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INFLUENCE OF CHANNEL GEOMORPHOLOGY ON RETENTION OF DISSOLVED AND PARTICULATE MATTER IN A CASCADE MOUNTAIN STREAM[1]

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INFLUENCE OF CHANNEL GEOMORPHOLOGY ON RETENTION OF DISSOLVED AND PARTICULATE MATTER IN A CASCADE MOUNTAIN STREAM[1]

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Abstract: Retention of particulate and dissolved nutrients in streams is a major determinant of food availability to stream biota. Retention of particulate matter (leaves) and dissolved nutrients (nitrogen) was studied experimentally during summer 1987 in four 300-500 m reaches of Lookout Creek, a fifth-order stream in the Cascade Mountains of Oregon. Constrained (narrow valley floor) and unconstrained (broad valley floor) reaches were selected within old-growth and second-growth riparian zones. Gingko leaves and ammonium were released into the channel and retention rates were measured. Retention of leaves and nutrients was 2-4 times higher in unconstrained reaches than in constrained reaches, in both old-growth and second-growth riparian zones. Retention was enhanced by increased geomorphic complexity of channels, diversity of riparian vegetation, presence of woody debris, and heterogeneity in stream hydraulics, sediments, and lateral habitats. Unconstrained reaches express these qualities and thus are critical areas for retention of particulate and dissolved nutrients in stream ecosystems.

Stream ecosystems face the fundamental challenge of retaining the dissolved and particulate nutrients delivered to them by their watersheds. Because the biota of many streams is dependent on input of nutrients from riparian zones (Vannote and others 1981), retention of these materials is essential to lotic food webs. Streams differ markedly from other ecosystems in that the unidirectional flow of water tends to transport nutrients to downstream reaches. As a consequence, mechanisms for retention of dissolved and particulate matter must be present within the stream reach before nutrients can be utilized effectively by the biota (Elwood and others 1983; Speaker and others 1984; Young and others 1978). The process of retention thus provides a critical linkage between nutrient input and biotic utilization in lotic ecosystems.

The premise of our research is that retention of dissolved and particulate matter is a function of valley floor landform, riparian vegetation, channel geomorphology, and stream hydraulics and substrate. Each of these factors can influence retention rates by modifying either the physical structure or the biological organization of stream ecosystems. In this paper, we focus on stream channel geomorphology as an important parameter regulating the retention of dissolved and particulate matter in streams. However, we also report on how the retention process is influenced by the interaction between channel geomorphology and other factors such as landform, riparian vegetation, and hydraulics. We used an experimental approach involving releases of leaves and nutrients into the channel to determine rates of retention in different geomorphic settings.

Study Area

Releases of leaves and nutrients were conducted in Lookout Creek, a fifth-order stream located within the H.J. Andrews Experimental Forest in the Cascade Mountains of Oregon, USA. We studied four discontinuous reaches in Lookout Creek (designated C, D, E, and G in this study), ranging from 336 - 547 m in length. Elevations of the study reaches ranged from 400-600 m, channel gradient was 2-3 percent, and summer baseflow discharge was 0.28-0.42 m^3/sec. Stream substrates were dominated by cobble and small boulders. Accumulations of large woody debris in the channel were significant features of some reaches.

The four reaches were classified on the basis of valley floor landform and riparian vegetation (Table 1). The valley floor is considered to be that portion of the valley that has been influenced by fluvial processes. Two categories of valley floors represented in this study were: (1) constrained reaches, in which the valley floor was less than 3 times the width of the active stream channel, and (2) unconstrained reaches, in which the valley floor was greater than 4 times the active stream channel width (Fig. 1). Based on these criteria, reaches C and E were constrained and reaches D and G were unconstrained.

Riparian vegetation was classified as old-growth conifer forest or second-growth mixed deciduous and conifer forest. Reaches C and D (one constrained and the other

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Table 1 – General characteristics of the four study reaches in Lookout Creek, Oregon.

	Reach			
Parameter	C	D	E	G
Valley Floor	Constrained	Unconstrained	Constrained	Unconstrained
Riparian Vegetation	Old-Growth	Old-Growth	2nd-Growth	2nd-Growth
Multiple Channels	Absent	Present	Absent	Present
Sediments	Shallow	Deep	Moderate	Deep
Canopy	Closed	Partly Open	Open	Partly Open
Lateral Stream Habitat	Limited	Abundant	Limited	Abundant
Woody Debris	Sparse	Abundant	None	Abundant
Dominant Channel Unit	Pool/Cascade	Riffle/Rapid	Rapid	Pool/Rapid

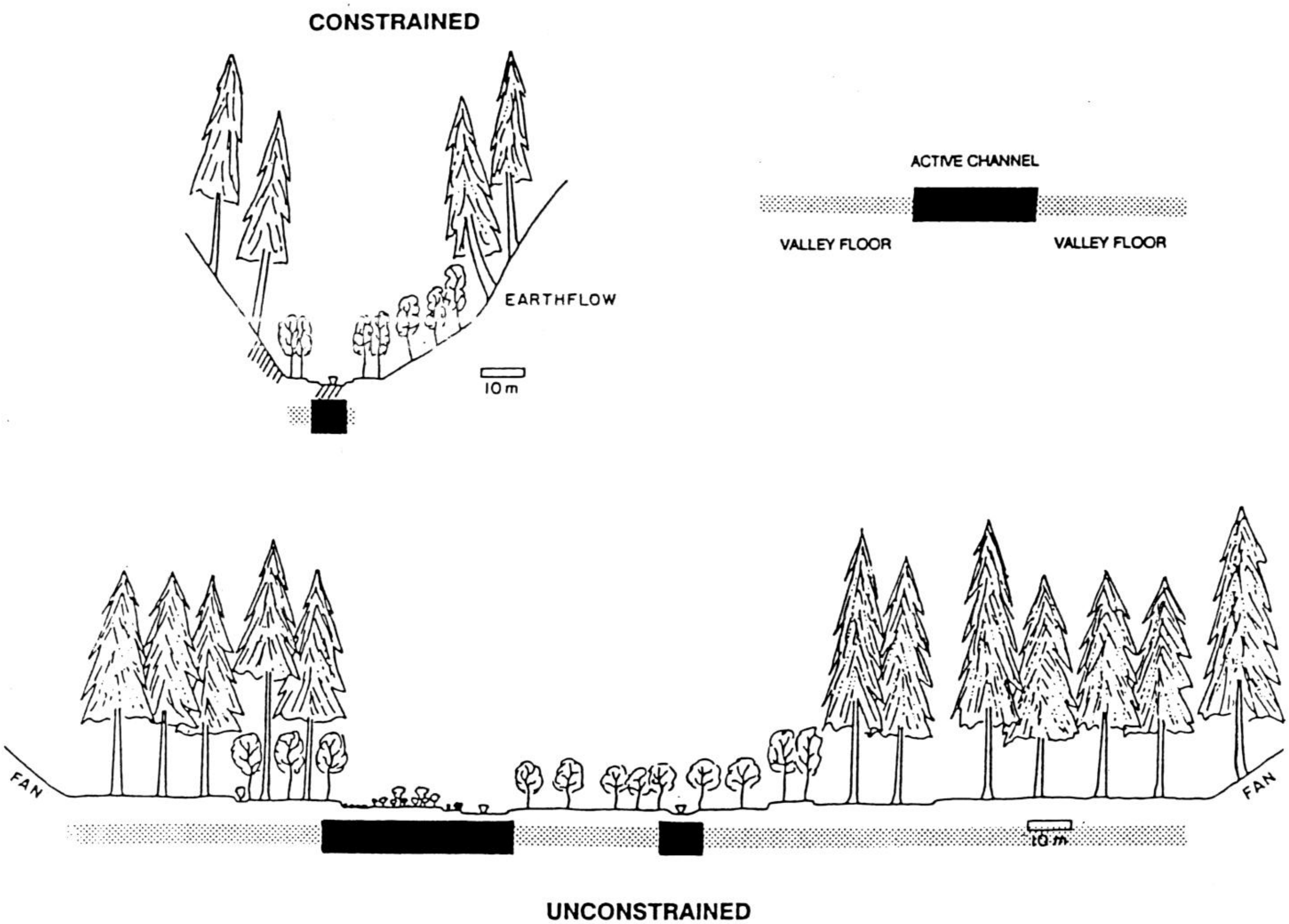

Figure 1– Schematic representation of constrained reach C and unconstrained reach D in Lookout Creek.

unconstrained) had old-growth riparian vegetation dominated by mature Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*). The other two reaches E and G were in second-growth riparian zones dominated by young stands of red alder (*Alnus rubra*), big-leaf maple (*Acer macrophyllum*), and some conifers.

Mapping of valley floor landforms and channel geomorphology was conducted prior to this study (G. Grant and F. Swanson, unpub. data). The unconstrained reaches had two channels that spanned most of the reach length, whereas the constrained reaches consisted of a single channel. Specific reaches were divided into channel units, which were identifiable geomorphic components of the channel at least as long as the channel was wide. Channel units in this montane stream included cascades, rapids, riffles, and pools.

Materials And Methods

Retention can be thought of as the difference between the quantity of particles or dissolved nutrients in transport at a given point in the stream and the quantity still in transport at some point downstream, given no significant new inputs over that distance. This difference is best expressed in some standardized form because quantities of released particles or nutrients, length of stream examined, or duration of measurement will vary from experiment to experiment. Previous releases of leaves indicate that retention is represented well by a negative exponential model (Speaker and others 1984):

$$T_d = T_i e^{-kd}$$

where T_i is the total amount of released leaves or nutrients, T_d is the amount of leaves or nutrient in transport at some distance d downstream of the release point, and k is the instantaneous rate of removal from transport (instantaneous retention rate or retention coefficient). The average travel distance of a leaf or nutrient atom is the inverse of the retention coefficient, or $1/k$ (Newbold and others 1981).

Leaf Retention

Ginkgo leaves (*Ginkgo biloba*) were released into the channel to measure particulate matter retention. Ginkgo leaves are about the same size as leaves of many riparian tree species, but gingko trees do not occur naturally in North American riparian zones. The leaves are bright yellow and thus easily distinguished from those of other riparian species. Ginkgo leaves were collected just after abscission, dried, and counted into 5000-leaf batches. Leaves were soaked in water for 12 hours prior to release to ensure neutral buoyancy in the stream. One batch of 5000 leaves was released at the top of each study reach. At 100 m downstream, a net was placed across the stream channel to capture any leaves that were not retained within that 100-m segment. All leaves caught by the net for 2 hr after the release were retrieved and counted. Leaf retention downstream of the release point conformed to a negative exponential model in most cases (Fig. 2).

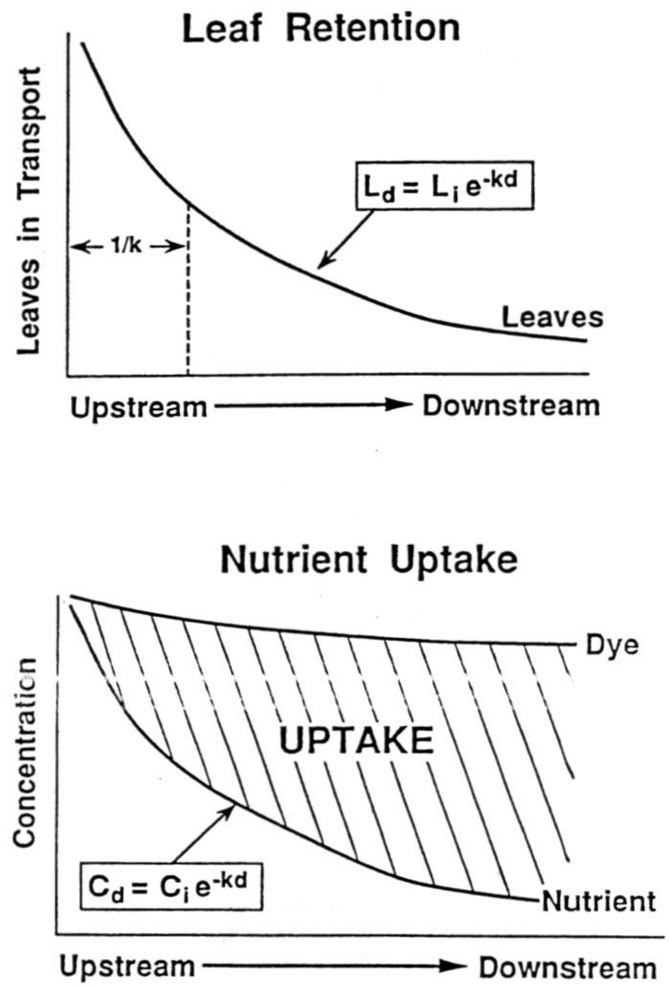

Figure 2 – Empirical models of leaf and nutrient retention in streams. A negative exponential model provided the best fit for observed retention of leaves and ammonium.

Nutrient Retention

Because ambient nutrient levels throughout Lookout Creek typically are about 15 ug/L total inorganic nitrogen (TIN = NO_3-N + NO_2-N + NH_4-N) and 15 ug/L soluble reactive phosphorus (SRP = PO_4-P) for a N:P ratio of 1:1, production is usually limited by the availability of nitrogen. Ammonium nitrogen (as NH_4Cl) was released into Lookout Creek to measure dissolved nutrient retention. NH_4Cl, the labile nutrient, was mixed in water with rhodamine-WT, a conservative dye tracer, to form a concentrated batch of nutrient and dye. This mixture was released at a constant rate into a turbulent area of the stream using a steady-head dripper system. Dye and nutrient usually mixed completely with stream water within 50 m of the release point. Sufficient ammonium was released to raise equilibrium TIN levels to between 50 and 70 ug/L (i.e., 3-5X above ambient) at the upstream end of the reach. When equilibrium was reached, two water samples were taken at the bottom of each channel unit within the reach. Dye concentration in one sample was measured on a Turner fluorometer. Ammonium concentation was determined in the other sample with a Technicon II autoanalyzer using the phenate method.

The conservative dye tracer provided a measurement of downstream dilution due to incoming tributaries, springs, seeps, and groundwater (Fig. 2). All nutrient measurements were adjusted for dilution using the correction NH_4-Nd . (Dye_i/Dye_d), where i is the concentration at the top of the reach and d is the concentration at some distance d downstream where the corresponding nutrient sample was taken. Dye releases also allowed measurement of discharge and hydraulic retention. All releases of leaves and nutrients were conducted at summer baseflow (0.3-0.4 m^3/sec) during August and September of 1987.

Results

Geomorphology and Hydraulics

The valley floor index, which is the ratio of the valley floor width to the active stream channel width, ranged from 1.3-2.8 in the constrained reaches C and E to >6.0 in the unconstrained reaches D and G (Table 2). Unconstrained reaches had 2-3 times the number of channel units as constrained reaches. This is due, in part, to the two parallel channels present in unconstrained reaches, which contributed units, wetted surface area, and total length to those reaches. For example, thalweg length was similar in the old-growth pair C and D and the second-growth pair E and G, but total length was two to three times higher in the unconstrained reach of each pair. Further, active channel area in unconstrained reach D was almost double that of constrained reach C. This areal difference was not as striking in the second-growth reaches E and G because constrained reach E was located on an alluvial fan, which resulted in a somewhat broader channel. However, downcutting through the fan still applied local constraint to reach E.

Discharge was 10-30 percent higher in unconstrained reaches than in constrained reaches, probably because of flow contributions from large stores of subsurface water in the deeper sediments of those reaches (Table 2). The time required for dye saturation of unconstrained reaches was about twice as great as for constrained reaches, indicating greater hydraulic residence time in the unconstrained reaches. In other words, unconstrained reaches retained water for a much longer time than did constrained reaches.

Table 2. – Geomorphic and hydraulic characteristics of the four study reaches in Lookout Creek, Oregon.

	Reach			
Parameter	C	D	E	G
Valley Floor Index[1]	1.3	6.9	2.8	[2]6.0
Thalweg Length (m)	410	547	349	336
Total Length[3] (m)	415	1198	391	663
Mean Width of Active Channel (m)	18.7	28.0	26.3	[2]30.0
Active Channel Area (m^2)	3948	7080	3005	3597
No. Channel Units	17	52	13	34
Discharge (m^3/sec)	0.31	0.40	0.28	0.31
Reach Saturation Time (h:m)	1:45	3:30	0:55	1:50

[1]Valley floor width (m) / Active channel width (m)
[2]Estimated
[3]Cumulative length of all channels

Table 3 – Leaf and nutrient (NH_4) retention in the four study reaches of Lookout Creek, Oregon. Length of experimental reach was 100 m for all leaf releases, and thalweg length for all nutrient releases.

	Reach			
Parameter	C	D	E	G
Leaf retention Coefficient k	0.008	0.031	0.008	0.045
Average Leaf Travel Distance (m)	132	33	125	22
NH_4 Retention Coefficient k	.0014	.0092	.0059	.0044
Average Ammonium Travel Distance (m)	732	109	171	229
Absolute Retention ($ug\ NH_4\text{-}N \cdot L^{-1} \cdot 100m^{-1}$)	6.0	15.3	17.8	25.8

Leaf Retention

Leaf retention coefficients ranged from 0.008 in both constrained reaches to 0.031-0.045 in the unconstrained reaches (Table 3). The average travel distance of an individual leaf was 125-132 m in the constrained reaches compared to only 22-33 m in the unconstrained reaches. In constrained reaches, slightly over 50% of released leaves were retained in the 100-m reach whereas >95% of leaves were retained in the unconstrained reaches. The riparian setting (old-growth or second-growth) did not appear to influence rates of leaf retention, but rather valley constraint was the predominant factor.

Within specific reaches, high-velocity channel units with high roughness, such as rapids and cascades, retained more leaves than lower-velocity units with limited roughness, such as pools. Units with significant amounts of bedrock trapped few leaves. We observed that most retained leaves were trapped in interstitial areas between rocks, especially cobble and boulders. Substrates along stream margins trapped leaves more efficiently than similar substrates in mid-channel areas. Sticks and branches, where present, trapped leaves with high efficiency. Accumulations of woody debris, which occurred along stream margins in Lookout Creek, also trapped large quantities of leaves. Thus, in general, stream margins were more retentive than mid-channel areas, especially when these lateral habitats had roughness elements such as protruding rocks or woody debris.

Nutrient Retention

Ammonium retention coefficients ranged from 0.0014 in the old-growth constrained reach to 0.0092 in the old-growth unconstrained reach (Table 3). Retention coefficients were intermediate and similar in the second-growth reaches. Nutrient retention was very low in the constrained old-growth reach, where the average nitrogen atom traveled over 700 m before being retained; in absolute quantities, only 6 *ug*/L of NH_4-N (or 10.9 percent of that released) was retained over 100 m. In contrast, the average nitrogen atom traveled only 109 m in the unconstrained old-growth reach, and absolute uptake was over twice that of the constrained reach. Over 25 percent of the released ammonium was retained in 100 m.

In the second-growth reaches, nutrient retention was slightly higher in the unconstrained reach, where about 26 *ug*/L of released nitrogen was retained in 100 m. However, nutrient retention was quite high in the constrained reach as well (18 *ug* NH_4-$N \cdot L^{-1} \cdot 100$ m), in particular when compared to the constrained reach in the old-growth. Over one-third of the released nutrient was retained in 100 m of the unconstrained reach, and about 25 percent was retained in the constrained reach.

Discussion

Geomorphic and Hydraulic Comparisons

The unconstrained reaches were characterized by broad valley floors bisected by two stream channels dominated by riffles, rapids, and some small pools. The relatively low gradient (2 percent) and reduced stream power of those reaches allowed accumulation of woody debris in the channel, which further increased channel complexity. Stream sediments were deep and heterogeneous. Lateral habitats were well developed and included secondary channels, backwaters, and isolated pools. Diversity of hydraulic environments was high, and water residence times were great due to considerable subsurface flow.

Riparian vegetation was diverse, and included herbaceous, shrub, deciduous, and coniferous species. Stratification of riparian vegetation was apparent, in that herbs and shrubs were located close to the active channel, whereas deciduous and coniferous trees grew at greater distances from the active channel. Because of this stratification, incident sunlight striking the channel was relatively high in unconstrained reaches, which resulted in substantial growths of benthic plants. For example, benthic algae and mosses covered 24-29 percent of the active channel in the unconstrained reaches.

Constrained reaches, by contrast, were characterized by a single channel with limited sinuosity and poor development of off-channel (lateral) habitat. In the Cascade Mountains, these gorge-like settings are often the result of either active hillslope processes such as earthflows, landslides, and deposition of alluvial fans or passive constraints such as bedrock outcrops that prevent lateral movement of the channel. Both mechanisms tend to funnel flow through a narrow slot on the valley flow. As a consequence, stream gradients are steeper (>3 percent), water depth is greater, and water velocity and stream power are higher than in unconstrained reaches. Due to scour at high flow, sediments tend to be shallow and woody debris accumulation is limited. In the old-growth constrained reach, vegetational diversity and stratification was low because conifers were perched close to the stream channel. Shading of the channel by hillslopes and nearby conifers limited benthic plant cover to only 10 percent of the channel. The second- growth constrained reach was somewhat unique in that it occurred on a broad but inactive alluvial fan. Although the channel was simple and linear, it was wide and its sediments were relatively deep. Light levels on the channel were high because of the absence of large conifers combined with low topographic shading. Accordingly, cover by benthic plants (46 pct.) was the highest of any reach.

Retention in Stream Ecosystems

Particulate and dissolved matter in transport provides a critical source of nutrients for a substantial portion of the aquatic biota. Particulate organic matter (POM) delivered from adjacent riparian zones into streams includes leaves, needles, seeds, twigs and woody debris. In the stream, this organic matter is decomposed by microheterotrophs such as bacteria and fungi or consumed by detritivorous invertebrates such as insects and snails (Cummins and others 1983). Often, a period of microbial conditioning is necessary before POM becomes palatable to invertebrate consumers (Anderson and Sedell 1979). Dissolved nutrients in streams include inorganic compounds such as nitrogen, often in the form of ionic ammonium (NH_4^+) and nitrate (NO_3^-), and phosphorus, as orthophosphate (PO_4^{-3}). These nutrients are utilized by stream plants such as benthic algae during photosynthesis, and by certain microheterotrophs such as bacteria during cellular metabolism (Triska and others 1983).

Particulate matter is retained in streams primarily by physical trapping. Channel roughness elements, such as coarse sediments and woody debris greatly enhance the retentive efficiencies of stream reaches (Speaker and others 1984). Leaves are trapped in the interstices of bed particles and within networks of woody debris accumulations. Along stream margins, low water velocities, shallow depths, and high roughness increase the potential for retention. Thus, complex lateral habitats will enhance leaf retention whereas simple (linear) stream margins will hinder retention.

Leaf releases in Lookout Creek indicated that unconstrained reaches were substantially more retentive of particulate matter than were constrained reaches. This retentive efficiency of unconstrained reaches was due to a number of factors, including (1) high roughness, (2) substantial development of lateral habitats (e.g., backwaters and side channels), (3) extensive wetted area, (4) low water velocities, (5) presence of woody debris along stream margins. These factors acted in concert to increase contact between leaves and streambed particles, and thereby enhance trapping of particulate matter. In contrast, constrained reaches were relatively unretentive of leaves. These reaches had lower roughness and wetted area, and thus there was reduced opportunity for contact between leaves and streambed. Poor development of lateral stream habitats in constrained reaches also limited leaf trapping along stream margins.

Dissolved Matter Retention

Dissolved nutrients can be retained in stream ecosystems by three different mechanisms: (1) uptake by primary producers, including benthic algae and mosses, (2) absorption or transformation by heterotrophic microorganisms, (3) chemical or physical sorption onto surfaces of inorganic substrates or detritus (adsorption). It is not clear which mechanism(s) was most important for nutrient retention in Lookout Creek. All three processes probably operated to some degree. Mechanism 1 was supported by our observation that retention was highest in reaches with the highest algal abundance, as in the constrained second-growth site. Microbial transformation (mechanism 2) also occurred because as ammonium declined in a downstream direction, nitrate increased slightly, indicating some microbial nitrification (conversion of ammonium to nitrate). Although we have no direct evidence for mechanism 3, as a cation ammonium is readily bound chemically and sorbed physically and thus some removal by this mechanism probably occurred. Regardless of whether the process was uptake, transformation, or sorption, retention serves to conserve nutrients in a specific reach. These nutrients may be used immediately as in the case of uptake or transformation, or stored for later use as in the case of adsorption.

High levels of nutrient retention in the unconstrained reaches are probably attributable to the geomorphic and hydraulic complexity of these reaches, which enhances opportunity for nutrient uptake and adsorption. In the old-growth, the unconstrained reach had 2.5 times the nutrient retention of the constrained reach. The unconstrained reach had more algae, higher hydraulic residence, greater water-sediment contact, and deeper sediments than the constrained reach. All of these factors could enhance mechanisms 1- 3 above and thus increase nutrient retention. The unconstrained second-growth reach also had substantial nutrient retention, probably because of high rates of algal uptake in this open reach. The alluvial fan that formed the streambed also may have provided the opportunity for ammonium adsorption during subsurface flow.

Summary

Retention of dissolved and particulate matter is of critical importance to the operation of stream ecosystems. Retention largely determines the availability of food resources to aquatic organisms. Long-term retention of detritus delivered from riparian zones, with its subsequent microbial colonization and consumption by detritivores, is critical to energy transfer in most streams. Retention of dissolved nutrients permits levels of primary production and microbial growth necessary to support grazing invertebrates. Higher consumers such as fish that rely on invertebrates for food are thus dependent on retention processes to supply food resources for their invertebrate prey.

Retention efficiency is intimately linked to riparian conditions and ultimately to valley floor landforms. Highly complex channels within broad valley floors display high retention, whereas simple channels within narrow valleys are less retentive. Channel geomorphology, including lateral habitat, bedform, and substrate characteristics, is a major determinant of rates of particulate and nutrient retention. Complex strata of riparian vegetation permit light gaps that encourage primary production and thus nutrient retention, while ensuring a steady source of detritus to the stream. Second-growth riparian zones may enhance nutrient retention due to algal uptake, but sacrifice particulate matter retention because of channel simplification. Retention is a complex interaction of valley floor geomorphology, riparian conditions, and in-stream biological demand that accentuates the intimate linkage between aquatic and terrestrial ecosystems.

Acknowledgments

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