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# Debris dam dynamics and coarse particulate organic matter retention in an Appalachian Mountain stream

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*Abstract.* Debris dam structure and retention of coarse particulate organic matter were examined during a 17-mo period in Powdermill Run, a 3rd-order Appalachian Mountain stream. Through the use of detailed feature maps, changes in debris dam morphology were recorded, including the complete "life-cycle" (i.e., initial formation to destruction) of a dam. Stream sections in which dams were naturally destroyed became markedly less retentive.

Leaves were used as tracers in retention experiments that varied in duration from 3 h to 4 wk. Results implied that migration over time occurred by a simple mechanism of leaves falling off rocks and settling into debris dams. A series of releases over 12 d showed increasing retentiveness as discharge decreased. Seasonal differences in retention potential were evaluated using 3-h releases conducted during winter, summer, and autumn. Summer was the most retentive season due to baseflow conditions. Debris dams were most retentive in autumn, less so in winter, and least retentive in summer. Cobbles showed the opposite pattern. Leaf retention ranged from 1.8 to 23.2% retained/m ($-k$: 0.02 to 0.26), depending on season. A significant negative relationship was found between mean depth and % retained/m, but the relationship of % retained/m to discharge was not significant. A consideration of season is necessary when comparing retentive abilities between streams.

*Key words:* retention, debris dam, CPOM, large woody debris, leaves, stream, discharge, season, forest succession.

The stability of a detritus-based system is dependent on factors regulating the availability of that detritus. For headwater streams, this pertains not only to riparian-derived input of resources such as coarse particulate organic matter (CPOM; particles ≥ 1 mm in diameter), but to retention of that material. The slowing of downstream transport of organic matter allows biological processing to occur, thus shortening the distance between "loops" in the nutrient spiraling model (Elwood et al. 1983, Minshall et al. 1983). The retention of CPOM in headwater streams is necessary for the processing of detritus, as detailed in the River Continuum Concept (Vannote et al. 1980), by allowing shredders to process CPOM into fine particulate organic matter (FPOM; particles < 1 mm in diameter).

Retention of detritus in streams has received considerable attention in recent years. Factors investigated have included the role of organic debris dams (e.g., Bilby and Likens 1980, Smock et al. 1989, Trotter 1990, Ehrman and Lamberti 1992), floodplain interaction (Jones and Smock 1991), burial in the substrate (Mayack et al. 1989), discharge (Snaddon et al. 1992), and channelization (Petersen and Petersen 1991). The influence of retention on invertebrates has also been examined (Hildrew et al. 1991, Prochazka et al. 1991). Speaker et al. (1988) recognized that the ability of a stream to retain material, referred to here as *retention potential,* is distinct from what is actually being retained. For example, a stream could have the ability to retain material (i.e., have a high retention potential), while actually retaining little material because of low riparian-derived input or high discharge events.

Large woody debris (LWD; pieces ≥ 10 cm in diameter and ≥ 1 m long) is critical to retention potential (Bilby and Likens 1980). Speaker et al. (1984) and Trotter (1990) described the mechanisms by which LWD retains CPOM. These mechanisms include (1) forming the stable base for debris dams, (2) trapping sticks, (3) increasing channel width, and (4) creating pools and side channels. Although the importance of debris dams to retention has been recognized, little is known about their dynamics through time.

The purpose of our study was to examine the retentive capabilities of a stream by using experimental leaf releases, and to observe debris dam morphology. Three experiments were conducted to examine short- and long-term patterns of retention, the influence of discharge and depth on retention, and the influence of seasonality on retention. We hypothesized that (1) leaves would migrate over time; (2) retention potential would increase as discharge and depth decreased; and (3) retention potential would be greatest in summer as a result of baseflow conditions.

## Study Site

This study was conducted from January 1993 to May 1994 in Powdermill Run, a 3rd-order brook-trout stream in the Allegheny Mountains of the Appalachian Plateaus Province (Barnes 1991). The stream originates within Forbes State Forest and drains a 24.9-km² watershed in the Laurel Mountains of Pennsylvania, USA. The study section of Powdermill Run was a 205-m reach completely contained within the Powdermill Biological Station. The study reach had an average width of 5.3 m, high gradient (3.2%), and approximately 90% of the bankfull channel consisted of riffle. Pools and backwater eddies were limited to areas influenced by large debris dams and boulders. Stream sediments were dominated by large cobbles, and to a lesser extent, gravel and pebbles.

The study reach had a closed canopy and flowed through a northern hardwood–mixed mesophytic forest that was selectively logged in 1940. Common riparian trees at the study site included: tulip poplar (*Liriodendron tulipifera*), American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), eastern hemlock (*Tsuga canadensis*), and yellow birch (*Betula alleghaniensis*).

## Methods

### *Mapping* and woody debris

Reference points were marked along the bank at 5-m intervals. An elevation-contour map was constructed as a framework for a feature map (Keller and Tally 1979). Stream width was measured at the 5-m intervals. Hydrologic features (e.g., pools, runs; Church 1992) were judged qualitatively. The locations of individual boulders and pieces of LWD were also measured. The largest debris dams were mapped and precise locations and orientations of individual logs were recorded by measuring distance from riparian benchmarks (e.g., standing trees). Following geomorphic alterations, debris dams were again mapped to record changes over time. Triangulation with two riparian benchmarks (established as fixed points on a computer-generated map) allowed subtle differences in LWD location and orientation to be quantified.

Volume of LWD was calculated assuming pieces of cylindrical shape, except for two pieces that were treated as cones. If possible, the species of debris was recorded. Two measurements of LWD volume were made: volume occupying bankfull channel, and volume occupying the wetted channel at baseflow. Bankfull channel was defined as the space delineated by the active channel or floodplain (when present).

### Leaf releases

All leaves released in each experiment were those of ginkgo trees (*Ginkgo biloba*). Ginkgo leaves have been used as tracers in past studies (e.g., Speaker et al. 1984), do not occur at the study site, are bright yellow at the time of abscission and remain so in the water, and can be easily identified in the stream by color and shape. Leaves collected after abscission were air-dried and selected for color and intact structure (petiole attached). All leaves were soaked for 12 h in cold water prior to release to achieve neutral buoyancy. Leaves were released into the thalweg of the channel.

For each leaf release, distance traveled by the leaves in 5-m intervals and features retaining leaves were recorded. Retention potential was evaluated as percent of leaves remaining in transport. Retentive features were compiled from Speaker et al. (1984), Prochazka et al. (1991), and Snaddon et al. (1992). All collections were made while moving upstream, and each leaf recovered was removed from the system. Only those leaves readily visible were collected; no destructive sampling was used to examine debris dams. A 30-m section of the stream that ended in a large settling pool, immediately below the study reach, was inspected for leaves that exited the system. Mean depth was measured on the day of each release, and discharge was measured directly on the day of most releases.

Retention potential was expressed as % retained/m [% ret/m = $(1 - e^{-k}) \times 100$]. This value is based on the negative exponential model of retention of released leaves: $T_d = T_o e^{-kd}$, where $T_d$ is the percentage of released particles in transport at distance d in meters, $T_o$ is 100%, and k is the instantaneous rate of retention (Speaker et al. 1984). Retention curves within experiments were compared by analysis of covariance (ANCOVA). The proportion of leaves retained by features was compared within experiments using the chi-square test of homogeneity.

### *Long-term and cohort release experiments*

In a long-term experiment, 10,000 leaves were released on 6 February 1993. The exceptionally large number of leaves was used in an attempt to counteract the potential for leaf decay. Two collections were made at 4-wk intervals following the release. Results from the long-term release were compared with the results of the Winter–1 release (see below).

A series of releases was conducted between 15 and 27 June 1993 to evaluate the effects of discharge and time on leaf retention over a period of 12 d. Four cohorts of 1000 leaves each were marked with orange or black indelible markers. The cohorts were released at 3-d intervals. A single collection was made 3 d after the last release. Thus, cohorts remained in the stream for 3, 6, 9, and 12 d. A hydrograph was constructed for the duration of this experiment by directly measuring discharge at one location at least once each day.

### *Seasonal evaluation of retention and additional releases*

Seasonal variation in retention potential was evaluated by releases of 500 leaves, which were collected after 3 h. Leaves were released on six dates during a 17-mo period: 17 January 1993 (Winter–1), 5 March 1994 (Winter–2), 11 August 1993 (Summer–1), 18 September 1993 (Summer–2), 31 October 1993 (Autumn–1), and 7 November 1993 (Autumn–2). A 1.0-cm-mesh net weir was erected at the bottom of the study reach for the Winter–1 release (the first release performed) to test whether leaves had the opportunity to traverse the entire system (Speaker et al. 1984).

A release of 500 leaves collected after 3 h was performed on 18 July 1993 (Debris-Dam Test) to evaluate the retentive capability of a newly formed debris dam (DD-1, see below). An additional release of 500 leaves collected after 3 h was performed on 14 November 1993, and is included in the analysis of retention potential and discharge. All 3-h releases except the Debris-Dam Test release, were included in the analysis of the influence of discharge and depth ($n = 10$). For all releases, data were $\log_e$-transformed to calculate retention potential.

Additional releases of 500 leaves collected after 3 h were performed on 4 April 1994, 20 April 1994, and 4 May 1994 (Debris Dam–A, –B, and –C, respectively), to evaluate the reach after structural changes in several debris dams (see below). To test whether debris dam alterations affected retentive abilities, % ret/m was calculated for a section of the stream in which alterations occurred (45–60 m). The retention values for this section were pooled from releases Debris Dam–A, –B, and –C, and compared with the retention within the same section in prealteration releases (Winter–1 and –2, Autumn–1 and –2) by analysis of variance (ANOVA). In total, 16 leaf releases were conducted in this study.

## Results

### *Large woody debris*

During the course of this study the structure of five major debris dams changed. As mapped in February 1993, the thalweg in the 5- to 10-m section of the reach flowed around a small debris dam in the center of the channel and under a root mass (Fig. 1). In May 1993, a large debris dam (DD-1) formed, supported by the root mass. In less than one month, fine sediment was stored upstream of the dam. The thalweg was now split, flowing both under the root mass (and through DD-1) and over a log in the center of the channel, forming a log-step and plunge pool. The orientation of a large birch log (Log-a: 2.7 m in length, 21 cm in diameter) was also altered. By July 1993, Log-a had been transported approximately 5 m downstream, and had broken another log which previously had been suspended 0.2 m above the surface of the stream (at base flow). One of the halves of this broken log was resting on top of Log-a. As mapped in July 1993, the entire DD-1 "complex" consisted of (from the left bank to the right in Fig. 1): a "pick-up-sticks" jumble of wood, a log step, and several pieces of wood parallel to each other and roughly perpendicular to the direction of flow. By April 1994, DD-1 had been completely destroyed, and the sediment flushed out. Thus the "life-span" of this dam, from creation to destruction, was approximately one year. Surprisingly, the orientation of Log-b became increasingly perpendicular to the direction of flow as time progressed.

DD-1 affected subsequent leaf releases (see cohort and seasonal releases below), and retained nearly 100% of the leaves released in the Debris-Dam Test release. Four other debris dams were either naturally destroyed or altered during April 1994, in addition to the destruction of DD-1 (all alterations were observed at the same time). We speculate that a single bankfull event (1-y flood) altered all the dams, but we did not make observations at the time. DD-2 had consisted of a large primary log spanning the channel, storing sediment upstream and creating a log step and plunge pool ("1°" log, Fig. 2). A fissure was observed in the primary log at the beginning of the study. Following the breakage of the fissure in late winter or early spring 1994, stored sediments and retained debris were flushed out. Half of the primary log remained in an altered orientation, while the other half was transported 40 m downstream.

DD-3 consisted of several retentive areas associated with one large log (Fig. 2). This log was moved, altering its orientation but maintaining its retentiveness away from the thalweg. DD-4 was a complex series of structures in February 1993 (Fig. 3). In April 1994, this dam was simplified into one retentive surface extending across the channel.

The volume of LWD (Table 1) in the study reach was 59 $m^3$/ha (estimated biomass = 23.6 Mg/ha, converted according to Harmon et al.

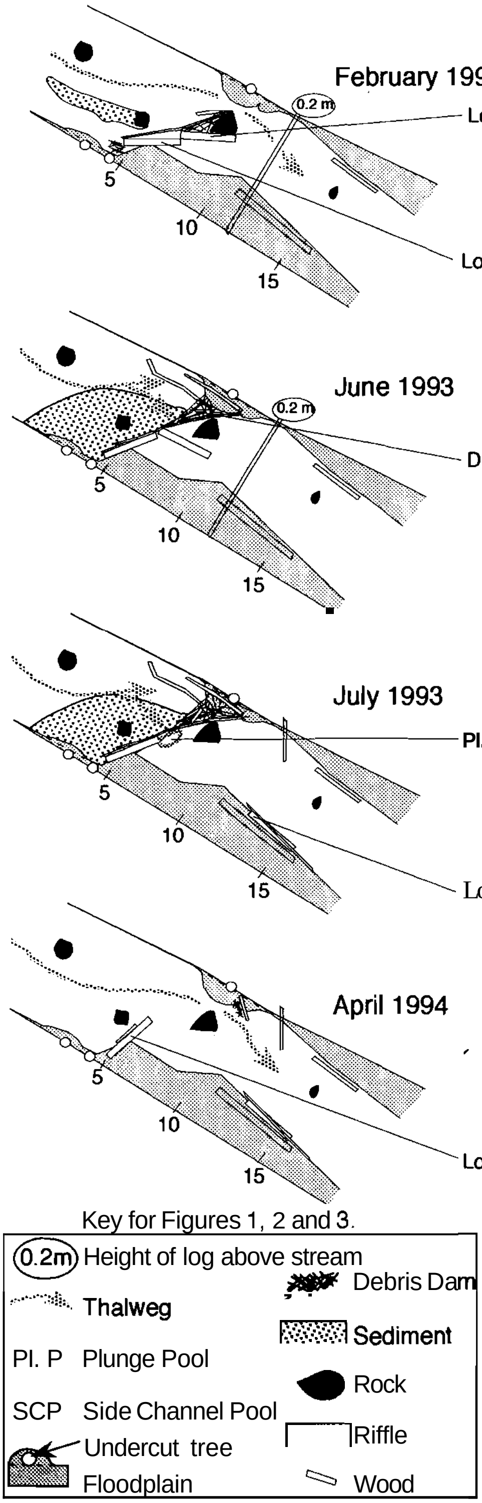

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FIG. 1. **The natural formation and destruction of a debris dam (DD-1). This dam formed in the 5- to 10-m section of the reach in May 1993. The location of the dam necessitated the movement of the leaf-release point from 0 m to 10 m for subsequent 3-h releases. By April 1994, the dam, including the log step, was destroyed.**

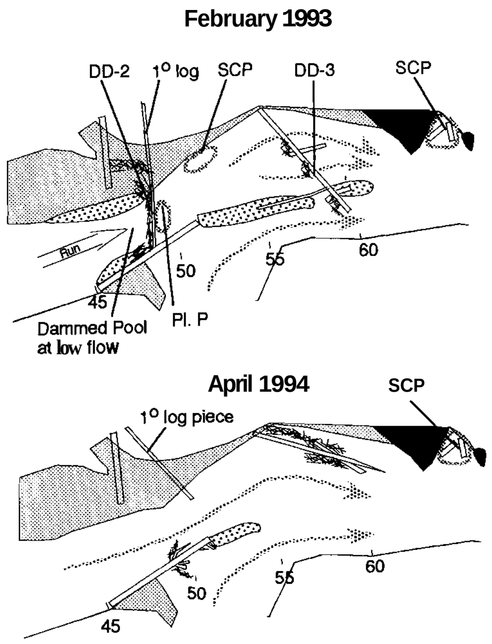

FIG. 2. The natural destruction of two debris dams (DD–2 and DD–3). Maul Spring, a 1st-order spring-fed tributary meets Powdermill Run at 50 m. This tributary did not influence the discharge regime of Powdermill Run. The log identified as DD–3 in the top panel is present in the lower panel in an altered position. See Fig. 1 for key.

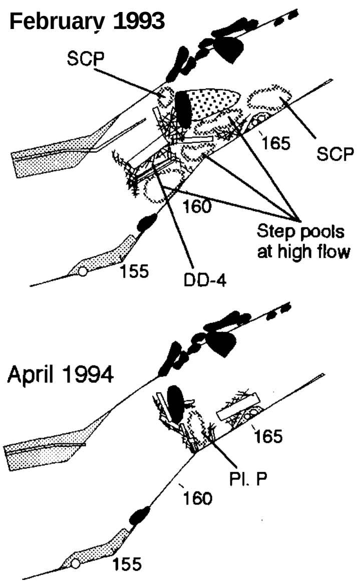

FIG. 3. The natural simplification of a debris dam (DD–4). See Fig. 1 for key.

[1986]). Within the study reach, the active channel was usually synonymous with the bankfull channel, with little active floodplain. Only 2% of all wood present within the bankfull space occurred within the wetted channel at summer baseflow. Yellow birch was the most numerically (28%) and volumetrically (41%) abundant species of LWD within the bankfull channel. All hemlock was represented by two large pieces, and most of the beech volume was represented by one log. These pieces did not intrude into the wetted channel at baseflow. Out of 63 pieces of LWD, 24% (volumetrically), and 49% (numerically) were not identifiable to species.

### *Leaf recovery proportion and effect of discharge*

Very few leaves, if any, were recovered in the 30-m section and settling pool below the study reach in each release experiment. Only <1% of the leaves in the Winter–1 release were recovered in the weir, although only 47% of the total released were found. We assumed that the remaining leaves were well-hidden within debris dams.

The proportion of leaves recovered decreased as discharge increased ($y = 36.35 - 32.18 \times \log(x)$, $r^2 = 0.81$, $p < 0.05$). The relationship between discharge and retention potential was not significant ($p = 0.13$). However, retention potential decreased with increasing depth ($y = 40.86 - 33.29 \times \log(x)$, $r^2 = 0.84$, $p < 0.01$).

### *Long-term retention and cohort releases*

A comparison of the long-term release and the Winter–1 release showed that Powdermill

TABLE 1. Volume of large woody debris (>1 m length and >10 cm diameter) in a 205-m reach of Powdermill Run expressed as volume occupying bankfull space and wetted channel at baseflow.

| Species | Bankfull | Baseflow |
|---|---|---|
| Yellow birch | 2.62 m$^3$ (40.6%) | 0.07 m$^3$ (58.3%) |
| American beech | 0.41 m$^3$ (6.3%) | 0 |
| Eastern hemlock | 1.86 m$^3$ (28.8%) | 0 |
| Unknown | 1.56 m$^3$ (24.2%) | 0.05 m$^3$ (41.7%) |
| Total volume: | 6.45 m$^3$ | 0.12 m$^3$ |

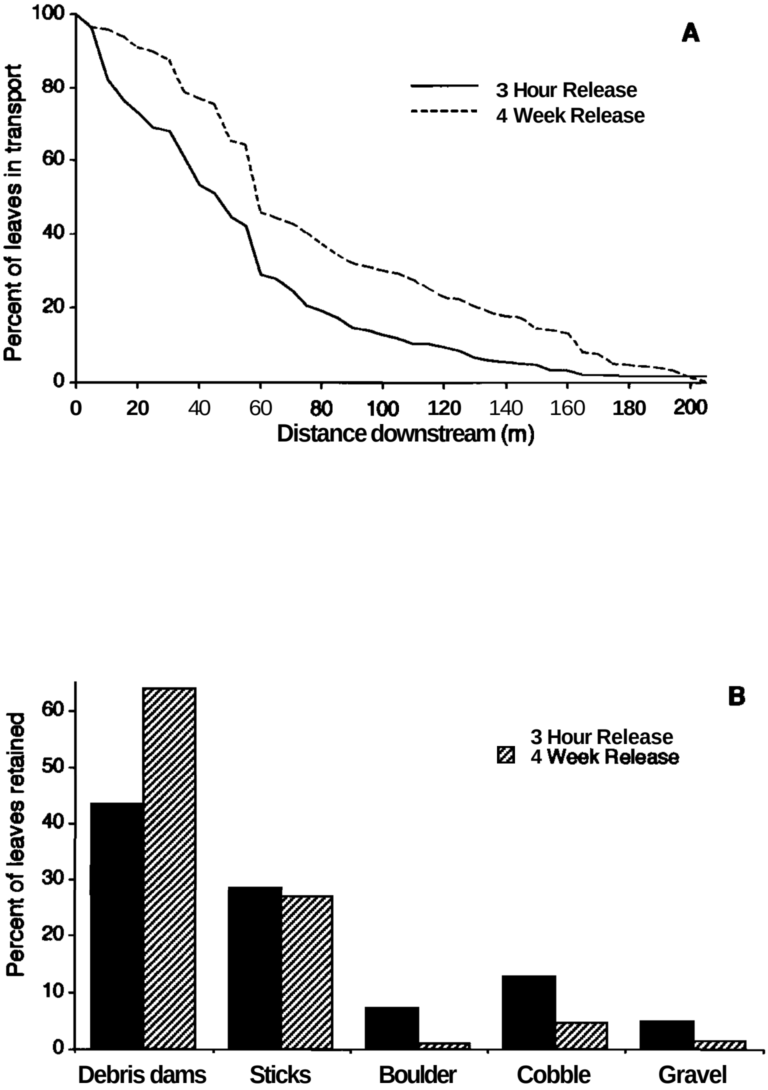

FIG. 4. A.—Comparison of retention of released leaves in two experiments with different residence times. B.—Comparison of selected retentive features in these experiments.

Run was slightly less retentive over a period of 4 wk than over 3 h (Fig. 4A, $p < 0.0001$), even though discharge was less on the day leaves were introduced for the long-term release (Table 2). Geologic features (boulders, cobble, and gravel) were less retentive over time, and debris dams were more retentive over time (Fig. 4B, $p < 0.001$). The retentiveness of sticks was nearly equal between 3 h and 4 wk. Leaves of the long-term release experiment decomposed surprisingly rapidly after 4 wk. No leaves were recovered in the second collection attempt of the long-term release (8 wk after the releasing of leaves). DD-1 formed after the long-term experiment was completed and before the cohort experiment had begun.

The retention values for cohorts remaining in the water (residence time) for 12, 9, and 6 d were nearly identical (Table 2, 12 d = 9 d = 6 d < 3 d, $p < 0.0001$). The leaves of the cohort remaining in the water for 3 d experienced the greatest retention. Discharge decreased steadily during the cohort release, from 0.974 L/s to 0.126 L/s (Fig. 5A). The effect of the newly

TABLE 2. **Parameters and results of leaf-release experiments in Powdermill Run ($p < 0.001$ for all regressions).**

| Release | Residence time | % Leaves recovered | $r^2$ | $-k$ | % Ret/meter | Discharge (L/s) |
|---|---|---|---|---|---|---|
| **Long-term** | 4 wk | 10.3 | 0.83 | 0.019 | 1.9 | 0.917[a] |
| **12-day Cohort** | 12 d | 30.7 | 0.85 | 0.066 | 6.4 | 0.974 |
| **9-day Cohort** | 9 d | 26.6 | 0.78 | 0.065 | 6.3 | 0.635 |
| **6-day Cohort** | 6 d | 39.8 | 0.94 | 0.064 | 6.2 | 0.431 |
| **3-day Cohort** | 3 d | 40.0 | 0.94 | 0.099 | 9.4 | 0.209 |
| **Autumn 1** | 3 h | 13.4 | 0.96 | 0.027 | 2.7 | 2.637[b] |
| **Autumn 2** | 3 h | 26.6 | 0.95 | 0.018 | 1.8 | 3.996[b] |
| **Winter 1** | 3 h | 45.8 | 0.99 | 0.022 | 2.2 | 1.197 |
| **Winter 2** | 3 h | 41.6 | 0.94 | 0.025 | 2.5 | 2.509[b] |
| **Summer 1** | 3 h | 61.2 | 0.95 | 0.177 | 16.2 | 0.162 |
| **Summer 2** | 3 h | 82.8 | 0.92 | 0.264 | 23.2 | 0.044 |
| **Debris dam A** | 3 h | 3.2 | 0.92 | 0.013 | 1.4 | 8.912[b] |
| **Debris dam B** | 3 h | 15.4 | 0.90 | 0.021 | 2.1 | 3.321[b] |
| **Debris dam C** | 3 h | 12.4 | 0.96 | 0.019 | 1.9 | 2.062[b] |

[a] **Based on linear regression of Powdermill Q vs. Loyalhama Q with 1-d time lag. The USGS gauging weir at Kingston (Pennsylvania) measures the discharge of Loyalhama Creek, into which Powdermill Run drains. ($y = -308.73 + 9.43x$, $r^2 = 0.93$, $p < 0.01$).**

**Based on linear depth regression ($y = -4321 + 578.39x$, $r^2 = 0.78$, $p < 0.001$).**

formed DD-1 in the 5- to 10-m section of the reach was evident in the rapid removal of leaves from transport over this section (Fig. 5B). Migration of leaves over time was suggested by the retentiveness of cobbles and debris dams 2 and 3 (see DD-2 and DD-3, Fig. 5C, $p < 0.001$). Cobbles became less retentive over time. The apparent increase in retentiveness for debris dams considered collectively (All debris dams, Fig. 5C) was not significant ($p = 0.07$).

### *Seasonal retention and additional releases*

The release point for all seasonal releases (except winter–1) was removed from 0 m to 10 m, immediately downstream from DD-1, in response to the results of the Debris-Dam Test release. The Debris Dam–A, –B, and –C releases showed that the mean retention value for the 5-m sections containing DD-2 and DD-3 (45-m to 60-m) was reduced from 2.8% ret/m to 0.7% ret/m following the natural alterations of these dams ($p < 0.05$).

Summer was the most retentive season (Fig. 6A), whereas autumn and winter were alike and less retentive (Table 2, $p < 0.0001$). The relative importance of retentive structures changed substantially during the course of the year (Fig. 6B, $p < 0.001$). Debris dams were most retentive in autumn, less so in winter, and least retentive in summer. Cobbles and large wood were most retentive in summer, and less so in autumn and winter. Sticks were retentive in winter and summer, but less so in autumn. Other structures retained few leaves, or did not display seasonal patterns.

## Discussion

### *Woody debris*

The complexity of a stream (measured by the index of channel irregularity or ICI, Snaddon et al. 1992), and therefore retention potential, tends to decrease as discharge increases. Our study showed that the amount of wood present in the wetted channel increased greatly as discharge increased, (i.e., more wood was present in the bankfull channel than in the wetted channel at summer base flow). The ability of LWD to retain leaves is potentially increased at flows higher than summer baseflow, because CPOM in the water column can encounter more obstructions while traveling downstream. However, the effect of increasing discharge evidently results in a net decrease in retention potential. The lower retention rates in those 5-m sections where debris dams were naturally altered verifies results of experimental debris dam manipulations (e.g., Trotter 1990).

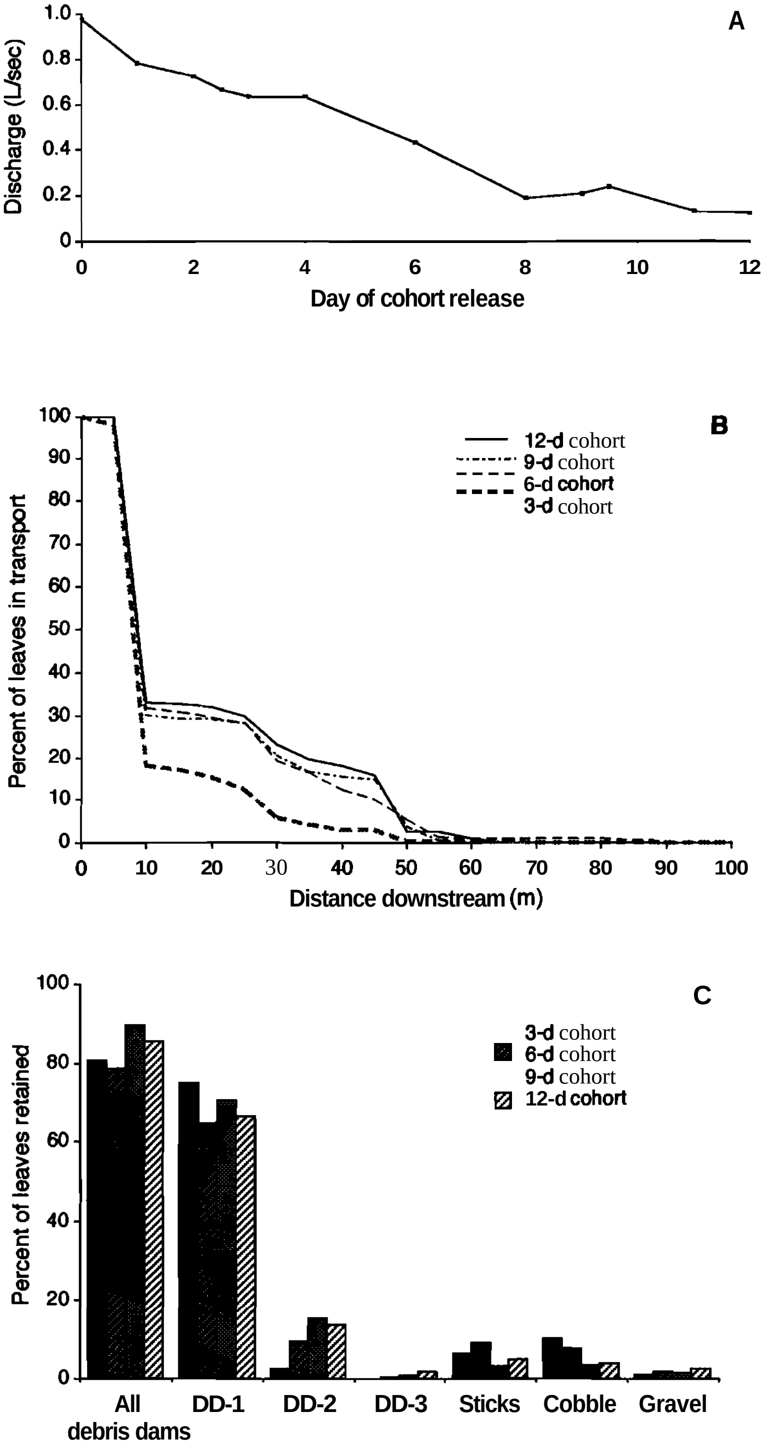

FIG. 5. A.—Hydrograph of Powdermill Run during the cohort-release experiment. B.—Retention of leaves in the cohort release. The effect of DD–1 is evident in the large drop in percent of leaves in transport over the 5- to 10-m interval. C.—Comparison of retentive features in the cohort release.

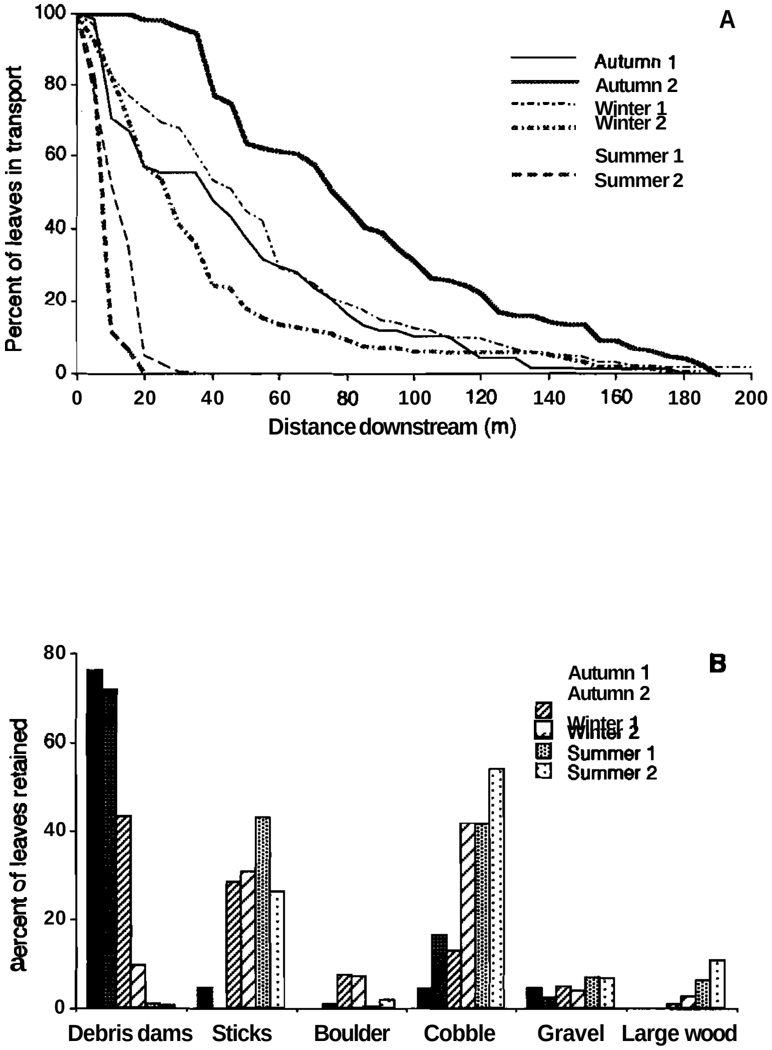

**FIG. 6. A.—Comparison of retention of leaves throughout the year. The highest discharge occurred during the Autumn-2 release. B.—Retentive features throughout the year. Data are arranged seasonally beginning with autumn, after abscission, when nearly all of the CPOM for the year enters the stream.**

Forest succession, LWD dynamics, and stream geomorphology should be integrated to understand and predict future changes in the physical structure of forested, headwater streams (sensu Smock et al. 1989). Numerous studies have shown that headwater streams flowing through young forests (e.g., mid-secondary succession) have fewer debris dams and less LWD than streams flowing through mature second-growth and old-growth forests (Harmon et al. 1986, Trotter 1990). Sedell et al. (1988) predicted that LWD loading increases with succession of the adjacent forest. The forest stand adjacent to Powdermill Run was primarily a combination of mature mid-successional tree species (e.g., tulip poplar) and understory "climax" species (e.g., sugar maple). The predominance of yellow birch debris in the stream channel is likely the result of reduced light availability for birch due to the growth and successional stage of the forest. Fallen yellow birch debris of similar size was also common on the forest floor and upstream of the study reach. It is likely that LWD quantity in Powdermill Run will increase with increasing input of mature deciduous trees and slow-decaying hemlock trees. Because the geomorphology of Powdermill Run is primarily cobble-dominated riffles, the theorized increased input of LWD as a function of forest succession should result in more debris dams per unit stream bottom, thereby increasing the proportion of stream area directly influenced by debris dams and increasing retention potential.

Debris dams evidently can be highly variable over time. The natural debris dam alterations in Powdermill Run showed that retention potential in a reach can be dramatically altered over short time periods. Although the "flushing" effects of winter spates have been described (e.g., King et al. 1987, Webster et al. 1994), material must be deposited downstream, as exemplified by the formation of DD–1.

### *Leaf retention*

Retention potential can be quantified by measuring the proportion of material that is removed from suspension and hence not transported. While the value used in the present study, "% retained/m", differs from previous formulations of retention, comparisons between studies can still be made. Most studies have reported retention curves that conform to the negative-exponential model (e.g., Young et al. 1978, Speaker et al. 1984, Speaker et al. 1988, Cummins et al. 1989, Trotter 1990, Hildrew et al. 1991, Jones and Smock 1991, Petersen and Petersen 1991, Prochazka et al. 1991, Ehrman and Lamberti 1992, Snaddon et al. 1992, Chergui et al. 1993). Retention potential can therefore be standardized by using $-k$ to calculate % ret/m. Retention potential should not be measured as a function of leaf recovery proportion, despite the observed decrease in percentage of released leaves recovered as discharge increased. We cannot assume that wecovered leaves were flushed from the system, based on the results on the Winter–1 release. Increased discharge most likely masked leaves, making their recovery more difficult.

The reduction in retentive potential with increasing discharge, as seen in the cohort release, is consistent with the results found in other studies (e.g., Snaddon et al. 1992), but a precise relationship is not clear. The argument by Webster et al. (1994) that depth is more important than discharge alone is supported by our study. The results of the cohort release experiment showed that retentive potential may be disproportionately increased at very low flow. Perhaps a "threshold" discharge existed, below which retention was greatly increased.

The cohort release method overcomes difficulties created by more usual release methods (i.e., one release followed by subsequent collections) to study CPOM movement over time. Ideally, the position of every leaf would have to be recorded *periodically* without creating any disturbances. Thus, leaves should not be removed, counted, and then replaced. Typical methods are also less than ideal because they remove leaves that are easily found, (not allowing them to migrate), while overlooking well-hidden leaves that may be more stably retained. The cohort method avoids these problems by allowing a comparison of the retention patterns of released leaves with varying residence times, while having only one collection at the end of the experiment. Our cohort release results reflect an integration of the effects of increasing channel complexity with decreasing discharge, and movement over time.

That leaves moved between 3 h and 4 wk was implied by the lower retention rate of the long-term release compared with the Winter–1 release, although less movement occurred than was expected. A simple mechanism for this movement was revealed by a comparison of the retentive structures of the two releases: leaves "fell off" rocks (geologic features), and settled into debris dams. This interpretation is supported by the way these different structures retain material. Boulders usually retain material when leaves are pushed up onto the surface above the water, and cobbles can also hold leaves in spaces between rocks. Both mechanisms are susceptible to forceful higher flows, which wash away leaves. Debris dams consist of a tangle of wood, sticks, and CPOM, and thus act as strainers.

Jones and Smock (1991) reported higher retention potential for CPOM and FPOM in summer than in winter. Webster et al. (1994) also reported greater retention potential in summer. Similarly, Powdermill Run was much more retentive in summer than in winter and autumn. The wide range of retention potential seen in Powdermill Run shows that inappropriate comparisons of retention ability between streams of different studies and experiments can be made if season is not considered. If within-stream variation in retention potential is wide, then comparisons among streams become difficult. Comparisons of retention potential must therefore be made within the contexts of discharge (or depth) and season, while noting in which seasons streams are more or less retentive.

The mechanisms of retention changed in Powdermill Run during the course of a year. Sticks have a high relative trapping efficiency (Speaker et al. 1984), as have cobbles (Prochazka et al. 1991). In summer, leaves became draped over sticks like towels on racks. During autumn, the stream was inundated with allochthonous CPOM. Numerous small leafpacks formed on cobbles and sticks, and these leafpacks retained additional leaves (also observed by Webster et al. 1994). Therefore the importance of cobbles and sticks changed from highly retentive features in their own right, to stable foundations for leafpacks (i.e., small debris dams), which then became the dominant retentive structure. Over autumn and winter, CPOM was processed and fewer leafpacks existed. Leafpacks fell off rocks and accumulated in large stable debris dams. Lower flows then reduced the profile of debris dams in the water column, decreasing the ability of dams to retain material. Debris dams thus became less important in the retention of new leaf material during summer.

The numerous small leafpacks that formed in autumn evidently offset the effect of discharge, which tends to decrease retentive potential. Powdermill Run was more retentive during a period of high discharge (Autumn–1) when the small leafpacks were present, than during a period of lower discharge when such leafpacks were not present (Winter–1).

The study of organic matter retention illustrates the integration of seasonal discharge regimes, LWD and other organic matter dynamics, geomorphology, and biotic processes that exist in streams. Thus, predictions of the retention potential of a reach should be based on the following parameters: amount of woody debris present (including debris dams), substrate type and channel features, hydrologic regime of the season, and amount of organic matter already present.

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## Literature Cited

BARNES, B. V. 1991. Deciduous forests of North America. Pages 219–344 in E. Rohrig and B. Ulrich (editors). Temperate deciduous forests (Ecosystems of the World 7). Elsevier, Amsterdam.

BILBY, R. E., AND G. E. LIKENS. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61:1107–1113.

CHERGUI, H., A. MAAMRI, AND E. PATTEE. 1993. Leaf litter retention in two reaches of a Moroccan mountain stream. Limnologica 23:29–37.

CHURCH, M. 1992. Channel morphology and typology. Pages 126–143 in P. Calow and G. Petts (editors). The rivers handbook: hydrological and ecological principles. Blackwell Scientific Publications, Oxford.

CUMMINS, K. W., M. A. WILZBACH, D. M. GATES, J. B. PERRY, AND W. B. TALIAFERRO. 1989. Shredders and riparian vegetation. BioScience 39:24–30.

EHRMAN, T. l?, AND G. A. LAMBERTI. 1992. Hydraulic and particulate matter retention in a 3rd-order Indiana stream. Journal of the North American Benthological Society 11:341–349.

ELWOOD, J. W., J. D. NEWBOLD, R. V. O'NEILL, AND W. VANWINKLE. 1983. Resource spiraling: an operational paradigm for analyzing lotic ecosystems. Pages 3–27 in T. D. Fontaine and S. M. Bartell (editors). The dynamics of lotic systems. Ann Arbor Science, Ann Arbor, Michigan.

HARMON, M. E., F. F. RANKLIN, F. J. SWANSON, P. SOLLINS, S. V. GREGORY, ]. D. LATIN, N. H. ANDERSON, S. P. CLINE, N. G. AMEN, J.R. SEDELL, G. W. LIENKAEMPER, K. CROMACK, AND K. W. CUMMINS. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133–302.

HILDREW, A. G., M. K. DOBSON, A. GROOM, A. IBBOTSON, J. LANCASTER, AND S. D. RUNDLE. 1991. Flow and retention in the ecology of stream invertebrates. Verhandlungen der Internationalen Vereinigung für Angewandte und Theoretische Limnologie 24:1742–1747.

JONES, J. B., AND L. A. SMOCK. 1991. Transport and retention of particulate organic matter in two low-gradient headwater streams. Journal of the North American Benthological Society 10:115–126.

KELLER, E. A., AND T. TALLY. 1979. Effects of large organic debris on channel form and fluvial process in the coastal redwood environment, adjustments of the fluvial system. Pages **169–172** in D. Rhodes and G. Williams (editors). 10th Annual Geomorphology Symposia Series. Kendall/Hunt Publishing Company, Dubuque, Iowa.

King, J. M., M. P. Henshell-Howard, J. A. Day, and B. R. Davies. **1987.** Leaf pack dynamics in a southern African mountain stream. Freshwater Biology 18:325–340.

Mayack, D. T., J. H. Thorp, and M. Cothran. **1989.** Effects of burial and floodplain retention on stream processing of allochthonous litter. Oikos 54:378–388.

Minshall, G. W., R. C. Petersen, K. W. Cummins, T. L. Bott, J. R. Sedell, C. E. Cushing, and R. L. Vannote. **1983.** Interbiome comparison of stream ecosystem dynamics. Ecological Monographs 53:1–25.

Petersen, L. B.-M., and R. C. Petersen. **1991.** Short term retention properties of channelized and natural streams. Verhandlungen der Internationalen Vereinigung für Angewandte und Theoretische Limnologie 24:1756–1759.

Prochazka, K., B. A. Stewart, and B. R. Davies. **1991.** Leaf litter retention and its implications for shredder distribution in two headwater streams. Archiv für Hydrobiologie 120:315–325.

Sedell, J. R., P. A. Bisson, F. J. Swanson, and S. V. Gregory. **1988.** What we know about large trees that fall into streams and rivers. Pages **47–79** in C. Maser, R. E Torrant, J. M. Trappe, and J. E Franklin (editors). From the forest to the sea: a story of fallen trees. USDA Forest Service General Technical Report PNW-GTR-299. Pacific Northwest Research Station, Portland, Oregon.

Smock, L. A., G. M. Metzler, and J. E. Gladden. **1989.** Role of debris dams in the structure and functioning of low gradient headwater streams. Ecology 70:764–775.

Snaddon, C. D., B. A. Stewart, and B. R. Davies. **1992.** The effect of discharge on leaf retention in two headwater streams. Archiv für Hydrobiologie 125:109–120.

Speaker, R., J. K. Lutchessa, J. F. Franklin, and S. V. Gregory. **1988.** The use of plastic strips to measure leaf retention by riparian vegetation in a coastal Oregon stream. American Midland Naturalist 120:22–31.

Speaker, R., K. Moore, and S. V. Gregory. **1984.** Analysis of the process of retention of organic matter in stream ecosystems. Verhandlungen der Internationalen Vereinigung für Angewandte und Theoretische Limnologie 22:1835–1841.

Trotter, E. H. **1990.** Woody debris, forest-stream succession, and catchment geomorphology. Journal of the North American Benthological Society 9:141–156.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. **1980.** The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130–137.

Webster, J. R., A. P. Covich, J. L. Tank, and T. V. Crockett. **1994.** Retention of coarse particles in streams in the southern Appalachian Mountains. Journal of the North American Benthological Society 13:140–150.

Young, S. A., W. P. Kovalack, and K. A. Del Signore. **1978.** Distances travelled by autumn-shed leaves introduced into a woodland stream. American Midland Naturalist 100:217–222.

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