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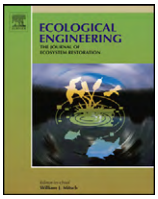

Salmon-derived nitrogen delivery and storage within a gravel bed: Sediment and water interactions

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ABSTRACT

Post-spawning salmon carcasses are broadly recognized as a source of organic matter- and marine-derived nutrients (MDN) in Pacific salmon streams, but MDN delivery and retention processes are not well understood. Recent studies emphasize the interaction of inorganic particulate matter and salmon organic matter, through flocculation, as a delivery mechanism for MDN to the streambed. This study builds upon previous flocculation studies to look at nitrogen delivery and storage within the gravel bed of a re-circulating flume. Findings indicate that nitrogen storage in surface and interstitial water is lower than sediment-associated nitrogen. Flocculation of salmon organic matter and inorganic sediment is presented as a delivery mechanism in spawning and post-spawning periods that helps to maintain ecological productivity within Pacific salmon streams. Based on these findings it is recommended that salmon enhancement activities should include leaving post-spawn carcasses in-stream and that fertilization programs should consider flocculation processes to increase nutrient delivery to the streambed.

1. Introduction

Pacific salmon can play a significant role in the nutrient cycle of their natal watersheds because they deliver substantial quantities of marine-derived nutrients (MDN) during spawning events (Bilby et al., 1996; Naiman et al., 2002; Schindler et al., 2003). Pacific salmon gain upwards of 95% of their mass during their marine growth phase (Groot and Margolis, 1991; Naiman et al., 2002) and therefore represent a net input of nutrients to natal watersheds if carcasses are retained. For example, Finney et al. (2000) identified that spawning salmon contribute between 25 and 75% of the annual nitrogen load in southeastern Alaskan streams.

Although the MDN delivered by spawning Pacific salmon is annually variable due to the number of spawning salmon that return to their natal streams, these nutrients have been observed to support both terrestrial and aquatic plant and animal populations, including juvenile salmon (Naiman et al., 2002; Drake et al., 2006; Hocking and Reimchen, 2006). The loss of MDN returns to salmon-bearing watersheds may further exacerbate stock decline (Scheurell et al., 2005). Salmon stock enhancement programs recognize the importance of MDN returns as indicated by stream-fertilization programs that include salmon carcass drops or the addition of salmon carcass analogues. Fertilization programs are designed to enhance low-productivity watersheds or restore those with declining salmon populations by increasing overall stream productivity and salmon production (Kohler et al., 2008; Wipfli et al., 1998). To effectively manage Pacific salmon streams and maximize the efficacy of salmon enhancement activities, MDN cycling processes must be understood including delivery and storage mechanisms.

MDN are delivered to the riparian zone by animals feeding on salmon carcasses including the remains of post-feeding carcass and defecation of the salmon predator and subsequent scavengers (Naiman et al., 2002). In-stream processes are not as clearly understood, but it has recently been reported that salmon-derived MDN can be delivered to streambeds by flocs (Rex and Petticrew, 2008). Flocs composed of salmon organic matter and clay enriched the gravel bed of a flume when suspended sediment concentration was 5 mg l^{-1}, which is similar to that observed during active spawning as a result of redd creation (Petticrew, 2005).

Flocculation refers to the group of physical, chemical, and biological processes that joins inorganic sediments with organic materials in aquatic environments (Droppo et al., 1997). Spawning activities create an optimal environment for floc formation because organic matter levels are elevated due to the presence of spawning and decaying salmon at the same time that ambient suspended sediment levels are elevated due to redd creation. Spawning salmon remove fine sediments from the streambed at the redd site (Bjornn

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and Reiser, 1991; Malcolm et al., 2005). Streambed excavation by the female salmon disturbs bed sediments, the finest of which (silts and clays) remain in suspension and flow downstream while the coarser sediments, such as sands and small gravels, settle out below the redd near the tailspill (Kondolf, 2000). The quantity of streambed material moved during spawning can be substantial, rivalling spring freshet when spawning populations are high (Poirier, 2004; Hassan et al., 2008).

Salmon organic matter-based flocs are expected to form in the water column due to the collision of organic matter and suspended sediment, but also due to the presence of bacteria that bind organic matter and suspended sediment together with extra-cellular polymeric substances (Petticrew and Arocena, 2003; Droppo, 2004; Wotton, 2007). Once formed, floc capture in the streambed is enhanced by the increased settling rate as compared to the component particles as well as the increased surface and intergravel water exchange due to redd creation. Salmon redds increase streambed roughness and surface water down-welling (Malcolm et al., 2005; Tonina, 2005). Increased surface and intergravel water exchange enhances the probability of water-borne flocs entering the streambed where they can be retained in intergravel pores. This study expands upon previous work by investigating flocculation as an MDN delivery process in the post-spawn period. At that time, salmon organic matter is present from decaying carcasses and suspended concentrations are low (<1 mg l^{-1}) because redd construction has ceased. Further, the study assesses nitrogen storage time in the water column, channel bed material, and interstitial water of a re-circulating channel to identify the potential for each compartment to retain MDN.

2. Materials and methods

2.1. Study location and channel description

The study was completed between August 4 and 31, 2008 at the Quesnel River Research Center in a re-circulating channel. The re-circulating channel was constructed from a decommissioned Chinook salmon fry rearing channel that had dimensions of 30 m × 2 m × 2 m. It contained approximately 1 m of fine gravels, sands, and some clay which was topped with 30 cm of clean gravel and small cobble ranging in size between 1 and 10 cm. This size range was selected because it is similar to that from local salmon spawning streams and is often identified as preferred by spawning Pacific salmon (Bjornn and Reiser, 1991). This top-dressing was washed prior to its placement in the channel.

The channel was designed to replicate the general hydrologic conditions observed at O'Ne-eil Creek, a productive sockeye salmon stream 210 km northwest of Prince George, BC (McConnachie and Petticrew, 2006). Specifically, instead of replicating all channel morphologic conditions (i.e. riffle pool complexes with large woody debris placement etc.) it has a similar slope of approximately 0.01 m m^{-1}, a water depth of 20–25 cm and a velocity between 5 and 10 cm s^{-1}. The channel was filled with 18,000 l of groundwater that was devoid of background salmon organic matter and suspended sediments. Water was re-circulated using a Gould's centrifugal pump that moved approximately 1800 l min^{-1}.

2.2. Stock solution description

The stock solution of salmon was made by rotting 6 kg of Pink salmon (*Oncorhynchus gorbuscha*) for 3 weeks and then combining the decay product elutriate with lab-grade kaolin clay. The quantity of salmon tissue rotted represents the lower range of salmon tissue areal density (100 g m^{-2}) observed in O'Ne-eil Creek in 2001 (Petticrew and Rex, 2006). A total of 378 g of salmon organic matter was added to the flume. The stock solution of clay was made by adding 9 g of kaolin clay to 2 l of water and then disaggregating the solution using an ultrasonic probe (Misonix Inc., Sonicator, Ultrasonic Processor XL 2020, 10 min exposure at amplitude setting 4) prior to its addition to the stock bucket. Adding 9 g of clay to the flume resulted in a concentration of 0.5 mg l^{-1}.

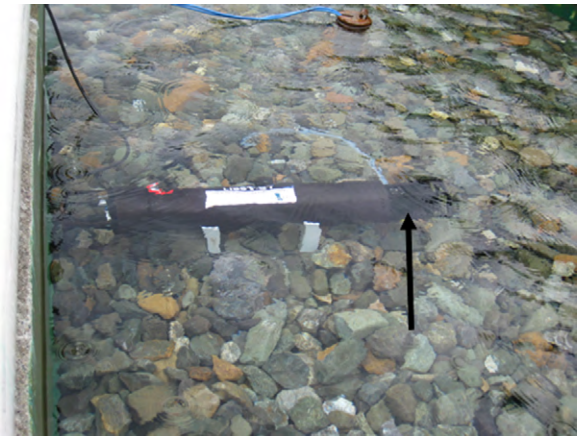

Fig. 1. Downstream view of the LISST-100 in the re-circulating channel. The arrow denotes location of the sample window for particle size analysis.

Stock solutions of clay and salmon were introduced at the same time to a stock bucket at the head of the channel that had a 200 cm^2 grid of sixteen 0.6 cm holes in the front and rear central portion of the container. The upstream grid was not screened but the downstream grid was screened with 200 μm Nitex to prevent large particles from entering the channel.

2.3. In situ suspended sediment particle sizing

Suspended sediment particle sizes were measured using the laser in situ scattering and transmissometry probe (LISST-100), from Sequoia Instruments. This probe measures suspended sediment size over 32 size classes ranging from 2 to 460 μm using laser scatter. It fires a laser into the water contained within a known sample volume and measures the scatter of laser light on to a series of 32 concentric ring detectors (Agrawal and Pottsmith, 2000). The LISST-100 was mounted on Perspex plastic blocks approximately halfway down the length of the flume (Fig. 1). It was positioned with the 5 cm sample orifice perpendicular to flow 12 cm off the channel bottom.

Prior to its placement in the channel, the LISST-100 probe was calibrated with ultrapure water to ensure that the background scatter of the instrument was within allowable factory calibration limits. This calibration file was then used to correct field data for background scatter. It was observed during the baseline period that the groundwater used in these flumes was indistinguishable from the laboratory and factory calibration traces with ultrapure water indicating very low particle content in the channel's water column before stock solutions were added. LISST-100 measurements for each exposure period commenced at the time stock solutions were introduced to the stock bucket at the head of the channel and continued for 60-min at a frequency of 3 s (n = 1200 samples).

Prior to statistical analysis, LISST-100 data were processed using MS Excel$^{\text{TM}}$ macros that verified proper probe functioning and calculated central tendency measures for sample comparison (Williams, 2006). To determine change in the particle size distribution of suspended sediments between sample date, a two-way analysis of variance (ANOVA, SYSTAT 12) of arc-sin transformed