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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

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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 Droppo[9] 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 Droppo[9] 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 than the maximum size of the constituent inorganic material comprising the composite structures.[3] Petticrew and Droppo[9] 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

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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	[a] N	Y[b]	N
1996	Aug. 26	Die-off	Ambient	10,772	0.93	0.22/0.23	Y	N	N
			Resupended gravel stored fines	10,772	7.22	0.22/0.23	Y	Y	Y
1997	May 28	Spring melt rising limb	Ambient	0	8.38	0.70/1.04	Y	Y	N
	May 30	Spring melt rising limb	Ambient	0	6.79	0.77/1.59	Y	Y	N
	Jun. 1	Spring melt rising 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
			Resupended 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
			Resupended 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
			Resupended 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
			Resupended 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

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

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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 0.14 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'Ne-eil 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 10 m. The images were then analyzed via a custom-developed

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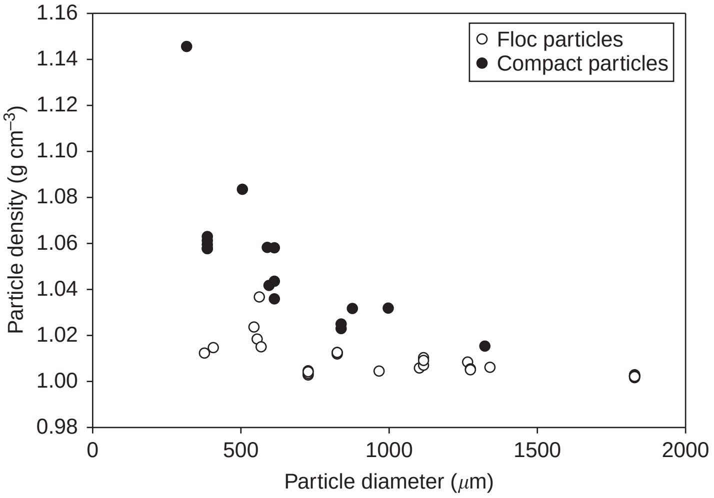
On July 13, 2001, twelve infiltration gravel bags were installed in two riffles near that some dense, dark particles had visual indicators that they were organics or parts


○ Floc particles
● Compact particles
Particle density (g cm^{-3})
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
0
500
1000
1500
2000
Particle diameter (μm)

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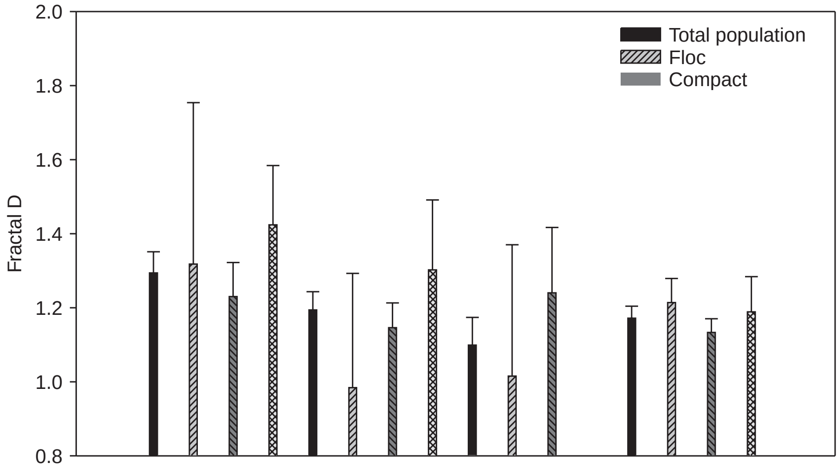
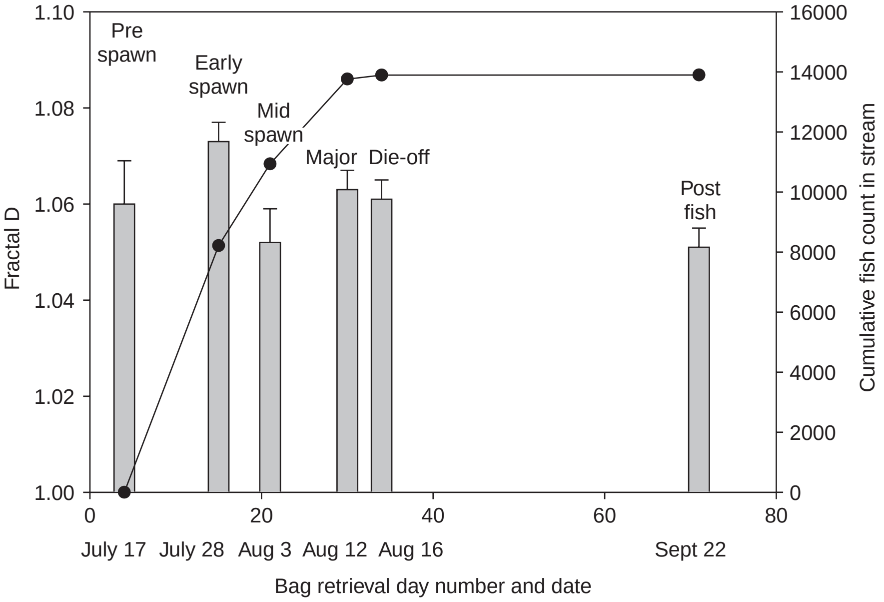
Date	Event	Sample type	Particle type	Percent of total population	Mean diameter and SE[a] (m)	Maximum diameter (m)	Smaller diameter % 500 (m)	Larger diameter % 500 m	Greater density % 1.10 g cm 3	Lower density %


2.0
1.8
1.6
1.4
1.2
1.0
0.8
Fractal D
Total population
Floc
Compact

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



3 2 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(

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 Arocena[17] 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 source[21] 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 differencesthatthe tiactalrementsonvelver ann 20Figure

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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 Arocena[17] presented scanning electron microscope evidence indicating that these mid-spawn 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 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 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 Stone[28] 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 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.

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

6