
4 The Composite Nature of Suspended and Gravel Stored Fine Sediment in Streams: A Case Study of O'Ne-eil Creek, British Columbia, Canada

Ellen L. Petticrew

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4.1 INTRODUCTION

In the past decade there has been a concerted research emphasis on the structure, settling, and storage of suspended sediments in freshwater riverine environments.¹⁻⁵ This body of work has recognized the significance of flocculation and aggregation (terms which are used interchangeably in the literature) in riverine sediment transport processes, and the concomitant implications for the storage of both sediments and

sediment-associated contaminants. While the mechanisms and factors regulating flocculation, defined as the combination of two or more particles of mineral or organic material to create larger composite particles, have been research interests in the marine literature for decades they were only reported as being significant in natural freshwater systems in the 1990's.⁶⁻⁸ While the process of flocculation increases both the effective size of the particle and modifies its density it has been shown that the propensity for particle settling is influenced more by the particles altered size rather than its density or porosity.⁵

While the literature details the conditions or mechanisms which promote the flocculation and aggregation of sediments in rivers (increased sediment concentrations, increased collision encounters, decreased shear velocities, high ionic strength, increased bacterial activity, and increased temperatures) there has also been some effort in the literature to subdivide composite particles into two separate populations comprising flocs and aggregates. Different processes and different composite structures have been suggested as a means to differentiate flocs and aggregates. Petticrew and Droppo⁹ differentiated flocs and aggregates by visual evaluation, with flocs being characterized as irregularly shaped and porous while aggregates appeared opaque and compact. It was postulated by them, and reiterated by Woodward et al.¹⁰ that the sources of the two structures were different with the fragile, loosely bound flocs being formed in the water column while aggregates are delivered to the stream from the catchment as robust, compact particles. Petticrew and Droppo⁹ also considered the fact that the floc structures stored in or on the gravels could be dewatered and potentially become more compact due to biological processes or physical reworking. Droppo et al.¹¹ have proposed a floc cycle for riverine composite particles that suggested a downsizing and consolidation of particles with increased exposure to bed shearing environments, indicating a change in structure over time spent in the river system. While it may be important to determine the source of the composite types it is also of interest to determine the relative abundance of aggregates and flocs in the stream channel and to determine if they behave differently in the context of settling and storage.

The objective of this chapter is to evaluate the morphology, settling behaviour, and characteristics of composite sediments that are transported and stored in a relatively undisturbed productive headwater stream. A case study of a highly productive salmon bearing stream is presented here with both the hydrologically important and biologically important periods of the open water season being investigated over several years. The focus of this chapter is the relationship of these changing environmental conditions with the sediment particle populations in both the water column and gravel storage. The changes in composite particle morphology and their resultant dynamic characteristics (settling rate and densities) were evaluated temporally over a range of open water conditions (May through October) while both the physical environment (suspended sediment load, stream velocities, and shear stresses) and the biological inputs to the stream changed.

Earlier work on O'Ne-eil Creek, reporting on the structure and composition of suspended and gravel stored sediment, indicated that in these biologically active headwater streams the fines (sediments < 63 μ m) were well flocculated.^{3,12} The aggregates or flocs exhibited maximum sizes 7 (suspended) to 14 (gravel stored) times greater

than the maximum size of the constituent inorganic material comprising the composite structures.³ Petticrew and Droppo⁹ visually identified different composite structures and observed that these loosely bound flocs and compact aggregates exhibited different settling behaviors and size ranges. As these data were collected during the 1996 die-off of 10,722 sockeye salmon (*Oncorhynchus nerka*) that had returned to the stream to spawn, follow-up work was undertaken to evaluate the importance of the biological and physical influence of the fish upon the morphometric and dynamic properties of the sediment.

The hydrologically important period in terms of sediment transport in streams of this region is the spring melt which occurs in late May. High flows on the rising limb of this flood event scour and break down the armoured layer in this creek¹³ mobilizing the supply of channel surface and gravel stored fine sediment. Terrestrial contributions from the floodplain and from the headwater slopes are also observed during this event. Cyclonic summer storms can also generate high intensity rainstorms which act to move sediment into and within the channel. The high flow spring melt events exhibit increased concentrations of suspended fine sediment, increased local shear stresses, and contributions of organic matter which are predominantly terrestrially derived. It was of interest to determine the resultant size, structure, and settling behavior of the composite particle population generated by these interacting set of factors.

Alternately the influence of the dominant biological influence in the stream was of concern, as this stream can have annual sockeye returns of up to 50,000, although on average it receives approximately 10,000 per year.¹³ The physical effect of the digging of redds, or egg nests dug to about 25 cm into the gravels, is to both modify the surface morphology of the gravel bed and to resuspend the gravel stored fines,¹⁴ possibly many times in one spawning season. Following this major physical disturbance of both the gravels and the water column, the fish die in the stream and decay in the late summer low flows. The flux of organic matter to the stream is immense and abrupt^{15,16} as these salmon spawn in only the lower 2 km of the channel and die in a period of about 10 days, resulting in a high unit area loading of fish breakdown products. Petticrew and Arocena¹⁷ observed a chemical signature of salmon flesh in the gravel stored sediments, indicating that either the breakdown products or bacteria with the salmon signature are associated with the fine grained gravel stored aggregates. Given the potential role of organic matter and microbial activity in the generation of composite particles this highly productive stream was seen as a good venue to evaluate the effect of both the supply of organic matter and the physical disturbance of spawning on the structure of flocs and aggregates being transported and stored in streams.

4.2 METHODS

4.2.1 STUDY AREA

The O'Ne-eil Creek catchment is approximately 75 km² and is located in an experimental forest in the central interior of northern British Columbia. It is a tributary to the Middle River which drains into the Stuart Lake system which is well known for its highly productive sockeye salmon runs. Fish escapements to streams in this region,

including O'Ne-eil, have been monitored using counting fences for nearly 50 years. The O'Ne-eil catchment drains part of the Hogem Range of the Omenica Mountains, and has its mouth at 700 metres above sea level (masl) and its drainage divide at approximately 1980 masl.¹⁸ The channel is approximately 20 km in length with a steep upper reach which drains well-developed cirques, a steeper middle reach that passes through a rock-walled canyon, and a gentle, low gradient depositional reach in the lower 2 km.¹⁹ In the lower reaches of the stream, the channel bed is comprised of clean gravel with very low concentrations of fine sediments, well suited for salmon redds. This lower reach is underlain by fine grained glaciolacustrine sediments and the only anthropogenic disturbance to date consists of a road (constructed in 1980) which cuts through this material. This road bridges the stream and allows access approximately 1500 m upstream of the river mouth. There has been no harvesting in the catchment, so the system represents a nearly pristine environment.

4.2.2 FIELD METHODS

Data collected over five seasons of sampling are presented here comprising various periods of 1995, 1996, 1997, 2000, and 2001. Within each year various hydrological or biological events were sampled including spring melt floods, active salmon spawning, post-spawning die-off, and low flows when no visual evidence of adult fish were evident, which in this chapter is called post-fish, were represented. Table 4.1 identifies the events, the conditions, and the variables that were collected each year. The conditions of sampling are characterized as either "ambient" or "resuspended" with ambient conditions representing the undisturbed, natural suspended sediment concentration conditions. In order to characterize the gravel stored fine sediment, a resuspension technique that was an attempt to rework the surface gravels using approximately the same energy expended by spawning salmon, was used. Several minutes after the collection of the ambient sample, a second sample of suspended sediment was taken, following the disturbance, or mixing, of the top layer (0.04 to 0.06 m) of gravels by a field assistant, positioned 3 to 5 m upstream of the collection site. This distance provided sufficient travel time for the resettling of heavier sand particles thereby allowing the collected material to comprise the aggregated fine sediment stored within the surface gravel matrix. In this chapter, that material is termed resuspended gravel stored fines.

Stream velocities and depths at the time of sampling were determined using a Swoffer current meter and are presented in Table 4.1.

4.2.3 SUSPENDED SEDIMENT MEASUREMENTS

Stream water with suspended sediment was collected approximately 10 cm below the surface of the water in several large mouthed 1 l Nalgene bottles for the determination of

- (i) suspended particulate matter (SPM) concentration
- (ii) the disaggregated or absolute particle size distribution (APSD)
- (iii) the aggregated or effective particle size distribution (EPSD)
- (iv) morphometric characteristics of the aggregated suspended sediment population
- (v) the fractal dimensions of the filtered particle population

TABLE 4.1
O'Ne-ail Creek Sampling Schedule, Conditions and Variables for Five Sample Years

Year	Date	Event type	Conditions sampled	Cumulative fish return	SPM (mg l^{-1})	Water depth (m) and velocity (m s^{-1})	SPM filter fractals	Settling chamber sizing	Settling chamber visual characterization
1995	Aug. 2	Active spawn	Ambient	26,456	11.70	0.20/0.26	N ^a	Y ^b	N
1996	Aug. 26	Die-off	Ambient	10,772	0.93	0.22/0.23	Y	N	N
			Resuspended gravel stored fines	10,772	7.22	0.22/0.23	Y	Y	Y
1997	May 28	Spring meltrising limb	Ambient	0	8.38	0.70/1.04	Y	Y	N
	May 30	Spring meltrising limb	Ambient	0	6.79	0.77/1.59	Y	Y	N
	Jun. 1	Spring meltrising limb	Ambient	0	8.70	1.40/1.28	Y	Y	N
2000	Aug. 10	Active spawn	Ambient	10,601	2.47	0.22/0.31	N	Y	Y
			Resuspended gravel stored fines	10,601	15.73	0.22/0.31	N	Y	Y
2000	Aug. 12	Active spawn	Ambient	10,709	3.76	0.21/0.28	Y	N	N
			Resuspended gravel stored fines	10,709	7.12	0.21/0.28	Y	N	N
2000	Sep. 21	Post-fish	Ambient	10,890	0.69	0.26/0.35	Y	N	N
			Resuspended gravel stored fines	10,890	15.48	0.26/0.35	Y	N	N
2000	Oct. 5	Post-fish	Ambient	10,890	1.00	0.20/0.29	Y	Y	Y
			Resuspended gravel stored fines	10,890	20.89	0.20/0.29	Y	Y	Y
2001	Jul. 17	Pre-fish arrival	Gravel stored fines	0			Y	Y	N
2001	Jul. 28	Early spawn	Gravel stored fines	8,211			Y	Y	N
2001	Aug. 3	Mid-spawn	Gravel stored fines	10,931			Y	Y	N
2001	Aug. 12	Die-off	Gravel stored fines	13,757			Y	Y	N
2001	Aug. 16	Die-off	Gravel stored fines	13,892			Y	Y	N
2001	Sep. 22	Post-fish	Gravel stored fines	13,893			Y	Y	N

^a N = no samples analyzed.

^b Y = yes, samples analyzed.

The water samples were returned to the laboratory and processed in a variety of ways. SPM was determined gravimetrically by filtering a known volume of water (commonly 1000 to 4000 ml, depending on concentration) onto preweighed and preashed 47 mm diameter glass fiber filters. A second, smaller volume (100 to 1000 ml) was filtered through preweighed 0.8 μm Millipore cellulose-acetate filters. These were used for determining the disaggregated inorganic grain size distribution also known as the ASPD. The weighed, dried filters were ashed in a low-temperature ashers (<60°C) and wet digested with an excess of 35% H_2O_2 before analysis on a Coulter counter.²⁰ A Coulter Multisizer IIE was used to determine the ASPD. Results are expressed as a volume/volume concentration in ppm and are plotted as smoothed histograms of log concentration versus log diameter.²⁰ The Multisizer was set to a lower detection limit of 0.63 μm and an upper detection limit of 1200 μm .

The EPSD was determined by filtering smaller volumes of water (10 to 100 ml, depending on the sediment concentration) through 0.45 μm Millipore filters at low levels of suction (<80 kPa). Care in handling the collected water and in the filtering process ensured minimal disturbance to the aggregate structures. EPSD was measured optically, using a method similar to that of de Boer²¹ and reported in Biickert.²² These filters were air dried, cut and mounted onto microscope slides to obtain particle morphometrics using the BioQuant OS/2 image analysis system which was connected to a microscope. The filtered particles were counted and characterized for perimeter, area, long axis, equivalent spherical diameter (ESD) and circularity. The population of particles counted per filter was in excess of 1000 and in most cases triplicate filters were analyzed to allow a determination of the variability. To obtain the ESPD, the population's equivalent spherical diameters were grouped into size classes which correspond to the same intervals as the Coulter counter and plotted as volume/volume concentration in parts per million against ESD. The lower limit of the image analysis technique when linked to the microscope is an areal size of 5.4 μm^2 and presumably the upper limit would be defined by the area of the filter visible at the given magnification setting which would be in the order of 100,000 μm^2 . However as the volume of water filtered is often small, because this minimizes overlap of particles on the filter, and because the probability of capturing the larger, rarer flocs is lower due to reduced sample volume, this method tends to artificially restrict the upper limit of the size spectra. For almost all filters analyzed for this study, the maximum aggregate diameter observed was of the order of 400 μm while larger aggregated particles (>700 μm) were observed in the bigger sample volume of the same origin in the settling chamber.

The morphometric parameters collected from the image analysis of the filtered population of aggregates were used to determine the fractal dimension (D) of the populations. D is a measure of the perimeter–area relationship for a set of objects. Collections of natural objects tend to have a perimeter–area (P , A) relationship of $A \propto P^{2/D}$.²³ Euclidean objects such as squares or circles have a D value of 1. Values of $D > 1$ indicate that as area increases, perimeter increases at a greater rate.^{21,24} This means that these larger particles have more edge complexity and are less Euclidean or evenly shaped. Fractal D values were determined from perimeter and

area relationships for populations of filtered aggregates as well as particle populations sized and characterized in the settling chamber.

4.2.4 SETTLING CHAMBER MEASUREMENTS

The collection of a larger volume of suspended sediment to determine the fall velocities and densities of suspended sediment structures employed a rectangular plexiglass settling box ($1.5 \times 0.14 \times 0.06$ m) with two removable end caps that was built to hold approximately 13 l of water. A scale was mounted on the outside back wall of the settling chamber using white adhesive paper which aided in photographing and sizing particles. The settling chamber was aligned into the stream flow such that water and suspended sediment passed through it. When a sample was required the ends were capped and the box carried in a horizontal position to the side of the creek, where it was placed vertically onto a stable platform 20 to 30 cm in front of a 35 mm single lens reflex (SLR) camera mounted on a tripod. After a period of several minutes, during which fluid turbulence decayed, a series of timed photographs were taken. Pairs of sequential images were then projected onto a large surface and examined to identify individual flocs. The particle size, shape, and position in the two images were determined using image analysis packages (Mocha and Bioquant) allowing an estimate of the fall velocity.

In the spring of 1997, the same settling chamber was used to collect suspended sediment samples from the snowmelt flood events in O'Neil Creek. Due to the fast overbank flows at this time the box was lowered and returned to the bridge platform using a winch system. The box was filled and capped by persons standing in the stream. The photographic system employed in the field at this time was a video capture system. A black and white digital camera (a charged-coupled device — CCD), with a resolution of 512×512 pixels, was connected to a personal computer running Empix Imaging's Northern Exposure software. This field setup allowed an automated image grabbing system, which recorded the current time (accurate to 10^{-2} s) on each image. A run of 45 images could be grabbed in just over a 90 sec. The resultant images had individual pixel resolution of $55 \mu\text{m} \pm 10 \mu\text{m}$. The images were then analyzed via a custom-developed²² settling rate measurement program.

Due to colder weather, and shorter day lengths that contributed to poor conditions for outdoor photography, the samples from October 5, 2000 were collected in the field but returned to the laboratory for analysis. In this case up to 12 l of ambient and resuspended sediment-laden water was collected and introduced into the settling chamber for analysis using the SLR camera.

Measurements of particle size and settling velocity for both the SLR and video imaging method allowed for the derivation of particle Reynolds numbers as well as particle density using the equations presented in Namer and Ganczarczyk.²⁵ The lower resolution of particle diameters using these techniques was approximately $150 \mu\text{m}$ while the upper limit would be defined by the field of view of the cameras, which given the distance from the settling chamber allows a photographic image of a particle with a long axis in excess of $10,000 \mu\text{m}$.

4.2.5 INFILTRATION GRAVEL BAGS

On July 13, 2001, twelve infiltration gravel bags were installed in two riffles near the bridge site of O'Ne-eil Creek. A hole approximately 25 cm in depth was dug and the gravels removed were cleaned through a 2 mm sieve. The bags are a modification of the design presented by Lisle and Eads²⁶ and consist of watertight bags, with a maximum volume of 10,000 cm³ clamped onto a 20 cm diameter iron ring. The bag is folded down on itself at the bottom of the hole, while straps attached to the ring are placed along the sides of the hole and left at the gravel-water interface. The cleaned gravel is then returned to the hole, being placed on top of the folded bag and left for a known period of time to accumulate fine sediments in the intergravel spaces. The bag traps were retrieved over a 71-day period following installation. The retrieval dates (cf. Table 4.1) represent (i) the period before the fish return to the river to spawn (July 17), (ii) the early spawn (July 28), (iii) mid-spawn (August 3), (iv) two dates during the major fish die-off (August 12 and August 16), and (v) a sample when there was no visual evidence of live or dead carcasses in the stream, termed post-fish (September 22).

Upon retrieval a lid is placed over the surface gravels between the emergent straps that are pulled up, moving the iron ring and the bag up through the gravels ensuring a minimal loss of fine sediment. The gravels and water collected in the bags were passed through a 2 mm sieve such that the finer sediment was collected in a calibrated bucket. This material was mixed to resuspend all grain sizes, settled for 10 sec to allow the settling of large sands from the top water layer from which a 250 ml subsample was taken for use in the settling chamber. These gravel stored fine sediments were introduced into the settling chamber which was filled with filtered (0.45 μm) O'Ne-eil Creek water. The CCD digital video method of image collection was used for these samples. Around 100–250 individual particles were tracked for each set of bags, providing size and settling characteristics while larger populations ($n = 1000$ to 2500) of particles photographed in the settling chamber were used to determine morphometric characteristics of the total population of gravel stored aggregated fine sediment.

4.2.6 VISUAL CHARACTERIZATION OF AGGREGATE PARTICLES

The images of particles captured in the settling chamber when the SLR camera is used were very clear and distinct such that more detailed structure of individual particles could be evaluated. It was obvious upon viewing the particles for the first time in the year 1995 that some were opaque, appearing to exhibit no open pores while others were a loose and open matrix of material attached together. In some cases the aggregates were a combination of both of these forms. In 1996, we decided to label each particle that we had tracked and for which we had estimated a settling velocity, in order to determine if differences in settling behavior existed between these visual subpopulations. The compact, opaque subset was termed compact particles while the open, loose matrices were called flocs. The combination particles and those which we were unable to define were classed in a group as mixed particles. A fourth subset was added in the year 2000 as visual evaluation of the compact subpopulation indicated

that some dense, dark particles had visual indicators that they were organics or parts of organisms. For further clarity these were separated and labeled compact-organic particles.

4.3 RESULTS

The settling chamber was used for the first time in August 1995, sampling ambient water during the active spawn of a very large return of salmon (26,456) to O’Ne-ail Creek. On this first use, 23 individual particles were identified and tracked for 46 settling velocity determinations, but the data set was not characterized visually for particle type (Table 4.2). The visual identification of floc and compact particles was first undertaken and reported⁹ for the 1996 settling population. When the two sub-populations (i.e., floc and compact particles) are plotted as diameter against density (Figure 4.1) it is clear that while both floc and compact particle diameters range between 300 to 1300 μm , the larger particles tend to be flocs and they exhibit lower densities. In this data set flocs with the equivalent diameter as compact particles are always of lower density. An exponential decrease of density with increasing size is apparent for the compact particle population as it exhibits a wider range of densities. Figure 4.2 shows the same general pattern for the August and October 2000 settling data. The total population of settled particles exhibits the exponential decrease in density with diameter more clearly than in the 1996 data in Figure 4.1. Note that a third set of particles, visually identified as compact-organic, is also shown here. They tend to fall into the central part of the size–density spectrum.

Table 4.2 provides a summary of particle numbers and types identified in the ambient and resuspended settling chamber runs of 1996 and 2000. Visual identification of particle types was not undertaken in 1995 or 1997. In each case

TABLE 4.2
Settling Chamber Image Analysis Characterization

Date	Event	Sample type	Number of individual particles	Percent floc	Percent compact	Percent mixed
Aug. 2, 1995	Active spawn	Ambient	23 ^a	N/A	N/A	N/A
Aug. 26+27, 1996	Die-off	Resuspended	43 ^b	35	23	42
May 28+30, 1997	Spring melt rising limb	Ambient	280	N/A	N/A	N/A
Aug. 10, 2000	Active spawn	Ambient	117	7	75	18
Aug. 10, 2000	Active spawn	Resuspended	113	13	77	10
Oct. 5, 2000	Post-fish	Ambient	37	14	51	35
Oct. 5, 2000	Post-fish	Resuspended	315	12	71	17

^a 46 settling counts performed.

^b 70 settling counts performed.

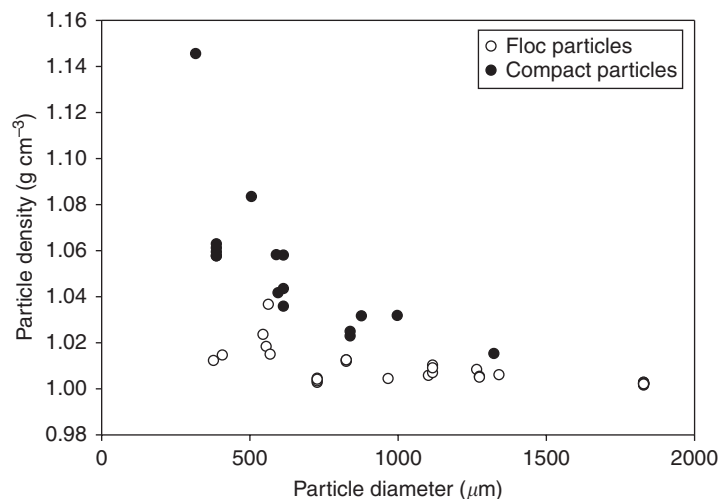


FIGURE 4.1 Size–density relationship for visually determined floc and compact particles from resuspended gravel stored sediment during the salmon die-off of 1996

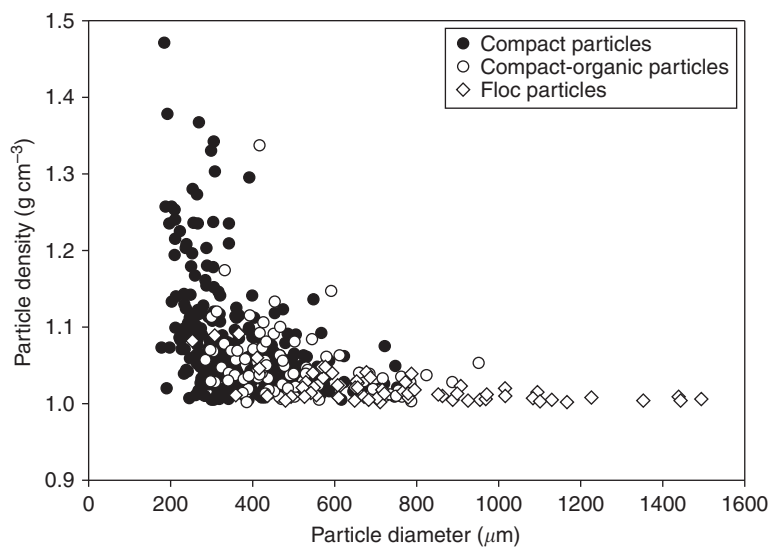


FIGURE 4.2 Size–density relationship for visually identified floc, compact and compact-organic particles from both ambient and resuspended sediment in mid- and post-spawn of 2000. Note the separation of flocs and compact particles into the arms of the distribution

when the particle subpopulations were differentiated the proportion of flocs never comprise as much as half of the population, although the maximum value occurs in the die-off period of 1996 when 35% were identified as flocs. Of note in Table 4.2 is the proportion of compact particles observed in the resuspended sediment in the

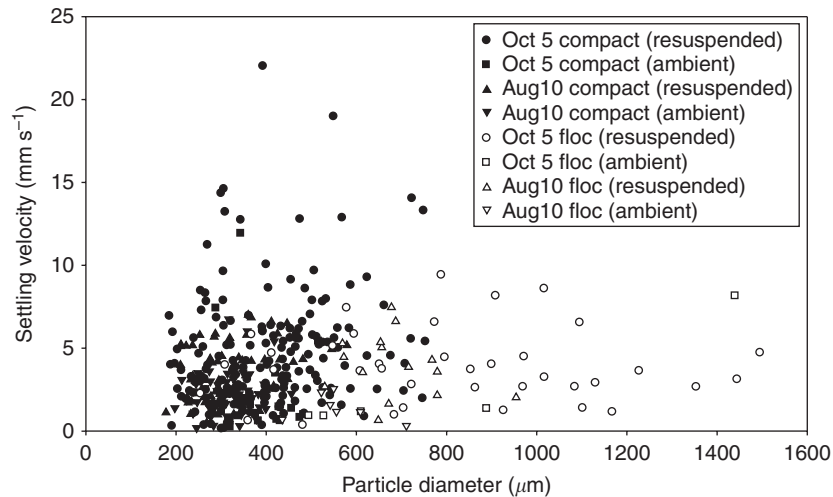


FIGURE 4.3 Settling velocities of aggregated particles observed in the ambient suspended and resuspended, gravel stored sediment in mid-spawn (August 10) and post-fish (October 5) 2000

active spawn and post-fish samples of 2000, calculated as 77% and 71% respectively. These values are similar to the 75% of compact particles observed in the ambient suspended sediment during the active spawn of 2000. The ambient waters of the October post-spawn period have only 51% compact particles in the suspended sediment.

When the data from August and October 2000 settling runs are plotted together the different sizes and behaviors of the two populations are apparent (Figure 4.3). The compact particles are generally smaller, all being $<760 \mu\text{m}$ and tend to exhibit the fastest settling rates with 6% actually exceeding the settling rate of $100 \mu\text{m}$ quartz sand (8.7 mm s^{-1}). The open matrix flocc particles exhibit the largest sizes as indicated by the fact that all particles in excess of $760 \mu\text{m}$ are identified as floccs that generally settle at slower rates. Note that there are few large floccs in the ambient suspended sediments of both August and October, but upon resuspension of the gravel stored sediment the flocc structures increase in number.

Table 4.3 summarizes the data from all available settling chamber runs and provides statistics for the particle populations' size (diameter), shape (sphericity), and density by particle type where possible. The data for the relative abundance of flocc and compact particles indicates that in all but the die-off period compact particles dominate both the suspended (ambient) and gravel stored (resuspended) samples. The proportion of flocc particles tracked for settling varied between 7% and 35% of the total population. The percentage of floccs exceeded the compact particles only during the fish die-off in August 1996. Once again it is clear that the compact particle sizes are significantly smaller than flocc sizes, as shown by viewing both the population means and maximum diameters. The largest sizes occur in the resuspended gravel stored sediments during the fish die-off of 1996. The compact particle population mean during die-off is significantly larger ($p = 0.05$) than compact particles observed at

TABLE 4.3
Size and Density Characterisation of Settling Chamber Particle Populations

Date	Event	Sample type	Particle type	Percent of total population	Mean diameter and SE ^a (μm)	Maximum diameter (μm)	Smaller diameter $\% < 500$ (μm)	Larger diameter $\% > 500$ (μm)	Greater density $\% > 1.10$ g cm^{-3}	Lower density $\% < 1.10$ g cm^{-3}	Shape as sphericity and SE
Aug. 2, 1995	Active spawn	Ambient	Total population	100	514 (58.2)	1162	52	48	42	58	N/A
Aug. 27, 1996	Die-off	Resuspended	Compact	23	704 (96.6)	1323	35	65	6	94	N/A
			Floc	35	897 (107.8)	1828	6	94	0	100	N/A
May 28+30, 1997	Spring melt rising limb	Ambient	Total population	100	276 (6.5)	712	96	4	32	68	N/A
Aug. 10, 2000	Active spawn	Ambient	Compact	75	342 (8.4)	685	96	4	10	90	0.62 (0.011)
			Floc	7	564 (31.8)	711	15	85	0	100	0.47 (0.025)
Aug. 10, 2000	Active spawn	Resuspended	Compact	77	365 (13.2)	723	86	14	30	70	0.63 (0.014)
Oct. 5, 2000	Post-fish	Ambient	Floc	13	685 (27.3)	954	0	100	0	100	0.56 (0.025)
			Compact	51	384 (15.5)	515	95	5	11	89	0.67 (0.020)
Oct. 5, 2000	Post-fish	Resuspended	Floc	14	791 (176)	1439	20	80	0	100	0.54 (0.058)
			Compact	71	400 (9.5)	752	79	21	22	78	0.67 (0.007)
			Floc	12	816 (52.4)	1494	19	81	0	100	0.56 (0.020)

^a SE = standard error shown in brackets.

any other time. The spring melt rising limb population was not visually differentiated into compact and floc particles but exhibits the lowest population particle diameter mean and its maximum particle size is similar to that of resuspended gravel stored compact particles of the active spawn of August 2000 and the post-spawn of October 2000. Note that the ambient active spawn particles (August 2000) exhibit the smallest floc and compact sizes even though water velocities are similar to those observed in September and October sampling periods (Table 4.1). In fact its maximum floc size is slightly smaller than the maximum aggregate measured in the 1997 spring melt when flows were four times as fast.

To differentiate size and density, each subpopulation was separated into size categories based on a criterion diameter of $500\ \mu\text{m}$ while low density and high density particles were separated at $1.10\ \text{g cm}^{-3}$. These values were selected as they characterize the boundaries of the bulk of overlapping data points in Figure 4.2. In Table 4.3 the floc subpopulations are classified as large ($>80\%$ of the particles always exceed $500\ \mu\text{m}$) and low density ($100\% < 1.1\ \text{g cm}^{-3}$). Compact particle subpopulations tend to be comprised predominantly ($>79\%$) of smaller ($<500\ \mu\text{m}$) particles. The exception is the 1996 die-off when larger compact particles comprised 65% of the population with the other 35% being $<500\ \mu\text{m}$. The compact particles also predominate in the high density classification with 11 to 30% of their population exhibiting densities $>1.1\ \text{g cm}^{-3}$, excluding the 1996 post-spawn die-off when only 6% were of higher density. Compact-organic particles were not included in this evaluation of compact particles but comprised a separate subpopulation not presented in Table 4.3.

In the data sets that were also characterized for sphericity (all 2000 settling runs) all floc populations are significantly less circular than the compact particles (Table 4.3). While the floc shapes are not significantly different ($p = 0.05$) over time or by source (suspended or gravel stored) the compact particles do exhibit differences over time. The compact particles become significantly more rounded in the post-fish ambient and resuspended samples.

Fractal (D) values and their 95% confidence limits for the population of particles measured for settling velocities in 2000 are shown in Figure 4.4. A fractal value for the total population is shown for each sample date as well as the fractal value for the floc, compact and compact-organic particle subpopulations. The fractal values for the total populations indicate that there is no significant difference by source (ambient versus resuspended sediment) but there is by time, in that the suspended (ambient) sediment has significantly smaller fractal values in October than in August for the total population. Fractals for gravel stored (resuspended) sediment do not vary significantly between these dates. An evaluation of the subpopulations indicates that the floc and compact-organic particles exhibit a large amount of variation, while the compact particles have smaller confidence limits, indicating less variability in shape.

A similar fractal analysis of particles collected on filters is shown in Figure 4.5 for the years 1996 through to 2000. The sampling dates are not graphed chronologically by year, but rather grouped by date within the season so that the periods of spring melt, active spawn, fish die-off, and post-spawn can be viewed consecutively. The fractal values are lowest for the ambient suspended sediment of the spring melt period

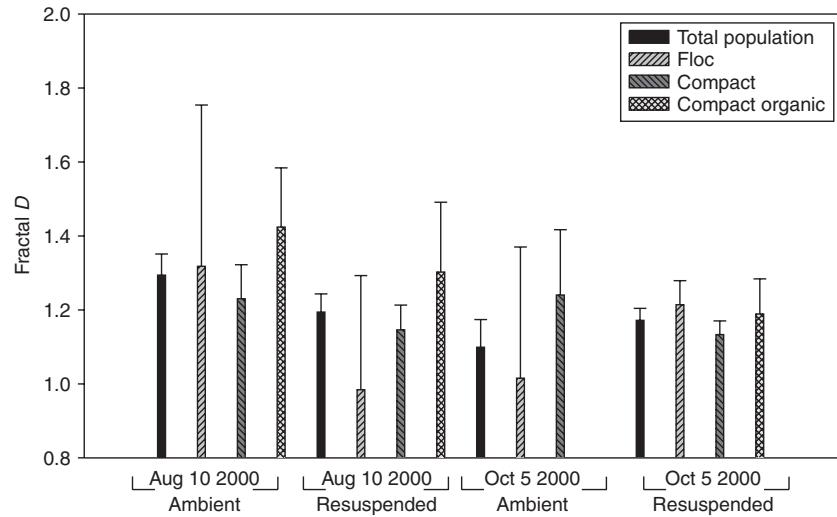


FIGURE 4.4 Fractal values for total particle populations and the visually identified subpopulations for ambient and resuspended sediment in the mid-spawn (August 10) and post-fish (October 5) periods of 2000. Error bars represent the 95% confidence intervals

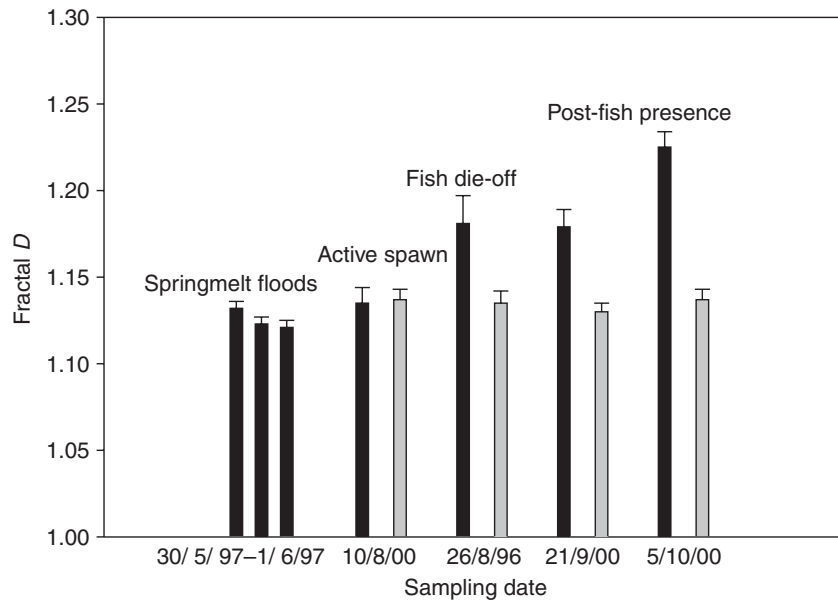


FIGURE 4.5 Fractal values for aggregates sampled and analyzed on filters over three years, comprising four different bio-physical open water conditions. Dark bars represent ambient suspended sediment conditions while lighter colored bars are resuspended, gravel stored fine sediments. Error bars represent the 95% confidence intervals

indicating that the particles are more rounded. In contrast to the results of the settling particle fractal analysis (Figure 4.4) the D values for filtered suspended sediment increase later in the season, becoming significantly less rounded during fish die-off and in post-fish periods (Figure 4.5). In the active spawn sampled in August 2000, the suspended and gravel stored fractals are not significantly different from each other. These low D values represent more rounded particles and are similar statistically to the suspended sediment of the spring melt flood and the gravel stored samples throughout the full sampling season.

In 2001, gravel stored fine sediments collected from infiltration bags were introduced into the settling chamber and analyzed for size, shape (fractal), and settling characteristics (density). Table 4.4 shows these data along with the cumulative number of spawning fish returned to O'Ne-eil Creek by that date. Particle diameters were largest pre-fish and post-fish with the smallest mean values occurring at mid-spawn. Particle densities increased chronologically until die-off when they significantly decreased. Density increases were significant again in the post-fish sediments. The temporal pattern is that pre-spawn gravel stored aggregates are large and low density, mid-spawn aggregates are small and high density while at seasons end (post-fish) the gravel stored aggregates are again large but high density. While the fractal values for all of the infiltration bag sediments are low, the smallest D values, representing the roundest particles, were noted at mid-spawn and post-fish which is also when densities were highest. Figure 4.6 shows the changing pattern of fractal values over time along with a temporal plot of the cumulative spawner numbers in 2001. This indicates the number of individual fish having passed the counting fence by that date. On August 3, when 10,931 have returned to the stream to rework the gravels for redd construction the particles are more rounded than at all times except for the period when no visual evidence of fish carcasses are apparent in the stream (post-fish).

TABLE 4.4
Characteristics of Gravel Stored Fine Sediment Collected in Infiltration Bags in 2001

Event type	Date in 2001	Cumulative fish returns	Particle diameter (μm)	Particle density (g cm^{-3})	Fractal D	95% CL D
Pre-fish arrival	Jul. 17	0	332 (109) b	1.047 (0.033) a	1.060	0.009
Early spawn	Jul. 28	8211	261 (112) a	1.092 (0.068) b	1.073	0.004
Mid-spawn	Aug. 3	10931	244 (89) a	1.116 (0.079) c	1.052	0.007
Die-off	Aug. 12	13757	262 (95)^a a	1.032 (0.048)^a a	1.063	0.004
Die-off	Aug. 16	13892			1.061	0.004
Post-fish	Sep. 21	13893	316 (157) b	1.121 (0.033) c	1.051	0.004

Note: Means (and standard deviations) of particle diameter and particle density are shown. In each column, means followed by similar letters are not significantly different ($p < 0.05$).

^a Values in bold represent composite value for Aug. 12 and Aug. 16.

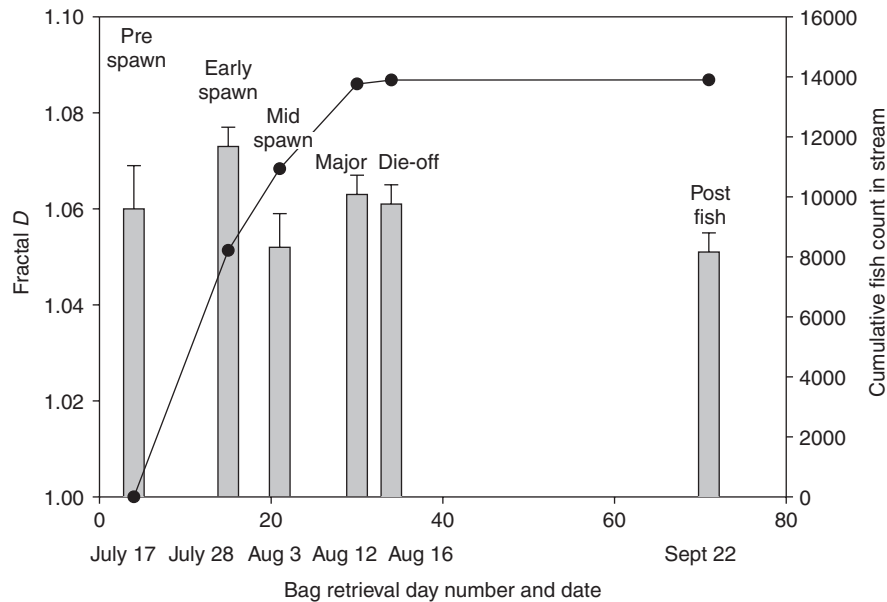


FIGURE 4.6 Fractal values for fine sediment collected in infiltration gravel bags in the summer of 2001 are shown as bars with the 95% confidence limits depicted. These sediment populations ($n > 1000$) were characterized for size and shape from charge-coupled device (CCD) images in the settling chamber. The 2001 cumulative fish count for O’Ne-eil Creek is shown by sample date (dots)

4.4 DISCUSSION

The particle populations sampled in O’Ne-eil Creek have been shown to be highly aggregated with floc factors (EPSD/APSD) exceeding 10^3 . All of the particles evaluated in this paper for size, morphology, and settling characteristics can be shown to be aggregates as the maximum particle sizes of the disaggregated inorganic sediment (APSD) of these samples do not exceed $130 \mu\text{m}$, while each of the particles evaluated visually (EPS) was larger than $150 \mu\text{m}$. The only particles which should be considered separately in this context are the compact-organics as they in fact may not be composite particles, but could be parts of organisms or aggregates of organism parts. The organics are removed from the sediment sample before characterizing the ASPD and so their constituent size is not determined.

Visual differentiation of aggregate particles in freshwater allowed an investigation of the size, shape, and behavior of particle subpopulations identified as flocs and compact particles. The loosely packed, open matrix floc particles are observed to be larger, less dense, less rounded, and slower settling than the opaque, compact particles. They were noted to be less abundant than compact particles in all periods sampled except for the fish die-off. While the smaller, rounder, denser compact particles are carried in ambient low flow conditions (0.23 to 0.35 m s^{-1}) their proportions are smaller in the post-fish quiescent flows (79%) than in low flows with active spawning

occurring (93%). In the resuspended gravel stored sediment of active spawn and post-fish they comprise 85% and 83% respectively (Table 4.3). It is unfortunate that the spring melt population could not be visually differentiated as the energy environment of that period was high and both the proportion of floc and compact particles would be of interest as well as their respective sizes and shapes.

In any case, the characteristics of the total population can still be useful as it is clear that the particle size of the populations change over the open water season with the smallest mean sizes observed during spring melt when local flows are deepest and fastest and the concentration of suspended sediment is higher (mean of 7.96 mg l^{-1}) for this system. The shear stress measured in spring melt flows of this scale in O'Ne-eil Creek has been reported as being approximately 70 N m^{-2} which would act to break apart weakly bound aggregate structures resulting in smaller mean and maximum population sizes as observed. Interestingly, aggregate particles are small during the active spawn of 1995 and 2000, while the largest sizes were observed during the die-off of fish in 1996. This variability in size occurs despite the fact that measured water velocities, which reflect local shear stresses of approximately 6 N m^{-2} at this site in O'Ne-eil Creek were not very different during these sample periods (Table 4.1). This implies that the activity of spawning fish resuspending sediment could be having a similar shearing effect. Evidence to support this can be seen in the concentrations of suspended sediment during ambient flow conditions. In 2000, the background concentrations were between 2.47 and 3.76 mg l^{-1} after approximately 10,700 fish had entered the stream to spawn, while in 1995 the ambient concentration was 11.70 mg l^{-1} with 26,985 spawners in the stream. Undisturbed ambient suspended sediment concentrations are measured in O'Ne-eil Creek as $<1 \text{ mg l}^{-1}$. The physical activity of these fish in digging their redds results in the reworking of the gravel bed, resuspension of the gravel stored fine sediments, and the downstream transport and deposition of these fines. The energy imparted in moving the gravels to release fine sediment, along with the action of being transported in the turbulent water column before settling again, would act to break apart weakly held structures, generating smaller and stronger and potentially more compact aggregates. In the ambient flow of active spawn in August 2000 only 7% of the total population of aggregate particles is loose floc structures. Alternately the largest aggregate sizes as well as the largest abundance of floc structures (35%) are observed in the salmon die-off period which exhibits low flow velocities with resuspended sediment concentrations of 7.22 mg l^{-1} . While these same low shear conditions and higher resuspended particle concentrations are sampled in post-fish periods (September and October 2000) the particle aggregates do not reach the same large sizes as during die-off. Clearly some other environmental factor aside from shear velocities and suspended sediment concentrations is controlling the size of these aggregate structures. The changing size and density of the infiltration gravel bag particle populations also supports the influence of the physical role of spawning salmon on the aggregate size. Smallest mean population sizes at mid-spawn, which are also associated with high densities, suggest that the smaller compact particles that predominate have been collected in the infiltration bags during spawn. The larger less dense aggregates collected in the bags earlier in the season have presumably been modified by the fish spawning activity. While the particles stored in the gravel bed during salmon die-off

are not statistically larger than at mid-spawn they are significantly less dense, which corresponds to the higher proportion of low density flocs observed in the water column (Tables 4.3 and 4.4). This could reflect the fact that the larger floc particles are less stable, breaking up when they enter the gravel matrix, or potentially being broken into smaller particles by the physical action of sieving through 2 mm mesh when the gravels are separated from the fines in the field.

The change in the particle composition and structure noted during fish die-off is associated with a temporal change in the organic composition of the aggregates. Petticrew and Arocena¹⁷ reported on these same gravel stored samples and stated that over the open water season the biofilms that cover gravel stored aggregates changed from weak, web-like structures at mid-spawn to a less porous, film-like covering in post-spawn. The stronger more extensive biofilm was associated with large aggregates while the weaker web structure existed when the aggregates were being exposed to repetitive reworking of the gravel bed (e.g., resuspension) during mid-spawn.

The sediment moving in the spring melt has the lowest mean particle size as well as the lowest fractal values, as determined from filtered samples (Figure 4.5). The sediment moving in the melt is small, dense, and rounded. In an evaluation of the filter fractals there is a significant decrease in D over the three day high flow sampling period in 1997. The suspended sediment becomes more rounded with time, indicating either a change of source²¹ or a modification of the particle shape with changing energy conditions. In Figure 4.5 there does not appear to be any significant differences between sediments resuspended from the gravel artificially over the season and the ambient suspended sediment from the active spawn of 2000. This would indicate that the sediments are from the same source, which we know to be the case, and experiencing similar energy conditions. This then would support the assumption that the energy imparted to the surface gravels to resuspend the stored fine sediments is similar to the work perpetrated by the fish. To corroborate this effect of physical resuspension note the timing of significant differences observed in the fractal dimensions and structure of the infiltration gravel bag sediments over the 2001 season (Figure 4.6, Table 4.4). Particles are growing more amorphous from pre-spawn through early spawn but then decrease in D values becoming rounder at the same time as becoming smaller and denser at mid-spawn when the majority of the physical reworking of the bed has been completed. As this reworking abates and die-off occurs, delivering carcass breakdown products to the stream the particle roundness decreases, density decreases, and particle size starts to increase again.

The ambient suspended sediments analyzed from the filtered populations show a significant increase in D following active spawn (Figure 4.5). This indicates that these particles are more amorphous than those of active spawn but also less rounded than the gravel stored sediment resuspended on the same dates. Intuitively this would make sense as there is less energy in the low flow water velocities which could break up the larger more amorphous particles.

In the post-spawn period the artificially resuspended (gravel stored) sediment has similar fractal values as the material comprising the ambient suspended sediment during the active spawn (August 2000) (Figure 4.5). This indicates that the material resuspended by spawning fish which remains in the water column is similar in shape to the gravel stored sediment later in the season. This is corroborated by looking at the

fractal results of the infiltration gravel bags (Table 4.4, Figure 4.6). The mid-spawn and post-fish fractals indicate they are the roundest populations of particles over the season, but as well they are the densest populations. Petticrew and Arocena¹⁷ presented scanning electron microscope evidence indicating that these mid-spawn aggregates were held together with a weak-looking web of biofilm while pre- and post-spawn periods exhibited a more extensive coating of biofilm. The strength of these biofilms may relate to the physical action these particles are exposed to (low flows, active spawning) and could also play a role in regulating their size.

4.4.1 FRACTAL CONCERNS

Note that the fractal results for the filtered populations (Figure 4.5) are not the same as is found in the fractal analysis of the settling chamber populations shown in Figure 4.4. In this latter data set there are no significant differences within the subpopulations by either source (ambient versus resuspended) or date but there is a statistically smaller D value for the total population of the ambient post-fish (October 2000) suspended sediment as compared to the ambient active spawn samples. This indication that the ambient suspended sediment is becoming more rounded with time is opposite to the results of the filtered samples. A comparison of fractal values for samples from the same date and source material indicates that the filtered particle populations are always lower than the settling chamber populations. This would be a result of both the larger number of particles that are counted by filters as well as the lack of inclusion of the larger particles ($>400 \mu\text{m}$) which have the higher proportion of amorphous, less rounded flocs. Inclusion of these bigger particles, which also exhibit larger variability, increases the fractal value of the settling chamber populations as seen in Figure 4.4. Another inconsistency is that the fractal values of the gravel stored sediment (Figure 4.6) are consistently much lower than that of the resuspended sediment shown in Figure 4.4, which is meant to represent the gravel stored sediment. This could be a function of the artificially disturbed samples being mixed with low concentrations of ambient sediment or the fact that the structure of the aggregates changes with depth in the gravels. The infiltration gravel bags collect material stored to a depth of approximately 25 cm while the artificial resuspension mobilizes only the top 5 or 6 cm. In Figure 4.3 it is clear that the majority of large floc particles are associated with the artificially resuspended gravel stored samples from August and October 2000, as opposed to being abundant in the ambient suspended sediment. Aside from periods of high flow, or just following scouring events, a layer of fine grained loosely aggregated sediment is often observed to be coating the surface of the channel.²⁸ These fine grained aggregates are more floc like than compact and are easily resuspended and moved downstream with increases in entrainment flows. These aggregates would be collected in both the artificially resuspended and the infiltration bag sediment sampling but would represent a larger portion of the population in the artificially resuspended sample as it disturbs a larger surface area and smaller depth of gravels. These surface fines would be less abundant in the gravel infiltration bag samples as they are deeper (25 cm) and have a specific surface area sampled (314 cm^2). This bias of surface sampling would then result in higher fractal D values

for the former (i.e., more amorphous) and lower D values, or more rounded particles in the gravel bags as observed in this comparison.

As the fractal values presented here reflect the measurement of potentially different populations (e.g., sediment populations with different upper and lower size limits as well as populations from different depths of gravel storage) care should be taken to compare results of fractal analyses between methods. Changing the upper and lower limits of the population analyzed in a fractal analysis has been found to have a significant effect on the results. For the settling chamber samples the lower limit was defined by the resolution of the image analysis technique (diameter approx. $150\ \mu\text{m}$) and the upper limit was not restricted. The regressions were always strong ($r^2 > 0.90$) and significant, but the subpopulation sizes were not always very large ($n = 5$ to 182). A test was done on the largest settling chamber data set (total population, Oct 2000 resuspended, $n = 315$), where the sample was altered to include only the aggregate population <600 , <500 , <400 , and $<300\ \mu\text{m}$ in order to determine the effect of the size limits on the fractal D values. While the D 's are not significantly different as the upper size limit is reduced and the sample size becomes smaller, the 95% confidence limits increase resulting in reduced ability to distinguish statistical differences. This observation is important if one plans to use fractals for identifying source sediments or for implying processes affecting sediment structure. The results of the filter population fractals presented in Figure 4.5 were analyzed using the same method as de Boer and Stone²⁹ who identified source differences in suspended sediment during a spring melt period. The lower limits and presumably the upper limits (as they are defined by the sampling technique) are similar to de Boer's which are detailed in his 1997 paper.²¹ Using this method between 1,500 and 15,000 particles can easily be counted ensuring a representative population size. In viewing this lower end of the aggregate population (7 to $400\ \mu\text{m}$) we see significant differences over a 3-day period in spring melt and a difference in the ambient suspended sediment over the season. As the data for Figure 4.4 are comprised of subpopulations of quite variable, and in some cases small sizes, these data would be considered problematic. A better method of evaluating the fractal dimensions of these samples would be to measure a large number of particles from the general population photographed in the settling chamber as opposed to using just particles that have been tracked for settling velocities. This approach was used to determine fractal values for the infiltration bag fine sediments from 2001. An excess of 1,000 particles were sized to determine the D values of the gravel stored sediment over the season. The fractal D values indicate that on all dates the particles are very rounded with the only significant differences being that the mid-spawn is rounder than the sample before it from early spawn and that the final post-fish sample is roughly the same roundness as mid-spawn with a significantly smaller D than in the period of fish die-off preceding it.

4.5 CONCLUSIONS

Visual differentiation of aggregated sediment particles both moving in the stream and stored in the gravel bed indicates the presence of variable subpopulations of particle types. The settling behavior of the particles is modified by their size, density, and

shape which appear to be modified by the hydrological, physical, and biological conditions within the stream. Both the energy of turbulent streamflow and the energy imparted by fish reworking the gravel bed are associated with a predominance of small, denser compact particles. In periods when internal stream energy is lower and when there is abundant organic matter delivery to the stream the composite structures are largest and are comprised predominantly of loosely bound flocs.

While structural and behavioral differences are associated with the different events occurring in the system, a more complete investigation of the open water season, incorporating storm events and summer base flows would be valuable. As well an evaluation of the types of organic matter comprising the composite structures throughout the season could potentially elucidate the processes which regulate the structure and morphology of these particles.

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