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PARTICULATE ORGANIC CARBON TRAPPING EFFICIENCY IN THE STREAM BED FOR COBBLES AND GRAVELS: A LABORATORY TEST

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Introduction

Carbon is unevenly distributed throughout terrestrial, oceanic, and atmospheric reservoirs. Recent studies have estimated that inland waters annually receive 1.9 $P_g C\ y^{-1}$ from the terrestrial landscape. It is estimated that 0.2 $P_g C\ y^{-1}$ is trapped in aquatic sediments, about 0.8 $P_g C\ y^{-1}$ is returned to the atmosphere and the remaining 0.9 $P_g C\ y^{-1}$ is delivered to the oceans (Cole et al, 2007). Furthermore, models indicate that only half of the total carbon that enters an aquatic system is exported to the sea. The other half is either trapped in the aquatic system or lost to the atmosphere.

Riverine carbon is classified in multiple forms and has different sources and origins. In particular, particulate organic carbon (POC) can originate from soil erosion, sedimentary rocks, or be autochthonous. In most rivers, the POC content ranges from 1 to 5 percent. However, in the Amazon, POC accounts for about 45 percent of the total organic carbon and 90 percent of the POC are found in fine sediments (Meybeck, 1993). The stream bed acts as filter layer influencing the exchange between dissolved fine materials and the substrate (Findlay, 1995). Thus, it is important to understand how the POC in fine sediments are clogged in the stream bed.

For a given stream bed, there are several different variables that influence the clogging process. The physical variables are defined by the flow conditions in the stream, the suspended load, the grain-size distribution and the shape of suspended particles, and the hydraulic gradient of the seepage flow. The biological variables consist of the variety of invertebrates, redds, algae and their concentrated amounts, and the extent of eutrophy in the water. The type and quantity of dissolved matter acts as the chemical variable (Schalchli, 1992). Water flux into and out of the stream channel's surrounding alluvium plays an important role in many ecological processes. This hyporheic exchange is an important component of good quality habitat for invertebrates and for fish spawning (Packman et al., 2004). Hyporheic exchange also influences the large scale transport of solutes and fine particles (Brunke and Gonser, 1997 in Packman et al., 2004). However, the deposition of fines into the stream bed can greatly reduce hyporheic exchange. While it is important to keep the different influences of hyporheic exchange in mind, this research will only examine the influence of the physical variables, especially the transport and deposition of fine sediments containing particulate organic carbon.

Literature Review

Deposition and Clogging

Fine sediments in suspension vary in each stream flow. Since the sediment is transported by the fluid, the deposition is controlled by turbulence and flow non-uniformity. As a result of these processes the fines are deposited on the river bed or are injected into the pore spaces of the substrate, progressively clogging the stream bed (Schalchli, 1992). Natural unsteady flow conditions will produce either periods of alternating transport and deposition, or at least spatial temporal variations in the rate of transport. This will produce dynamic variations in hyporheic exchange rates (Packman et al., 2004). However, the turbulence and flow non-uniformity can also impede the clogging process. The more a grain of sediment is projected above the general bed level the more it is exposed to the flow. Thus, the disturbing forces acting on the grain becomes greater than the resisting forces resulting in the sediment being washed down stream (Abbot and Fenton, 1977).

During deposition the fine sediment acts as the matrix material while the porous substrate acts as the framework material through which the fine sediment passes (Lisle, 1989). Suspended particles are carried into the bed at inflow regions, and particle deposition then occurs within the pore spaces (Packman et al., 2004). Suspended particles which are larger than the pores in the framework are excluded from the bed. The fine sediment particles that are smaller than some pore spaces but larger than others are deposited in a layer just beneath the bed surface. Once the surface interstices are plugged, it becomes less likely that the suspended sediment will enter the stream bed. Substantial accumulation of fines at these inflow locations can then reduce the overall water influx to the bed (Packman et al., 2004). Furthermore, the matrix material size not only affects the level of the stream bed but also the total amount of deposition. It has been suggested by Packman and MacKay (2003) that even a relatively amount of fine sediment can plug the uppermost layer of the stream bed causing a decrease in hyporheic exchange fluxes.

The clogging process of a stream bed is based on the intrusion of the suspended sediment that is deposited on or in the top layer of the substrate. The clogging process is predominately characterized by the dimensionless flow shear stress, the concentration of the suspended load, and the hydraulic gradient between the stream and groundwater. If groundwater enters the river, the clogging process is reduced resulting in a loosely-packed bed (Kustormann, 1962). Active bed sediment transport limits clogging near the top layer of the bed, however, theory presented by packman et al., [2004] suggests that sediment clogging can still occur below the region of active bed sediment transport. Thus, the structure of fine sediment deposits in natural streams should depend on the dynamics of large scale sediment transport processes. Also, the greater the concentration of suspended sediment the more deposition and clogging will occur. The clogging process can take between a few days and several months until a constant hydraulic conductivity is reached (Schalchli, 1992).

When the stream discharge reaches the critical value of the stream bed, the substrate material will become mobilized and the intruded fine sediment is re-suspended and flushed down stream. However, this scouring of the bed material exposes lower levels of the bed to infiltration of the suspended particles, and as the substrate subsequently fills up after a high discharge event much deeper layers of the bed can be infiltrated (Lisle, 1989). Therefore, a large flow event may release trapped sediment but it may also allow for even more sediment to permeate into the stream bed. Fine sediments are expected to accumulate primarily below the region of active bed sediment transport, and the depth which accumulation occurs will change with the amount of mobilization in the bed due to a high flow event (Packman et al., 2004).

Objective

The objective of this study is to investigate particulate organic carbon (POC) trapping efficiency in the streambed for cobbles and gravels in order to better understand the carbon cycle from source to sink.

Methods and Procedures

Experimental Setup

This study will employ two recirculating hydraulic flumes, both 65 feet long by 2 feet wide running parallel to each other set at a slope of 0.0013 m/m. The flume frame was constructed of wood panels and plexiglass for the walls with a floor that consists of three layers of ¾ inch thick plywood coated with two layers of marine resin for waterproofing. Also, a waterproof liner covers the bottom of each flume. The upstream end of the flume has higher walls to prevent the splashing of water out of the flume as it is discharged into the flume. This upstream end of each flume is equipped with a honeycomb structure to ensure rectilinear flow. The downstream end of each flume empties into a large wooden tank that is lined with a waterproof liner. Suspended off the bottom of each tank is a foot valve that is attached to the suction end of the piping system which connects to a variable speed pump. These pumps recirculate water and sediment to the upstream end of each flume channel via 6 inch PVC return pipe. Thus, the flume represents a closed system for bed sediments. One flume has a loose substrate, approximately 5 inches deep, comprised of 3-5 inch black Mexican beach pebbles chosen for their rounded smooth features and dark color. The second flume also approximately 5 inches deep is comprised of ½-1 inch black Mexican beach pebbles. One flume has a representative gravel stream bed while the other will be used to model a cobble stream bed. This flume is an appropriate device for the study of stream–subsurface interactions because it provides a realistic, controlled stream flow over a loose sediment bed. Furthermore, several tests can be conducted with varying flow rates (Q) and sediment discharge rates (Qs). These tests will compare the fine sediment trapping efficiency of a cobble stream bed with a gravel stream bed.

Prior to each flume test, the following physical parameters will be controlled by the experimental setup: the depth of the stream and streambed, the stream velocity, and the channel slope. Natural bed forms should be created for each flume by starting with a storm event to insure intensive Qs so that the top layer of the substrate is built up in a natural way. If not, the clogging processes may not be reproduced correctly since the unnatural positioning of the particles may lead to sudden changes in the texture of the top layer (Packman et al., 2004). Once the flumes are acclimated to natural conditions, the same amount of light colored, fine sediment (106 μm silica flour) will be poured slowly into the downstream well of each flume over one stream recirculation period at steady stream flow conditions.

Unfortunately, due to the leaking of the downstream tanks a proper experiment was unable to be conducted. Several methods were tried to better seal the tanks to prevent the leaking but all failed. However, a preliminary test was preformed which allowed for better predictions of what would occur during the actual experiment. The following is the experimental design, procedures, and analysis. It is important to keep in mind that the designed experiment was not able to be carried out, only a preliminary test was conducted. Hopefully, a solution can be found for the leaking tanks and the designed experiment will be conducted.

photograph of 2 flumes running parallel to each other, the flume on the right contains the cobbles and the flume on the left contanis the gravels

Experimental Design

The position in the flow in which a particle is entrained is determined by the Rouse number (z), which is determined by the density ρ_s and diameter *d* of the sediment particle, and the density ρ and kinematic viscosity v of the fluid.

$$z = \frac{w_s}{kU_*}$$

Here, the Rouse number is given by *P*. The term in the numerator is the sediment fall velocity w_s. The upwards velocity on the grain is given as a product of the von Kármán constant, $\kappa = 0.4$, and the shear velocity, U_*. The following table gives the approximate required Rouse numbers for transport as bed load, suspended load, and wash load.

Table 1:

Mode of Transport	Rouse Number
Initiation of motion	>7.5
Bed load	>2.5, <7.5
Suspended load: 50% Suspended	>1.2, <2.5
Suspended load: 100% Suspended	>0.8, <1.2

Wash load	<0.8

For the purpose of this research a Rouse number of 1 was chosen.

A sediment fall velocity of 1 cm/sec was calculated for the 106 μm silica flour using Stoke's Law,

$$w_s = \frac{gd^2}{18}(\frac{\rho_s - \rho}{\mu})$$

Where g is gravity, d is sediment diameter, ρ_s is sediment density, ρ is water density, and μ is viscosity. Integrating the Rouse equation with Stoke's Law the design shear velocity can be calculated.

$$U_* = \frac{w_s}{kz}$$

$$U_* = \frac{0.01\frac{m}{s}}{(0.4)(1)} = 0.025\frac{m}{s}$$

Furthermore, the shear velocity can also be calculated in the following way,

$$U_* = \sqrt{gHS}$$

Where g is gravity, H is water depth above the substrate, and S is the slope of the channel. Thus, the preceding equation can be used to determine the design water depth.

$$H = \frac{U_*^2}{gS}$$

$$H = \frac{0.025^2\frac{m}{s}}{(9.81)(0.0013)} = 0.049\ m = 5cm$$

The design flow rate was calculated using the following equation,

$$Q = \frac{1}{n}\left(\frac{A^{\frac{5}{3}}}{P_w^{\frac{2}{3}}}\right)\sqrt{S}$$

Where Q is the flow rate, A is the channel area, S is channel slope, and P_w is the surface area of the flume which the water touches.

$$Q = \frac{1}{0.03}\left(\frac{0.03m^2}{0.71m}\right)\sqrt{0.0013} = 0.0044\frac{m^3}{sec} = 69\frac{gallons}{minute}$$

Furthermore, using the design flow rate the velocity of water in the 6 inch return pipe can be calculated.

$$Q = VA = V\frac{\pi d^2}{4}$$

$$V = \frac{4Q}{\pi d^2}$$

$$V = \frac{4(69\left(\frac{gallon}{\text{min}}\right))}{\pi(6^2 inch)} = 0.76 \text{ ft/sec}$$

The following table summarizes the preceding calculations:

Table 2:

Sediment Fall Velocity	0.01 m/s
Shear Velocity	0.025 m/s
Water Depth	0.05 m
Flow Rate	69 gal/min
Water Velocity in 6’’ Pipe	0.76 ft/sec

A suspended sediment concentration of 1000 mg/l was used because it is representative of field conditions. Since each of the tanks holds 7700 liters of water the amount of fine sediment needed for each flume can be determined in the following way:

$$\frac{7700L}{1} \times \frac{1000mg}{L} \times \frac{1g}{1000mg} \times \frac{1kg}{1000g} \times \frac{2.2\ lbs}{1kg} = 17\ lbs \text{ fine sediment}$$

Experimental Procedure

The following are the experimental procedures. Once the two tanks are full of water 17 pounds of 106 μm silica flour is poured into each tank over one recirculation period. Next the pumps are turned on and an acoustic velocimeter is used on the 6 inch PVC pipe to insure that the water is flowing with a velocity of 0.76 ft. /s. Once the flow rate is set, the water depth is checked. If the desired depth is not constant some substrate material may be moved around until the water is at the designed depth. Once all of the physical parameters are checked a turbidity probe is mounted in each flume and used to monitor the suspended sediment concentration over the duration of the 30 day experiment.

Experimental Analysis

Throughout the 30 day experiment photographs of each flume bed should be taken every day to catalog the sediment deposition over time. Photographs should be taken every eight feet from the side of the bed and the top of the bed. The contrasting colors of the dark bed material and the white fine sediment allow for a Photoshop analysis of percent color throughout the experiment. This analysis can provide a percentage of white sediment compared to the dark substrate, which can then be correlated to the amount of sediment clogged in each bed. Then, using past point POC trapping data from previous research, the amount of streambed clogging can be directly correlated to the amount of POC trapped in the different study sights. However, it is important to keep in mind that this is a laboratory experiment that cannot be directly related to the field.

Expected Results

It is anticipated that for the gravel bed sediment will only intrude into the top portion of the bed and the rest will be deposited on top of the bed. Since the pore spaces within the gravel bed are small they should become clogged prohibiting the fine sediment from protruding deep into the bed (Packman and MacKay, 2003). It is expected that the fine sediment will be well deposited throughout the entire depth of the cobble bed. The pore spaces in the cobble substrate are relatively large allowing for more fine sediment to pass through. Also, these pore spaces will not clog as easily as in the gravel. Thus, it is also predicted that the cobble bed will trap more sediment than the gravel bed due to more pore spaces for the sediment to become trapped in.

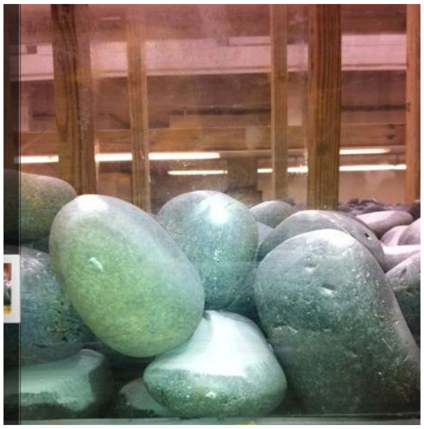
Preliminary Test Results:

A preliminary test was conducted according to the methods and procedure section. Due to time constraints and leaking issues the test was only conducted for 1 hour and the velocity in the 6 inch pipe was maintained at 1.8 ft/sec. The following is the results from the turbidity probe for each flume over the 1 hour period.

Table 3:

Time	Turbidity of Gravel Bed	Turbidity of Cobble Bed
10:08	100	-
10:14	-	120
10:18	96	-
10:24	-	103.5
10:26	88.5	-
10:28	-	-
10:30	-	-
10:35	83	-
10:39	-	98
10:51	71	-
10:52	-	88
11:13	-	78
11:14	62	-

The turbidity in each bed decreased over time, revealing that sediment was being constantly deposited in both beds. Pictures of each flume bed were taken throughout the test and at the conclusion of the test.



(a)

Photograph (a) is a side view of the cobble bed after the preliminary test was completed. It can clearly be seen that the white fine sediment was deposited throughout the entire depth of the bed. Thus, my expected result about the cobble bed was correct.

(b)

Photograph (b) is a side view of the gravel bed after the preliminary test. This photograph reveals that the fine sediment was also deposited throughout the entire bed depth. This contradicts my expected results. Therefore, the pore spaces in the gravel bed were large enough for the fine sediment to pass through and they did not clog as predicted.

Without photographically analyzing the photographs which bed trapped more of the fine sediment is unable to be determined. It is important to keep in mind that this is just a preliminary test and may not be representative of the actual experiment.

Further Research Recommendations

For this experiment to be properly conducted the test should be ran for 30 days to allow for hydraulic conductivity equilibrium (Schalchli, 1992). A deeper bed depth should be considered to see how deep the fine sediment is able to travel into the gravel bed. Also, more efficient experimental analysis techniques should be researched and implemented for a better quantitative analysis of the amount of fine sediment trapped by each bed.

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