Vol. 6: 29–42, 2014
doi: 10.3354/aei00116

AQUACULTURE ENVIRONMENT INTERACTIONS
Aquacult Environ Interact

Published online November 11

Size, settling velocity and density of small suspended particles at an active salmon aquaculture site

B. A. Law[1,2,*], P. S. Hill[2], I. Maier[2], T. G. Milligan[1], F. Page[3]

[1]Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y 4A2, Canada
[2]Department of Oceanography, Dalhousie University, Halifax, Nova Scotia B3H 4J1, Canada
[3]Fisheries and Oceans Canada, St. Andrews Biological Station, St. Andrews, New Brunswick E5B 2L9, Canada

ABSTRACT: Scientific understanding of aquaculture interactions with the environment is limited, especially concerning the far-field transport and possible impacts of particulate wastes. A pilot study was carried out in southwest New Brunswick, Canada, in November 2008 to determine the size, settling velocity, and density of suspended particles at an active salmon aquaculture cage site. The model of Khelifa & Hill (2006) was fit to size-versus-settling velocity data to estimate the fractal dimension of flocs and the density of the component particles within flocs. Flocs had a larger fractal dimension and smaller component–particle density than in other studies, suggesting that particles from the aquaculture operation may be incorporated into suspended flocs with average settling velocities of 1 mm s^{-1}. Variability in particle size and packaging was interpreted in the context of near bed velocity, tidal stage, and wind speed and direction. This analysis indicated that advection dominated observed variations in particle size and packaging. Indicators of resuspension, aggregation, disaggregation, and deposition were not detected in the time series. Advection of flocs away from the study site provides a mechanism to transport wastes over distances greater than 1 km prior to deposition; thus a settling class of 1 mm s^{-1} should be considered in depositional models of aquaculture wastes.

KEY WORDS: Aquaculture · Flocs · Particle size · Size-versus-settling velocity · Effective density · Waste transport

INTRODUCTION

As of 2007, over 75% of the world's natural fish stocks were overexploited (Food and Agriculture Organization data 2007, www.fao.org). To meet the demand of the world for fish and to lessen the pressure on over-exploited fish stocks, aquaculture has grown rapidly over the last quarter century. Aquaculture operations in Canada doubled from 1996 to 2007, and by 2007 the industry was generating almost one billion dollars annually in 'landings' (Aquaculture Canada data 2007, www.aquacultureassociation.ca). In 2009, aquaculture in Canada produced about 155 000 tonnes, 76% of which was finfish. Of that, 95% was farmed salmon.

With the expansion of salmon farming, environmental concerns have been raised regarding the fate of aquaculture waste materials such as feed pellets and fecal material. To date, research has focused primarily on the deposition of organic waste immediately under or adjacent to salmon net pens, termed the 'near-field'. Increasingly accurate models use the settling characteristics of feed pellets and feces to map the areal extent of the near-field depositional footprint under net pens (Panchang et al. 1997, Cromey et al. 2002, Chamberlain & Stucchi 2007).

*Corresponding author: brent.law@mar.dfo-mpo.gc.ca

Publisher: Inter-Research · www.int-res.com

The settling velocities of fecal material and pellets, determined primarily from laboratory studies, are fast (40 and 100 mm s^{-1}, respectively), so the depositional footprint of this waste material usually does not extend more than several hundred meters from the pen (Chen et al. 1999, Cromey et al. 2002, Sutherland et al. 2006). The far-field, which can extend several km away from farming operations, has received less attention (Chamberlain & Stucchi 2007, Droppo et al. 2007, Reid et al. 2009). Transport of waste to the far-field may occur by advection of finer, slower-sinking suspended particles away from the pens or by post-depositional resuspension and transport of degraded feces and pellets from under the net pens. Measurements of finer, slower-sinking particles near salmon aquaculture pens are lacking, however, which limits understanding of potential far-field impacts.

In the ocean, settling of fine-grained particulate material is affected by the process of flocculation, which is the aggregation of small particles into larger, faster-settling agglomerations known as 'flocs' (Kranck 1973, McCave 1984, Kranck & Milligan 1985, Milligan & Kranck 1992, Milligan et al. 2007). The controls on flocculation include particle encounter rate, which depends nonlinearly on concentration, particle contact efficiency and stickiness, and particle break-up due to turbulence (Hill 1996, Milligan & Law 2005, Hill et al. 2013). Large particle concentrations, large particle stickiness, and low-to-moderate turbulent shear increase flocculation rates, which in turn increase the settling velocity and associated vertical flux of fine-grained material to the seabed. In contrast to faster-sinking waste material such as pellets and fecal material, flocs *in situ* generally have settling velocities on the order of 1 mm s^{-1} (Hill et al. 2001, Fox et al. 2004, Curran et al. 2007).

Based on interpretation of particle size distributions from a core collected near a site of salmon net pens in the L'Etang Inlet in the Bay of Fundy in New Brunswick, Canada, Milligan & Law (2005) showed that an increase in the fraction of fine sediment deposited in flocs coincided in time with the placement of pens. Grain size distributions in grab samples of surficial sediments showed that floc deposition increased throughout the areas of mud deposition in the inlet, both in the near- and far-fields. Milligan & Law (2005) attributed the increase in floc deposition to increases in particle concentration and stickiness associated with salmon aquaculture. They inferred that concentrations increased because of the introduction of fine particles shed from feed and feces, and stickiness increased because of the organic nature of the introduced particles. The study of Milligan & Law (2005) provides evidence that small particles associated with salmon feed and waste interact with natural suspended particles to form flocs that can be transported from the near-field to the far-field.

Transport of flocs away from aquaculture sites may degrade the health of a bay or inlet because contaminants are generally transported within flocs to the marine environment (Milligan & Loring 1997, Milligan & Law 2013). Because flocs typically contain large amounts of organic material, they are a preferred source of food for suspension-feeding organisms such as scallops, clams, and mussels (Ward et al. 1994, Cranford et al. 2005, Kach & Ward 2008). Incorporation of contaminants into these flocs therefore makes the contaminants readily available for ingestion by filter feeding organisms.

Elevated levels of trace metals and organic matter have been documented in several studies around salmon aquaculture operations (Schendel et al. 2004, Smith et al. 2005, Sutherland et al. 2006, Dean et al. 2007, Milligan & Law 2013). In these studies, elevated concentrations of metals such as zinc (Zn) and phosphorus (P) have been linked to feed pellets and fecal material, while elevated concentrations of copper (Cu) have been linked to increases in anthropogenic inputs such as anti-fouling paints. Metals such as molybdenum (Mo) and cadmium (Cd) in concentrations exceeding background levels have been linked to the precipitation of authigenic phases, usually in the presence of anoxia in the sediments associated with large organic loading to the seabed around fish farms (Smith et al. 2005). Floc transport away from net pens may transport these contaminants into the far-field, potentially affecting ecosystem health.

The relationships between flocculation, settling, and contaminants indicate that understanding of floc size, settling velocity and density may be required for accurate modeling of the far-field fate of aquaculture wastes, but *in situ* measurements of these parameters at aquaculture sites are limited (Reid et al. 2009). Understanding these parameters will not only improve predictive modeling capability for the far-field, but will also enhance the design and integration of Integrated Multi-trophic Aquaculture Systems (IMTA), in which particle wastes are utilized by farmed suspension feeders such as mussels, and excess nutrients are utilized by farmed macroalgae (Reid et al. 2009). Particle size and packaging information is needed to help determine which species can be grown at an IMTA site, and particle settling and transport information is needed to determine optimal locations for particle interception by selected species.

We used optical instrumentation to measure the particle size, particle packaging, and settling velocity of material in suspension at an area of active salmon farming. These data were combined with physical forcing data such as current velocity, wind speed and direction and water temperature to explore the mechanisms controlling the particle size at the farm site. The size-versus-settling velocity data were fit with a model developed by Khelifa & Hill (2006) to determine the effective *in situ* density of particles, and a floc size-versus-density relationship was constructed.

MATERIALS AND METHODS

Overview

Particle size, settling velocity, and particle packaging of suspended material was measured *in situ* at an area of active salmon aquaculture in Charlie Cove, southwest New Brunswick, Canada (Fig. 1). Charlie Cove is sheltered from the outer Bay of Fundy by small islands around the site. The bathymetry at the site is sloped, with water depths ranging from 18 m at the landward side to 33 m at the seaward end. The average water depth is approximately 23 m; tidal range is 6 m during spring tides. The aquaculture site occupies an area of about 400 m in length by about 200 m in width, and is made up of 8 circular pens, 50 m in diameter in 2 parallel rows of 4. At the landward end is an IMTA site where mussels are grown on lines adjacent to the pens.

For 1 wk in November 2008, a custom digital floc camera (DFC), a Sequoia Scientific LISST 100X type C (LISST) and digital video camera (DVC) with attached settling column were deployed at the Charlie Cove salmon aquaculture site. The DFC and LISST were mounted side-by-side on an aluminum frame, and were tied off to the outside edge of the salmon pen on the landward side of the site. The DFC and LISST were always 7 m below the sea surface and measured the particle stream entering and exiting the cage site, depending whether the tide was flooding or ebbing. The DFC and LISST were deployed at 17:00 h GMT on 24 November (i.e. year day 329) and recovered 2 d later, at which time the battery pack of the DFC was changed, and the LISST and DFC particle size data were downloaded. The DFC and LISST pair were then returned to the same location and water depth early on 28 November and finally recovered on 1 December (year day 336).

The DVC with settling column was mounted on a frame and placed on the seabed, directly under the outside edge of the cage, immediately below the DFC and LISST. Current velocity measurements were made throughout the study period using a 1200 KHz,

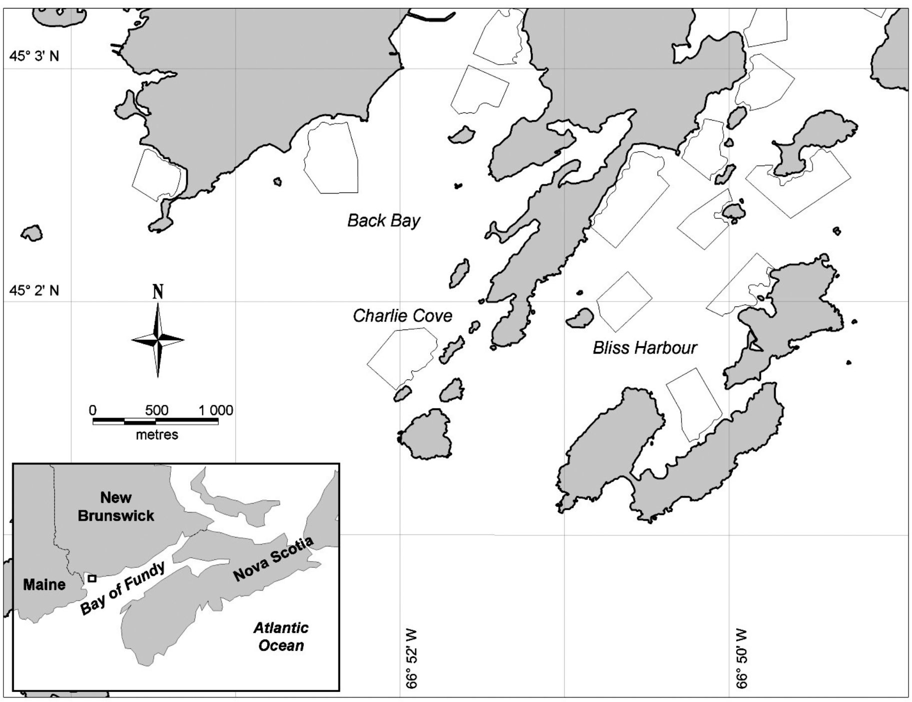

Fig. 1. Southwest New Brunswick, showing the study site at Charlie Cove. Aquaculture sites are outlined by gray lines

RD Instruments acoustic Doppler current profiler (ADCP), which was positioned 5 m off the bottom and in a downward-facing position to resolve the near-bottom current velocity. The ADCP was positioned adjacent to the DVC.

Particle size distributions

The LISST measured suspended particle sizes from 2.50 to 500 µm. The DFC had a resolvable size range from ~45 µm to 40 mm in diameter. Data from the 2 instruments were merged to provide a size distribution that extended across most of the particulate size ranges found in the ocean (Mikkelsen et al. 2005, Curran et al. 2007, Hill et al. 2013). The LISST measured the intensity of light (670 nm) scattered by particles onto 32 logarithmically-spaced ring detectors. It also measured the amount of light that was was transmitted across a 5 cm path-length. The patterns of scattered light were inverted into particle size distributions using instrument-specific calibrations based on the scattering patterns for particles of known size and volume concentrations (Agrawal & Pottsmith 2000, Mikkelsen et al. 2005). Assuming spherical geometry, the particle size distributions were converted to area and volume distributions. Sequoia Scientific's spherical-shape matrix was used to invert the data. LISST volume and area concentrations were estimated every 10 min, and were calculated based on the average of 12 burst samples comprising 100 measurements each.

The DFC captured silhouette images of suspended particles every 10 min on the same schedule as the LISST. The field of view for the DFC was 4 × 4 cm, with the depth-of-field set at 2.5 cm. The pixel size for the DFC was approximately 15 µm, and using 9 pixels (3 × 3) to define a particle, the minimum resolvable particle diameter was approximately 45 µm. For each image, an area of interest (AOI) was selected that was relatively free of gradients in lighting or debris and organisms on the camera's glass plates. The images were cropped to the AOI, and for each image the threshold greyscale value used to define particle edges from the image background was defined using Otsu's method of particle edge detection to create a binary image (Otsu 1979). The particle areas in each image were converted to equivalent spherical volumes. Particle areas and volumes were divided into 35 logarithmically-spaced diameter bins. For a complete description of the image analysis and particle size distribution processing of the DFC images, see Mikkelsen et al. (2004).

Entropy analysis

Entropy analysis was used to separate particle size distributions into groups. The analysis formed groups in which similarity within groups was maximal, as were differences among groups (Curran et al. 2007, Mikkelsen et al. 2007, Li et al. 2011). The number of groups was user-defined. There are 5 major processes that affect particle size in coastal waters: resuspension, deposition, aggregation, disaggregation, and advection (e.g. Hill et al. 2013). A total of 5 groups were selected to explore if there was evidence of these 5 processes governing size distributions during the deployment. For a complete description of entropy analysis and its application to marine particle size distributions, see Mikkelsen et al. (2007). For a description of ways to choose the number of groups for analysis, see deGelleke et al. (2013).

Particle parameters in each group were calculated and compared. Specifically, macrofloc, microfloc, and single-grain fractions were calculated for each group (cf. Eisma 1986, Mikkelsen et al. 2006, Curran et al. 2007). Single grains (<33 µm) are transported and settle as individual grains. Microflocs (between 33 and 133 µm) are small, tightly packed flocs that are composed of single grains and organic matter. Macroflocs (>133 µm) are porous, loosely bound structures that are composed of microflocs, and have been shown to attain diameters of several thousand µm.

Particle size-versus-settling velocity

The size-versus-settling velocity of flocs was measured using a Sony DCR-VX2000 DVC held in a stainless steel pressure housing with an attached plexiglass settling column. The DVC settling column had a baffle installed at the top to minimize the flow disturbance of settling particles. The DVC used miniDV tapes to record 80 video clips, each 1 min in duration, recorded every 120 min for the duration of the deployment. The viewing volume of the DVC was 4.1 × 3.2 × 2.5 cm with a pixel size of 75 µm. For quality control in the image analysis, only particles that comprised 9 or more pixels were analyzed, so the minimum resolution was ~220 µm (3 × 3 pixels).

Particle size and settling velocity from the DVC were calculated for each of the 1 min clips. A sequence of 4 frames separated by 1 s was used to estimate, for each particle, the equivalent spherical diameter, settling distance, and settling time. In order for a particle to be included in the analysis, it had to be present in 3 of the 4 frames. Floc size-versus-settling velocity and floc size-versus-effective density relationships were constructed for the entire deployment (Fox et al. 2004, Curran et al. 2007, Hill et al. 2011).

Ancillary data

A 1200-KHz RDI ADCP was moored 5 m off the bottom in a downward-facing orientation and was positioned adjacent to the DVC and the DFC and LISST. The instrument collected magnitude and direction data at 5 cm bin intervals in the lower 4.4 m of the water. The first bin was 0.6 m below the transducer, which was considered the instrument blanking distance. The ADCP data were collected and averaged over 5 min intervals.

Shear stress (τ_b) is expressed as:

$$\tau_b = \rho(u_*)^2 \quad (1)$$

where ρ is the fluid density (in this case taken to be 1025 kg m^{-3}), and u_* is the shear velocity in m s^{-1}. Shear velocity can be estimated using the law of the wall defined by:

$$u_* = kU(z) / \ln(z / z_o) \quad (2)$$

where k is von Karman's constant (= 0.4), $U(z)$ (m s^{-1}) is the velocity at some height, z (m), above the bottom (in this case 1 m), and the roughness length, z_o (m), was taken to be 2.0×10^4 based on Soulsby's (1983) estimate for a muddy seabed. The value for z_o used in this study is the value used by Cromey et al. (2002) in the resuspension module of DEPOMOD, which is a model typically used to predict the depositional footprint of net pens.

Tidal amplitude was based on the prediction from DFO Webtide (Dupont et al. 2005) for Back Bay, which is immediately adjacent to the Charlie Cove aquaculture site. Wind direction and magnitude were obtained from the Environment Canada weather station in St. Stephen, NB, the closest station to the study site and representative of prevailing conditions. Conductivity, temperature and depth (CTD) casts were performed at the site opportunistically using a Sea-Bird 25. Water samples at the site were collected and filtered onto Millipore 8.0 µm filters, which have excellent trapping efficiency (Sheldon et al. 1972) and have been used to determine the disaggregated inorganic grain size in suspension (Law et al. 2008) when analyzed on a Coulter Counter Multisizer (Kranck & Milligan 1991, Milligan & Kranck 1991).

RESULTS

Winds at the study site were variable, with the highest speeds originating predominantly from the east to northeast, and reaching up to 30 km h^{-1} on the night of 25 November and morning of 26 November (year day 331). The remainder of the study had light and variable winds below 15 km h^{-1}, usually from the northeast or southwest (Fig. 2a,b). Due to lack of exposure to the open waters of the Bay of Fundy, the effect of wind waves at Charlie Cove was considered negligible and therefore not included in interpretation of the near-bed velocity measurements. Tidal current velocities at the site were generally less than 20 cm s^{-1}, with a mean tidal range of 5 m (Fig. 2c,d). Current direction was generally to the northeast during flood tides and to the southwest during ebb tides. Water density estimated from periodic CTD casts at the study site was 1025 kg m^{-3} based on a water temperature of 8.5°C and salinity of 32 PSU. Suspended sediment samples collected at the site had a median, disaggregated diameter of approximately 7 µm, which is similar to the bottom sediment. The seabed sediments at Charlie Cove were fine-grained mud with median diameter (D_{50}) values under the cage and at the side of the cage of 9.2 and 8.8 µm, respectively. These values were consistent over most of Charlie Cove, and there were no bed forms present in the vicinity of the aquaculture operations.

The DFC only collected images for the first 2 h of the first deployment and then failed. As a result, area and volume concentrations are based on LISST measurements alone. Particle size spectra based on area concentration, and to a lesser extent volume concentration, show diameter modes at approximately 6 and 300 µm (Fig. 3).

Particle area and volume distributions were used to calculate single grain (<33 µm), microfloc (33 to 133 µm), and macrofloc (>133 µm) fractions (Fig. 4). For the first deployment, the area concentration was dominated by the single grain fraction which represented approximately 75% of the suspension, whereas in the second deployment, single grains accounted for roughly 65 to 70% of the suspension. The macrofloc population dominated the volume concentration in both the first and second deployment and on average accounted for 65 to 70% and then 80% of the suspension, respectively (Fig. 4). Tidal signals in particle size were not evident in the time series of percentages of the single grain, microfloc and macrofloc populations. Just prior to year day 336 (1 Dec) there was a large increase in the macrofloc fraction with a corresponding decrease in

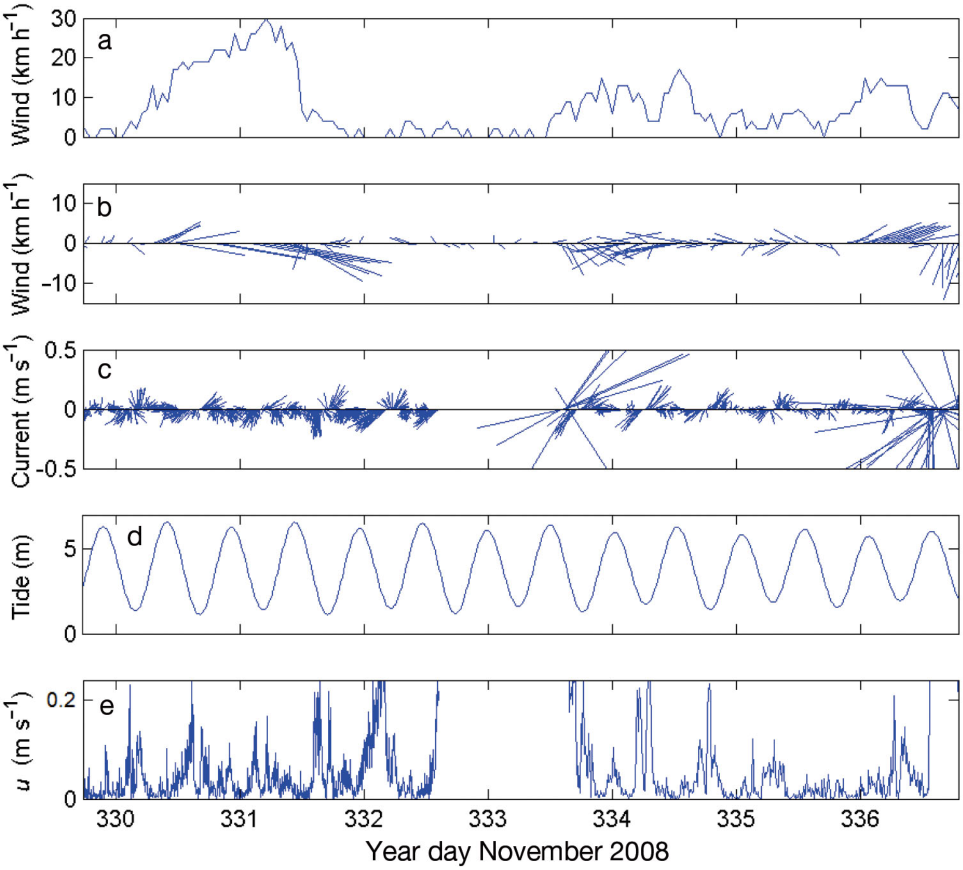

Fig. 2. Forcing conditions at the study site from year day 330 to 336, which extends from 25 November to 1 December 2008. (a) Wind speed, (b) wind speed and direction; positive values are winds from the south. (c) Current speed and direction at the site, with positive values indicating a flow from south to north. (d) Predicted tide at Back Bay, which is immediately adjacent to Charlie Cove. (e) Velocity 1 m above the bottom

the single grain fraction, and to a lesser extent a reduction in the microfloc fraction (Fig. 4). Over a 4 to 5 h period, the macrofloc population accounted for over 50% of the area concentration and over 95% of the concentration by volume (Fig. 4).

Averaged particle size distributions based on area and volume from 5 entropy groups were similar (Fig. 5). Groups 1 and 2 occurred during the first deployment, and they were finer than groups 3 and 4, which occurred during the second deployment. Compared to groups 1 and 2, groups 3 and 4 had smaller single-grain and microfloc fractions and larger macrofloc fractions (Table 1). Group 5, which was the coarsest group with a macrofloc fraction >90%, appeared during the 4 to 5 h period of larger particle sizes on year day 336 (Fig. 5). Group 5 distributions occurred at a time when wind stress remained low (close to 5 km h^{-1} for over 1 d), and during the only time when current velocities remained low (<0.10 m s^{-1} for longer than 12 h). Overall, however, groups did not correspond to specific stress levels or stages of the tide (Fig. 5).

The DVC produced 796 estimates of floc size-versus-settling velocity and floc size-versus-effective density (Fig. 6). Settling velocities ranged from 0.195 to 39.9 mm s^{-1} for floc sizes that ranged from 226.1 to 997.1 µm (Fig. 6a,b). The average size and settling velocity for the population of flocs measured during the deployment were 331 µm and 0.83 mm s^{-1}, respectively. Of the 796 flocs observed, 20 had settling velocities >2 mm s^{-1}, and only 8 (about 1% of the population) had floc settling velocities >10 mm s^{-1}. The commonly observed, order-of-magnitude scatter in settling velocities for a given particle diameter has been attributed to variable particle packaging and composition within flocs (e.g. Hill et al. 1998). Particle densities were calculated with a modified form of Stokes' Law (cf. Khelifa & Hill 2006).

The size-versus-settling data were fit to the model of Khelifa & Hill (2006) (Fig. 6a,b). The model describes settling velocity and density as a function of aggregate size (cf. Hill et al. 2011). The model requires inputs of water density, ρ, and dynamic viscosity, µ, which were estimated based on a mean temperacomponent grains. The fractal dimension describes a relationship between the diameter and mass of a particle, with the fractal dimension of largest aggregates *in situ* generally falling within a range of 1.8 to 2.4 (Hill et al. 1998, 2011, Sternberg et al. 1999, Fox et al. 2004). In this study, the value of F_{max} was 2.7 and ρ_s was 1060 kg m^{-3}.

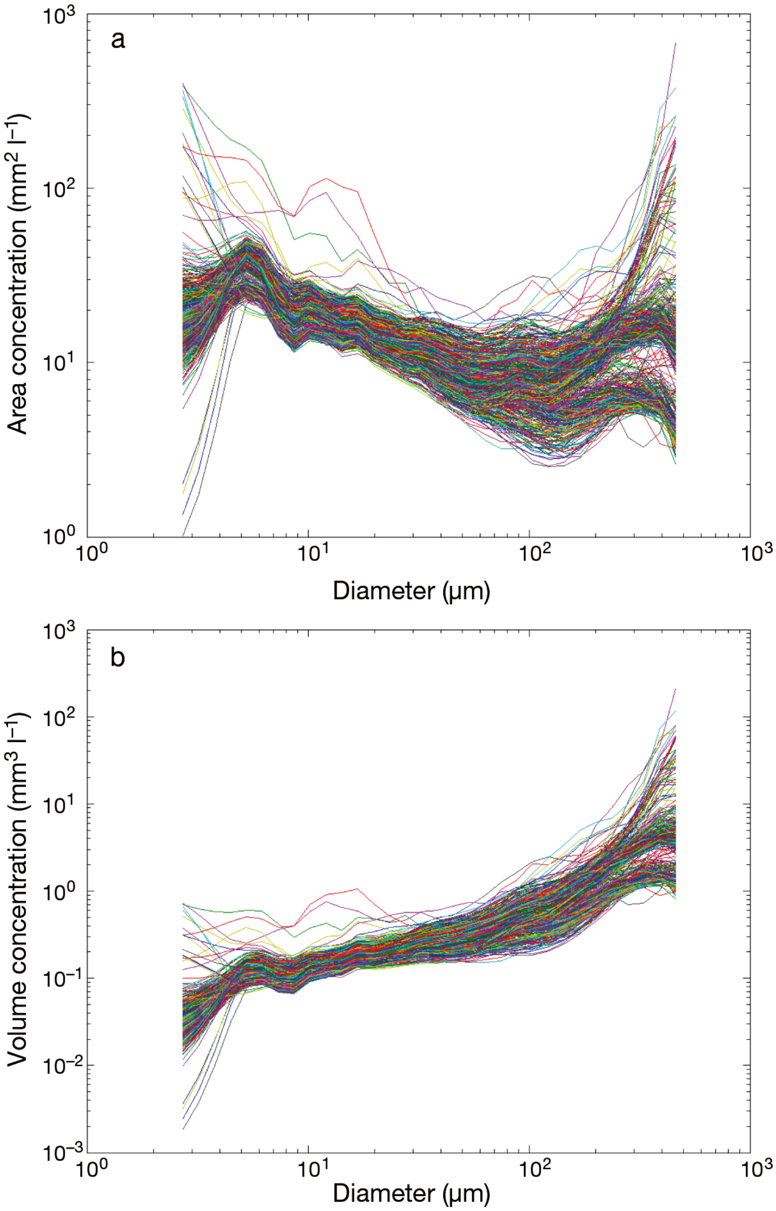

Fig. 3. LISST 100X particle size distributions for both (a) area concentration and (b) volume concentration

ture of 8.5°C and salinity of 32 PSU. It also requires the component particle diameter, D_c, and the diameter of the largest flocs in suspension, D_{max}. D_c was determined from the disaggregated inorganic grain size distribution (DIGS) in the water samples. It was taken as the volumetric mean diameter of the DIGS samples, which was 7 µm. D_{max} was determined as the 95th percentile of particle diameters observed with the DVC; its value was 594 µm. The model fit to the size-versus-settling velocity data yielded estimates of 2 parameters: F_{max}, the fractal dimension of largest flocs in suspension, and ρ_s, the density of the

DISCUSSION

Particle size and packaging

Floc size and abundance in the ocean is controlled by 5 basic mechanisms: advection, resuspension, aggregation, disaggregation, and deposition (Jago et al. 2006, Mikkelsen et al. 2006, Hill et al. 2013). A change in floc size or abundance due to advection is distinguishable when floc size is decoupled from bottom stress (Jago et al. 2006). Resuspension is distinguishable by coupling between floc size and seabed stress (Milligan et al. 2001, Fugate & Friedrichs 2003, Hill et al. 2013). Aggregation occurs when turbulence is low to moderate, and particle concentration is large (Milligan et al. 2007). The process of aggregation occurs most often in a tidally-dominated system during slack water, when the coincidence of elevated concentration and low to moderate turbulence allows flocs to grow (Jago et al. 2006). Disaggregation is the process of floc destruction and occurs under energetic conditions. Its signature is an inverse correlation between floc size and turbulence (Winterwerp 1998, Hill et al. 2001, Mikkelsen et al. 2006, 2007). Hill et al. (2001) reported that marine aggregates or flocs break up when turbulent stress is at or above 0.1 Pa. Deposition occurs when stress is low enough for flocs to settle from the water column, and is associated with decreases in concentration and overall particle size. As a suspension settles, however, a temporary increase in concentration near the seabed can occur (Milligan et al. 2001, Voulgaris & Meyers 2004, Mikkelsen et al. 2006, Hill et al. 2011).

Particle packaging at the study site was relatively consistent during deployment 1 and again during deployment 2, but the packaging observed during the 2 deployments differed, with entropy groups 1

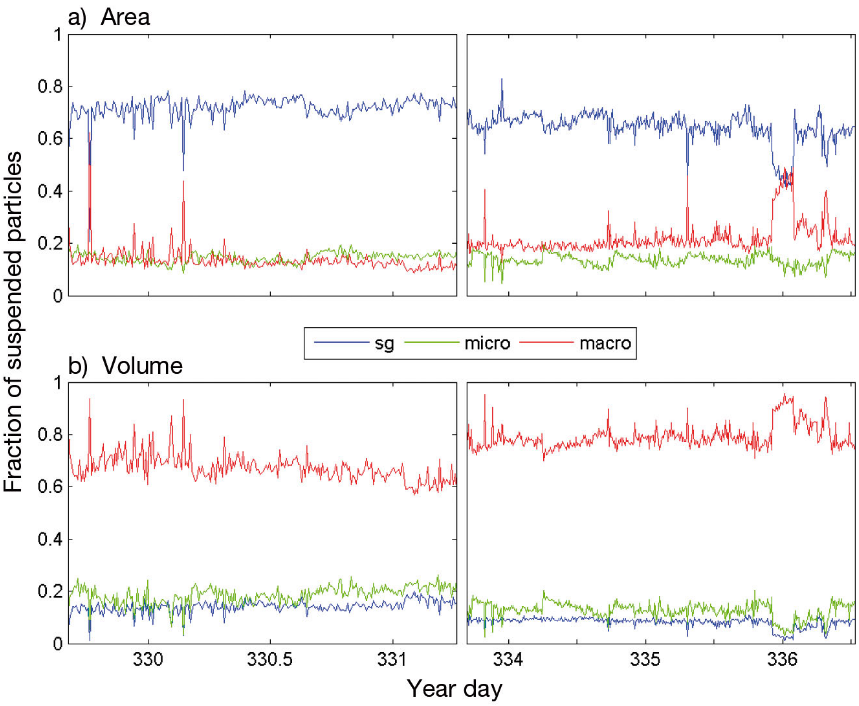

Fig. 4. Single grain (<33 µm), microfloc (between 33 and 133 µm), and macrofloc (>133 µm) fractions in suspension for (a) area and (b) volume based on the LISST 100X particle size distributions during 2 deployment periods (no. 1, left; no. 2, right)

and 2 appearing in deployment 1, and groups 3 and 4 appearing in deployment 2 (Fig. 5). The single grain fraction was smaller and macrofloc fraction was larger during the second deployment. The changes in particle size were not associated with changes in bottom shear stress, which were similar during the 2 deployments (Figs. 2, 4 & 5). Decoupling of particle size from shear stress is associated with advection of water masses with different particle populations (Jago et al. 2006).

Entropy group 5 was characterized by the largest macrofloc fraction. Size distributions in this group occurred at the end of year day 335, after a period of prolonged low winds and currents (Fig. 2). The co-occurrence of large particles and low energy is diagnostic of aggregation. Interestingly, the flocs in suspension at this time dominated the water column for just under 5 h. Based on average floc settling velocities of roughly 1 mm s^{-1}, it would take

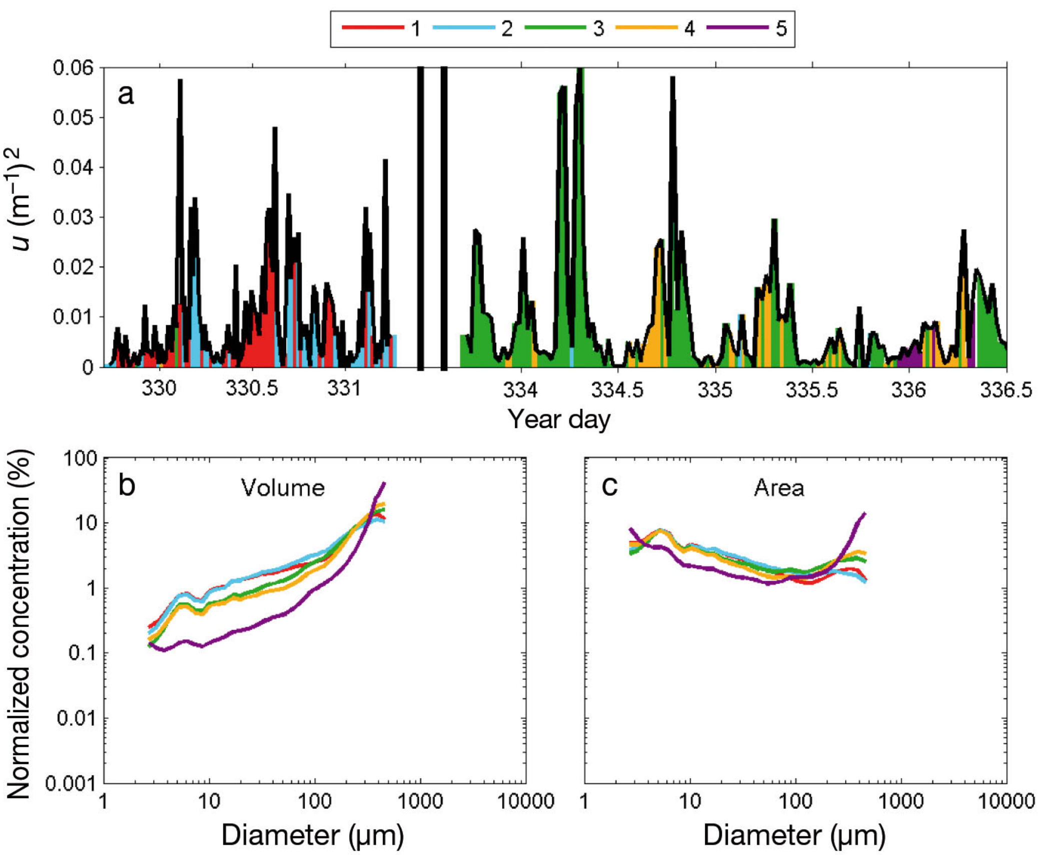

Fig. 5. Particle size distributions (n = 634) sorted into 5 groups using entropy analysis. (a) Particle size distribution within each group versus the square of the velocity from the acoustic Doppler current profiler (ADCP) for currents throughout the 2 deployment periods (no. 1, left; no. 2, right). (b,c) Mean particle size distributions per group, presented as normalized (b) volume and (c) area concentration. See Table 1 for percentages of single grains, microflocs and macroflocs in each group

Table 1. Results from the 5 entropy particle size groups and the percentages of single grains (SG), microflocs (Micro) and macroflocs (Macro) in each group

	Red	Blue	Green	Yellow	Purple
SG	14.4	14.2	9.0	8.2	2.7
Micro	20.4	24.8	18.3	13.8	6.5
Macro	65.2	61.0	72.7	78.1	90.8

about 5 h to clear a 20 m water column, roughly the average depth at our study site. Alternatively, the change in particle size during this event could also be due to advection. Time series of beam attenuation can help to resolve which process was the more likely cause of the change in particle size.

Beam attenuation (C_p) has been successfully used as a proxy for mass concentration in suspension (e.g. Boss et al. 2009a). C_p generally is not sensitive to changes in particle size caused by aggregation or disaggregation, so changes in C_p usually result from resuspension, deposition or advection (Boss et al. 2009b, Hill et al. 2011). In this study, C_p was generally just above 2 m^{-1} for the first deployment of the LISST and just below 4 m^{-1} for the second deployment (Fig. 7b). This change in C_p between deployments can be explained by advection. The appearance of entropy group 5 at the end of year day 335 was associated with an increase in C_p. Changes in particle size due to aggregation alone should not create significant changes in C_p (as evident by a jump in C_p from ~3 to 10 m^{-1}), so it is likely that this event was due to advection of a water mass with different particles.

Increases in C_p occurred generally on flood tides and were mainly associated with small changes in water temperature, another indication that particles could have been advected into the study site (Figs. 2 & 7). Water sampling as part of a companion study (Milligan & Law 2013) showed background suspended particulate matter below 2 mg l^{-1} during year day 330, and below 3 mg l^{-1} during year day 335. Despite the low number of water samples, the change in concentration supports the hypothesis that the water mass at the study site changed between the 2 LISST deployments.

Evidence for a limited role for resuspension in shaping particle size distributions is available in the time series of shear velocity. Shear velocity remained below 0.01 m s^{-1} for the entire deployment period and was lower than 0.005 m s^{-1} for long periods of time (Fig. 7a). Fluff layers, primarily composed of flocs, can be resuspended by shear velocities as low as approximately 0.003 m s^{-1} (Law et al. 2008, Milligan & Law 2013), but more consolidated marine muddy bottom sediments have been shown to resuspend at shear velocities as low as 0.006 m s^{-1} (Schaaff et al. 2006) although they generally require shear velocities to be greater than 0.009 m s^{-1} (Wiberg et al. 1994, Maa et al. 1998, Law et al. 2008, Dickhudt et al. 2011). A bottom shear velocity of 0.009 m s^{-1} was rarely exceeded during the deployment period, and when seabed shear velocity did approach 0.01 m s^{-1} during year day 334, there was no corresponding increase in floc size, abundance, or suspended mass concentration, which would be indicative of resuspension at the study site (Fig. 7).

Data from NOAA Buoy 44027 (not shown), which is located 20 nautical miles SE of Jonesport, Maine, indicate that a large wave event (up to 6 m) with long period swell (>10 s) went through the area on 26 and 27 November (year day 331 and 332), not long before the end of the first deployment. This event offers an alternative hypothesis to that of the

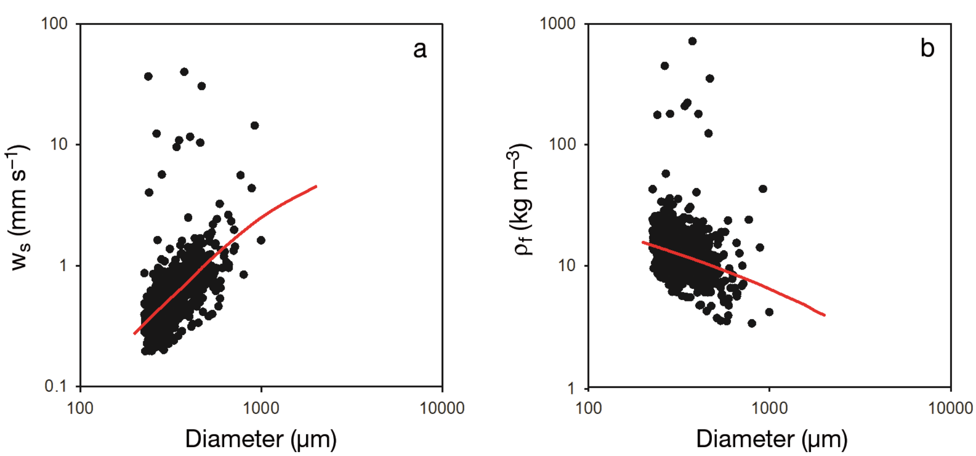

Fig. 6. Unbinned particle (a) size-versus-settling velocity (w_s) and (b) size-versus-effective density (ρ_f). The particle effective densities were estimated using a modified Stokes' Law. The red line in each of the panels represents the Khelifa & Hill (2006) fit of the data

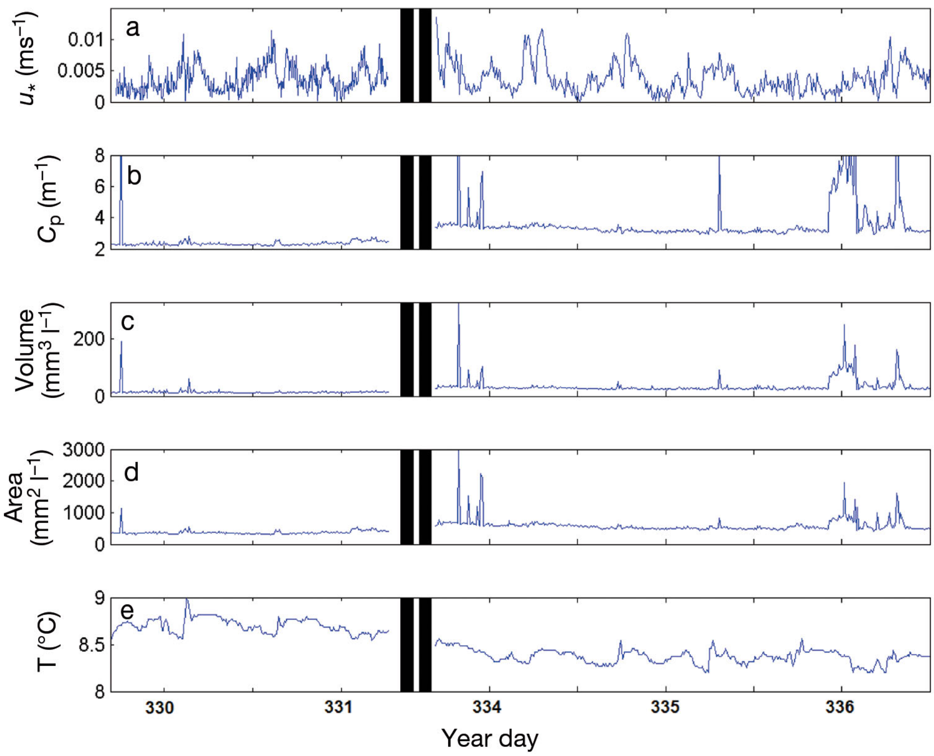

Fig. 7. (a) Shear velocity (u_*) calculated over the study period (deployment 1, left; deployment 2, right) using the law of the wall and a bottom roughness parameter of 2.0×10^{-4} from Soulsby (1983) for a muddy seabed; the next 4 panels show (b) beam attenuation (C_p), (c) volume concentration, (d) area concentration and (e) water temperature, all collected by the LISST over the study period

advection of particles and may explain the different particle sizes and beam attenuation coefficients between deployments 1 and 2. While the instruments were not in the water, the large wave event may have resuspended bottom sediment in the region. Therefore, concentrations may have been larger during the second deployment because freshly resuspended material had not yet settled. There were no operations directly related to aquaculture activities such as feeding or cleaning of net pens that could be hypothesized as a reason for changes in mass concentration.

Size-versus-settling velocity

The values of F_{max} and ρ_s from this study are higher and lower, respectively, than published literature values for these parameters. The low density of ρ_s suggests that they were rich in organic matter, whereas the high value of F_{max} indicates that the aggregate components were relatively tightly packed. F_{max} values of large flocs *in situ* generally fall within a range of 1.8 to 2.4, with an average value near 2 (Syvitski et al. 1995, Hill et al. 1998, 2011, Sternberg et al. 1999, Fox et al. 2004). Estimated densities of ρ_s ranged from 1150 kg m^{-3} in a study by Hill et al. (2011) to 1600 kg m^{-3} in the study of Curran et al. (2007). One hypothesis is that the lower estimated density of ρ_s within aggregates at our study site could have resulted from the release of fine organic particles into the water column from salmon aquaculture operations, either in the form of fecal material or bits of broken down feed. The relatively large F_{max} could have resulted from denser packing of feces in salmon digestive tracts or denser packing of feed during the production process. Alternatively, because this area of the Bay of Fundy is energetic, with limited inputs of fresh fine sediment, flocs may be densely packed due to multiple resuspension and deposition cycles. Feed and fecal material could have initially settled to the seabed, became consolidated and then reworked and resuspended into the water column, thus altering their initial conditions and making them small enough to be incorporated into flocs. The input of organic material may have also been from operations other than aquaculture.

Modelled floc effective densities ranged from 1030 to 1040 kg m^{-3} for floc sizes ranging from 200 to 2000 µm (Fig. 6b). These densities were similar to those found for fecal density in studies conducted by Ogunkoya et al. (2006) and Moccia et al. (2007). Both of these studies measured the properties of rainbow trout feces in the laboratory, and the observed densities ranged between 1022 and 1052 kg m^{-3}. Marked differences between this study and those of Ogunkoya et al. (2006) and Moccia et al. (2007) were seen in the settling velocities, but they can be explained by different sizes of settling particles among studies. Unfortunately, no particle size data accompanied the other studies. Moccia et al. (2007) reported settling velocities between 43.3 and 60.6 mm s^{-1}, while Ogunkoya et al. (2006) reported settling velocities of 27 to 34 mm s^{-1}. Our study observed a maximum settling velocity of 39.9 mm s^{-1}, and only 3 of the 796 measurements were >30 mm s^{-1}, which is generally used as the lower estimate of intact salmon fecal material settling velocity based on laboratory studies under controlled conditions. Chen et al. (1999) speculated that as fecal pellets settle in the water column they may break up into smaller pieces, which would slow their settling rate. The measurements of the size settling velocity in our study were made using a settling column and video that was sitting on the seabed in 20 m of water. Settling particles analyzed in this study would have been subjected to water column turbulence from the time they were released until they entered the settling column.

Possible implications for aquaculture waste transport

A review of the biophysical properties of salmonid feces and implications for waste dispersal models and IMTA by Reid et al. (2009) stated that information in the literature was limited on particle size, density, and the settling velocity of material in aquaculture cage environments. The estimated floc fractal dimension (which describes the packaging of material in suspension) in this study was higher than in previous studies in the marine environment (Mikkelsen et al. 2006, 2007, Curran et al. 2007, Hill et al. 2011, 2013). Also, the density of the component particles in flocs was lower at this study site compared to other floc populations measured in a variety of marine environments (Mikkelsen et al. 2006, 2007, Curran et al. 2007, Hill et al. 2011, 2013). Interestingly, they were similar to densities of aquaculture waste material described previously in laboratory studies (Ogunkoya et al. 2006, Moccia et al. 2007). Together, these observations provide indirect support for the hypothesis that particles associated with finfish aquaculture activities are incorporated into easily transported flocs (Milligan & Law 2005).

Floc sizes in this study were generally <600 µm based on observations from the DVC, with an average size of ~340 µm. Average floc settling velocities were approximately 1 mm s^{-1}, and although compositional data were not available, the flocs may have contained small bits of food or fecal material based on their estimated density. With an average water depth of 20 m and a floc settling velocity of 1 mm s^{-1}, it would take 20 000 s, or about 5 h, for a particle to settle to the seabed. At Charlie Cove, current velocities are regularly >10 cm s^{-1}. Based on a horizontal velocity of 10 cm s^{-1} and a settling time of 20 000 s, the horizontal distance a particle would travel would be on the order of 2 km — a distance larger than the normally defined near-field zone (<500 m) where aquaculture activities have documented effects on the environment. The 2 km estimated horizontal distance of travel for settling flocs is likely a minimum because it does not include post-depositional resuspension and transport of these organic-rich flocs.

A recent study by Graydon et al. (2012) around an aquaculture site in the southwest Isles region of New Brunswick showed the incorporation of aquaculture-derived waste material from feed pellets (canthaxanthin) in sea urchins 1 km from the active salmon farming cage site, both near the surface and 1 m off the bottom. The 1 km represented the farthest distance measured in that study. Graydon et al. (2012) hypothesized that a background concentration of pigments may exist from widespread dispersal of salmon-derived particles from all the salmon farms in the area. Sarà et al. (2004) used isotopic analysis to detect aquaculture waste material in the water column and in the seabed. They found evidence of farm-derived material at distances up to 1 km, which was also the furthest distance measured. Sarà et al. (2004) proposed that post-depositional resuspension and transport of waste explained the occurrence of waste in the far-field. If feed pellets are broken down either by the fish themselves during feeding or by hydrodynamic processes and are subsequently incorporated into flocs like those observed in this study, the calculations above show that transport distances of wastes could be greater than 1 km.

The modeling of aquaculture waste solid fraction has focused on the deposition of fecal material and feed pellets to the seabed. Models indicate that enhanced flux of these materials is limited to the near-field area <500 m from the cage edge (Findlay & Watling 1994, Cromey et al. 2002, Chamberlain & Stucchi 2007). Typical settling velocities used to model these components are 40 mm s^{-1} (feces) and 100 mm s^{-1} (feed), respectively. These particles were not completely resolved in this study because the maximum observable settling velocity by the DVC as configured approached that of fecal settling as previously determined in laboratory studies. Feces and feed have been observed *in situ* and obviously need to be included in aquaculture waste models. Observations here indicate that flocs captured near an aquaculture site were different from those observed in other marine environments. They sank at roughly 1 mm s^{-1} and may provide a mechanism for exporting aquaculture-derived waste material to the far-field. Based on these findings, flocs should also be considered in aquaculture waste transport models. Models such as DEPOMOD or other transport models could include material that sinks at 1 mm s^{-1}, in addition to the already included feed pellets (100 mm s^{-1}) and fecal material (40 mm s^{-1}).

To fully elucidate the particle size, packaging, composition and settling velocity of material around aquaculture sites, further studies are required. Isotopic analysis as performed by Sarà et al. (2004) may prove useful for quantifying the amount of aquaculture-derived particles in each of the proposed classes of waste material (i.e. those that settle at 100, 40 and 1 mm s^{-1}). These studies should be conducted in areas in close proximity to farming operations as well as in background sites remote from farming operations.

The inferred dominant process influencing floc properties during this study was advection. Clear indicators of resuspension, aggregation, disaggregation, and deposition were not detected. The dominance of advection may have been due to our relatively sheltered study site, which had moderate tidal currents and water depths that limited the effects of wave resuspension. It would be beneficial to cover the entire range of hydrodynamic conditions that could be experienced at farming operations in the southwest Isles region of New Brunswick. In this region, winter storms produce high winds and large waves that have the potential to resuspend and transport waste material from under cage sites. This full range of hydrodynamic conditions would help to capture and quantify the 5 mechanistic processes that control particle size and transport.

CONCLUSIONS

Particle size and packaging are controlled in the marine environment by the processes of advection, resuspension, aggregation, disaggregation and deposition. At the Charlie Cove site in the macrotidal Bay of Fundy, particle size and concentration were controlled generally by advection, although resuspension of material between the first and second deployments could not be ruled out.

The size-versus-settling velocity data collected with the DVC and attached settling column were fit to the model of Khelifa & Hill (2006) to produce a floc size-versus-density relationship. Component particles had an estimated density of 1060 kg m^{-3}, and the fractal dimension of the largest particles was 2.7. These parameters suggest that the flocs observed at this site were tightly packed and had low densities, typical of organic matter. These values differed from those in the published literature where observations were made in the absence of aquaculture-related activities. The effective densities of particles observed in this study were comparable to those obtained from studies on fish fecal matter observed in previous lab studies.

The average settling velocity of aggregates observed in this study was on the order of 1 mm s^{-1}. This settling velocity, combined with current velocities of 10 cm s^{-1} would mean that flocs could have been transported over distances of ~2 km. We propose that flocs that settle on the order of 1 mm s^{-1}, in addition to settling fecal material and feed, be included in aquaculture waste transport models to elucidate the entire particle population.

Acknowledgements. This research was supported by the Department of Fisheries and Oceans, Center for Aquaculture Integrated Science Fund awarded to B.A.L. and F.P. Sincere thanks to Randy Losier and Shawn Roach for field support and sampling, and to John Newgard for help with the entropy analysis and Khelifa & Hill (2006) model applications.

LITERATURE CITED

Agrawal YC, Pottsmith HC (2000) Instruments for particle size and settling velocity observations in sediment transport. Mar Geol 168:89–114

Boss E, Slade WH, Hill PS (2009a) Acceptance angle effects on the beam attenuation in the ocean. Opt Express 17: 1535–1550

Boss E, Slade W, Hill P (2009b) Effect of particulate aggregation in aquatic environments on the beam attenuation and its utility as a proxy for particulate mass. Opt Express 17:9408–9420

Chamberlain J, Stucchi D (2007) Simulating the effects of parameter uncertainty on waste model predictions of marine finfish aquaculture. Aquaculture 272:296–311

Chen YS, Beveridge MCM, Telfer TC (1999) Settling rate characteristics and nutrient content of the faeces of Atlantic salmon, *Salmo salar*, L. and the implications for modelling of solid waste dispersion. Aquacult Res 30: 395–398

Cranford PJ, Armsworthy SL, Mikkelsen OA, Milligan TG (2005) Food acquisition responses of the suspension-feeding bivalve *Plactopecten magallanicus* to the flocculation and settlement of a phytoplankton bloom. J Exp Mar Biol Ecol 326:128–143

Cromey CJ, Thomas TD, Black KD (2002) DEPOMOD—modelling the deposition and biological effects of waste solids from marine cage farms. Aquaculture 214:211–239

Curran KJ, Hill PS, Milligan TG, Mikkelsen OA, Law BA, Durrieu de Madron X, Bourrin F (2007) Settling velocity, effective density, and mass composition of suspended sediment in a coastal bottom boundary layer, Gulf of Lions, France. Cont Shelf Res 26:2299–2318

Dean RJ, Shimmield TM, Black KD (2007) Copper, zinc and cadmium in marine cage fish farm sediments: an extensive survey. Environ Pollut 145:84–95

deGelleke L, Hill PS, Kineast M, Piper DJW (2013) Sediment dynamics during Heinrich event H1 inferred from grain size. Mar Geol 336:160–169

Dickhudt PJ, Friedrichs CT, Sanford LP (2011) Mud matrix solids fraction and bed erodibility in the York river estuary, USA and other muddy environments. Cont Shelf Res 31(Suppl):S3–S13

Droppo I, Jaskot C, Nelson T, Milne J, Charlton M (2007) Aquaculture waste sediment stability: implications for waste migration. Water Air Soil Pollut 183:59–69

Dupont F, Hannah CG, Greenberg D (2005) Modelling the sea level in the upper Bay of Fundy. Atmos-Ocean 43: 33–47

Eisma D (1986) Flocculation and de-flocculation of suspended matter in estuaries. Neth J Sea Res 20:183–199

Findlay RH, Watling L (1994) Toward a process level model to predict the effects of salmon net-pen aquaculture on the benthos. In: Hargrave BT (ed) Modelling benthic impacts of organic enrichment from marine aquaculture. Can Tech Rep Fish Aquat Sci 1949:47–77

Fox JM, Hill PS, Milligan TG, Boldrin A (2004) Flocculation and sedimentation on the Po River Delta. Mar Geol 203: 95–107

Fugate DC, Friedrichs CT (2003) Controls on suspended aggregate size in partially mixed estuaries. Estuar Coast Shelf Sci 58:389–404

Graydon CM, Robinson SMC, Scheibling RE, Cooper AJ (2012) Canthaxanthin as a potential tracer of salmon feed in mussels (*Mytilus* spp.) and sea urchins (*Strongylocentrotus droebachiensis*). Aquaculture 366–367:90–97

Hill PS (1996) Sectional and discrete representation of floc breakage in agitated suspensions. Deep-Sea Res I 43: 679–702

Hill PS, Syvitski JP, Cowan EP, Powell RD (1998) In situ observations of floc settling velocities in Glacier Bay, Alaska. Mar Geol 145:85–94

Hill PS, Voulgaris G, Trowbridge JH (2001) Controls on floc size in a continental shelf bottom boundary layer. J Geophys Res 106:9543–9549

Hill PS, Boss E, Newgard JP, Law BA, Milligan TG (2011) Observations of the sensitivity of beam attenuation to particle size in a coastal bottom boundary layer. J Geophys Res 116:C02023

Hill PS, Newgard JP, Law BA, Milligan TG (2013) Flocculation on a muddy intertidal flat in Willapa Bay, Washington, Part II: observations of suspended particle size in a secondary channel and adjacent flat. Cont Shelf Res 60(Suppl):S145–S156

Jago CF, Jones SE, Sykes P, Rippeth T (2006) Temporal variation of suspended particulate matter and turbulence in a high energy, tide-stirred, coastal sea: relative contributions of resuspension and disaggregation. Cont Shelf Res 26:2019–2028

Kach DJ, Ward JE (2008) The role of marine aggregates in the ingestion of picoplankton-size particles by suspension-feeding molluscs. Mar Biol 153:797–805

Khelifa A, Hill PS (2006) Models for effective density and settling velocity of flocs. J Hydraul Res 44:390–401

Kranck K (1973) Flocculation of suspended sediment in the sea. Nature 246:348–350

Kranck K, Milligan TG (1985) Origin of grain size spectra of suspension deposited sediment. Geo-Mar Lett 5:61–66

Kranck K, Milligan TG (1991) Grain size in oceanography. In: Syvitski JPM (ed) Principles, methods, and application of particle size analysis. Cambridge University Press, New York, NY, p 332–345

Kranck K, Milligan TG (1992) Characteristics of suspended particles at an 11-hour anchor station in San Francisco Bay, California. J Geophys Res Oceans 97:11373–11382

Law BA, Hill PS, Milligan TG, Curran KJ, Wiberg PL, Wheatcroft RA (2008) Size sorting of fine-grained sediments during erosion: results from the western Gulf of Lions. Cont Shelf Res 28:1935–1946

Li Z, Lee K, King T, Niu HB, Boufadel MC, Venosa AD (2011) Application of entropy analysis of *in situ* droplet-size spectra in evaluation of oil chemical dispersion efficacy. Mar Pollut Bull 62:2129–2136

Maa JPY, Sanford LP, Halka JP (1998) Sediment resuspension characteristics in Baltimore Harbour, Maryland. Mar Geol 146:137–145

McCave IN (1984) Size spectra and aggregation of suspended particles in the deep ocean. Deep-Sea Res 31: 329–352

Mikkelsen OA, Milligan TG, Hill PS, Moffatt D (2004) INSSECT—an instrumented platform for investigating floc properties close to the seabed. Limnol Oceanogr Methods 2:226–236

Mikkelsen OA, Hill PS, Milligan TG, Chant RJ (2005) In situ particle size distributions and volume concentrations from a LISST-100 laser particle sizer and a digital floc camera. Cont Shelf Res 25:1959–1978

Mikkelsen OA, Hill PS, Milligan TG (2006) Single-grain, microfloc and macrofloc volume variations observed with a LISST-100 and a digital floc camera. J Sea Res 55: 87–102

Mikkelsen OA, Curran KJ, Hill PS, Milligan TG (2007) Entropy analysis of in situ particle size spectra. Estuar Coast Shelf Sci 72:615–625

Milligan TG, Kranck K (1991) Electroresistance particle size analyzers. In: Syvitski JPM (ed) Principles, methods, and application of particle size analysis. Cambridge University Press, New York, NY, p 109–118

Milligan TG, Law BA (2005) The effect of marine aquaculture on fine sediment dynamics in coastal inlets. In: Hutzinger O (ed) The handbook of environmental chemistry, Vol 5: water pollution. Springer-Verlag, Berlin, p 239–251

Milligan TG, Law BA (2013) Contaminants at the sediment-water interface: implications for environmental impact assessment and effects monitoring. Environ Sci Technol 47:5828–5834

Milligan TG, Loring DH (1997) The effect of flocculation on the size distributions of bottom sediment in coastal inlets: implications for contaminant transport. Water Air Soil Pollut 99:33–42

Milligan TG, Kineke GC, Blake AC, Alexander CR, Hill PS (2001) Flocculation and sedimentation in the ACE basin, South Carolina. Estuaries 24:734–744

Milligan TG, Hill PS, Law BA (2007) Flocculation and the loss of sediment from river plumes. Cont Shelf Res 27: 309–321

Moccia RD, Bevan DJ, Reid GK (2007) Composition of feed and fecal waste from commercial trout farms in Ontario: physical characterization and relationship to dispersion and deposition modeling. Technical Report for Environment Canada. Ontario Sustainable Aquaculture Working Group, University of Guelph

Ogunkoya AE, Page GI, Adewolu MA, Bureau DP (2006) Dietary incorporation of soybean mael and exo-genous enzyme cocktail can affect physical characteristics of faecal material egested by rainbow trout (*Oncorhynchus mykiss*). Aquaculture 254:466–475

Otsu N (1979) A threshold selection method from gray-level histograms. Syst Man Cybern 9:62–66

Panchang V, Cheng G, Newell C (1997) Modeling hydrodynamics and aquaculture waste transport in coastal Maine. Estuaries 20:14–41

Reid GK, Liutkus M, Robinson SMC, Chopin TR and others (2009) A review of the biophysical properties of salmonid faeces: implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture. Aquacult Res 40:257–273

Sarà G, Scilipoti D, Milazzo M, Modica A (2004) Effects of fish farming waste to sedimentary and particulate organic matter in a southern Mediterranean area (Gulf of Castellammare, Sicily): a multiple stable isotope study ($\delta^{13}C$ and $\delta^{15}N$). Aquaculture 234:199–213

Schaaff E, Grenz C, Pinazo C, Lansard B (2006) Field and laboratory measurements of sediment erodibility: a comparison. J Sea Res 55:30–42

Schendel KE, Nordstrom SE, Lavkulich LM (2004) Floc and sediment properties and their environmental distribution from a marine fish farm. Aquacult Res 35:483–493

Sheldon RW, Prakash A, Sutcliffe WH Jr (1972) The size distribution of particles in the ocean. Limnol Oceanogr 17: 327–339

Smith JN, Yeats PA, Milligan TG (2005) Sediment geochronologies for fish farm contaminants in Lime Kiln Bay, Bay of Fundy. In: Hutzinger O (ed) The handbook of environmental chemistry, Vol 5: water pollution. Springer-Verlag, Berlin, p 221–238

Soulsby RL (1983) The bottom boundary layer of shelf seas. In: Johns B (ed) Physical oceanography of coastal and shelf seas. Elsevier, New York, NY, p 189–266

Sternberg RW, Berhane I, Ogston AS (1999) Measurement of size and settling velocity of suspended aggregates on the Northern California continental shelf. Mar Geol 154:43–54

Sutherland TF, Amos CL, Ridley C, Droppo IG, Petersen SA (2006) The settling behaviour and benthic transport of fish feed pellets under steady flows. Estuaries Coasts 29: 810–819

Syvitski JPM, Asprey KW, Leblanc KWG (1995) In-situ characteristics of particles settling within a deep-water estuary. Deep-Sea Res II 42:223–256

Voulgaris G, Meyers ST (2004) Temporal variability of hydrodynamics, sediment concentration and sediment settling velocity in a tidal creek. Cont Shelf Res 24:1659–1683

Ward JE, Newell RIE, Thompson RJ, MacDonald BA (1994) *In vivo* studies of suspension-feeding processes in the eastern oyster, *Crassostrea virginica* (Gmelin). Biol Bull (Woods Hole) 186:221–240

Wiberg PL, Drake DE, Cacchione DA (1994) Sediment resuspension and bed armoring during high bottom stress events on the northern California inner shelf: measurements and predictions. Cont Shelf Res 14:1191–1219

Winterwerp JC (1998) A simple model for turbulence induced flocculation of cohesive sediment. J Hydraul Res 36:309–326

Editorial responsibility: Kenneth Black, Oban, UK

Submitted: February 3, 2014; Accepted: October 3, 2014
Proofs received from author(s): October 29, 2014