Influence of Aggregation on Storage of Fine-Grained Sediments in Salmon-Bearing Streams

Petticrew, E. L. Geography Program, University of Northern British Columbia, 3333 University Way, Prince George, BC V2N 4Z9

Abstract

An assessment of the role of aggregation of fine-grained sediment in salmon-bearing streams was undertaken as part of the larger in-stream processes component of the Stuart-Takla Fisheries/Forestry Interaction program. Fine-grained sediment (<63 μm) in suspension moves not only as single-grained particles but also as aggregates of fines that are held together by physical, chemical, and biological forces. The aggregates have different settling properties than do individual clay and silt particles, and they can potentially be stored in channels, on the bed surface, and within the gravel matrix. The hydrodynamic models that predict sediment transport in gravel bed streams do not account for these altered sizes. Consequently, the models mistakenly predict quicker flushing of fine sediments during extreme loading events (debris flows, bank slumping, and roadside erosion). This preliminary study of in situ particle size using underwater photography and image analysis techniques has indicated that aggregates in excess of 1200 μm diameter occur in these headwater salmon-bearing streams. The aggregates, comprising inorganic particles that do not exceed 130 μm are stored within the gravel matrix of the channel bed and within the sand matrix of the deltas formed at the mouths of the creeks. While the watersheds are currently limited by the sediment supply, future forest-harvesting activities could alter this balance, and much larger loads may be delivered and stored in their streams.

Introduction

The movement of sediment through a watershed depends on both hydrologic and geomorphic processes. Together, they regulate sediment erosion, transport, deposition, and resuspension, which, within the stream channel, has the potential to affect fish habitat (Petticrew 1996). Forest harvesting practices help determine the response of this coupling of hydrologic and geomorphic processes in headwater salmon-bearing streams.

An extremely important characteristic of the watershed that is modified by harvesting activities is the supply of sediments. Several studies within the larger, multi-disciplinary Stuart-Takla Fisheries/Forestry Interaction Program currently involve the collection of background data in order to differentiate the effects of forest-harvesting techniques on sediment supply and delivery to these highly productive salmon streams (Macdonald and Herunter 1998).

While surficial materials are generally abundant in glacially modified landscapes, the pre-harvest data indicate restricted availability of these sediments for erosion and transport in these systems (Beaudry 1998), which are supply limited. Future forest harvesting in these watersheds will modify variables such as vegetation cover and the timing and quantity of streamflow, which is expected to change the availability of sediment supply and drastically modify sediment routing in the system.

The forested watersheds of the Stuart-Takla area in the northern interior of British Columbia (B.C.) are underlain by extensive glaciolacustrine deposits (Ryder 1995) that are composed of high concentrations of silts and clays (<63 µm), hereafter referred to as fine-grained sediment. When roads are built and the forests are harvested from these watersheds, the probability of increased sediment loads being delivered to the streams is high (Bilby 1985; Bilby et al. 1989). As the streams in the Stuart-Takla study are high-quality salmon habitat (Macdonald and Herunter 1998), it is important to know how the processes of fine-grained sediment delivery and removal are regulated so that we can evaluate their storage time in the system.

Currently, hydrodynamic models indicate that fine-grained sediments should be carried quickly out of the system because they are moving as individual micron-sized particles that have very slow settling speeds. Evidence from many aquatic systems, both marine and freshwater, indicate that the particles aggregate, becoming larger and less dense, which then modifies their transport and erodibility (Kranck et al. 1993; Droppo and Onley 1994). If fine-grained particles are entering the systems as aggregates or flocculating in the streams as a function of the chemical or biological conditions (Muschenheim et al. 1989), the systems response to a large delivery of fines from slope failures, roadside erosion, or debris flows could be quite different from that predicted. The objectives of this work were to: 1) measure the size and concentration of suspended sediments to determine if the particles are transported as aggregates in salmon-bearing headwater streams; and 2) to determine if these aggregated fines are stored in river-bed gravels and river-mouth deltas.

Methods

Gluskie, Forfar, and O'Ne-ell creeks were sampled in August 1994 following the peak of sockeye salmon (Oncorhynchus nerka) spawning. Each of these creeks exhibit similar watershed size and channel slope structure. The last 2-3 km of the creeks cuts through a lowland area that is underlain by a belt of fine-grained glaciolacustrine sediment a few metres thick (Ryder 1995). The lower stream reaches exhibit low gradients (0.5-2.0%) and gravel sizes favorable for spawning. Each stream supports an extensive sockeye salmon spawning stock (Macdonald et al. 1992). Forfar and O’Ne-ell creeks have small, well-formed classic deltas where they empty into the Middle River, while Gluskie Creek has a smaller, less well developed sedimentary structure where the creek empties into Takla Lake.

A stream cross-section in the lower depositional zone of each watershed was selected. Sites were designated in regions where sockeye salmon redds were abundant, as it indicated quality spawning habitat. A stationary underwater silhouette camera was used to photograph the particles suspended in the water column. While it was securely positioned on the gravel bed, photographs of a water column 7.4 cm in diameter and 4.0 cm wide were taken at 2-s intervals. Timed water samples, collected for analysis of suspended sediments, were taken behind the aperture of the underwater camera. Current velocities were measured using a Marsh-McBirney current meter.

In each creek a series of photographs and water samples were collected during the undisturbed low flow conditions experienced in late August. A second set of samples was taken following a staged disturbance upstream. In an attempt to mimic the spawning effects of sockeye salmon, the gravels 4-5 m upstream of the camera site were artificially disturbed by a field assistant who reworked the bottom...
gravels to a depth of several centimetres with his feet. The sediments resuspended by this disturbance were photographed and sampled; they referred to as post-disturbance samples.

Scuba-divers collected hand-held, plexiglass-encased sediment cores (approximately 30 cm in length, 6.0 cm in diameter) from the delta plains, slopes, and prodeltas at the mouths of each creek. Visual observation of the predominantly sandy cores allowed for the recognition of textural changes along their length. Regions of the core where strata breaks were exhibited (apparent fining of sediment) were extruded and subsampled. The core subsections were then transferred to the laboratory where they were processed for Coulter size fractionation (Milligan and Kranck 1991). This process includes the removal of organic matter using 35% hydrogen peroxide.

The water samples were filtered through triplicate, pre-weighed 8-µm SCWP Millipore cellulose-acetate filters. Suspended particulate matter (SPM) was determined gravimetrically on the dried filters and reported in mg L⁻¹. The weighed, dried filters were ashed in a low-temperature asher (<60°C) and wet digested with an excess of 35% H₂O₂ before analysis on a Coulter counter (Milligan and Kranck 1991). This process includes the removal of organic matter using 35% hydrogen peroxide.

A Coulter Multisizer IIIE was used to determine the constituent or disaggregated inorganic grain size distribution of both the cored and filtered sediments. Results are expressed as a volume/volume concentration in ppm and are plotted as smoothed histograms of log concentration vs. log diameter (Milligan and Kranck 1991).

The in situ size distribution and concentration of aggregated particles were obtained by image analysis of the photo negatives obtained from the silhouette camera (Milligan 1995). The images were transferred to CD-ROM and imported into Jandel Scientific’s Mocha image analysis program. The equivalent spherical diameter of the detected flocs was determined, and the particles were counted and grouped into size classes that correspond to the class intervals from the Coulter counter. They were plotted in the same fashion and on the same plots as the constituent particles. In the configuration used, the Multisizer has a lower detection limit of 0.63 µm and an upper detection limit of 1200 µm, while the floc camera has a lower detection limit of approximately 100 µm.

Results

The artificial disturbance of the salmon redd gravel beds resulted in an increase in both the concentration of suspended sediments and the size of particles transported. A staged disturbance of channel gravels would be expected to increase suspended sediment concentrations and maximum particle size in suspension, as the stored sands and fines would be resuspended. In each creek, post-disturbance suspended sediment concentrations increased by an order of magnitude (Fig. 1). The maximum grain size of the photographed suspended sediments also shows an order of magnitude increase following the disturbance of the gravel bed (Fig. 2). The constituent particles, which are the sediments sampled in the water column immediately after being photographed (but are disaggregated in the laboratory), did not exhibit a large change in maximum size following disturbance. The photographed particles that were released from channel storage from gravel bed disturbance are as large as 1290 µm. Coulter analysis indicates that these large aggregates are made up of the smaller constituent materials, which do not exceed 128 µm.

Fine-grained material is stored in channel gravels and is also observed in the delta sediments at the mouths of the creeks. Figure 3 portrays several samples taken from O’Neill Creek watershed and includes a delta core sample that indicates the presence of fines in the predominantly sandy material. The sediment spectra of the roadside gully sample is rich in fines (mode about 8 µm). This extensive and deep glaciolacustrine deposit is a major sediment source in the lower portion of the watersheds; it delivers sediment to the creeks during runoff events such as spring melt and rainstorms. Grain size spectra of the delta cores from different water depths and different depths along the core (Fig. 4) also indicate that fines are being stored at positions along the delta slope (6- and 10-m samples) and in the prodelta (16-m sample). The evidence of similar concentrations and spectra slopes of fines in the deeper (20-cm) section of the cores indicates that the processes of aggregation and storage have been operating in the system in the past.

Discussion

Sizing of the suspended sediments by in situ photography combined with laboratory analysis of the inorganic grains, which comprise the suspended material, allows us to determine that aggregates of
Figure 1. Grain size spectra for three creeks before and after gravel bed disturbances. The suspended aggregates represent the in situ particles that were sized from image analysis of underwater photographs. The constituent particle spectra were analyzed by Coulter counting and indicate the inorganic grain sizes that comprise the aggregates photographed in the water column.

Fine-grained sediments are moving in the streams at low flows and following disturbances of the gravel beds. The observations of aggregates being transported in the stream and stored in the gravels (Figs. 1 and 2) indicates that settling rates of fines have been modified in these headwater streams. Therefore, the assumption of single-grained sediment transport for silt- and clay-sized particles is inappropriate for these systems.

Information about the origin and modification of the transported fines can be obtained from Figure 3. The mode size (8 µm) of the inorganic suspended sediment moving in O'Ne-ell Creek during low, undisturbed flow is identical to that of the gully material that represents the glaciolacustrine sediments underlying the lower portions of the three watersheds. The slopes of these two spectra below the mode size are different, indicating either that the riverine suspended sediment is not composed solely of the glaciolacustrine materials or that the gully sediments are not delivered directly to the stream as consolidated or aggregated particles. A recombination of the particles smaller than 8 µm has created the sediment spectra for the low-flow, pre-disturbance suspended sediments in O'Ne-ell Creek.

The spectrum representing the post-disturbance suspended sediment has a slope similar to that of the fine-grained sediments that are stored in the delta (Fig. 3). The lower portion (<20 µm) of these two spectra represents the constituent particles that constitute the aggregates that naturally settle out or are trapped in the gravel beds and delta sands. The constituent particle mode size (about 20 µm) of these samples is greater than that of the material moving during low flow (mode of 8 µm) implying an in-stream mixing of sediment source materials and/or a downstream reworking of the aggregated glaciolacustrine material.

Sediment size spectra of the delta cores indicate that fines are settling on the slope and prodelta regions and throughout the depths of all cores (Fig. 4). The composition (slope) of the fine-grained end of
Practices Affecting Aquatic Ecosystems

Figure 2. The maximum grain size of the suspended sediments sampled in each of the three creeks before and after gravel bed disturbance. The constituent particle and aggregate sizes are determined as mentioned in Figure 1.

the spectra is surprisingly similar over a range of energy environments (depths) and core depths (time of deposition). While the concentration of fines changes in the different energy environments (note position on the y-axis), the relative abundance of each particle size is maintained, indicating an aggregation or flocculation process is operating in these systems.

It should be reiterated that, while this baseline sample year (1994, pre-harvesting) indicates that the observed mass of fine material is small, relative to the sand-sized portion in these samples, the effects of forest harvesting are expected to result in changing conditions in the watershed (flow regime and sediment supply) that would increase fine-grained sediment delivery. Fine-grained retention in the gravel beds and delta is predicted, as we have observed that aggregation processes and storage of these sediments occurs over a range of energy conditions in these systems. The degree of change in the storage of fines and the effects on the quality of fish habitat will be studied in the next few years of the Stuart–Takla project as experimental cutting of the watershed is undertaken.

Conclusion

The presence of aggregates in headwater streams indicates that sediment transport in these systems is modified. This implies that the storage of fine-grained sediments (<63 μm) is accentuated in these environments, as the settling velocities of the aggregates is greater than the settling speeds of the individual or constituent particles. This is verified by the observation that aggregates are being stored in both the gravel bed and in the sandy delta. Currently they do not comprise a large percentage of the mass of sediments, as fines are not being delivered to the channels in large quantities. It is unclear from this study if the aggregates are forming in the stream as a function of water chemistry and/or biological activity as noted in other freshwater and marine systems (Kranck et al. 1993; Droppo and Ongley 1994), or if some portion of them are being delivered to the stream as consolidated particles from the erosion of the glaciolacustrine deposits in the watershed.

The results of this preliminary, pre-harvesting study indicate that the quantity of fines stored in the channels and deltas is currently not significant relative to the mass of sands and gravels in the channels, and the small amount that is being stored is not reducing the quality of the fish habitat. An increased supply of fine-grained sediment is expected to result in increased gravel bed storage of fines and a concomitant decrease in habitat.
While the conditions influencing the process of aggregation is uncertain, fines are being transported as much larger aggregates, which allows them to be stored in the channel gravels and delta sands. The modified settling rates and resultant storage capacity are extremely important in the context of sediment routing, as they influence how quickly these systems can transport future deliveries of sediment loads that may occur as a function of disturbances in the watershed.

**Acknowledgments**

Funding for this project was provided by B.C. Ministry of Forests and Fisheries and Oceans Canada. Thanks are extended to I. Droppo (Environment Canada, National Water Research Institute) and D. Nolan (University of Northern British Columbia) who assisted with field work, and to T. Milligan, A. Prior, and K. Saunders (Fisheries and Oceans Canada, Bedford Institute of Oceanography) who provided field equipment and analytical support.

---

**Figure 4.** Inorganic sediment spectra of O'Ne-ell Creek delta samples at three water depths that represent the delta slope and prodelta sedimentary environments. Grain size composition from the core surface and at depth are presented to reflect recent and past settling conditions.
References


