Rapid flow through the sediments of a headwater stream in the southern Appalachians

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SUMMARY. 1. The flow of water through the sediment layer (underflow) of streams can influence nutrient uptake dynamics and the supply of materials to microbes, meiofauna and macroinvertebrates living within stream sediments. We examined the extent of underflow in Hugh White Creek, a headwater stream in the southern Appalachian Mountains and compared underflow at different depths and at different sites within the stream.

2. Initially rhodamine dye was used to trace the flow of water through the sediments; however, the dye was strongly absorbed by the sediments in Hugh White Creek. Thus rhodamine was not suitable as a tracer of water flow. Chloride reacted conservatively in laboratory experiments and was used as a tracer.

3. The tracer infiltrated the sediments within 5 min to depths of 10 cm at all six sites. Chloride infiltration tended to decrease with depth of sediments at all sites although there was no consistent statistical pattern in chloride concentration with depth for the different sites. Equilibrium between the water column and sediments was reached rapidly, within minutes for the sites with coarse sediments and within a few hours for sites with finer sediments. Minimum rates of chloride infiltration into the sediments ranged between 1.0 cm min^{-1} for the sites with cobble substrate to 0.2 cm min^{-1} for sites with fine sand sediments associated with debris dams. These data suggest that underflow may be a major component in the functioning of Appalachian mountain streams.

Introduction

Solute transport in streams is determined by hydrological and chemical processes (Hynes, 1983; Bencala, 1984) as well as by biological processes (Gregory, 1978; Elwood *et al.,* 1981). The availability of chemically and biolo-

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gically active sites within the streambed is determined by the rate of channel flow and the size fraction of streambed sediments (e.g. Bencala *et al.,* 1983). Transport studies in Californian streams have demonstrated that there is considerable exchange capacity in coarse-sand to granule-size sediments that have not been filled in with fine particles to reduce permeability (Kennedy *et al.,* 1984). These coarser sediments can be accessible

through thick sediment layers and have a large reactive capacity, especially with ions under strong biotic control (e.g. Elwood *et al.*, 1981). In comparison with channel flow, movement of underflow (interstitial water) has traditionally been considered to be relatively slow and unimportant to stream processes (see Kennedy *et al.*, 1984). However, when streamflow is low or in low-order streams, the ratio of underflow to channel flow is increased with a resultant increase in opportunity for active contact between the solutes and the sediments (Bencala, 1983; Kennedy *et al.*, 1984; Grimm & Fisher, 1984).

While the importance of surface stones and underlying sediments as major sites of nutrient uptake is recognized (e.g Mickleburgh, Lock & Ford, 1984), the importance of underflow to nutrient uptake has not been assessed. Underflow has the potential to increase the number of active sites for nutrient uptake. Furthermore, part of the spatial and temporal variation observed in nutrient uptake dynamics (e.g. Mickleburgh *et al.*, 1984) may result from local differences in hydrological patterns and differing permeability of different-sized sediments in different regions of the streambed.

While the amount of underflow is an important consideration for nutrient uptake studies, it is also important when calculating the supply of new materials to microbes, meiofauna and macroinvertebrates living within the sediments. If the flow rate is high, the growth potential of these organisms can also be high. Thus, community metabolism of deep sediments (30 cm) in a Sonoran Desert stream was approximately equal to the respiration of surface sediments, emphasizing the importance of the flux of water within the sediments (Grimm & Fisher, 1984). Moreover, considerable densities of benthic invertebrates have been found down to at least 25 cm in a mountain trout stream (Hynes, Williams & Williams, 1976). Infiltration at riffle heads of a Michigan River influenced temperatures as deep as 50 cm (White, Elzinga & Hendricks, 1987). Such examples of high streambed permeability suggest that underflow is an important factor influencing processes occurring within some streams.

The significance of underflow is recognized in streams with deep sandy or coarse sediments but its influence is less obvious in streams with shallow sediments. The purpose of this study was to determine the extent of underflow in a headwater stream in the southern Appalachian Mountains and to compare underflow at sites with sediments of different size fractions. Bacterial density and organic matter content were measured in both shallow and deep sediments to test for differences in biotic properties of the sediments with depth.

Methods

Site description

This study was conducted in Hugh White Creek at the Coweeta Hydrologic Laboratory located in the southern Appalachian Mountains of North Carolina, U.S.A. This is a second-order stream draining a mixed mature hardwood forest that has been undisturbed for 60 years. Mean annual discharge is $19.5\ \mathrm{l\,s^{-1}}$ and mean mid-stream water depth is 6.4 cm (Webster *et al.*, 1983). Dissolved nutrient concentrations are low (Webster *et al.*, 1983). The sediments range in depth from 0 to 10 cm and overlie deeply weathered granitic bedrock (Swank, 1986).

Biotic measurements

Bacterial density and organic matter (OM) content of the sediment were determined from cores at two depths. Ten cores (2 cm diameter) were taken from a range of fine to coarse sediment during August 1987. Sediment from 0–2 and 6–8 cm depths were separated from the rest of the core and subsampled; subsamples to determine bacterial density were preserved in formalin and subsamples to determine OM content were frozen. Bacteria density was estimated using the acridine orange direct count technique (Hobbie, Daley & Jasper, 1977) and OM content was estimated from weight loss at combustion (500°C) as weight of organic material per g dry weight of sediment.

Dye application – verification of method

In preliminary field experiments, rhodamine dye that had been injected into Hugh White Creek was detected within minutes at sediment depths up to 10 cm. A laboratory experiment

was then conducted to determine whether rhodamine dye reacts conservatively with sediments from the stream. Sediments (5 ml) of different size were collected and incubated in solutions (100 ml) of either rhodamine dye or chloride on a Lab-Line shaker table. Samples (4 ml) were removed from the incubation flasks every 30 min for 3 h and analysed for either rhodamine dye (Turner fluorometer) or chloride concentration. Strong absorption of dye by sediments was observed, especially by the finer sediments with greater surface area (Fig. 1A). Chloride was not absorbed by the stream sediments (Fig. 1B) and therefore is an

appropriate tracer to compare underflow in different sized sediments. Thus, for further field work, chloride was used as a conservative tracer to examine flow through the stream sediments.

Field tracer additions

Lengths of 1 cm bore rigid plastic tubing, sealed at one end, were attached to 20 ml polyethylene syringes. Two small holes (diameter 3 mm) were cut in each tube at a depth of either 2, 5 or 10 cm. The syringes (with plungers completely depressed) were inserted into the sediments to the appropriate depth (five syringes at each of 2, 5 or 10 cm) before chloride additions were started. Chloride was continuously injected into the stream at a constant rate 10 m upstream from the point where the syringes were inserted; chloride concentration in the streamwater was increased from a background concentration of 3 mg l^{-1} to approximately 40 mg l^{-1}. 5 min after the beginning of chloride injection, one syringe was removed from each of the three depths. To remove a syringe, light suction was applied, sufficient to retain any water within the tubing but not to pull water from around the tube opening; only 1–2 ml of water were removed with each syringe. Syringes were removed at 5-min intervals for 25 min; a water column sample was also taken at 5-min intervals. It was not possible to replicate each depth at each time point because of the limited space to place syringes in this small stream.

The syringes were placed at six different sites in Hugh White Creek during September and October 1987. Two sites were in cobble-riffle sections (Cobble I and II) and thus had coarse sediments (62–256 mm), two were within debris dam sections (Debris Dam I and II) with fine sediments (<2 mm) and two were in gravel sections (Gravel I and II) with sediments of intermediate size (2–16 mm). Stream flow during the chloride additions was low (5.8 l s^{-1}) and stable.

To examine the equilibration of chloride between the water column and interstitial water, chloride was injected into the water column at the Gravel I site for 3 h. A syringe was removed from a depth of 5 cm every 5 min for the first 30 min and every 30 min thereafter.
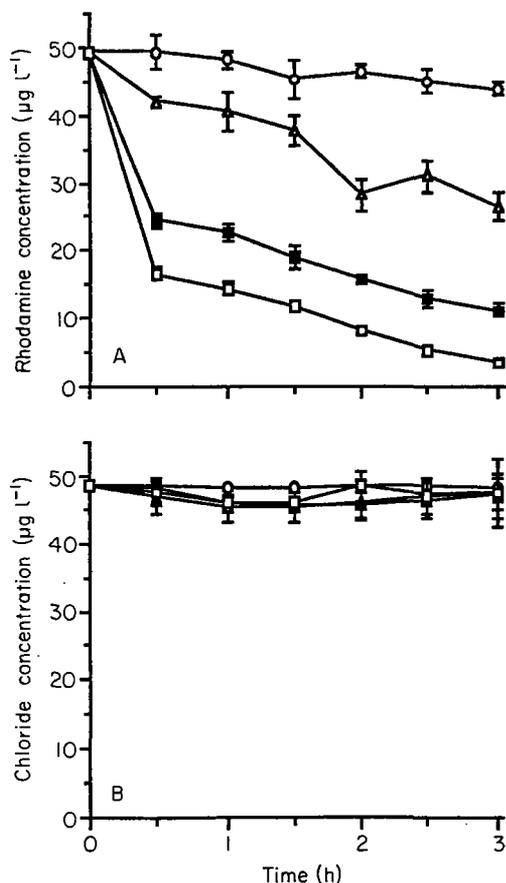

FIG. 1. Absorption of rhodamine dye (A) and chloride (B) by sediments from Hugh White Creek over 3 h. Bars represent standard error (n=4); error bars may be within the data point. The four treatments include no sediments (open circles), coarse sediments (64–256 mm; open triangles), intermediate-sized sediments (2–64 mm; dark squares) and fine sediments (<2 mm; open squares).

In the laboratory, water removed by syringe was centrifuged to separate any fine sediment particles, and chloride concentration of the supernatant was determined by an automated ferricyanide method (American Public Health Association, 1985).

Results

Bacterial densities were similar in shallow and deep sediment (Fig. 2) for both rod-shaped bacteria (t-test, $P=0.66$) and coccoid bacteria (t-test, $P=0.96$). However, OM content was slightly greater in the deeper sediments (t-test, $P=0.045$). These data, along with meiofaunal population data from the sediment of Hugh White Creek (E. O'Doherty, pers. comm.), indicate that the biotic properties are similar in shallow and deep sediments there. Bacteria and organic matter data from three other watersheds with different treatment histories also show a lack of consistent variation with depth (J. Meyer, unpublished data).

When chloride was injected into the water column, the tracer infiltrated the sediments within 5 min to all depths at all six sites. Chloride concentrations after 5 min were at least 4 times the concentration before the addition began. When chloride concentrations
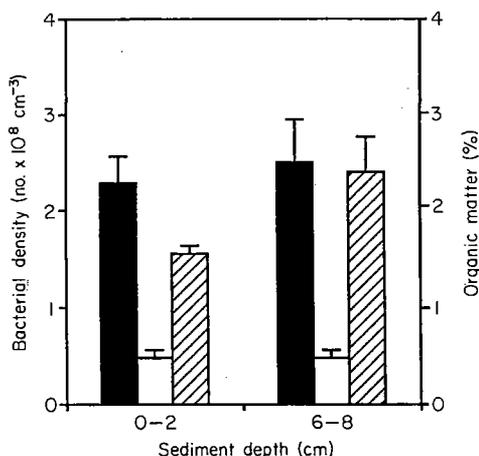

FIG. 3. The concentration of chloride (mg l^{-1}) at three depths within the sediment averaged over a 25 min period at six sites in Hugh White Creek. The three depths are 2 cm (dark bars), 5 cm (open bars) and 10 cm (hatched bars). Background chloride concentration was 3 mg l^{-1}) (D=debris dam; G= gravel; C=cobble).

were averaged over time for each site, the mean concentrations showed a consistent decrease with depth (Fig. 3). However, results of paired t-tests to determine significant differences with depth did not indicate a pattern between depths at all sites. For example, there were significant differences ($P<0.05$) between all three depths for the Gravel I site but no significant differences between any depth for the Gravel II site. There were no differences with depth for the Debris Dam II site although the chloride concentration at 2 cm was greater than that at 10 cm for the Debris Dam I site.

To compare infiltration between sites, the chloride concentration in the water column was divided by the chloride concentration in the sediments. A ratio of 1 would indicate that the water column and interstitial water were mixing completely whereas a ratio >1 would indicate incomplete mixing. All six sites approached equilibrium with the water column chloride concentration over the course of the 25 min addition (Fig. 4A). The sites with coarser sediments (Cobble I and II, Gravel II) were near equilibrium within 5 min. The sites with finer sediments had greater chloride concentration in the water column relative to the sediments at the early time points and thus had a slower approach to equilibrium. The chloride concentration in the interstitial water was equal to the chloride concentration of the water column 2.5 h after chloride addition for the Gravel I site (Fig. 4B).

FIG. 2. Bacterial density (rod-shaped bacteria are given as dark bars and cocci as open bars) and per cent organic matter (hatched bars) in shallow (0–2 cm) and deep (6–8 cm) sediments in Hugh White Creek ($n=10$). Error bars indicate one standard error.
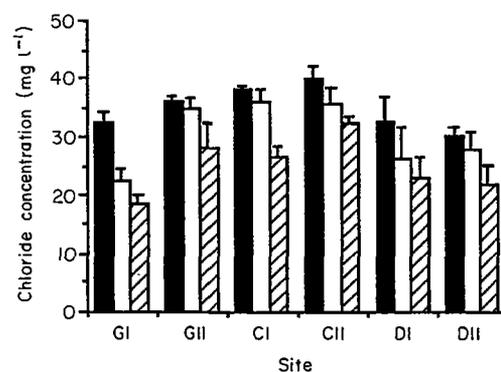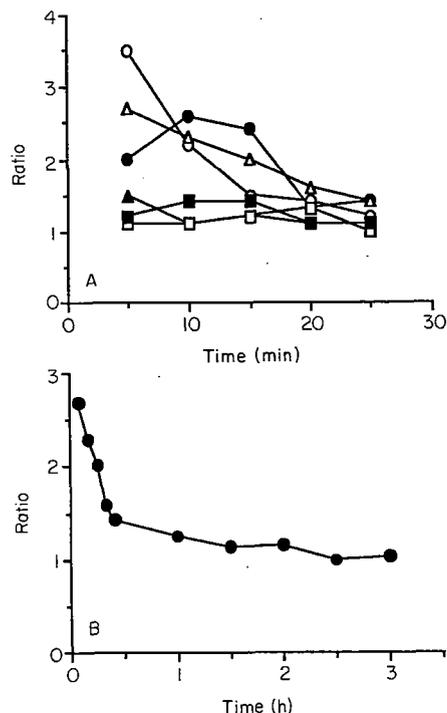
FIG. 4. (A) The ratio of chloride concentration in the water column to the chloride concentration in the sediments (at 5 cm depth) at five time points over 25 min at each of the six sites (Debris Dam I and II are open and dark circles, respectively; Gravel I and II are open and dark triangles, respectively; Cobble I and II are open and dark squares, respectively). A large number on the Y axis indicates a greater concentration of dye in the water column relative to the concentration within the sediments. (B) The ratio of chloride concentration in the water column to chloride concentration in the sediments during the course of a 3 h addition at the Gravel I site.

Minimum infiltration rates of chloride to a depth of 5 cm were calculated from the amount of time it took for equilibrium between the water column and interstitial water to be reached and not from the leading edge of the added chloride (Table 1). Sites with coarser sediment particles (i.e. cobble sites) had higher infiltration rates than sites with finer sediments.

Discussion

These results demonstrate that flow through the sediments in Hugh White Creek is sufficient to bring a fresh supply of materials to

TABLE 1. The minimum rate of chloride infiltration to a depth of 5 cm in different types of sediment in Hugh White Creek

Site	Sediment size (mm)	Infiltration rate (cm min^{-1})
Cobble	64–256	
I		1.00
II		1.00
Gravel	2–64	
I		0.06
II		0.50
Debris Dam	<2	
I		0.25
II		0.20

microbes and meiofauna living deep in the sediments, especially in cobble sites with greater streambed permeability. Infiltration of the tracer was surprisingly fast, demonstrating that the traditional model of slow underflow does not apply to Hugh White Creek; rather, the models described for California mountain streams (Kennedy *et al.*, 1984) and the Sonoran Desert stream (Grimm & Fisher, 1984) are more appropriate. This suggests that underflow may be a major component in the functioning of Appalachian Mountain streams.

Flow through the sediments has important implications for nutrient cycling due to the greater surface area available for retention of nutrients. If biological activity is high in a stream with deep and permeable sediments, the rate of nutrient recycling will be high and the spiraling length short (Newbold, Elwood & O'Neill, 1981). In streams with less flow through the sediments, less retention of nutrients would be expected, resulting in longer nutrient spirals and lower ecosystem stability (i.e. an exporting ecosystem). Hence, flow through the sediments should increase ecosystem stability by reducing the rate of downstream loss of materials (see Minshall *et al.*, 1983). Headwater streams in the Cascade Mountain range of Oregon are likely to have longer nutrient spirals than Hugh White Creek since the Cascade streams are frequently scoured, so that the amount of sediment covering the bedrock is reduced. In these western streams, the importance of the sediments in the biotic functioning (primarily nutrient–microbe–meio-faunal interactions) of the stream ecosystem is probably low compared to large debris dams (e.g. Buckley & Triska, 1978) and stream banks.

The importance of underflow will be reduced during high flow periods when there is less water flowing through the sediments relative to channel flow and when water flowing through sediments tends to have a scouring effect. This may also apply to a river continuum of increasing stream order; as stream order increases in a drainage network, the ratio of underflow to channel flow should decrease with a resultant decrease in contact with and through the streambed, although this will be dependent on channel geomorphology. Such a shift in the relative importance of underflow may be one factor causing the spiralling length of carbon to increase from 8–15 km in small streams to 426 km in a ninth order river in the boreal forests of Canada (Naiman *et al.*, 1987). Minshall *et al.* (1983) attribute the shorter turnover length found in headwater streams to the slow velocity of materials due to retention devices. However, the influence of increased uptake sites due to underflow in headwater streams could be another important factor contributing to the retentiveness of these streams.

Acknowledgments

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