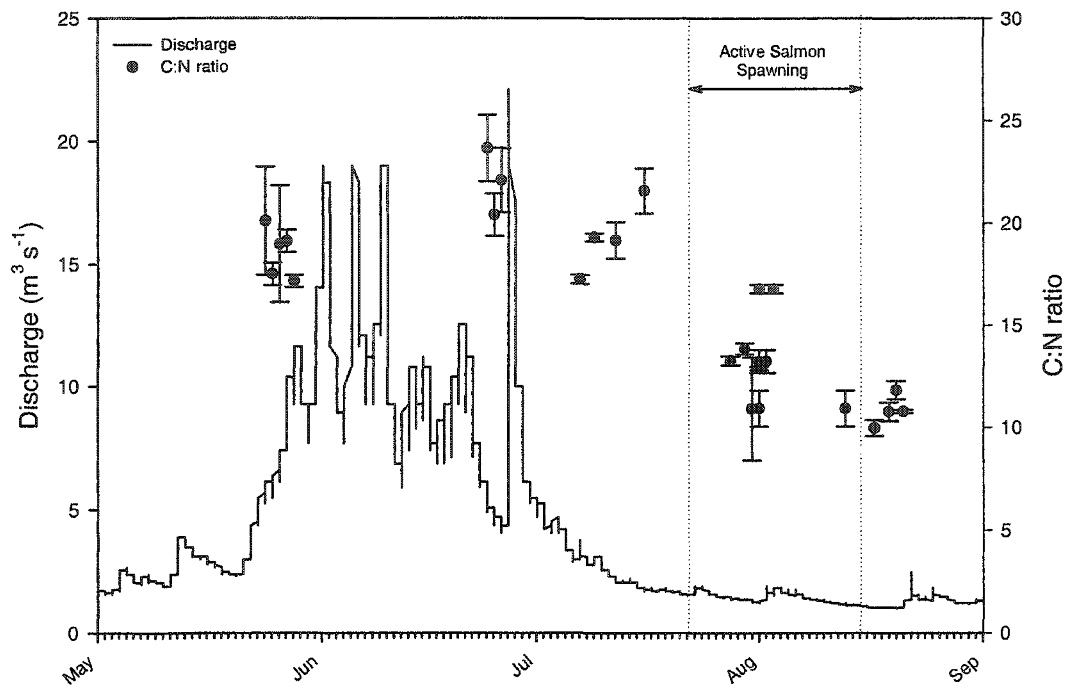

Figure 4.9 Seasonal trend in C:N ratio of suspended sediment. Dotted lines indicate active spawning start (July 18th) and end (August 15th) dates. Error bars are ± 1 SE.

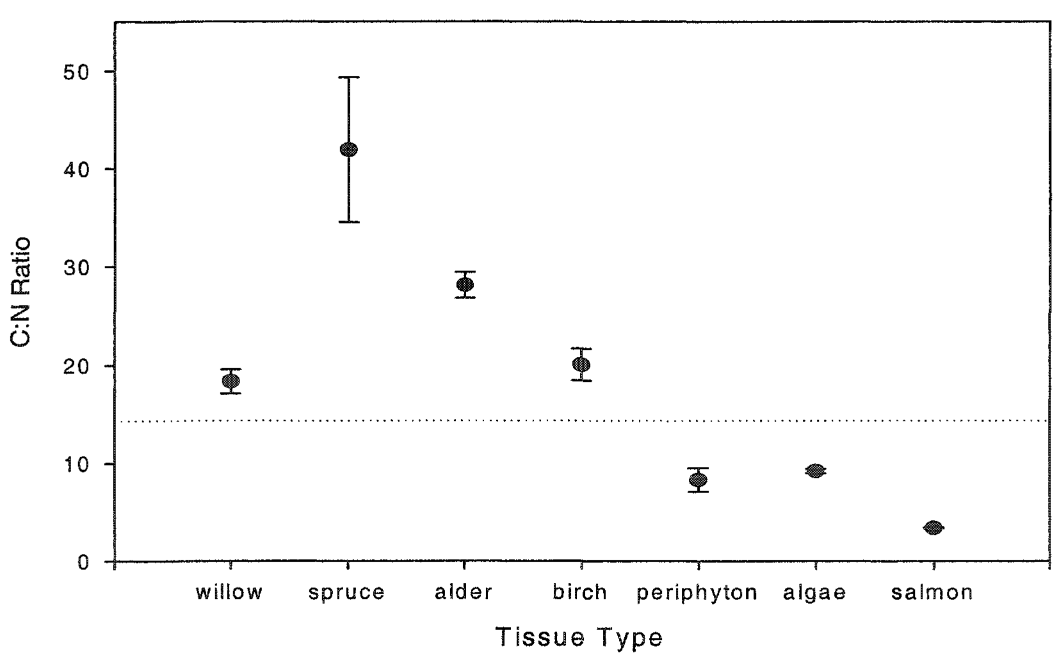

Figure 4.10 Averaged C:N ratios for different types of organic material sampled in or adjacent to O'Ne-eil Creek. Dotted line separates allochthonous (terrestrially-derived) from autochthonous (produced in stream) organic material.

exhibits C:N ratios greater than 15, ranging from 18.4 ± 1.23 ‰ for willow leaves and 41.9 ± 7.42 ‰ for spruce needles. Autochthonous organic matter is characterized here by ratios < 15; the lowest values being for salmon flesh with 3.4 ± 0.07 ‰, while periphyton and algae ratios are 8.3 ± 1.22 and 9.2 ± 0.21 ‰, respectively.

Stable isotope analysis of O'Ne-eil Creek suspended sediment reveals a trend of enrichment of the heavier isotope, as shown in Figure 4.11 over the season for both carbon and nitrogen, although the latter is much more pronounced. A slight increase in

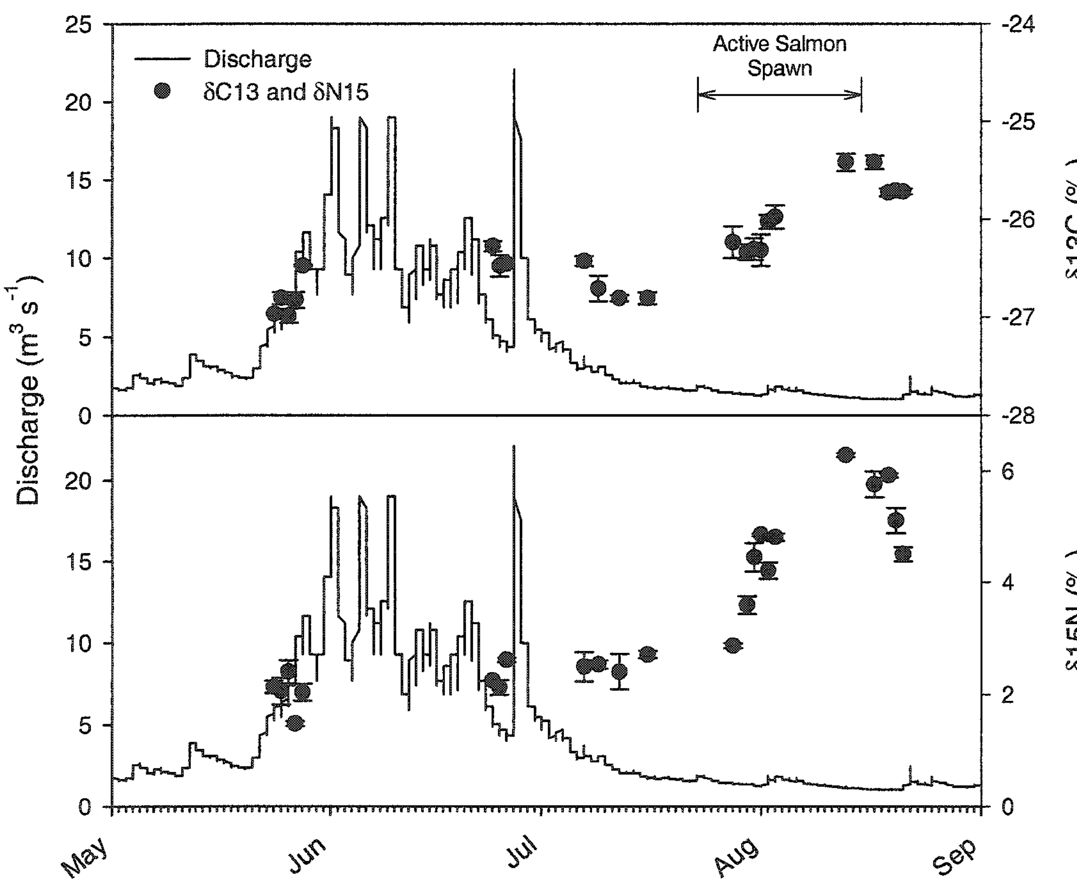

Figure 4.11 Seasonal trends for stable isotopes of carbon and nitrogen from suspended sediment. The dotted lines designate the salmon spawning period. Error bars are ± 1 SE.

carbon isotope ratio is seen from springmelt to low flow with $\delta^{13}C$ values of –26.8 ± 0.09 and –26.6 ± 0.10 ‰, respectively. Once salmon enter the reach, the isotopic signal increases to –26.1 ± 0.18 ‰. The peak of enrichment occurs just prior to the post-spawn period, where some salmon are still alive, but earlier returns have already begun to rot *in situ*. After this point, the isotopic ratio decreases towards a signal more similar to the period prior to salmon presence; however, the measured trend ends before the decline is complete, so the grouped average for the post-spawn event shows the highest enrichment as compared to all other event types (-25.6 ± 0.07 ‰). The nitrogen isotope exhibits a similar pattern with enrichment of $\delta^{15}N$ from springmelt to low flow of 2.02 ± 0.11 to 2.42 ± 0.09 ‰, a steep increase over the active salmon spawning period with a average of 4.27 ± 0.38 ‰, and further enrichment after salmon die-off is complete (5.60 ± 0.18 ‰).

The combined effect of the two elements is typically shown as in Figure 4.12, and

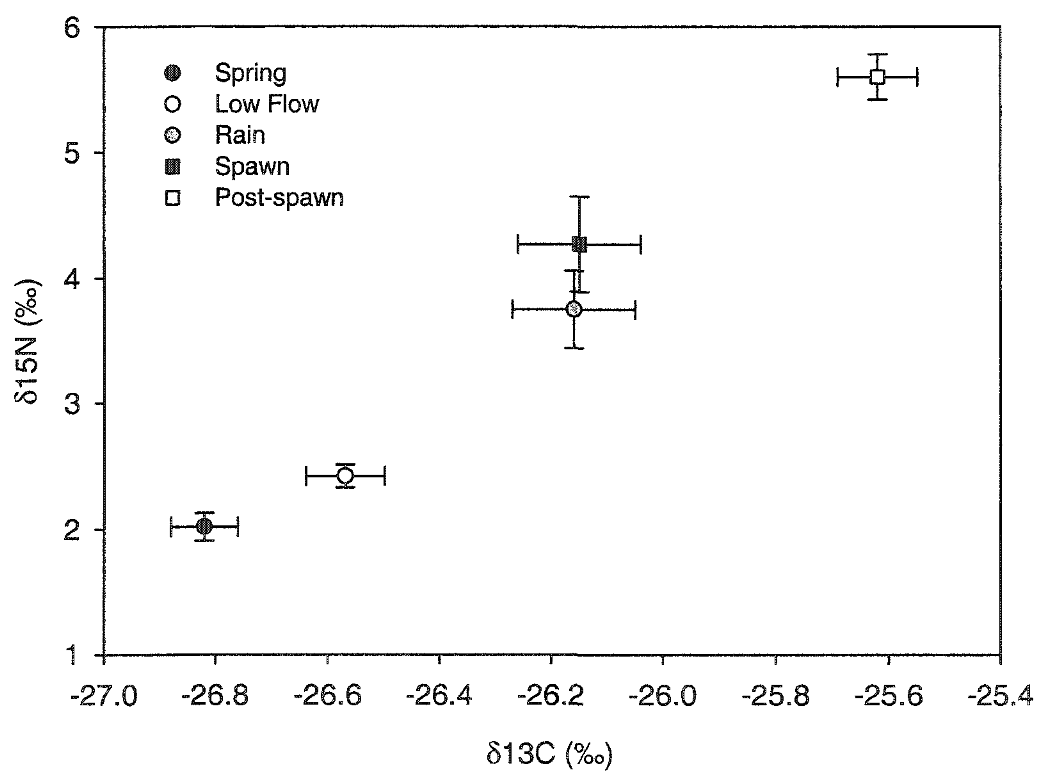

Figure 4.12 Stable isotopes for suspended sediment filters as grouped by event type. Bi-directional error bars are ± 1 SE for both variables.

there is clearly an increasing trend, where springmelt < low flow < rain ≈ spawn < post-spawn. Discharge associated with rain events was sampled over three different event types (low flow, spawn, and post-spawn), and the average is approximately equal to that of the salmon period due to the linearity of the relationship (Figure 4.12). In fact, linear regression was applied to the semi-logged ungrouped data, and the linear relationship is significant with $r^2 = 0.663$ for $N = 46$ and $\alpha = 0.05$.

For modeling purposes, the data derived from the suspended sediment filters were compared to the tissue samples, using the dual isotope, three endmember format developed by Phillips and Gregg (2001). The results are presented in Table 4.2. The results indicate that the predominant source of organic matter to the suspended sediment load changed over the season, although the 95% error bars are very large. For the springmelt period, the model suggests that all organic material is derived from terrestrial vegetation, while the salmon and algal sources are contributing minimal amounts to the suspended sediment supply. Similarly, terrestrial vegetation dominates the low flow source organics. A shift begins toward a positive salmon contribution for the rain events category, with between 66 and 95% of the proportion remaining terrestrially-derived and 21 to 34% being of salmon origin. The divergence continues for the active salmon spawn, where the suspended sediment samples were composed of anywhere from 56 to 81% of vegetative tissue, 27 to 38% of salmon flesh, and 0 to 6.1% of algae. The post-spawn period was characterized by an overlap of terrestrial and salmon inputs, 46.0 ± 8.6 and 46.8 ± 3.7%, respectively, and minimal algal inputs (7.2 ± 5.2%). Periphyton was excluded from the model because it utilizes nutrients from the water column (Johnston et al., 1998), which complicates modelling because the periphyton isotopic

Table 4.2 Partitioning of organic matter source contributions to suspended sediment load in O'Ne-eil Creek as modeled for the five event types of springmelt, low flow, rain events, spawn, and post-spawn using dual isotopic signatures ($\delta^{13}C$ and $\delta^{15}N$).[1]

	Mixture (Sediment)	Terrestrial Vegetation	Salmon Flesh	Algae
Springmelt				
$\delta^{13}C$ [‰] (se)	-26.8 (0.06)	-28.8 (0.94)	-21.0 (0.50)	-35.3 (0.76)
$\delta^{15}N$ [‰] (se)	2.0 (0.11)	1.1 (2.68)	10.8 (0.09)	0.5 (0.25)
Sample Size	10	14	4	3
Source proportions [%] (se) – calculated		110.9 (20.0)	8.7 (8.8)	-19.7 (11.6)
95% Confidence limits (%)		68.4-100	0-27.8	0-4.5
Low flow				
$\delta^{13}C$ [‰] (se)	-26.6 (0.07)	-28.8 (0.94)	-21.0 (0.50)	-35.3 (0.76)
$\delta^{15}N$ [‰] (se)	2.4 (0.09)	1.1 (2.68)	10.8 (0.09)	0.5 (0.25)
Sample Size	10	14	4	3
Source proportions [%] (se) – calculated		105.8 (19.0)	12.9 (8.4)	-18.6 (11.0)
95% Confidence limits (%)		65.3-100	0-31.0	0-4.4
Rain events				
$\delta^{13}C$ [‰] (se)	-26.2 (0.11)	-28.8 (0.94)	-21.0 (0.50)	-35.3 (0.76)
$\delta^{15}N$ [‰] (se)	3.8 (0.31)	1.1 (2.68)	10.8 (0.09)	0.5 (0.25)
Sample Size	10	14	4	3
Source proportions [%] (se) – calculated		80.8 (16.5)	27.1 (7.3)	-7.9 (9.5)
95% Confidence limits (%)		46.6-100	11.8-42.4	0-11.6
Spawn				
$\delta^{13}C$ [‰] (se)	-26.2 (0.11)	-28.8 (0.94)	-21.0 (0.50)	-35.3 (0.76)
$\delta^{15}N$ [‰] (se)	4.3 (0.38)	1.1 (2.68)	10.8 (0.09)	0.5 (0.25)
Sample Size	10	14	4	3
Source proportions [%] (se) – calculated		68.6 (15.7)	32.8 (7.0)	-1.4 (9.0)
95% Confidence limits (%)		36.2-100	18.3-47.2	0-17.1
Post-spawn				
$\delta^{13}C$ [‰] (se)	-25.6 (0.07)	-28.8 (0.94)	-21.0 (0.50)	-35.3 (0.76)
$\delta^{15}N$ [‰] (se)	5.6 (0.18)	1.1 (2.68)	10.8 (0.09)	0.5 (0.25)
Sample Size	6	14	4	3
Source proportions [%] (se) – calculated		46.0 (9.5)	46.8 (4.1)	7.2 (5.7)
95% Confidence limits (%)		26.2-65.8	38.1-55.5	0-18.9

[1] Note that the model used here limits the total percentage of the three sources types to be 100. This explains the presence of negative values to balance those that are > 100%.

signature is then a mixture of the endmembers. Phillips and Gregg (2001) suggest that samples from the three source populations should be independent.

4.3.5 Bacterial Content

The sediment-attached bacteria content is high during springmelt, decreases for the lower flow period of June, July, and early-August, but then increases again in late August during the post-spawn session. Table 4.3 details the numbers averaged from triplicates with associated standard error for attached-bacteria. In terms of grouped data, springmelt

Table 4.3 Attached and free-floating bacteria numbers per volume for samples extracted from O'Ne-eil Creek over the 2001 field season. Attached numbers are averages of triplicates (SE) while free-floating values are reported from individual samples. Percentage attached cells are derived from addition of attached and free-floating cell counts.

Event Type	Date	Attached Bacteria (x 10^5 cells mL^{-1})	Free-floating Bacteria (x 10^5 cells mL^{-1})	% Attached
	May 24	6.39 (0.06)		
Spring	May 25	6.57 (0.59)	2.30	74.0
	May 26	5.58 (0.53)		
	June 24	3.49 (0.23)		
Low Flow	June 26	3.04 (0.13)	0.81	79.0
	July 12	3.24 (0.40)		
	July 7	3.42 (0.16)	1.23	73.5
Rain	August 2	5.57 (0.17)		
	August 3	3.98 (0.23)		
	July 28	3.60 (0.35)		
Spawn	July 31	2.86 (0.38)		
	August 1	3.51 (0.30)	1.70	67.4
	August 17	8.54 (0.45)	1.81	82.5
Post-spawn	August 20	5.05 (0.13)		
	August 21	5.48 (0.18)		

and post-spawn consist of similar concentrations of cells per volume ($6.18 \pm 0.30 \times 10^5$ and $6.36 \pm 0.11 \times 10^5$ cells mL^{-1}, respectively) with the latter having greater within group variation. Low flow ($3.26 \pm 0.13 \times 10^5$ cells mL^{-1}), rain ($4.32 \pm 0.23 \times 10^5$ cells mL^{-1}), and spawn ($3.32 \pm 0.23 \times 10^5$ cells mL^{-1}) periods exhibit similar values. Analysis of variance for log-normal data revealed significant differences attributed to this pattern (i.e., springmelt and post-spawn differ from all other events, but not each other, while low flow and rain differ from each other, but not spawn).

The same pattern is expressed in free-floating bacterial concentration (Table 4.3), although these numbers are always lower than their sediment-attached counterparts. The percentage sediment-attached values indicate the dominance of attached cells, as all values are much greater than 50%. The lowest percentage occurs on August 1st, during the active spawning period, while August 17th, when no live salmon are present in the stream, exhibits the highest percentage.

4.3.6 Correlational Analysis

Analysis was undertaken to assess association occurring between variables presented here, as well as those presented in the previous chapter, using Spearman Rank Correlation. In terms of effective particle size distributions (EPSD), the variables derived from the spectra (D_{99}, D_{84}, and D_{50}) were significantly correlated with each other, but not with any other environmental variables with the exception of D_{50} and SPM ($r_s = 0.527$, N = 15). Other significant outcomes were that discharge and shear stress were significantly associated ($r_s = 0.583$, N = 24), as were SPM and SOM with $r_s = 0.731$ for N = 70, and SOM with all of DOC, a_{320}, and a_{320}:DOC ($r_s > 0.9$). Conversely, Spearman rank correlation analysis was not able to detect association between air and water temperature. As listed in Table 4.4, SPM was also correlated positively with pH and DOC-specific absorbance (a^{320}:DOC) and negatively with the enrichment of the $\delta^{13}C$ isotope. SOM related positively to pH, DOC, a_{320}, a_{320}:DOC, and S, but negatively to $\delta^{13}C$ and $\delta^{15}N$. Discharge was positively correlated to SPM, SOM, pH, DOC, all colour variables, and C:N, but negatively associated with carbon and nitrogen isotopes. Air temperature

Table 4.4 Spearman rank correlation coefficients for all data collected over the season. Italicized values are significant to $\alpha = 0.05$, N = 24. Note that Q = discharge and D_{99}, D_{84}, and D_{50} values are from EPSD.

	SPM	**SOM**	**Q**	**Air T**	**Attached Bacteria**	**D_{99}**	**D_{84}**	**D_{50}**
SPM	-	*0.731*	*0.424*	-0.301	-0.044	0.297	0.357	*0.527*
SOM	*0.731*	-	*0.649*	*-0.600*	0.168	0.093	0.165	*0.451*
Water T	-0.151	-0.404	-0.198	0.338	*-0.562*	0.242	0.226	0.151
Conductivity	0.280	0.264	-0.050	-0.017	*0.795*	-0.220	-0.330	-0.104
pH	*0.634*	*0.479*	*0.559*	*-0.421*	0.226	-0.055	-0.022	0.201
DOC	0.258	*0.549*	*0.919*	*-0.879*	0.124	-0.236	-0.159	0.082
a_{320}	0.385	*0.610*	*0.955*	*-0.884*	0.069	-0.154	-0.049	0.187
a_{320}:DOC	*0.531*	*0.718*	*0.882*	*-0.785*	0.094	-0.025	0.085	0.182
S	0.315	*0.650*	*0.806*	*-0.737*	-0.231	-0.094	0.055	0.180
E_4/E_6	0.368	0.192	*0.655*	*-0.455*	0.110	0.170	0.214	0.286
C:N	0.049	0.214	*0.792*	*-0.784*	-0.289	-0.121	-0.005	0.137
$\delta^{13}C$	*-0.505*	*-0.516*	*-0.834*	*0.736*	0.165	0.187	0.093	-0.313

exhibited the reverse relationship with the same variables, but was not significantly related to SPM. And, attached-bacteria was negatively associated with water temperature and positively correlated to conductivity.

4.4 Discussion

4.4.1 *In situ* Variables and Particle Structure

The patterns of shear stress and temperature fit with the accepted paradigm of seasonal variation. Shear stress correlated well with discharge, which is appropriate considering their mutual reliance on velocity in their derivation. Both shear stress and discharge are directly proportional to velocity as it is inherent in their calculation (Gordon et al., 1992), although shear stress increases with the square of velocity so the rate of increase is much less than discharge. The range in shear stress values displayed in Figure 4.5 are large, but the majority fall in the range of typical values for natural systems stated by Milligan and Hill (1998). In terms of the relationship with the effective particle size diameters found in chapter 3 (summarized in Table 4.5), shear stresses are higher when floc sizes are smaller and vice versa. This pattern corroborates the laboratory findings of Spicer and Pratsinis (1996) and Milligan and Hill (1998), who observed an inverse relationship between turbulence and maximal floc size, although the range of shear stress was much larger for the former study. Other researchers (e.g., Tsai et al., 1987 and Burban et al., 1989) have reported a similar relationship in natural systems. It appears that increasing shear stress in natural systems, where O'Ne-eil Creek is no exception, induces floc breakage, which results in more compact aggregates, and continued breakup and reformation eventually results in much more stable particle structures (Milligan and Hill, 1995; Petticrew and Droppo, 2000).

The increasing trend of air and water temperature shown in Figure 4.6 is important in that the highest values correspond to the largest diameter flocs. Lau (1990) and Phillips and Walling (1995) suggest that a positive relationship between temperature and floc size occurs due to increased biological activity. In other words, bacterial cells could become more active at higher temperatures, producing more floc-binding agents to bridge particles together. Conversely, the lowest temperatures in this data set occur in the spring, when much smaller particles exist. However, a statistical association was not apparent between floc size and temperature. This could simply mean that the resolution of particle size was insufficient to detect the relationship and that a more sensitive analysis is required. Alternatively, the temperature connection may be secondary to other factors, such as the biochemical or electrochemical components.

Conductivity and pH did not follow a detectable seasonal pattern. Traditional theory suggests that flocculation in marine systems is predominantly caused by electrochemical processes (van Leussen, 1999). However, this factor does not appear to hold true for freshwater systems (Droppo and Ongley, 1994) due to the low salt content. In fact, contemporary research has identified the importance of sediment-adsorbed organic coatings (see van Leussen, 1999) and biological derivatives from microorganisms and organic decay (Droppo, 2001) in floc-building processes. The data here appear to conform to the idea that a factor or a suite of factors other than conductivity are more important for regulating suspended sediment structure in O'Ne-eil Creek. The minimal range in conductivity over the season, and the lack of observable and statistical association between conductivity and floc size, emphasizes this point.

Similarly, pH is probably not an important factor for flocculation in the study stream. The main role of pH in flocculation is to alter the charge associated with clay and organic particles. Particles will exhibit a net negative charge in neutral pH conditions. The negative charge causes repulsion between particles and thus inhibition of flocculation (Evangelou, 1998). The range of pH measured in O'Ne-eil Creek was approximately half a pH unit, and the seasonal overview lacked any identifiable pattern. This range and pattern suggest that pH does not change electrostatic conditions experienced by suspended sediment particles sufficiently to cause the pattern of floc sizes seen in Figure 3.12. This relationship is further complicated by sediment mineralogy because the magnitude of charge depends on the type and size of minerals present. Mineralogy was not assessed directly in this study, however, based on the size of the particles, the observed texture, and the glaciolacustrine origination, it is speculated that the inorganic particles measured were comprised mainly of clay. Further, Kranck and Milligan (1983) and Kranck et al. (1996) recognize that the 1 to 10 μm slopes extracted from absolute particle size distributions (APSD) reveal differences in source material. The spectral analysis of APSD presented in Figure 3.9A show little variation in source slope, which implies that no significant change in source material occurred over the season. As well, the spectra are similar in terms of slope and mode to those found by Petticrew (1996) for the surficial glaciolacustrine sediment presumed to represent the source inorganic material for this system. Thus, the mineralogy of the suspended sediment load does not appear to have changed over the season.

4.4.2 Organic Matter and Particle Structure

Flocculation in freshwater systems is unique compared to marine environments mainly due to lower salt concentrations and the difference in organic matter inputs. The current belief is that organic matter is an important control on composite particle structure (Woodward et al., 2002). The previous chapter revealed the probable importance of salmon presence for increasing particle size by influencing SPM and organic matter source and supply. Petticrew and Droppo (2000) and Soulsby et al. (2001) recognize the role of salmon in resuspending settled particles from the gravels during spawning, which should mean that larger particles will be observed in the water column compared to low flow periods devoid of salmon activity. However, little attention has been paid to the relationship between salmon-derived organics and flocculation. Here, several indices of organic matter supply and source were measured in order to assess seasonal changes in the magnitude and type of organic material existing within O'Ne-eil Creek, and determine if such patterns could be related to particle structure. Vannote et al. (1980) discusses the concept of temporal adjustments to energy flow in streams due to species replacement. They identify the importance of energetic equilibrium in stream systems to the overall functioning of the local ecosystem, and suggest that this balance requires a seasonal shift in the contributions from different organic sources, namely autochthonous versus allochthonous, especially in temperate areas. Evaluating the two general types of source material necessitates the use of distinctive techniques.

4.4.2.1 Chlorophyll *a*

Chlorophyll *a* is measured typically as a surrogate for in-stream or autochthonous productivity because it is the most abundant pigment in plants (Steinman and Lamberti, 1996). Here chlorophyll *a* was measured in an effort determine the relative contribution of in-stream sources to aggregate development compared to terrestrial sources (see next section). Essentially, a correlation between the primary productivity pattern and floc size may indicate an interaction between in-stream organics and flocculation.

In a general overview of lake productivity, Kalff (2002) recognizes the importance of a spring bloom to lake ecosystems due to rising levels of solar radiation and water temperature. This period is typically followed by a clear water phase caused by algal grazing, although this may not be detectable in oligotrophic or highly eutrophic lakes. Then, an increase in aquatic productivity in lakes, and thus chlorophyll *a*, is expected in response to the higher temperatures and longer periods of light exposure occurring during the summer months. The seasonal pattern of chlorophyll *a* measured in O'Ne-eil Creek appears to follow a similar trend. Table 4.1 indicates that the highest pigment values were measured during springmelt, with a decrease thereafter, and little fluctuation through the summer. Post-spawn chlorophyll *a* was not significantly different than springmelt. The chlorophyll *a* concentration is also much lower than lakes. This is probably because chlorophyll *a* is regulated by discharge in lotic (flowing water) systems much more than in lakes.

Although no statistical correlation between discharge and chlorophyll *a* was found, the availability of aquatic biomass to the water column where samples were extracted is likely controlled by water level and flow rate. Two possible mechanisms are (1) longitudinal patterns of aquatic productivity and (2) the inverse relationship between discharge and residence time (Reynolds, 1988; Basu and Pick, 1995). The first possibility relates to the high chlorophyll *a* values found during the springmelt period. Downstream changes in algal biomass occur in a step-wise pattern, where reaches exhibiting net growth, net loss, or no change in growth exist throughout the longitudinal profile (Reynolds, 1988). In the spring, algal productivity increases, but so does discharge. In O'Ne-eil Creek, organisms that are either rooted to the streambed or stationary due to some blockage or still water are probably forcibly entrained in periods of high discharge, and/or organisms such as periphyton that are attached to large substrates are scoured off of surfaces by the rolling and colliding actions of these substrates during mobilization due to high discharge. Both actions will facilitate suspension of chlorophyll *a*-containing tissues, and downstream progression of large quantities of biomass should inevitably move through the study reach to be sampled.

Conversely, after this initial flush of spring bloom biomass, the continued flow of water in O'Ne-eil Creek likely translates to a short retention period. Basu and Pick (1995) acknowledge that the flowing action of rivers probably limits colony growth by preventing establishment. Observations made in the study reach support this idea in that little periphyton growth could be seen on bed substrates. As well, the relatively higher chlorophyll *a* values found after salmon die-off are likely due to unattached algae colonies, such as the ones collected during this time for stable isotope purposes, inhabiting slower moving areas (i.e., small pools sheltered by rocks, large woody debris, or immersed riparian vegetation) within the study reach. The growth rate of these organisms would be enhanced due to the large influx of marine-derived nutrients from decomposition of post-reproductive salmon carcasses (Johnston et al., 1998; Wold and Hershey, 1999).

Chlorophyll *a* does not appear to be associated directly with particle size, as the seasonal pattern does not match that of the dimensional characteristics of the EPSD shown in Figure 3.12. This implies that the important particle-binding mechanism present in O'Ne-eil Creek is independent of pigment-containing organisms (i.e., primary aquatic productivity). Colour and stable isotope analysis should corroborate this finding, and provide greater insight into the problem.

4.4.2.2 Colour

Water colour is widely used to assess the concentration of humic substances in aquatic systems. Colour enables characterization of allochthonous organic sources because humic substances are of terrestrial origin and autochthonous production contributes little to water colour (Meili, 1992). Many different techniques are available to quantify water colour, some of which were used in this study. The combination of these variables enables reconstruction of the pattern of terrestrial organic matter introduction to O'Ne-eil Creek. This parameter was used to establish the seasonal pattern of terrestrially-introduced organic matter, and to determine any relationship that may exist between this source type and aggregate development.

Green and Blough (1994) sampled and compared inland, coastal, and offshore waters. They found a range in S of -0.014 to about -0.030 nm^{-1}, where the lowest values were obtained from inland waters, which are much more susceptible to coloured, humic substances. As well, the lowest S values were associated with the highest a_{300} values. On a different scale, the same pattern is expressed within this data set (Table 4.1). Green and Blough (1994) studied spatial variability, while data presented here are an assessment of temporal changes. Low S and high a_{320} values for the spring, as compared to the reverse relationship for post-spawn, indicates a decrease in colour, and thus humic substances, over time. Both of these indices correlate well with discharge (Table 4.4), which implies that the quantity of terrestrial material introduced to the stream decreases due to either (1) decreased area from which source material is drawn (i.e., higher floodplain delivery of material and flushing of watershed soils in spring), (2) settling of terrestrial substances to the streambed and floodplain, or (3) flushing of material out of the system. This trend is exasperated by the seasonality of riparian vegetation, specifically the autumnal shedding of leaves (Koetsier et al. 1997). Once shed, the leaf litter is typically stored in the watershed until spring, when it is then introduced to the stream in one large pulse. Examination of the E_4/E_6 ratio may clarify this point.

According to Stevenson (1994), E_4/E_6 ratios for humic acids are typically less than 5.0, while the range for fulvic acids is 6.0 to 8.5. The data listed in Table 4.1 for this study exceed both these ranges considerably. The reason for this may be discrepancies in techniques, where the standard method involves extraction in $NaHCO_3$ (Chen et al. 1977) and this study measured the values directly from filtered water samples. However, the pattern may still be meaningful. The E_4/E_6 comparison has been used to indicate mean residence times (e.g., Baes and Bloom, 1990), where the ratio is inversely proportional to mean residence time. The trend seen in Table 4.1 is a general decrease from spring to late summer. Two possible interpretations are that (1) high discharge flushes the humic material out of the system quickly and organic matter in the stream during low discharge remains there longer, and/or (2) the sources of organic matter changes over the season. Stevenson (1994) states that low ratios denote aromatic constituents, while high values indicate more aliphatic structures. Thus, aliphatic-rich compounds probably dominate the spring period and a transition toward aromatics occurs over the season.

The indices of a_{320}, DOC, and their ratio (a_{320}:DOC) denotes optical quality and quantity of organic matter, respectively, and, because of this, probably provides an estimate of changing source type. The quantity of organic carbon appears to be regulated by discharge in that the source area of organic material is much higher during springmelt and so is the DOC concentration (Table 4.1). However, calculating the ratio of a_{320} to DOC appears to decrease the difference between event types. This could indicate that, although there is more organic material introduced to the stream in the spring, a greater contribution of higher optical quality material occurs during the salmon spawn and post-spawn periods, as shown by lower ratios (Table 4.1). A plausible explanation for this is that these periods are dominated by different sources of organic matter; terrestrially-versus salmon-derived. The implications of this are that the nutritional quality of sources differs between sampling events. Material that is readily degraded releases nutrients more efficiently (Webster et al., 1999), and is said to be of higher quality (not to be confused with optical quality). Decomposition of terrestrial vegetation takes considerable time, unless facilitated by microorganisms (Webster et al., 1999). Salmon decompose relatively quickly, especially in the presence of insect larvae (personal observation). Thus, salmon are of higher nutritional quality than terrestrial material, which implies that they are able to quickly provide microbial enhancing nutrients (Wold and Hershey, 1999) and floc-binding macromolecules.

4.4.2.3 Stable Isotopes of Carbon and Nitrogen

A potential reason for significantly lower DOC concentrations during the spawn period compared to springmelt could be that salmon exhibit a much lower C:N ratio than do plants. In other words, although there is a considerable amount of organic material available in the stream during the spawning process, the carbon content is much less than spring terrestrial inputs. The seasonal signal of C:N from suspended sediment filters shows that the water column reflects the seasonal change in organic matter type. Figure 4.9 displays the transitional decrease in C:N ratio caused by salmon presence within the study reach from a ratio greater than 15 to one less than 15. Figure 4.10 emphasizes the different C:N ratios for terrestrial- versus aquatic-derived organic matter. C:N ratios of autochthonous (i.e., in-stream productivity) are generally much lower than those of allochthonous (i.e., terrestrially-derived) materials (Owen et al., 1999). The data from this study confirm this as terrestrial sources for O'Ne-eil Creek are characterized by ratios greater than 15, whereas the in-stream supply falls below 15. Thus, it appears that the suspended sediment load adopts an elemental signal related to changing type of source material. And, although, the ratio does not decrease as far as to match the measured ratio for salmon flesh, the presence of salmon detritus is detectable in the sediment load.

Stable isotopes provide even more specific information for characterizing organic matter sources. Different types of organic tissue exhibit distinctly different isotopic signals, which enables differentiation between samples and even tracing of trophic pathways through systems (Peterson and Fry, 1987). The data presented in Figure 4.10 indicates little temporal variation in $\delta^{13}C$ (-27 to –26 ‰) and $\delta^{15}N$ (2 to 3 ‰) until the salmon enter the reach. At this point, a steep increase in the heavier isotopes of each element occurs; steeper for nitrogen than carbon. Then, when live salmon are no longer present in the stream, both carbon and nitrogen isotopes fall off; probably as salmon-introduced nutrients are utilized or flushed downstream. This trend is supported by Ben-David et al. (1998), who reported that spawning Pacific salmon exhibit higher proportions of heavier carbon and nitrogen isotopes ($\delta^{13}C = -18.65 \pm 0.18$ ‰ and $\delta^{15}N = 13.01 \pm 0.13$ ‰) than terrestrial plants (means of $\delta^{13}C \approx -27$ ‰ and $\delta^{15}N \approx 0$ ‰; France, 1997).

Dual isotope, three endmember modeling corroborates the visual stable isotope pattern (Table 4.2), although a significant amount of variation in proportion of contributors exists. Phillips and Gregg (2001) performed sensitivity analysis of this linear mass balance model. They found that large differences in isotopic signal between sources reduced the error (i.e., doubling the difference reduced the uncertainty by half). Further, sample size is important when dealing with source samples exhibiting similar isotopic signatures. Thus, increasing the number of samples collected, especially for terrestrial vegetation, which varies significantly in terms of species and season (France, 1995), should improve the resolution of this model. As well, collecting tissue samples in a more continuous manner over the season, rather than the episodic approach presented here, and applying the model to sources collected at the same time as the mixture may also assist investigation of natural patterns.

The stable isotope analysis substantiates earlier indications that organic source type is of significant importance for flocculation in O'Ne-eil Creek. Larger particles were found during the salmon spawn (Table 4.5), a time when the dominant organic source type changes from terrestrial material, to higher quality, marine-derived organic matter introduced to the freshwater system by the salmon vector. Both carbon and nitrogen signals changed considerably in terms of the heavier isotopes, and DOC concentrations were much less during the spawn period compared to the spring. POC concentrations did increase slightly for the spawn compared to the low flow period; however, they were equal to or less than the springmelt concentrations. With this in mind, it appears that either (1) the quality of salmon is more conducive to floc-building, or (2) nitrogen may have an important role. This could be either due to the 'sticky' nature of nitrogenous substances or because of the high nutritional value for microorganisms that nitrogen compounds provide (France, 1998; Bouillon et al., 2000).

Table 4.5 Summary of particle size, stable isotopes of carbon and nitrogen, and sediment-attached bacteria variables grouped by event type. Numbers in parentheses are standard error.

Event Type	EPSD D_{99} (μm)	EPSD D_{84} (μm)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Attached Bacteria ($x10^5$ cells mL^{-1})
Spring	847 (185)	668 (121)	-26.8 (0.06)	2.0 (0.11)	6.18 (0.30)
Low Flow	896 (230)	749 (260)	-26.6 (0.07)	2.4 (0.09)	3.26 (0.13)
Rain	1340 (367)	1107 (384)	-26.2 (0.11)	3.8 (0.31)	4.32 (0.64)
Spawn	1366 (204)	1177 (225)	-26.2 (0.11)	4.3 (0.38)	3.32 (0.23)
Post-spawn	832 (43)	553 (81)	-25.6 (0.07)	5.6 (0.18)	6.36 (0.11)

4.4.3 Bacterial Content

Composite particles are comprised of both inorganic and organic particles. The latter component provides a nutrient source for bacteria (Paerl, 1975; Goulder, 1976; Droppo and Ongley, 1994). Bacteria facilitate floc-building by producing extracellular polymeric fibrils that act to bind together primary inorganic particles (Droppo et al., 1997). These biological structures provide stability for otherwise incredibly fragile particles (Dade et al., 1990).

The relationship between sediment-attached and free-floating bacteria is not well-defined. However, studies indicate a general trend of higher sediment-attached numbers in freshwater systems, and larger free-floating populations in marine environments (Bell and Albright, 1981; Kirchman and Mitchell, 1982). Regardless of the relative proportions of sediment-attached versus free-floating bacteria, sediment associated bacteria are more metabolically active (Kirchman, 1983). This indicates great potential for biologically-induced floc-building. The pattern of sediment-attached bacteria in O'Ne-eil Creek is that the majority of bacteria are sediment-attached and high numbers were counted for spring and post-spawn periods. Because smaller flocs were observed for the springmelt period, the high value for sediment-attached bacteria probably reflects the high SPM concentrations (7 to 17 mg sediment L^{-1}) measured here. The same relationship is not likely for the post-spawn period (SPM ~ 1 to 6 mg L^{-1}), rather the quality of organic matter (derived from salmon) adsorbed to particles probably provides appealing sites for bacterial colonization. As well, the spawn period exhibits slightly higher attached bacteria counts than low flow conditions, which probably reflects a combined effect of increased SPM and salmon-derived nutrients as this period exhibited high spawning activity (resuspension of gravel-stored material) and dying (introduction of carcass-derived nutrients).

One might expect the spawn period to possess greater incidences of sediment-attachment than post-spawn because of the continual introduction of microbial enhancing salmon nutrients and high SPM concentrations due to resuspension of gravel-stored sediment, but it is possible that salmon activity exerts high particle shear stresses that may make it difficult for particle colonization. Thus, the causative factor for seasonal variation in sediment-attached particles is not singular, but rather likely due to a combination of changes in temperature, supply of organic matter, and suspended sediment concentration. As well, determining the relative importance of each of these factors is dependent on obtaining valid and reliable bacterial cell counts.

There are several observed limitations to the Acridine Orange Direct Count (AODC) method that may have impeded the collection of accurate bacterial counts. First, large cells that may not have been attached to sediment particles were counted on the larger pore size filters. Most of these were rod-like cells >> 1 μm in length, which would probably pass through the filter if there were aligned on their long axis. High incidences of these cells may have caused overestimation of attached-sediment counts. Second, photofading of fluorescing cells forced counting to occur quickly, to the point of possibly decreasing count accuracy. Also, the rate of fading was unequally distributed over the filter, so cells in one sector may have faded out before counting commenced.

4.5 Conclusion

There are definite seasonal patterns in the environmental, chemical, and biological variables that are known to influence flocculation in O'Ne-eil Creek. Shear stress, suspended sediment concentration, chlorophyll *a*, colour, and DOC appear to be regulated by hydrologic processes. The combined analyses of colour and stable isotopes strongly indicate that seasonal changes in dominant organic matter sources are important for freshwater flocculation. The data presented provide promising evidence for the ability of stable isotopes to detect the presence of salmon versus terrestrial organics in suspended sediment samples. The results indicate that the presence of salmon in streams may increase observed particle size within the water column due to some combination of biotic resuspension of large, settled particles and introduction of high quality, nitrogen-based, microbial enhancing organics. High quality organics lead to improved bacterial activity, which means greater probability for attachments through increased production of extracellular polymeric substances. Although statistical association between organic matter and particle size was not found, the apparent relation between seasonal patterns necessitates further examination of the importance of the organic component in the complex process of freshwater flocculation. Controlled laboratory experimentation involving different types of organic matter could enable better characterization of the relationships seen here. This information should assist in the understanding of potential land use impacts to this system, and possible consequences for fish habitat, with respect to freshwater flocculation.

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Chapter 5—Conclusions

Sediment is eroded from the terrestrial land base and delivered to surficial waters, where it is eventually transported downstream. Biologic, climatic, hydrologic, and geomorphic factors regulate the magnitude and timing of sediment delivery. As well, storage of material on floodplains and in-channel controls the particulars of sediment conveyance downstream. Specifically, the composition of suspended material is dependent on the nature of the particles (e.g., cohesiveness and size) and discharge. Fine-grained sediment typically comprises the majority of the suspended load, which is generally not stored, over long time periods in the channel. However, it has been found that modification of the fine-grained size fraction by flocculation can potentially lead to underestimation of storage. Researchers have tended to address the factors contributing to flocculation, including sediment mineralogy, ionic concentration, bacterial concentration, shear stress and velocity, suspended sediment concentration, and organic matter source and supply individually, in order to assess the causal linkages. However, the complexity of the process of flocculation indicates that isolation of influential factors in natural environments may be difficult. In addition, the difficulty in obtaining representative *in situ* data on floc structure impedes the process of relating particle morphology to the influential factors.

Despite the difficulties, the previously identified flocculation factors have been widely studied, with the exception of the influence of organic matter source and supply. Organic material in aquatic systems is derived from both in-stream and terrestrial sources. The quality depends on the ease of assimilation by microbes, which is reliant on the specific source (e.g., leaves versus large woody debris). Both the quantity and quality of sources vary spatially and temporally. At the seasonal scale variability is caused by climatic factors (e.g., temperature, precipitation, insolation) and lifecycle patterns of biological organisms (e.g., spawning salmon). Spatial variation in source material occurs in the form of changing inputs longitudinally from headwater to mouth, as well as due to changes in lateral flux of riparian contributions.

There is an apparent need to characterize suspended sediment structure and organic matter sources in freshwater systems because of the implications for aquatic habitat quality. As well, anthropogenic impacts have been found to increase sediment inputs to surficial waters, so investigation of pristine watersheds could provide insight into land use planning strategies. The purpose of this study was to assess temporal changes in suspended sediment structure in a single stream, O'Ne-eil Creek. This stream is located in the northern headwaters of the Fraser River in the Stuart-Takla region of northern British Columbia (BC), which is the setting for the first interior BC fish/forestry interaction project. As a relatively pristine mountainous watershed with well-documented annual migration of Pacific sockeye (*Oncorhynchus nerka*) salmon for spawning purposes, this watershed is ideal for assessment of suspended sediment dynamics prior to land use activities.

In chapter 3, temporal analysis of suspended sediment structure in relation to important hydrodynamic events and seasonally changing organic matter sources demonstrated that sediment moving in O'Ne-eil Creek is predominantly flocculated. The maximum size of particles in O'Ne-eil Creek exceeds that of other, more energetic Canadian watersheds, which is probably related to the system's inherent productivity. Increases in suspended sediment concentration and effective size occur during the presence of migrating salmon and are probably attributed to a combined effect of physical resuspension of gravel-stored sediment by spawning activities and the introduction of a pulse of nutrients from post-reproductive carcasses.

Chapter 4 indicated that there are definite seasonal patterns in the environmental, chemical, and biological variables that are known to influence flocculation in O'Ne-eil Creek. Hydrologic processes appear to regulate most measured variables, including shear stress, suspended sediment concentration, chlorophyll *a*, colour, and DOC. The data presented here supports the use of stable isotopes in the detection of changing organic source material. The similarity in seasonal patterns for the combined analyses of colour and stable isotopes and effective floc size strongly suggests that seasonal changes in dominant organic matter sources are important for freshwater flocculation. In fact, the results indicate that the presence of salmon in streams may increase observed particle size within the water column due to some combination of biotic resuspension of large, settled particles and introduction of high quality, organics that improve bacterial activity and enhance bacterial attachment to particles.

Although statistical association between organic matter and particle size was not found, the apparent relation between seasonal patterns necessitates further examination of the importance of the organic component in the complex process of freshwater flocculation. Controlled laboratory experimentation involving different types of organic matter could enable better characterization of the relationships seen here. As well, more sensitive microscopic techniques could assist in identifying which organic constituents are more important for the floc-building process. Further studies in watersheds having a range of productivity levels and source types should also help clarify the role of organic matter in freshwater flocculation.

In terms of aquatic habitat quality, studies assessing sedimentation (i.e., quantity and residence time) and changes in inter-gravel oxygen regimes should indicate whether current levels of flocculation are detrimental to salmon survivorship. This present study will assist in the understanding of potential land use impacts to this system, and possible consequences for fish habitat, with respect to freshwater flocculation. Overall, the findings presented here necessitate careful planning of any anthropogenic disturbances in watersheds that support migratory salmon stocks to ensure suitability and availability of spawning habitat.