AN ABSTRACT OF THE THESIS OF

Robert W. Speaker for the degree of Master of Science in Fisheries presented on March 13, 1985

Title: Distribution and Retention of Particulate Organic Matter in Streams in the Cascade Mountains of Oregon

Signature redacted for privacy.

Abstract Approved: ______________________
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The rate of removal of introduced leaves from transport was used as a measure of leaf retention in streams. Leaf retention rates (LRR) were expressed as the slope of a negative exponential model of the percent of leaves in transport vs. the distance below the point of introduction into the stream. LRRs were measured in reaches of several second- and third-order streams on the western slope of the Cascade Mountains in Oregon. The effects of riparian vegetation, stream channel structure and discharge on leaf retention were evaluated in streams flowing through old-growth coniferous stands, deciduous stands, and herb-shrub (recently clear-cut) riparian zones. Retention characteristics of stream reaches and the amount and form of detritus stored in different habitats in the reaches were compared to evaluate the application of experimental measures of retention to transport and storage processes in natural streams and to refine our concepts of retention.

Leaf retention rates ranged from 0.017 to 0.383 m-1 and were influenced by the amount of large organic debris in the channel and the ratio of the wetted perimeter of the channel to the cross-sectional area of flow in riffles. LRRs were approximately twice as high in channels with large organic debris present as in channels with no debris. Streams flowing through coniferous and deciduous stands had significantly higher LRRs than streams with herb-shrub riparian zones, primarily because of the influence of large organic debris in the channel. LRR increased exponentially with increasing relative channel roughness in riffles. Leaf retention and 1/R were reduced at higher stream discharges. Average travel distances (1/LRR) of leaves in transport were short, ranging from 2.6 to 58.8 m.

The length of time required for evacuation of 90% of the dye released in a reach (reach residence time) was strongly correlated with pool volume in the reach. Reach residence time was not correlated with LRR over the range of residence times most commonly encountered in this study.

Sticks trapped ginkgo leaves more efficiently than all sizes of inorganic substrates, large wood and aquatic vegetation. Trapping efficiencies of all features other than sticks were not significantly different. The introduction of boulders, sticks and large pieces of wood to cleared stream reaches resulted in increased leaf retention in the reaches. The increase in retention was directly proportional to the amount of boulders, sticks or wood added.

More leaves per unit area were retained along the stream margin than in any other aquatic habitat. Riffles retained more leaves per unit area than pools, and pools retained more than backwaters. This comparison of the relative trapping efficiency of the different habitats is biased by the assumption that leaves in transport are equally available to all parts of the stream.

The standing crop of detritus and the ratio of coarse particulate organic matter (CPOM) to fine particulate organic matter (FPOM) in storage were higher in streams with forested riparian zones than in streams with recently clear cut riparian zones. Detrital standing crops and CPOM to FPOM ratios tended to be higher in habitats that were further removed from the central axis of the stream channel (eg. stream margins and backwaters).

Leaf retention rates of stream reaches and the leaf trapping efficiencies of individual retention features reflected patterns of detrital storage in three intensively studied reaches. In reaches with forested riparian zones, leaf retention rates and detrital standing crops were approximately four times higher than in a stream with an herb-shrub riparian zone. Large organic debris dams were highly efficient leaf retention features and detrital standing crops in pools and backwaters associated with large organic debris were as high as those found in any habitat. Stream margins had higher leaf retention rates and detrital standing crops than riffles and pools located near the central axis of the stream.

DISTRIBUTION AND RETENTION OF PARTICULATE ORGANIC MATTER IN STREAMS IN THE CASCADE MOUNTAINS OF OREGON

by

Robert Speaker

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed March 13, 1975 [i.e. 1985]

Commencement June 1985

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Date Thesis is Presented March 13, 1985

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INTRODUCTION

The continuous unidirectional flow in lotic ecosystems transports matter to downstream reaches. This has led to the common misconception that streams are primarily conduits through which most organic matter is rapidly exported. The process of retention removes organic matter from transport and makes it available for utilization by the stream biota. The average travel distance (S_w) of an organic particle in transport (Newbold et al. 1981) and its location and duration of storage are important determinants of the rate and extent of in-stream processing of organic matter (Kaushik and Hynes 1971, Bärlocher and Kendrick 1974, 1975, Anderson and Sedell 1979, Cummins et al. 1980).

Retention in streams consists of both entrapment of organic matter in transport and its storage at that location for some period of time. Entrapment of a particle in transport is a function of the frequency of obstacles in the stream and the probability that the particle will be caught once it comes into contact with an obstacle (Young et al. 1978). A particle will also be retained when current velocity drops below the fall velocity of the particle, as determined by its size and density (Leopold et al. 1964). Thus, the retentiveness of a stream is related to the size and frequency of riffles, pools, and backwaters and the number and type of obstructions to flow in the channel. Streams with an abundance of riffles and relatively uniform channel structure retain little organic matter, while heterogeneity of channel structure and of water velocity creates obstructions and slack water areas that enhance retention.

Channel structure and gradient, longitudinal profile, and flow regime are major factors that determine patterns of transport and storage of inorganic sediments (Megahan 1976, 1982, Beschta 1979, Beschta et al. 1981, Kelsey et al. 1981), and affect retention of particulate organic matter (POM) in streams and rivers. Large organic debris dams have been shown to be important storage devices for inorganic and organic matter in streams and their presence may greatly reduce inorganic and organic export (Swanson et al. 1976, Bilby and Likens 1980, Beschta et al. 1981, Bilby 1981). These structures are significant geomorphic features in small streams that flow through mature forests, but their size, abundance, and influence on the channel decrease as the size of trees in the riparian zone decreases and as stream size increases (Swanson et al. 1976, Likens and Bilby 1982). The role of depositional areas in the stream and the importance of smaller wood and sticks, streambed composition and aquatic vegetation in retaining organic matter has received little attention.

Riparian vegetation affects retention patterns by regulating the amount, form, and timing of organic inputs (Fisher and Likens 1973, Cummins 1975, Hynes 1975) and through its influence on channel structure (Swanson et al. 1982). The regulation of organic inputs by riparian vegetation is most pronounced in small streams and usually decreases as streams get larger (Vannote et al. 1980). Small streams flowing through forested watersheds are detrital based systems (Hynes 1975) and more than 90% of their energy may be derived from the terrestrial environment (Fisher and Likens 1973). Retention of a large portion of the organic matter in these streams depends on the type of organic material (e.g. bole, branch, leaf, needle, etc.) entering the stream and streamflow at the time of entry.

Riparian vegetation affects channel structure through the encroachment of roots on the stream channel, by stabilizing the stream bank, and by providing a source of bole and branch material that obstructs flow. In first- to third-order forested watersheds, large organic debris is a major feature of the stream channel. If a stream is large enough to float some of this debris at high flows, large organic debris dams may be set up at intervals along the channel (Swanson et al. 1976). These debris dams increase channel width, increase the number of obstructions in the channel, and decrease the effective gradient of the stream by creating a stepped channel profile, which reduces the amount of physical energy available for sediment transport. They may also facilitate the development of mid-channel bars, bars along stream margins, and braided channels (Zimmerman et al. 1967, Swanson and Lienkaemper 1978, Keller and Swanson 1979). In small streams riparian vegetation can create pools by diverting the flow and provide obstructions where branches and roots are in the active channel. Stream side vegetation can also affect channel geometry in small streams by influencing stream width and cross-sectional profile (Zimmerman et al. 1967). Most of these interactions tend to increase retention of organic matter.

Newbold et al. (1981) used spiralling length, the average distance downstream travelled by a nutrient atom in completing one cycle through the system, as an index of the "tightness" of nutrient cycling in streams. In their model, spiralling length is the sum of the average length a nutrient atom moves in the water compartment (S_w=uptake length), the particulate compartment (S_p), and the consumer compartment (S_c). They found that the distance required for removal of introduced ^{32}P from transport in the water compartment of their model (S_w) was 86.5% of the total spiralling length for this nutrient. Downstream transport in the particulate phase accounted for the remaining 13.5% of the spiralling length. Transport in the consumer compartment was negligible. The uptake length of POM includes both the average travel distance in the water compartment and in the particulate compartment. The spiralling length of POM, therefore, is primarily dependent on the distance required for removal of this material from transport (S_w+S_p).

This research attempts to identify some of the major factors that affect retention of leaves in streams and to examine the relative importance of these factors. Leaves were released into several streams with different types of riparian vegetation and the location of retention of each leaf was observed. This method was used to:

1) identify major retention features in second- and third-order streams in the Cascade Mountains in Oregon and quantify the retention efficiency of each of these features,

2) measure the effects of discharge on retention,

3) measure the effects of riparian vegetation on retention.

The rate of accumulation and the amount of detritus in different stream habitats was measured to gain insights into retention patterns of other forms of organic matter in streams. Retention characteristics of stream reaches and the amount and form of detritus stored in these areas were compared to evaluate the application of experimental measures of retention to transport and storage processes in natural streams and to refine our concepts of the process of retention.

METHODS

Leaf Retention and Trapping Efficiency

Retention can be expressed as the difference between the quantity of particles in transport at a given point and the quantity of those particles still in transport at some distance downstream. In this study, ginkgo (Ginkgo biloba) leaves were used to trace the movement and retention of leaves in streams. A known number of ginkgo leaves was introduced into study reaches and the distance travelled and location of retention of each leaf was recorded. Ginkgo leaves are good indicators of leaf transport and retention because they are about the same size as leaves of many common riparian trees, they are bright yellow and easily spotted under water, and they do not occur naturally in North America. Ginkgo leaves were collected immediately after abscission, air dried and stored until use.

Leaves were soaked in stream water for 12 hours prior to release. The density of the leaves increased from 0.82 g/cm^3 when dry to 0.95 g/cm^3 after 12 hours in water (Fig. 1). The water content of the leaves increased from 5% to 68% by weight. Approximately 12% of the leaves had a density of more than 1 g/cm^3 after soaking for 12 hours. Unsoaked leaves tended to float but wetted leaves were nearly neutrally bouyant and were distributed throughout the water column by the turbulent flows.

Leaves were released into 50-m study reaches in second- and third-order streams on the west slope of the Cascade Mountains in Oregon. These reaches were sufficiently long to contain many of the

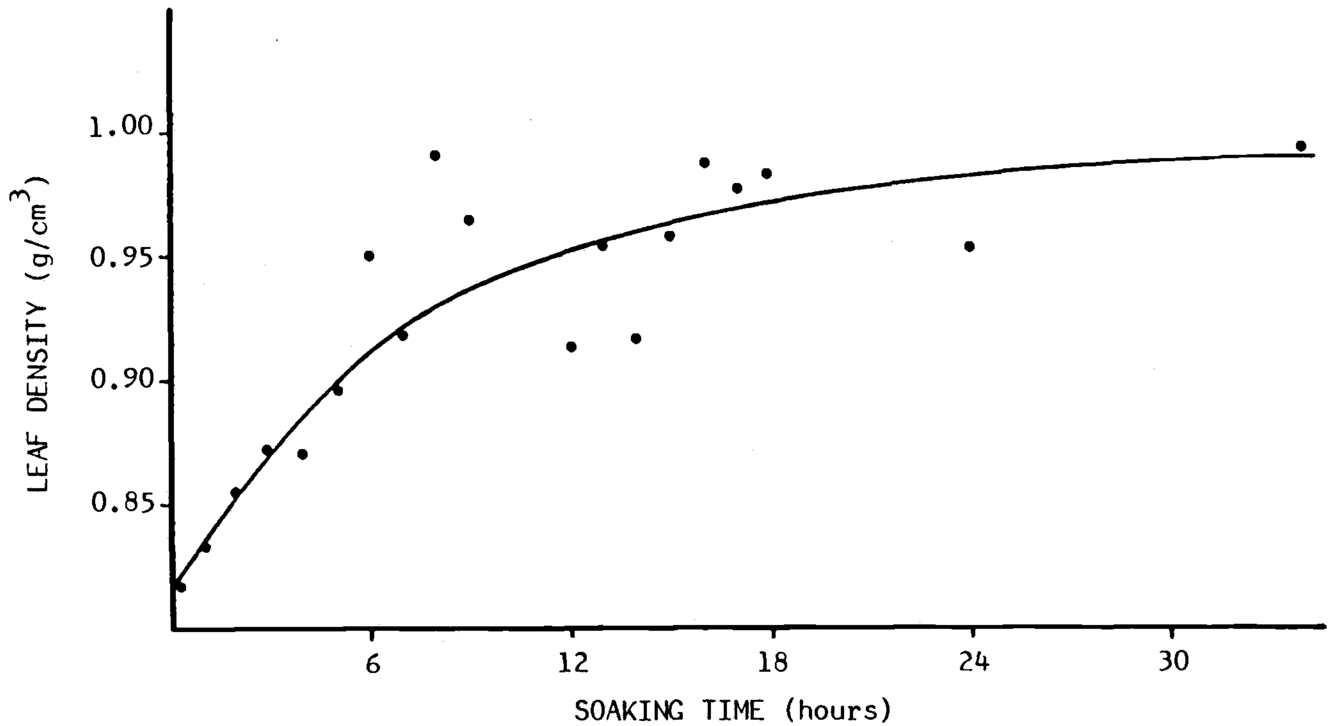

Figure 1. Changes in the density of ginkgo leaves after soaking in 5°C water (each point represents the mean of 10 leaves).

structural features found in streams in this area. Leaves were released into several reaches in most streams, therefore much of the geomorphic diversity found in these streams was sampled.

Three thousand leaves were released at the upper end of each study reach. It was found in preliminary investigations that releasing 3000 leaves resulted in leaves being transported throughout most 50-m study reaches in less than three hours. If too few leaves were released, the lack of availability of leaves in transport to different retention features in the channel affected the retention of released leaves in the reach. If too many leaves were released, large accumulations of retained leaves became significant retention features themselves and increased reach retention. A net was placed at the lower end of the study reach and leaves that travelled through the reach were collected and counted. Leaf transport rate decreased with time and after 3 hours fewer than sixteen leaves were leaving the study reach per hour (Fig. 2). Three hours after the leaves were released into the stream the reach was thoroughly searched for leaves, beginning at the downstream end of the reach. When leaves were found, the distance travelled and the location of retention (riffle, pool or backwater, and type of obstruction) were recorded for each leaf. Leaf retention was then calculated from the initial number of leaves introduced and the number of leaves in transport at 1-m intervals below the point of introduction. A negative exponential model was used to represent leaf retention (Young et al. 1978):

$$L_d = L_o e^{-kd} \qquad \text{(Equation 1)}$$

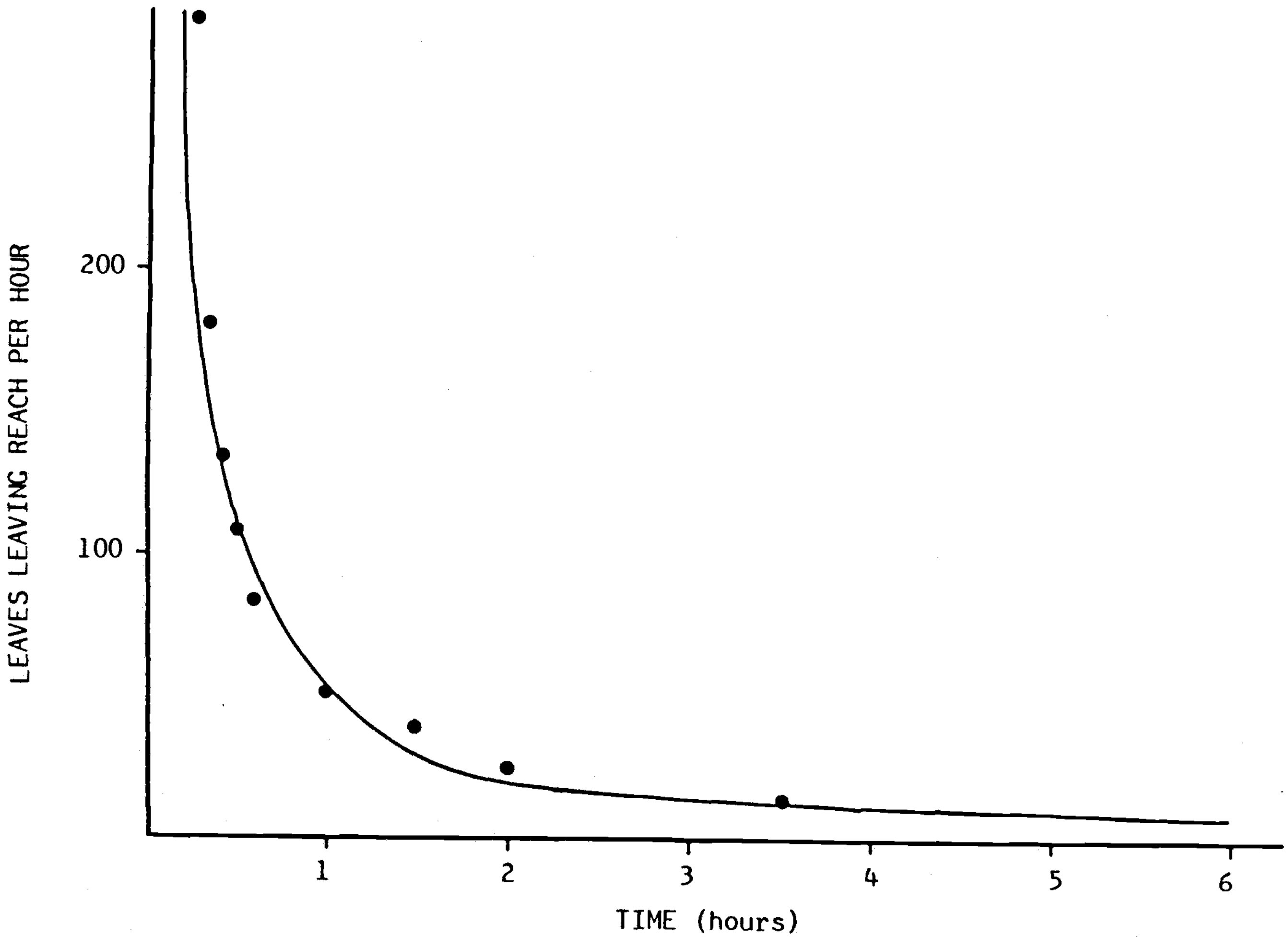

Figure 2. Leaf export rate versus time in a 50-m reach in Mack Creek.

Where: L_d = percent of introduced leaves in transport (not retained) at some distance (d) below the release point.

L_o = initial input (100%).

d = distance downstream from the release point in meters.

k = instantaneous rate of removal of leaves from transport (the instantaneous leaf retention rate=LRR in m^{-1}).

The percent of leaves in transport is used in this model to facilitate comparison of sites where different numbers of leaves were introduced.

Several features in the stream were identified as important locations of leaf retention. These features were categorized according to their location in the channel, flow characteristics, and substrate type (Table 1). The relative importance of these structures in retaining leaves was determined by measuring the planar area of each feature within a study reach and the number of leaves trapped by the feature. The area occupied by each feature was measured in two ways. First, each reach was divided into 10-m subsections and the area of each major retention feature was measured in each subsection. These were then summed to get the total area occupied by each retention feature. Second, the area of specific retention features was estimated in conjunction with transect measurements of the wetted perimeter, cross-sectional area of flow and determinations of inorganic substrate composition. Cross-sections (5 to 11) were measured at intervals ranging from 3 to 10 m along the stream channel. Water depth, flow characteristics (riffle, pool, backwater), and substrate type were recorded at 20-cm intervals along each cross-section. Inorganic substrates were classified according to size

Table 1. Retention features identified by their location in the channel, flow characteristics and the object providing obstruction to flow.

Location	Flow Characteristics	Obstruction
Main Channel	Riffle	Sand
Side Channel	Pool	Gravel
Stream Margin	-Rock Control	Cobble
	-Organic Debris Control	Small Boulder
	Backwater	Large Boulder
		Bedrock
		Wood
		Terrestrial Vegetation
		Aquatic Vegetation

(Wentworth 1922) with sand measuring less than 2 mm along its longest axis, gravels between 2 and 64 mm, cobbles between 64 and 256 mm, small boulders between 256 and 640 mm and large boulders greater than 640 mm. The area (diameter times length) of sticks (less than 10 cm in diameter) in each study reach was estimated by counting the number of sticks in riffles and pools in the reach. An average area per stick was generated using mean diameter data from Lammel (1972) and from stick length and diameter measurements made at Lookout Creek and Mack Creek. The inverse of the hydraulic radius (1/R = wetted perimeter / cross-sectional area of flow) was used as an index of relative channel roughness.

Leaf trapping efficiencies (percent of available leaves retained / m^2 of retention feature) for each major retention feature were estimated by dividing the number of leaves trapped by the retention feature by the number of leaves in transport at the midpoint of a 10-m subsection and the area of the retention feature in the subsection. This number was then multiplied by 100 to facilitate comparisons of the trapping efficiencies of different retention features.

$T = (N_r * N_a^{-1} * A^{-1}) * 100$

where: T = trapping efficiency (% of available leaves trapped/m^2).

N_r = number of leaves retained by the feature.

N_a = number of leaves in transport at the midpoint of the reach subsection.

A = area of the retention feature in the reach subsection in m^2.

Through this procedure trapping efficiency was determined one to five times in each 50-m reach. If the number of leaves in transport at the midpoint of a 10-m subsection was less than 1000 (33.3% of the initial number introduced), I assumed that leaf availability might limit trapping efficiency and these subsections were not used in trapping efficiency estimates.

To measure the effects of leaf type on retention, leaves from four common riparian trees and ginkgo leaves were introduced into a stream reach simultaneously. Six hundred big leaf maple (*Acer macrophyllum*), red alder (*Alnus rubra*), vine maple (*Acer circinatum*) and willow (*Salix spp.*) and ginkgo leaves were introduced into three 30-m sections of Simmons Creek and leaves that were not retained were collected in nets at the lower end of each section.

Discharge and Reach Residence Time

The stream discharge and residence time of water flowing through each study reach were measured by introducing a known amount of fluorescein dye into the upstream end of the reach and collecting water samples at the downstream end until it appeared that all of the dye had passed through. Four and one-half grams of dye were diluted with water to a volume of 1 liter and 100 to 500 ml of this solution was released into each reach, depending on the discharge. Water samples were collected at intervals ranging from 15 seconds to 2 minutes depending on the rate of dye movement through the reach. The concentration of dye in each sample was determined using a Turner fluorometer. Discharge was calculated as (Replogle et al. 1976):

$$Q = \frac{M}{\int_0^{\alpha} c\, dt}$$

where: Q = discharge.

M = total amount of dye added.

c = dye concentration passing the sampling point at t.

t = time from introduction.

In some reaches, small amounts of dye persisted for long periods of time and the total turnover time of water in the reach was not measured. The persistence of small amounts of dye did not have a major effect on the time required for discharge of 90% of the water in a reach however, therefore this was used as an index of the residence time of water in a reach. Reach retention curves (dye concentration vs time) provide information about several important flow characteristics (Fig. 3). The maximum flow velocity over the reach can be calculated from the time it takes the dye to travel from the release point to the sampling point (Fig. 3, Point A). Median residence time can be estimated as the time when half of the dye has passed through the reach (Fig. 3, Point B). Reach residence time can be expressed as the time required for 90% of the dye to pass through the reach (Fig. 3, Point C) and discharge can be calculated from the initial amount of dye released and area under the curve. The peak dye concentration and the shape of the curve also provide information about hydrologic retention in the reach. In reaches with high peak dye concentrations, reach residence time is typically lower than in reaches with low peak dye concentrations. Reach retention curves for all study reaches are shown in Appendix A.

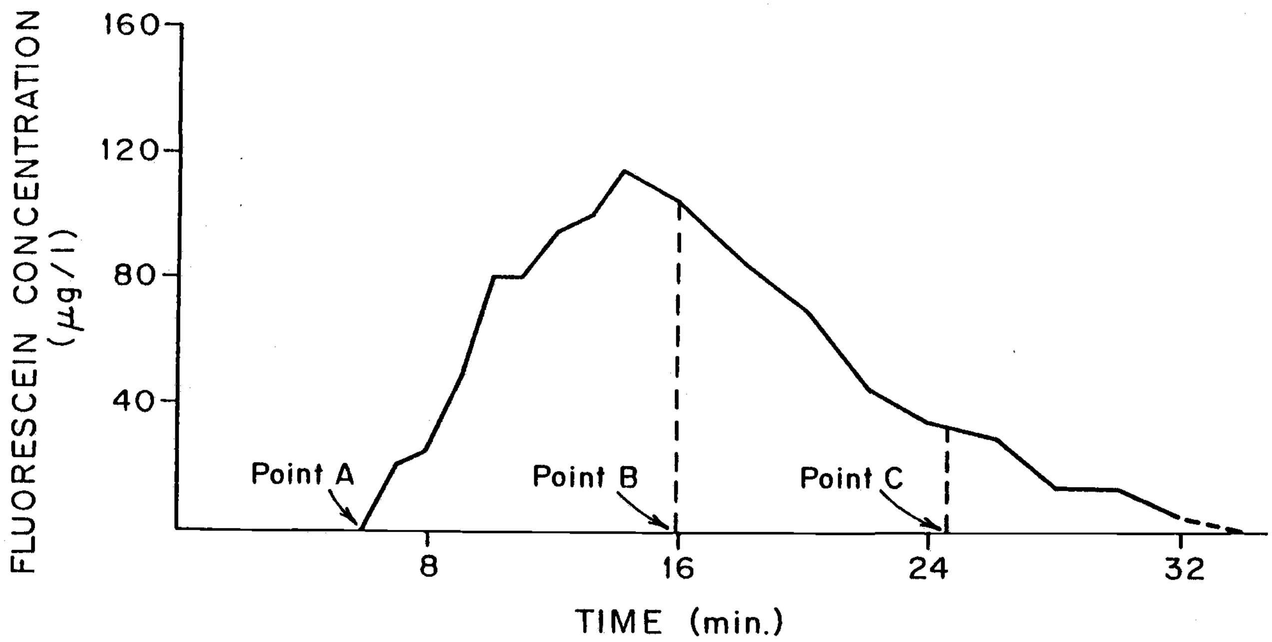

Figure 3. Changes in fluorescein concentration after input of a known amount of dye at a point 50 m above the sampling location. At point A, dye has reached the sampling location. At point B, 50% of the dye has passed through the reach. At point C, 90% of the dye has passed through the reach. The curve represents a dye release at Wycoff Creek.

Trapping Efficiencies in Manipulated Channels

Trapping efficiencies of specific retention features were measured under controlled conditions by releasing ginkgo leaves into stream reaches in which the amount and type of retention features had been manipulated. Three 20-m sections of Lookout Creek were cleared of wood, sticks, and most large and smallboulders. Study reaches were then divided approximately in half by a plywood wall running down the center of the active channel. Cobbles and gravels were built up along both sides of the wall to simulate the stream margin and to minimize exchange of particulate matter between the two sides. All three reaches were entirely riffles after the channels had been cleared and divided. One side of each reach was not manipulated and served as a control. In the opposite side, the quantity of various retention features was systematically increased (Table 2). Discharge and reach residence time were measured in the experimental side of each section initially and after each manipulation of retention features. Cross-sections of both the experimental and control sides of each reach were measured before leaf releases and water depth and substrate were recorded at 10-cm intervals along each cross-section. These measurements were repeated in the experimental side after each manipulation.

Three replicate releases of 1000 wetted ginkgo leaves were conducted in the control and experimental side of each reach initially. Leaves not retained in a reach were collected in nets at the lower end and counted after one hour, then all of the retained leaves that could be found were removed from the reach. Retention was measured over

Table 2. Retention feature changes in three 20-m reaches of Lookout Creek in August 1983.

Reach I - Cobbles and Small Boulders

Treatment Level	Number of Rocks Added to Section	Number of Rocks Added per m^2 Stream	m^2 Rocks added per m^2 Stream
0	0	0	0
1	20	0.49	0.046
2	60	1.46	0.126
3	120	2.93	0.223
4	180	4.39	0.320

Reach II - Sticks

Treatment Level	Number of Sticks Added to Section	Number of Sticks Added per m^2 Stream	m^2 Sticks added per m^2 Stream
0	0	0	0
1	57	1.26	0.0003
2	140	3.08	0.0006
3	207	4.56	0.0009

Reach III - Large Wood

Treatment Level	Pieces of Wood Added to Section	Pieces of Wood Added per m^2 Stream	m^2 Wood added per m^2 Stream
0	0	0	0
1	4	0.11	0.029
2	8	0.22	0.062
3	12	0.33	0.096

only one hour because of the large number of leaf releases that were conducted. These retention rates may be used to compare the relative effects of changes in the number of retention features in a reach but are higher than retention rates measured over a three hour period.

In reach I, the amount of cobbles and small boulders was increased by distributing additional amounts of these substrates uniformly throughout the reach. The abundance of sticks was increased in reach II and large pieces of wood (length: x=1.2 m, range=0.9 to 1.4 m, diameter: x=0.25 m, range=0.19 to 0.36 m) were added to reach III. Three releases of 1000 leaves each were made in the experimental side at each level of the retention features. In each of the control sections, a total of six releases were made during the course of the experiments. The reaches were cleared of leaves after each run. All leaf releases in a given reach were made within a 48 hour period.

Trapping of Detritus in Inorganic Substrates

To test the effects of inorganic substrate size and current velocity on patterns of detritus retention and storage, plastic trays (22.6 cm x 22.6 cm x 7.6 cm) filled with different sizes of rocks were placed in riffles and pools, and the rateof detritus accumulation was measured. The experiment was conducted concurrently at the three intensively-studied riparian sites: Mack Creek (old-growth coniferous stand), Quartz Creek (35-year-old red alder stand) and Grasshopper Creek (recently clear-cut). Gravels and cobbles from the channel margin were sieved into three size classes: 0.6 to 3.4 cm (small gravel), 3.4 to 7.8 cm (large gravel) and 7.8 to 15.0 cm (cobble). The rocks were washed free of detritus in the stream and 21 trays were filled with rocks of each size class at each site. Nine trays of each substrate size were placed in riffles and 12 trays of each size were placed in pools at each site. Trays were put in the streams during the first week of July 1983.

Three trays of each substrate size were removed from a pool and a riffle at each site after approximately 2, 4 and 7 weeks. The last group of pool trays was removed from the streams after 14 weeks. The rocks in each tray were carefully washed in buckets to remove as much detritus as possible. The detritus was then rinsed through a 53-μm sieve in the field (Fig. 4). The detritus larger than 53-μm was stored in a plastic bag. Water and detritus that passed through the 53- m sieve was saved in a large bucket. A 1- to 6-L subsample of this water was put through a 10-μm sieve and detritus larger than 10- m was stored in a plastic bag. A 350- to 500-ml subsample of the water and detritus that passed through the 10-μm sieve was returned to the laboratory. In the laboratory, detritus larger than 53-μm was sieved into the following size classes: >16 mm, 4 to 16 mm, 1 to 4 mm, 0.25 to 1 mm, 0.106 to 0.25 mm, 0.053 to 0.106 mm. The subsample of detritus smaller than 10-μm was filtered through a pre-ashed (500°C) 0.7-μm glass-fiber filter. All detrital samples were transferred to petri dishes and dried at 50°C for at least one week. The amount of organic matter in each sample was determined by weighing the sample after it had been dried at 50°C, ashing it at 550°C for 4 to 24 hours and reweighing it.

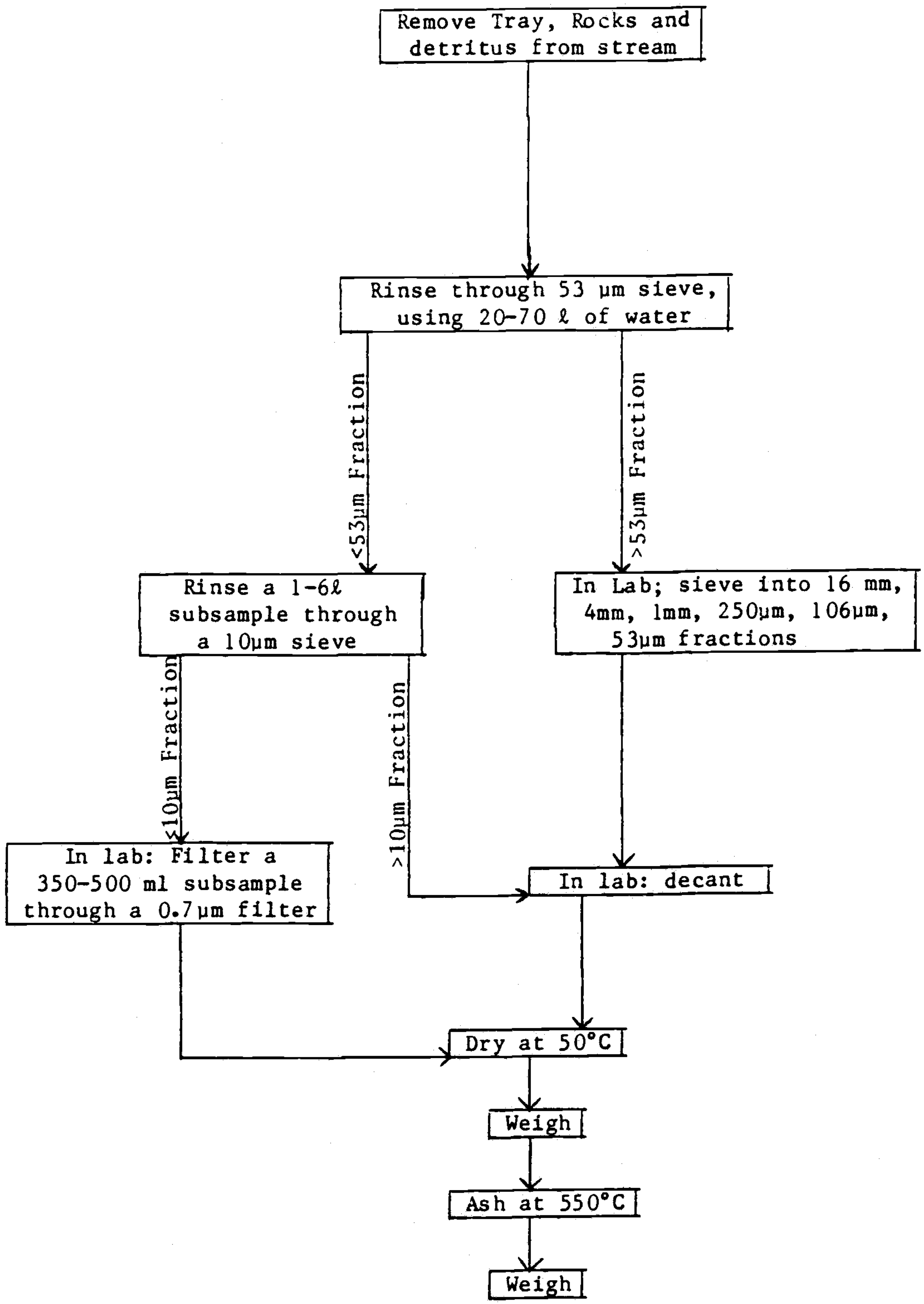

Figure 4. Processing of benthic detritus samples.

Detritus Standing Crop

Between August 24 and 26, 1982 and again between March 9 and 11, 1983, the standing crop of detritus was measured at the three intensively-studied sites. Ten replicate samples were obtained from riffles and pools and a minimum of five samples were obtained from backwaters and stream margins in each stream. Samples were also obtained from pools associated with large organic debris dams at Mack Creek. Of the ten riffle and pool samples, five were taken from gravel substrates and five from cobble substrates.

Samples were taken using one of three cylindrical, stainless steel core samplers (McNeil and Ahnell 1964): 12.4-cm diameter, 15.4-cm diameter and 25.2-cm diameter. A core sampler was driven into the substrate, surface rocks were removed from within the core, and the associated detritus was rinsed into buckets. The remaining sediments were stirred vigorously and the suspended material was pumped into buckets. Twenty liters of water, detritus and sediment were pumped from most samples. The samples were then processed in a manner simmilar to that described in the previous section (Fig. 4). The detritus was rinsed through a 53-μm sieve and the water passing through the sieve was saved. The detritus larger than 53-μm was stored in a plastic bag. A 1- to 10-L subsample of the remaining material was then passed through a 10-μm sieve. Detritus larger than 10-μm was stored in a plastic bag. A 350- to 500-ml subsample of the material less than 10-μm was taken. In the laboratory, the detritus larger than 53-μm was sieved into the same size classes as before. The 10 to 53-μm detritus was sieved into 35 to 53-μm and 10 to 35-μm fractions and the less than 10-μm subsample was filtered through a preashed (500° C) 0.7-μm glass-fiber filter. All samples were put in petri dishes and dried at 50°C for at least one week. The organic content of each sample was determined by weighing the sample after it had been dried at 50°C, ashing it at 550°C for 4 to 24 hours and reweighing it.

STUDY SITES

The streams examined in this study are located in or around the H.J. Andrews Experimental Ecological Reserve on the western slope of the Cascade Mountain Range in Oregon (Fig 5). Elevations at the study sites ranged from 400 to 1000 m. This region receives about 80% of its annual precipitation between October and March and is characterized by high winter flows and low summer base flows. Large storms are common during the winter months. Channel gradients are generally steep (4 to 15%) in these second- and third-order streams and substrates are dominated by cobbles and boulders.

Three general types of riparian vegetation are common in this area. Stands of large, old-growth Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) dominate most undisturbed watersheds. Large organic debris from these stands is an important geomorphic feature of streams with this type of riparian zone (Swanson and Lienkaemper 1978). After clear-cut logging the riparian vegetation is dominated by shrubs and herbs for several years and, because of stream clean-up after logging, the amount of large organic debris in the stream is typically reduced. Fifteen to twenty years after clear-cutting or a natural disturbance of the riparian vegetation, deciduous trees (e.g. red alder, big leaf maple, and vine maple) are commonly the dominant riparian species. Several streams with each of these types of riparian vegetation were chosen for study (Table 3 and Appendix B). When long reaches of a stream had different types of riparian vegetation, different sections were studied as examples of reaches with different types of riparian zones.

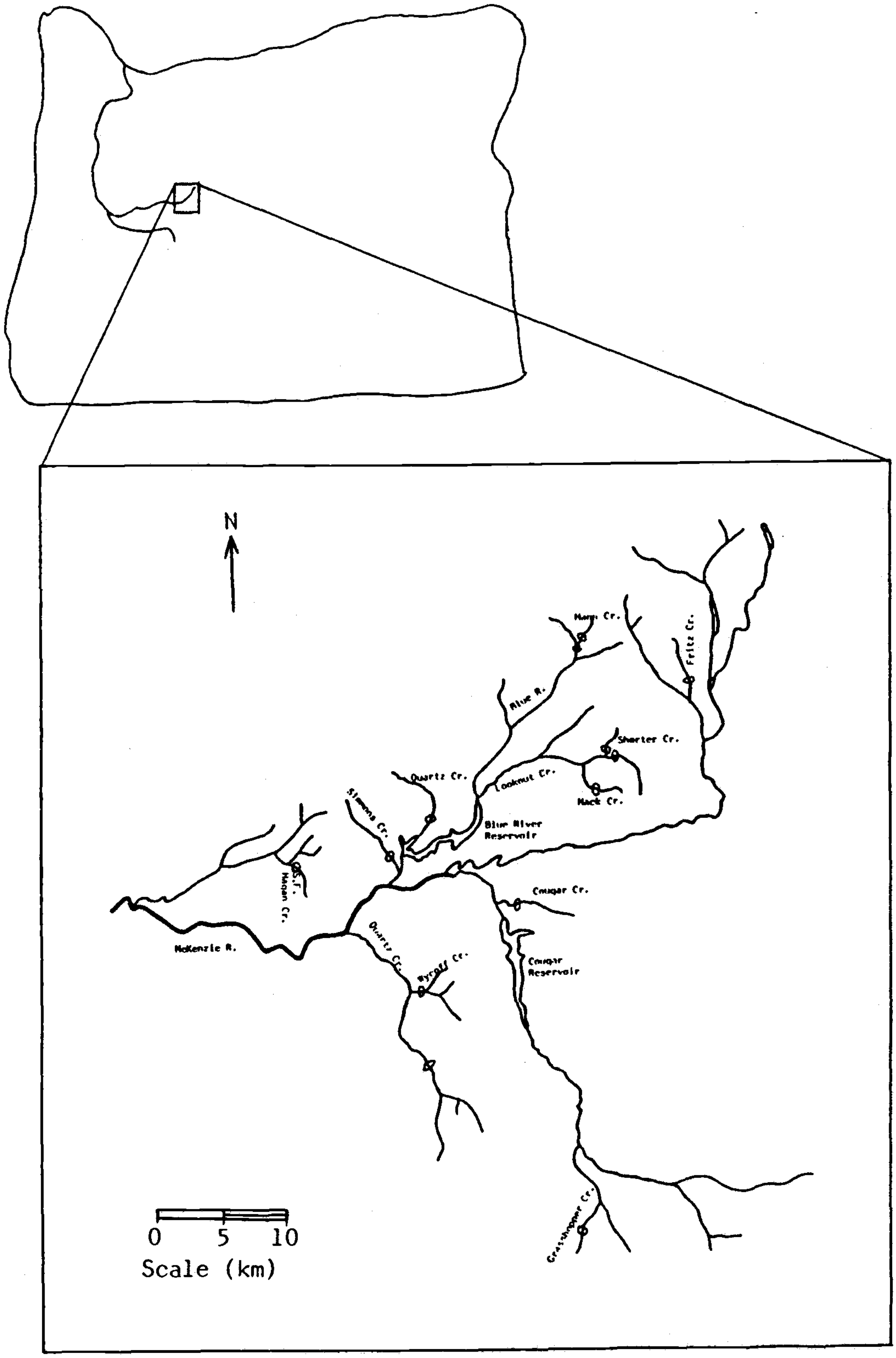

Figure 5. Location of study reaches.

Table 3. Reach numbers and stand ages for study sites with different riparian zones (* denotes intensively studied site).

Old-Growth Coniferous			Deciduous			Open		
Site	Reach #	Stand age (yrs)	Site	Reach #	Stand age (yrs)	Site	Reach #	Stand Age (yrs)
Mack Cr.*	1,2,4,5	~450	Quartz Cr.* (Blue R.)	1,2	35	Grass-hopper Cr.*	1,2	8
Lookout Cr.	1	~450	Wycoff Cr.	1	24	Quartz Cr. (McKenzie R.)	1,2	10
Cougar Cr.	2	~300	Cougar C.	1	34	Mann Cr.	1,2	10
Grass-hopper Cr.	4	~450	Simmons Cr.	1	32	Mack Cr.	3	20
Fritz Cr.	1	~450	S.F. Hagan Cr.	1,2,3,4	110			
Mann Cr.[a]	3	~300						
Shorter Cr.	1	~450						

[a] Recent debris torrent through channel.

LEAF RETENTION

RESULTS

Leaf Retention and Reach Residence Time

Leaf retention rates (LRR) for the 29 leaf releases ranged from 0.017 to 0.383 m^{-1} (Table 4). Leaf retention was enhanced by the presence of large trees in the riparian zone, large organic debris dams in the stream, and higher relative channel roughness in riffles (1/R). The effects of these factors are discussed in detail in later sections. Leaf retention curves for the most retentive (Fritz 1), least retentive (Roseboro-Quartz 1), and an intermediate reach (Lookout 1) are shown in Figure 6. The observed patterns of retention fit the negative exponential model well in most cases. Coefficients of determination (r^2) ranged from 0.42 to 0.99 with 24 of the 27 leaf releases having r^2 greater than 0.87 (Table 4). Two of the three reaches in which r^2 was below 0.87 contained large organic debris dams near mid-reach. These debris dams retained almost all of the leaves in transport and caused a large deviation from the values predicted by the model. Average travel distances for the leaves ($S_{w=1/LRR}$) were between 2.6 and 58.8 m. The distance required for retention of 90% of the introduced leaves, calculated from the measured leaf retention rates and Equation 1, ranged from 6.0 to 135.4 m. Leaf retention curves for all study reaches are in Appendix C.

Table 4. Results of leaf releases.

Riparian Zone	Study Reach	Gradient (%)	LRR (m^{-1})	r^2	Leaves Recovered (%)	Average Travel Distance (M)	90% Retention Distance (m)
Coniferous	Mack 1	7.0	0.134	0.94	59.9	7.5	17.2
	Mack 2	11.0	0.159	0.88	51.1	6.3	14.5
	Mack 4	6.0	0.165	0.42	68.6	6.1	14.0
	Mack 5	10.0	0.288	0.97	80.8	3.5	8.0
	Lookout 1	7.4	0.079	0.99	53.0	12.7	29.1
	Grasshopper 4	12.0	0.155	0.55	83.8	6.5	14.9
	Cougar 2	6.0	0.100	0.96	68.3	10.0	26.0
	Fritz 1	14.6	0.383	0.94	92.9	2.6	6.0
	Mann 3[a]	6.0	0.021	0.99	79.2	47.6	109.6
	Shorter Control		0.204	0.88	69.2	4.9	11.3
	Mack 2[w]	11.0	0.034	0.95	34.5	29.4	67.7
Deciduous	Quartz 1	5.5	0.281	0.90	68.3	3.6	8.2
	Quartz 2	4.8	0.102	0.95	66.9	9.8	22.6
	Wycoff 1	11.6	0.148	0.98	79.0	6.8	15.6
	Cougar 1	5.8	0.169	0.81	31.6	5.9	13.6
	S.F. Hagan 1	5.0	0.146	0.95	90.9	6.8	15.8
	S.F. Hagan 2	5.0	0.077	0.97	73.0	13.0	29.9
	S.F. Hagan 3	5.0	0.082	0.98	84.7	12.2	28.1
	S.F. Hagan 4	6.0	0.196	0.91	82.0	5.1	11.7
	Simmons 1	2.0	0.030	0.94	60.1	33.3	76.8
	Quartz 2[w]	4.8	0.030	0.91	40.7	33.3	76.8
Open	Grasshopper 1	5.2	0.024	0.97	67.6	41.7	95.6
	Grasshopper 2	9.6	0.025	0.97	52.8	40.0	92.1
	Mann 1	12.4	0.056	0.96	54.7	17.9	41.1
	Mann 2	24.4	0.145	0.97	44.6	6.9	15.9
	Rbro Quartz 1	5.0	0.017	0.97	64.7	58.8	135.4
	Mack 3	9.2	0.060	0.95	62.1	16.7	38.4
	Grassho per 1[w]	5.2	0.021			47.6	109.6
	Mack 3[w]	9.2	0.031			32.2	74.3

[a] Recent debris torrent through channel.
[w] Leaves released in the winter (higher flows).
1-4 Reach Numbers

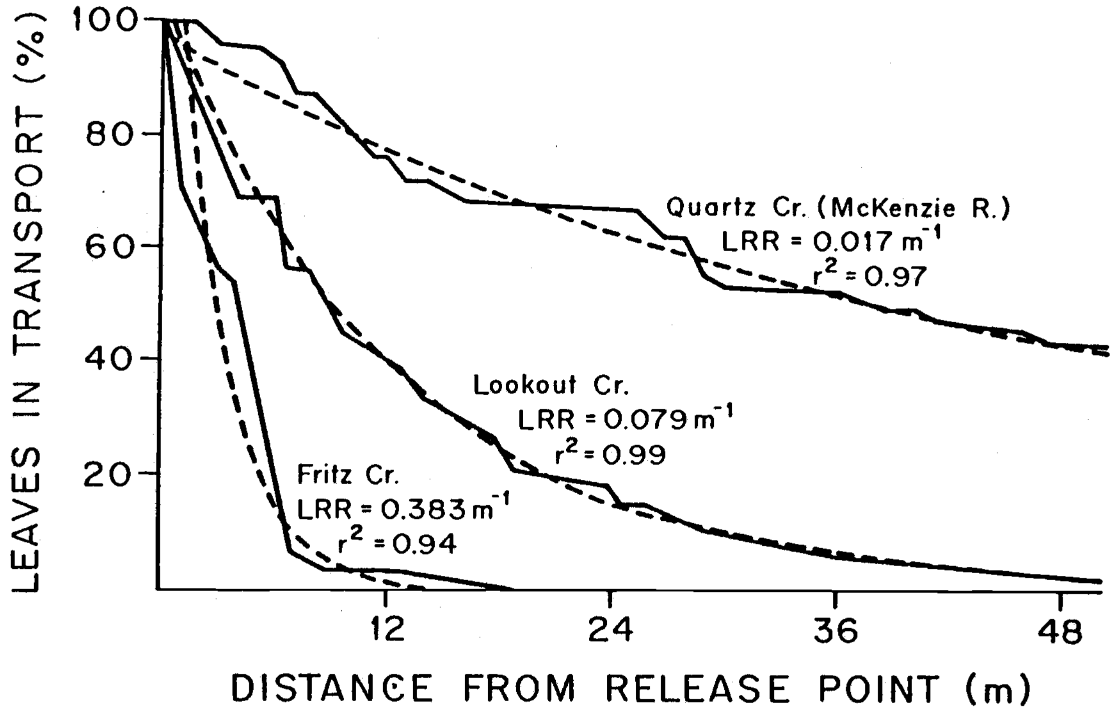

Figure 6. Leaf retention curves for a reach with high leaf retention (Fritz Cr.), intermediate retention (Lookout Cr.), and low retention (Quartz Cr. - McKenzie R.). The solid lines are the observed patterns of leaf retention. The dashed lines are negative exponential curves fit to the data.

The majority of leaves released into study reaches were recovered; recovery averaged 65% (sd=17%) and ranged from 32% to 93%. This included leaves that were transported through the reach, into the nets at the downstream end, and leaves that were found when the reach was searched after 3 hours. Recovery of leaves tended to be greater in smaller streams. All unrecovered leaves were retained within the reach, therefore I assumed that they were retained by the various retention features in the same proportion as leaves that were found. This probably resulted in underestimation of the number of leaves that were retained by large, unmovable features such as boulders and debris dams.

The retention rate of ginkgo leaves was not significantly different than that of other leaves (ANOVA, $p>0.2$). Leaf retention rates in an experimental release in Simmons Creek were 0.039 m^{-1} for ginkgo, 0.050 m^{-1} for red alder and vine maple, 0.053 m^{-1} for big leaf maple and 0.069 m^{-1} for willow. If any bias for leaf type does exist, ginkgo leaves would provide conservative estimates of leaf retention.

Dry and soaked ginkgo leaves were released into the same 50-m section of a stream flowing through an old-growth conifer stand. The leaf retention rate for soaked (12 hours) leaves was 21% higher than the that for dry leaves (0.055 and 0.044 m^{-1} respectively). This difference is relatively small when compared with differences observed between sites (0.017 to 0.383 m^{-1}). Most of the dry leaves remained near the surface of the water and were retained primarily on sticks and branches associated with large organic debris dams. Presoaked, neutrally bouyant leaves were transported throughout the water column and were retained on the streambed as well as on retention features at the surface. The effects of presoaking leaves may be much greater in streams where there are no debris dams. In the absence of debris dams, most of the major leaf retention features are on or near the streambed.

The abundance and size of pools and backwaters were important factors in determining the transit time of water through the study reaches. Reach residence times ranged from 3.2 to 40.0 minutes (Table 5) and were linearly correlated with pool and backwater volume in the reach ($p<0.001$; $r^2 = 0.84$)(Fig. 7). Mid-channel pools tend to be larger than pools and backwaters along the stream margin, therefore, they probably have a greater effect on reach residence time. Backwaters and pools along the stream margin have slower rates of exchange with the main flow and strongly influence the overall turnover time of the reach (M.S. Moore, Oregon State University, personal communication).

In four study reaches, reach residence time was measured at summer and winter base flows (Table 5). In all four reaches, residence time was much lower at the higher discharge. In Quartz 1, pool volume decreased from 45.4% of the total volume to 12.0% as discharge increased from 0.053 to 0.820 m^3/s, thus accounting for much of the decrease in residence time from 29.4 minutes to 4.2 minutes. This was the largest change in residence time observed.

Reach residence time was significantly correlated ($p<0.01$) with leaf retention rate (Fig. 8). Although the relationship was significant, the explanatory power of the correlation was low ($r^2 = 0.41$).

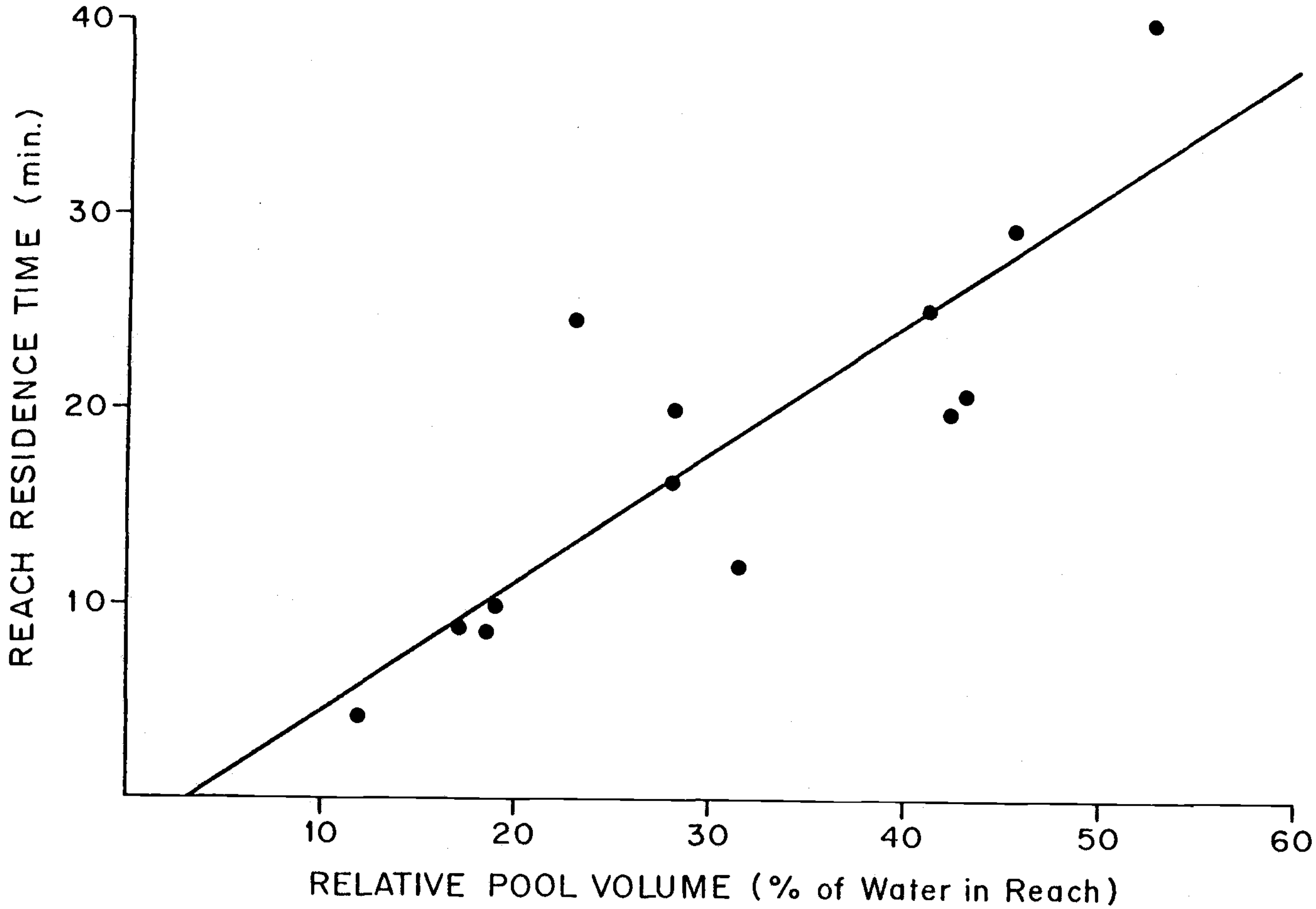

Figure 7. Residence time of water in a reach versus the percent of total volume of water in the reach that is in pools and backwaters.

Table 5. Results of fluorescein introductions and relative pool volume in the study reaches.

Study Reach	Discharge (m^3/s)	Dye Appearance at End of Reach (min.)	50% of Dye through Reach (min.)	Reach Residence Time (min.)	Reach Turnover Time (min.)	Total Volume of Water in Reach (m^3)	Relative Pool Volume (%)
Coniferous							
Mack 1	0.041	5.3	10.1	20.0	30.0	20.1	28.1
Mack 2	0.061	4.6	9.4	16.3	28.0	22.1	28.1
Mack 4	0.037	3.5	6.8	13.2	18.0		
Mack 5	0.027	4.3	9.3	14.9	26.0		
Lookout 1	0.137	2.8	5.4	8.6	16.0	25.8	18.5
Grasshopper 4	0.068	4.4	9.1	13.7	23.7		
Fritz 1	0.022	9.3	23.6	40.0	45.0	8.6	52.5
Mann 3[a]	0.107	2.5	4.7	6.6	9.0		
Shorter-control	0.023	1.7	2.8	3.2	5.0		
Mack 2[w]	0.353	1.8	3.5	6.0	12.0		
Deciduous							
Quartz 1	0.053	6.0	16.2	29.4	40.0	34.8	45.4
Cougar 1	0.114	3.8	6.4	9.0	12.0		
Wycoff 1	0.026	6.0	15.6	24.6	34.0	6.4	23.0
S.F. Hagan 1	0.040	3.6		8.5	13.0		
S.F. Hagan 2	0.043	3.9		10.1	15.0		
S.F. Hagen 3	0.029	2.9		11.9	17.0		
S.F. Hagen 4	0.040	3.5		10.5	17.3		
Quartz 2[w]	0.820	1.8	2.9	4.2	6.0	77.9	12.0
Open							
Grasshopper 1	0.073	4.9	14.6	20.9	26.0	27.8	43.1
Grasshopper 2	0.072	3.8	9.6	20.0	30.0	31.3	42.3
Mann 1	0.107	3.3	6.4	10.0	14.0	21.4	19.0
Mann 2	0.072	6.2	17.2	25.2	30.0	11.9	41.2
Rbro Quartz 1	0.073	4.7	8.5	12.0	16.0	46.2	31.4
Mack 3	0.084	2.6	5.6	8.8	13.0	20.7	17.1
Grasshopper 1[w]	0.208	1.8	5.7	9.2	13.0	53.0	
Mack 3[w]	0.221	1.7	4.8	7.2	10.3	48.2	

[a] Recent debris torrent through channel.
[w] Leaves released in the winter (higher flows).

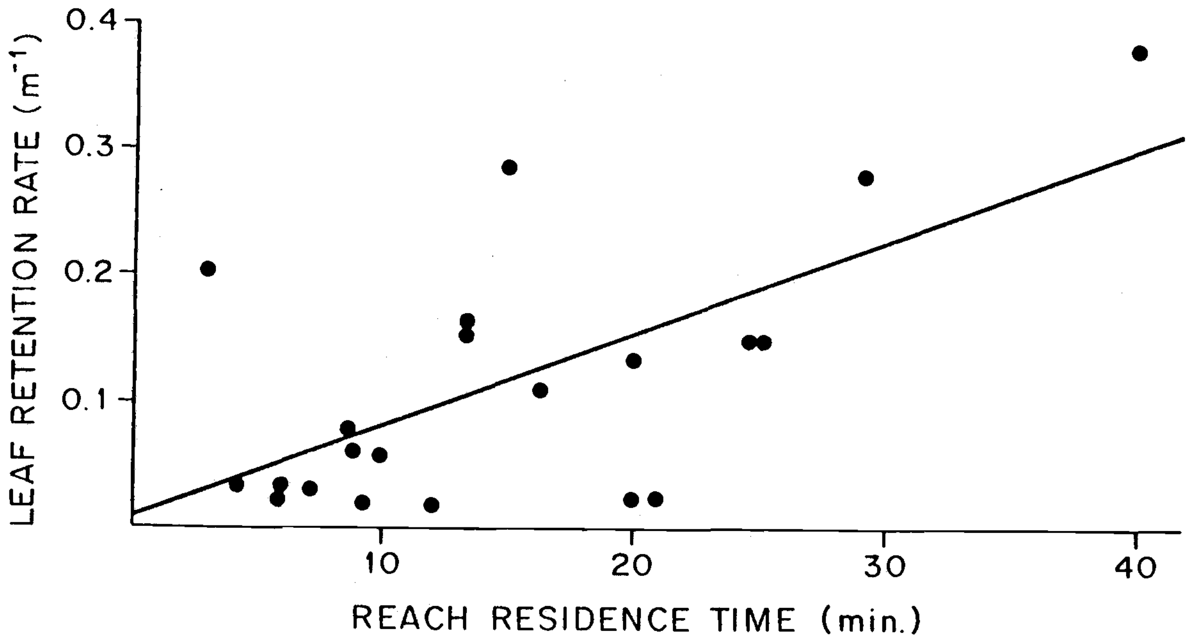

Figure 8. Leaf retention rate versus residence time of water in a reach.

Reach residence time was less than 29 minutes in 19 of the 21 reaches and when only these 19 reaches were plotted, the relationship was not significant ($r2 = 0.07$; $p>0.80$). Therefore, over the range of residence times most commonly encountered in this study, reach residence time is not an adequate indicator of leaf retention rate.

Effects of Large Organic Debris on Leaf Retention

Large organic debris dams that spanned or nearly spanned the entire width of the active channel greatly increased leaf retention. There was a significant difference (ANOVA, $p<0.04$) between the mean of leaf retention rates in the 13 reaches that did not contain debris dams ($\overline{x} = 0.093$, s.d. = 0.075) and the mean of LRRs in the 7 reaches that did contain debris dams ($\overline{x} = 0.186$, s.d. = 0.089). The presence of large debris dams in a reach reduced average travel distance from 10.6 to 5.3 m. In reaches with debris dams, leaf retention was significantly higher (ANOVA, $p<0.01$) in the area of debris dam influence on channel morphology and most of the leaves were retained in the short section (1 to 3 m) where logs and sticks were directly obstructing the flow (Table 6).

The influence of large organic debris on leaf retention was examined further by releasing leaves into an undisturbed section of stream and a downstream section from which all wood greater than 10-cm in diameter had been removed. In the summer of 1978, all large wood was removed from a 44-m section of Shorter Creek in the H.J. Andrews Experimental Ecological Reserve. Shorter Creek is a second-order stream that flows through an old-growth Douglas-fir stand. The sec-

Table 6. Leaf retention rates for sections of study reaches where large organic debris dams are not directly obstructing the flow, where debris dams directly contact the flow and where debris dams influence channel structure by storing sediment but are not in direct contact with the flow.

Study Reach	Debris Dam Not Directly Obstructing flow		Debris Dam Influencing Channel Structure		Debris Dam Directly Obstructing flow	
	Length (m)	LRR (m^{-1})	Length (m)	LRR (m^{-1})	Length (m)	LRR (m^{-1})
Mack 2	25.0	0.047	19.0	0.178	2.0	0.685
Mack 4	18.5	0.090	20.0	0.290	2.0	2.134
Lookout 1	25.0	0.077	9.0	0.081	2.0	0.132
Fritz 1	0.0		7.0	0.402	2.0	0.807
Grasshopper 4	20.0	0.095	24.0	0.242	1.0	3.324
Quartz 1	0.0		15.0	0.198	2.0	1.077
Quartz 2	50.0	0.094	7.0	0.214	3.0	0.484
$\bar{x}$ =		0.081		0.229		1.114
sd =		0.020		0.100		1.088

tion from which debris was removed (cleared section) and the upstream control section are illustrated in Figures 9 and 10 respectively. One thousand ginkgo leaves were released at the top of each section in February 1984 and leaf retention rates were determined.

LRR was higher in the section with wood ($0.204\ m^{-1}$) than in the cleared section ($0.110\ m^{-1}$)(Fig. 11). In the upstream control section more than 90% of the leaves were retained in the small debris accumulation above meter 7. Leaf retention was also high in the cleared section because of the shallow channel, but leaves were recovered throughout the section and five leaves reached the net at meter 44. These results agree well with the between site comparisons of leaf retention. In both cases leaf retention rates were approximately doubled when large organic debris was present in the stream channel.

Effects of Channel Geometry and Discharge on Leaf Retention

The retention of an object in transport in a riffle is a function of the probability of the object encountering an obstruction and the probability of its being caught on the obstruction (Young et al. 1978). The streambed is a major obstruction to flow in riffles in small streams. As the depth of the water decreases, the probability of a particle encountering the streambed increases. Assuming that a neutrally bouyant particle in transport has an equal likelihood of occupying any position in the water column of a turbulent stream, the probability of the particle encountering the streambed is directly proportional to the wetted perimeter of the active channel divided by

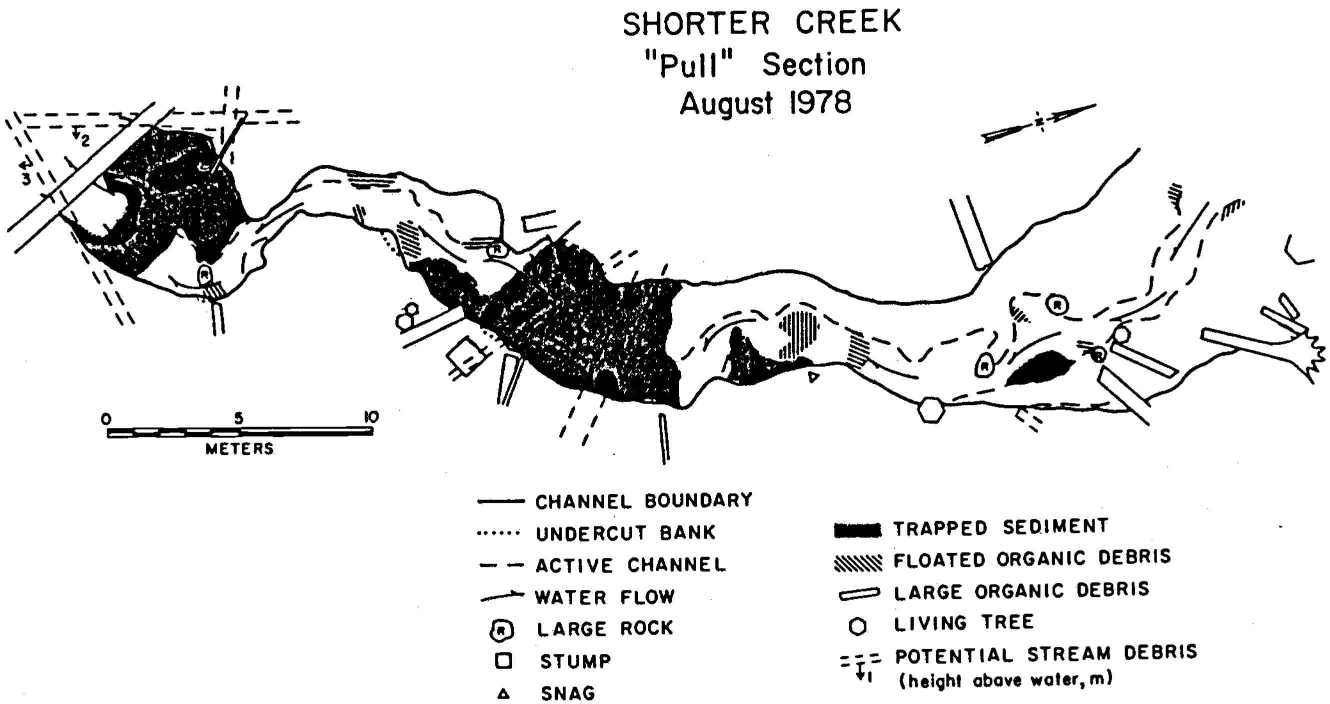

Figure 9. Map of the cleared section of Shorter Creek (from G.W. Lienkaemper, USDA Forest Service, PNW Forest and Range Experiment Station, Corvallis, OR).

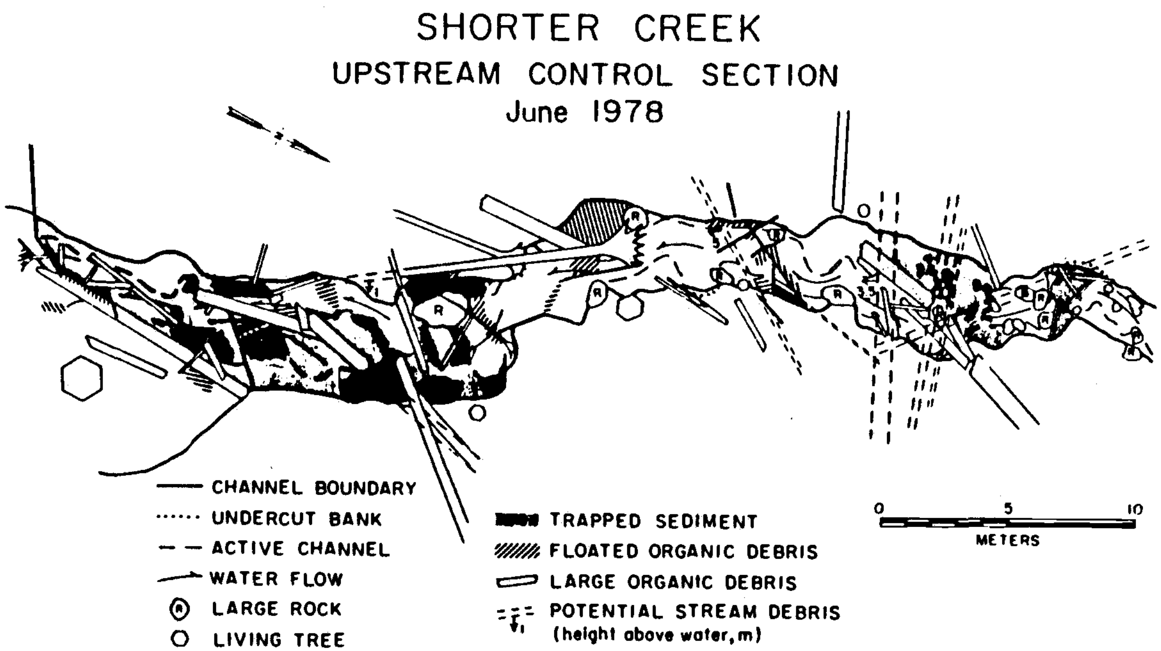

Figure 10. Map of the undisturbed section of Shorter Creek (from G.W. Lienkaemper, USDA Forest Service, PNW Forest and Range Experiment Station, Corvallis, OR).

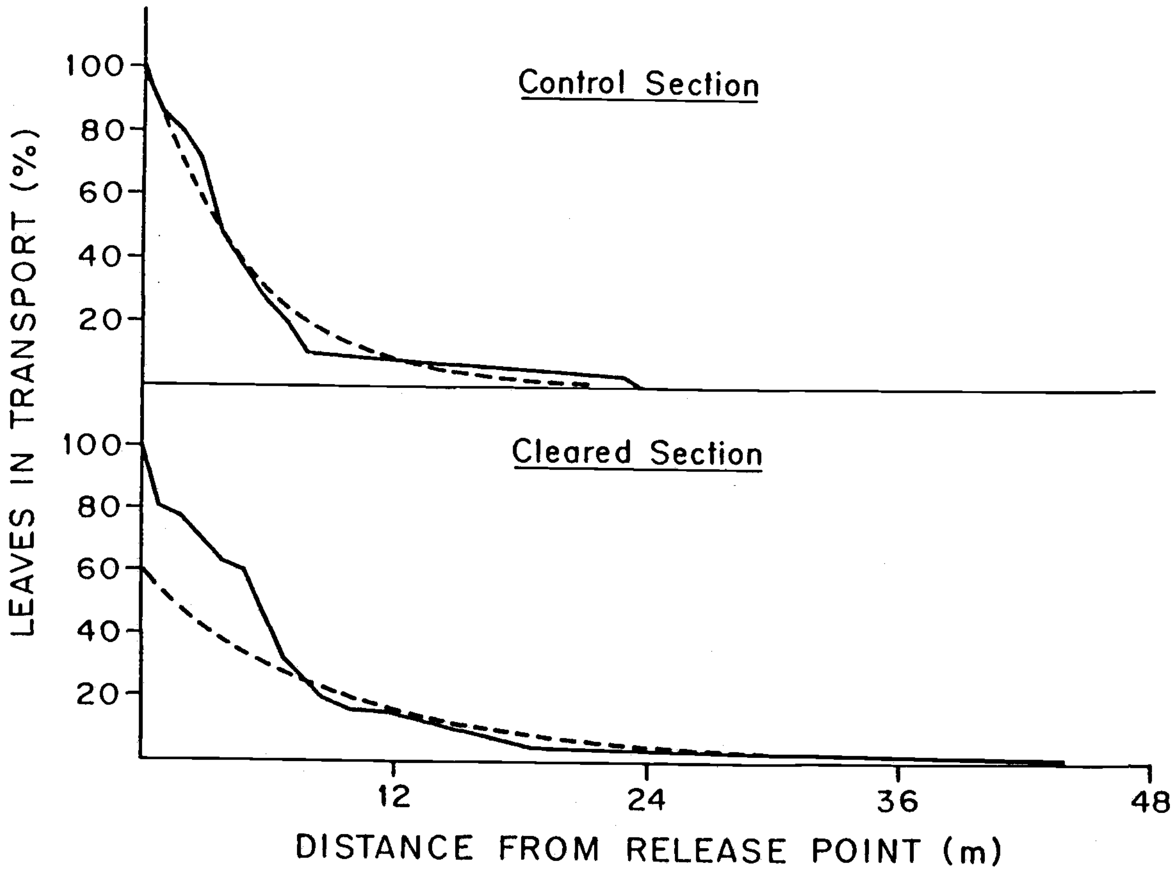

Figure 11. Leaf retention curves for the cleared and control sections of Shorter Creek. The solid lines represent the percent of leaves in transport as calculated from the leaf recoveries. The dashed lines are negative exponential curves fit to the data.

the cross-sectional area of flow. This ratio (1/R) is the inverse of the hydraulic radius (R) and varies with cross-sectional profile, water depth and the development of the streambed. Streams with shallow channels and/or high substrate heterogeneity will have a high 1/R and the probability of a particle in transport contacting the streambed will be high. Leaf retention rate was significantly correlated with 1/R in riffles for the 20 reaches and sections of reaches without debris dams ($p<0.001$; $r^2 = 0.79$) (Fig. 12). As 1/R in riffles increased from 5.77 to 18.36 m/m^2 the corresponding increase in leaf retention rate was approximated by:

$$LRR = 0.0075\, e^{(0.18)(1/R)} \qquad \text{(Equation 2)}$$

Leaf retention rate decreased with increasing streamflow (Fig. 13A). The rate of change of retention relative to discharge was different between sites however. The slope of the relationship between LRR and discharge depended on the initial values of these parameters and channel morphology and geometry. At all four sites, the lowest streamflows at which retention was measured were similar but LRRs were different, ranging from 0.159 m^{-1} at Mack 2 to 0.024 m^{-1} at Grasshopper 1 (Fig. 13A). These differences in retention correspond to differences in 1/R at summer base flow at these sites (Fig. 13B). As discharge increased, leaf retention decreased most rapidly in Mack 2 and 3 and much more slowly in Quartz 2 and Grasshopper 1. This same pattern was observed in the relationship between discharge and 1/R.

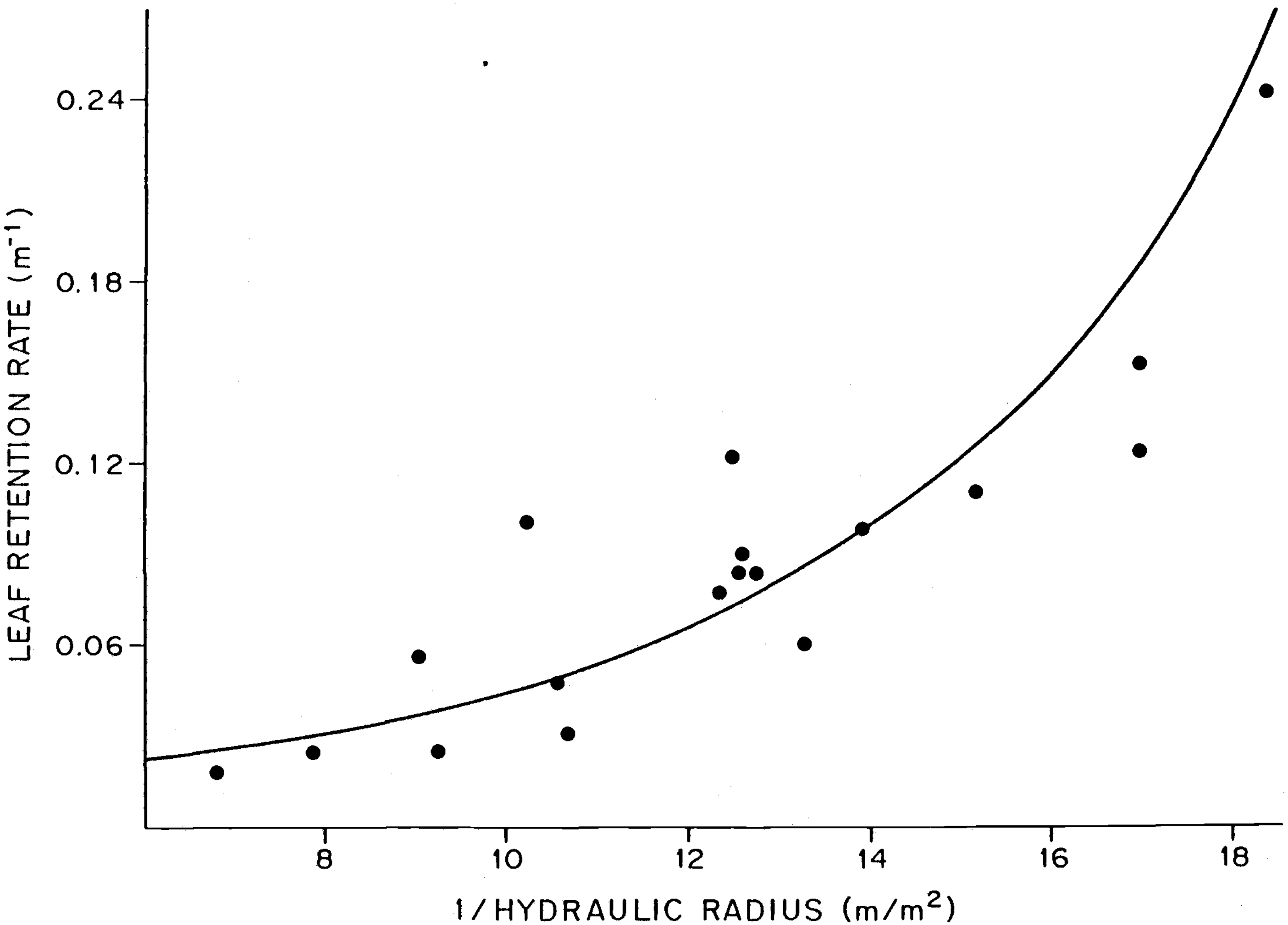

Figure 12. Exponential regression of leaf retention rate against the inverse of the hydraulic radius in riffles ($y = 0.0075\ e^{0.182x}$).

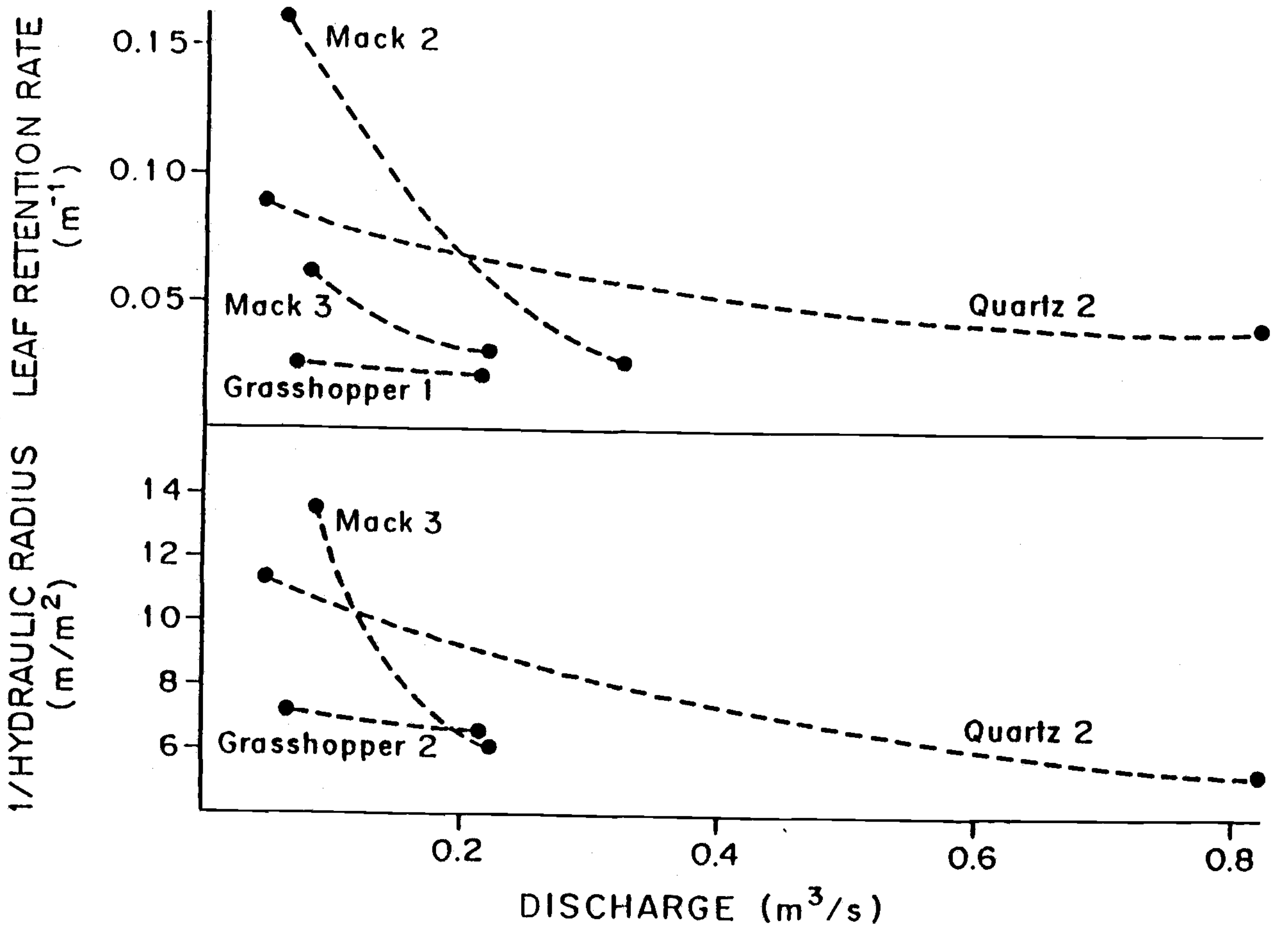

Figure 13. A: Leaf retention rate versus stream discharge for four sites at summer and winter base flows.

B: The inverse of the hydraulic radius versus stream discharge at three sites at summer and winter base flows.

Trapping Efficiency of Retention Features

Trapping efficiency is a function of the probability of a leaf in transport encountering a retention feature (availability) and the probability of a leaf being trapped on the feature (capture). In riffles, capture occurs when a leaf is either pinned against an obstruction or is driven into spaces between obstructions. Capture in pools is less dependent on the feature encountered and is usually a result of the current velocity being relaively slow in relation to the fall velocity of a leaf in transport. The trapping efficiency of retention feaures is expressed as the percent of leaves in transport that were trapped by the feature divided by the planar area of the feature (%/m^2).

Sticks in riffles and pools had higher trapping efficiencies than any other retention feature (Least Significant Range, $p<0.05$)(Table 7). There were no significant differences between trapping efficiencies of gravels, cobbles, small boulders or large boulders in riffles and pools. Trapping efficiencies for wood (>10 cm diameter) and terrestrial vegetation extending into the flow were not different from those of all inorganic substrates. There was a trend towards high trapping efficiency in the cobble to small boulder size classes and very low trapping efficiency in sand and on bedrock in both riffles and pools (Fig. 14).

The size of interstitial spaces between rocks increases as substrate size increases. Spaces between gravel particles are much too small to hold leaves, and spaces associated with large boulders are sometimes large enough to hold several hundred leaves. This

Table 7. Trapping efficiency of retention features [(leaves retained/leaves in transport/m^2 of retention feature) x 100].

	Sand <2mm	Gravel 2-60mm	Cobble 60-260mm	Small Boulder 260-640mm	Large Boulder >640mm	Bedrock	Sticks <100mm	Wood >100mm	Terrestrial Vegetation
Riffle		0.95	1.30	1.18	0.80	0.02	76.51	0.94	1.16
Pool	0.02	0.57	0.85	0.94	0.20	0.00	30.68	0.78	
Backwater	0.00	0.00	0.02	0.00	0.00				
Riffle Margin		1.26	1.75	0.17					1.90
Pool Margin		4.48	4.62	0.22	0.46				

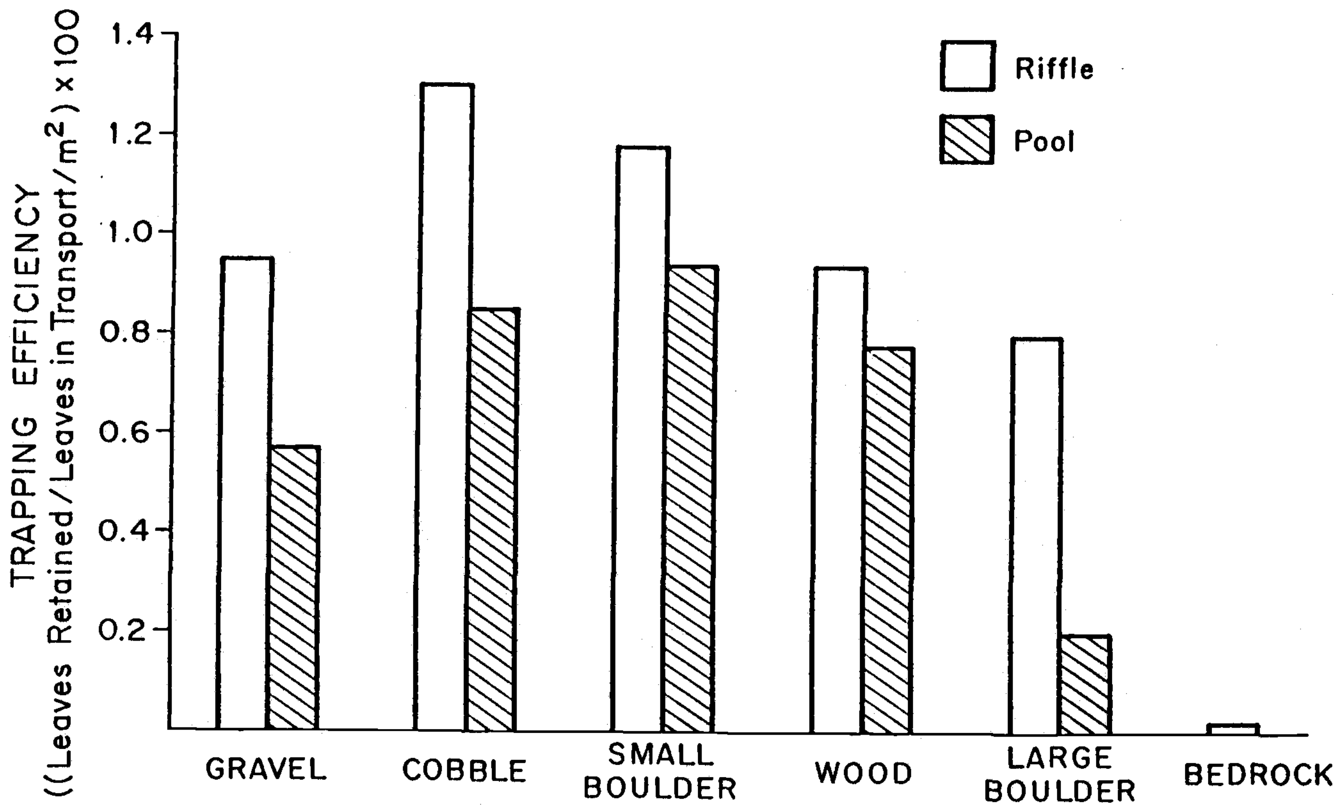

Figure 14. Trapping efficiencies of substrates in riffles and pools.

difference was not reflected in the trapping efficiencies of gravels, cobbles and boulders. It is possible that the velocity profiles associated with larger substrates caused fewer leaves to be pinned against these substrates. Leaves were rarely observed to be pinned against substrates larger than cobbles, but this was the primary method of retention on gravel. The tendency to be carried around larger substrates may have counterbalanced the increase in interstitial volume, resulting in approximately equal trapping efficiencies for gravels, cobbles, and boulders. Bedrock, which has no interstitial space and a relatively smooth surface, was ineffective at retaining leaves. Sand was not found on the streambed in riffles in streams in the Cascades, but in lower gradient, small streams in Sequoia National Park the trapping efficiency of sand in riffles was found to be very low (0.0004 $\%/m^2$). Trapping efficiency of gravels in riffles may have been increased by the tendency for gravels to occur in shallow areas (high 1/R) with lower current velocity in riffles. Gravels were generally not found on the surface of the streambed in deeper and faster flowing sections of the stream due to scouring at high flows.

Retention of leaves on small boulders, large wood and sticks in riffles was examined further by systematically increasing the abundance of these features in 20-m study reaches that had been cleared of most major obstructions. In the first experiment, leaf retention rate increased from 0.002 to 0.068 m^{-1} when small boulders were added to the channel (Table 8). There was a significant positive linear correlation ($p<0.001$) between the number of small boulders added to the channel and LRR. For each small boulder added to the stream, an

Table 8. Substrate composition, leaf retention rate and reach trapping efficiency (% of leaves retained/m^2 stream) in a manipulated stream reach. The number of small boulders in the reach was increased after each set of leaf releases.

Treatment Level	Gravel (%)	Cobble (%)	Small Boulder (%)	Trapping Efficiency (%/m^2)	LRR (m^{-1})
Control	44.0	36.0	16.3	0.21	0.004
0	50.5	35.4	12.6	0.08	0.002
1	45.8	35.0	17.5	0.54	0.011
2	36.6	35.0	27.4	1.01	0.021
3	22.0	34.5	42.5	2.11	0.046
4	7.8	34.5	57.3	2.89	0.068

additional 0.39% of the leaves in transport were retained. Trapping efficiency over the entire reach increased from 0.08 %/m^2 initially to 2.90 %/m^2 after 180 small boulders had been added to the reach (Table 8).

Measured trapping efficiencies in natural channels were 0.95 %/m^2 for gravels, 1.30 %/m^2 for cobbles and 1.18 %/m^2 for small boulders in riffles. The efficiencies estimated in the manipulation experiment were 0.08 %/m^2 for the initial 80% gravel and cobble substrate and 8.70 %/m^2 for the small boulders that were added. These differences in trapping efficiencies of small boulders in natural and manipulated channels were probably caused by the artificial arrangement of substrate particles in the manipulated channel. Small boulders rested on top of the predominantly gravel bed with no filling in around their edges in the manipulated channel. This increased the amount of exposed margin on each rock relative to similar sized rocks in natural streams and created an abrupt edge at the point of contact with the bed. Most of the retained leaves were trapped at this point of contact.

Leaf retention in the manipulated channel increased exponentially with increasing 1/R ($p<0.001$; $r^2 = 0.97$)(Fig. 15). LRR increased more than five times faster with increasing 1/R in the manipulated channel (0.033/(1/R)) than in natural streams (0.006/(1/R)). Greater retention in the manipulated channel may also be caused by the artificial arrangement of the substrates and indicates that both the distribution of inorganic substrates and 1/R can be important determinants of leaf retention.

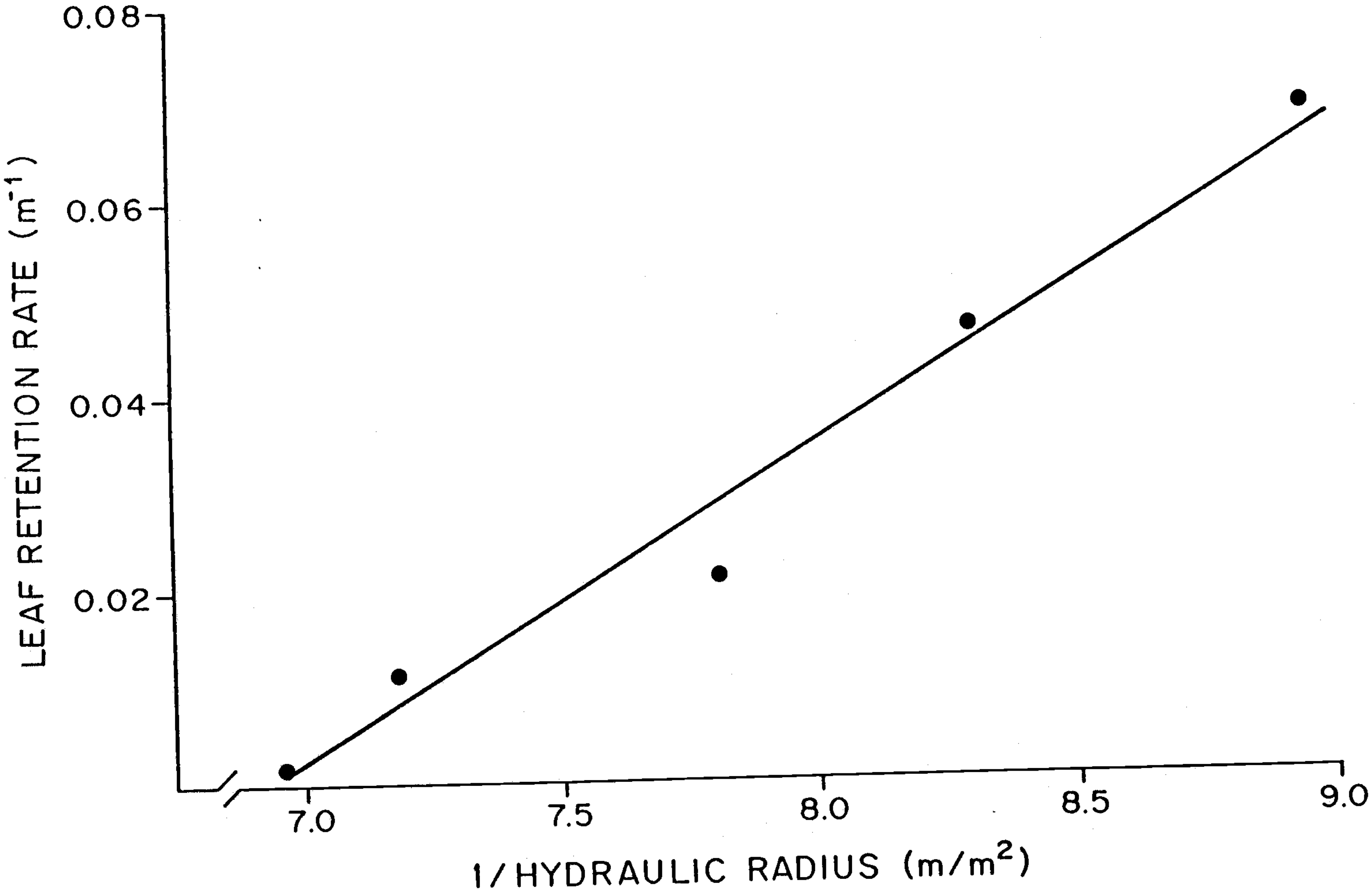

Figure 15. Leaf retention rate versus the inverse of the hydraulic radius in a stream reach where 1/R was altered by adding small boulders to the channel.

When large pieces of wood (mean length=2 m, mean diameter=0.25 m) were systematically added to a cleared reach (mean channel width=1.8 m), leaf retention rate increased at a rate of 0.0024 / piece of wood added (Fig. 16). If it is assumed that all of the additional leaf retention was a result of wood in the stream, trapping efficiency for wood was 15.4%/m^2 at level 3 (12 pieces of wood; wood area = 3.50 m^2). After most leaf releases, the number of leaves retained by each piece of wood and in the substrate around each piece of wood was counted. The mean trapping efficiency obtained from these counts was 13.2 %/m^2. The trapping efficiency of large wood in natural streams was only 0.97 %/m^2. It appears that the retention of leaves in substrates adjacent to large pieces of wood in the stream may be a more important process than the actual trapping of leaves on logs. Large wood in the channel increased the distance water travelled by deflecting the current laterally, around the wood, and vertically, toward the streambed (Fig. 17). This caused an increase in the retention of leaves in the inorganic substrates around the wood. With no wood in the experimental channel discharge was 0.63 m^3/s and turnover time for water in the experimental side was 1.25 minutes. After 12 pieces of wood had been added (treatment level 3) discharge was only 0.08 m^3/s and reach turnover time had increased to 2.25 minutes (Fig. 18). The longer transit time of leaves in the reach after wood had been added may have increased the probability of leaves being retained in the reach. Large wood increases the distance of travel for water flowing in natural channels, but because the wood in natural streams in this study was usually too large to be moved and often occurred in large

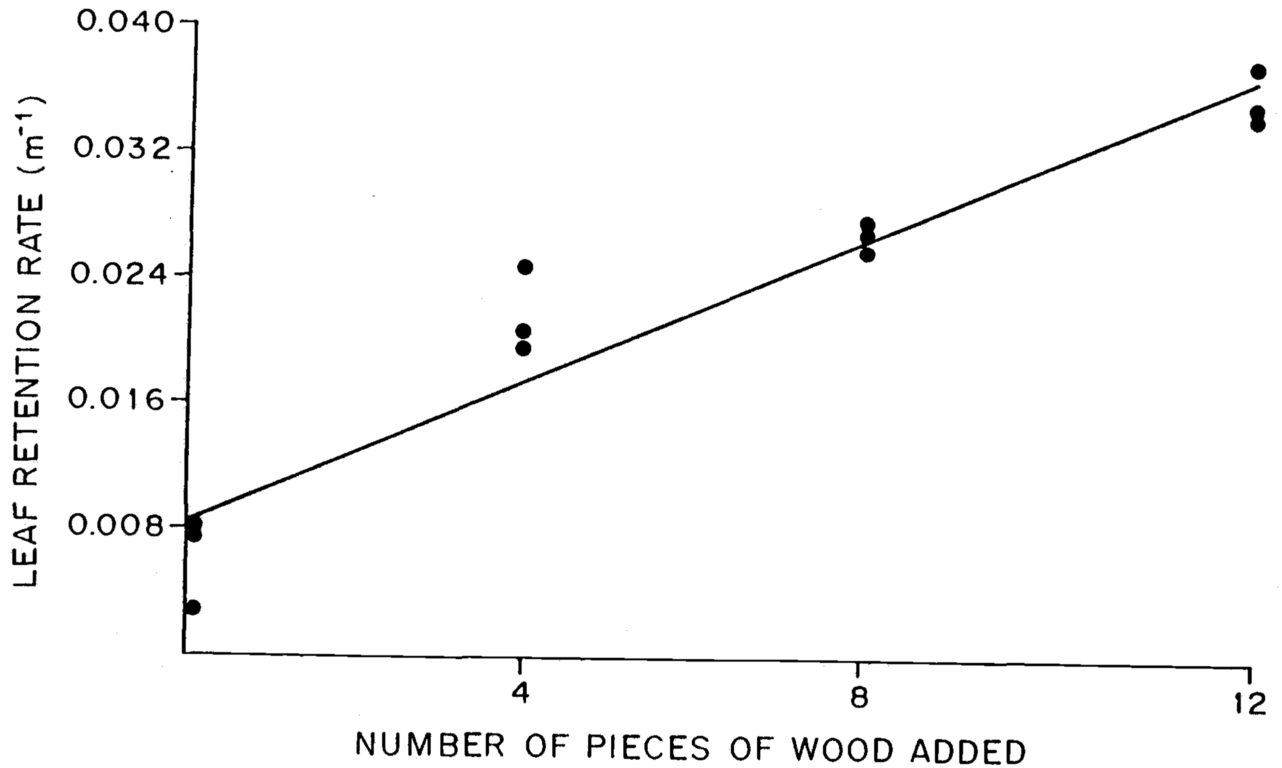

Figure 16. Leaf retention rate versus the number of pieces of wood added to a cleared stream reach.

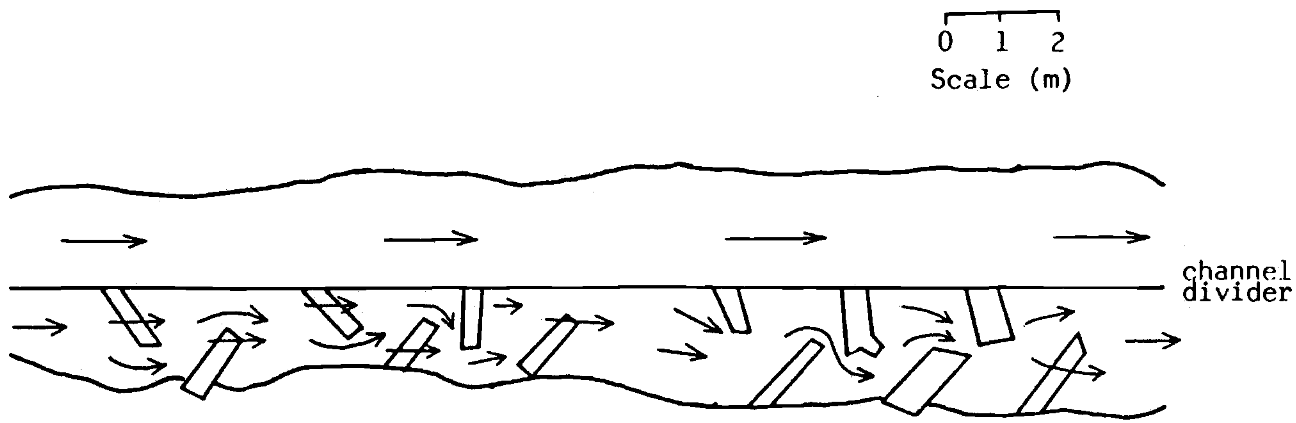

Figure 17. Experimental section of Lookout Creek after 12 pieces of wood (mean length = 1.20 m; mean diameter = 0.25 m) had been added to the channel.

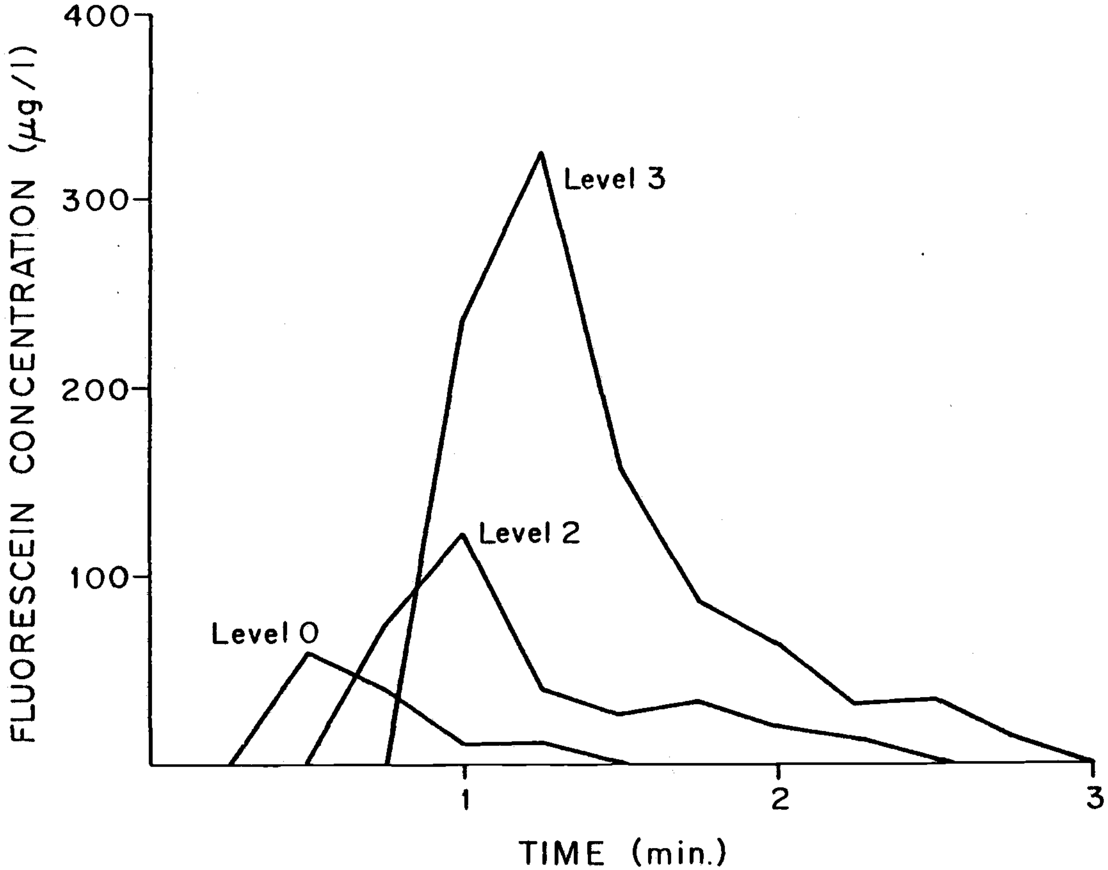

Figure 18. Movement of dye through a cleared (level 0) 20-m section of Lookout Creek, and after 8 (level 2), and 12 (level 3) pieces of wood had been placed in the channel.

accumulations, it was difficult to measure whether this wood increased leaf retention in adjacent substrates. The decrease in dischage may have also resulted in a decrease in 1/R as wood was added to the channel, and this may have contributed to the increased leaf retention on the streambed.

Leaf retention rate increased at a rate of 0.00018 per stick added to the cleared study reach (Fig. 19). This is slightly more than half of the rate of increase per small boulder added. However, the average stick size was only 0.00021 m^2 and the trapping efficiency for sticks in this experiment (1900 %/m^2) was more than two orders of magnitude greater than that of small boulders (8.7 %/m^2). The much higher trapping efficiency of sticks in riffles was due to their small diameter and extension into the water column. Because of their small diameter, leaves tended to wrap around individual sticks and were retained. Small branches with numerous fine twigs attached were often observed at the leading edges of debris dams. Since water easily passed through these accumulations of twigs, they acted as sieves, and almost all leaves that encountered such assemblages were retained.

The trapping efficiency of 1900 %/m^2 found in the manipulated channel is much higher than the 77 %/m^2 measured in natural riffles. This difference is probably caused by the location and orientation of the sticks in the riffles. Under natural conditions most sticks are lodged in the interstitial spaces of cobbles and boulders and are not exposed to the main flow to the same degree as sticks in this experiment. In the manipulations, most of the sticks extended from the stream bottom to or nearly to the surface of the water.

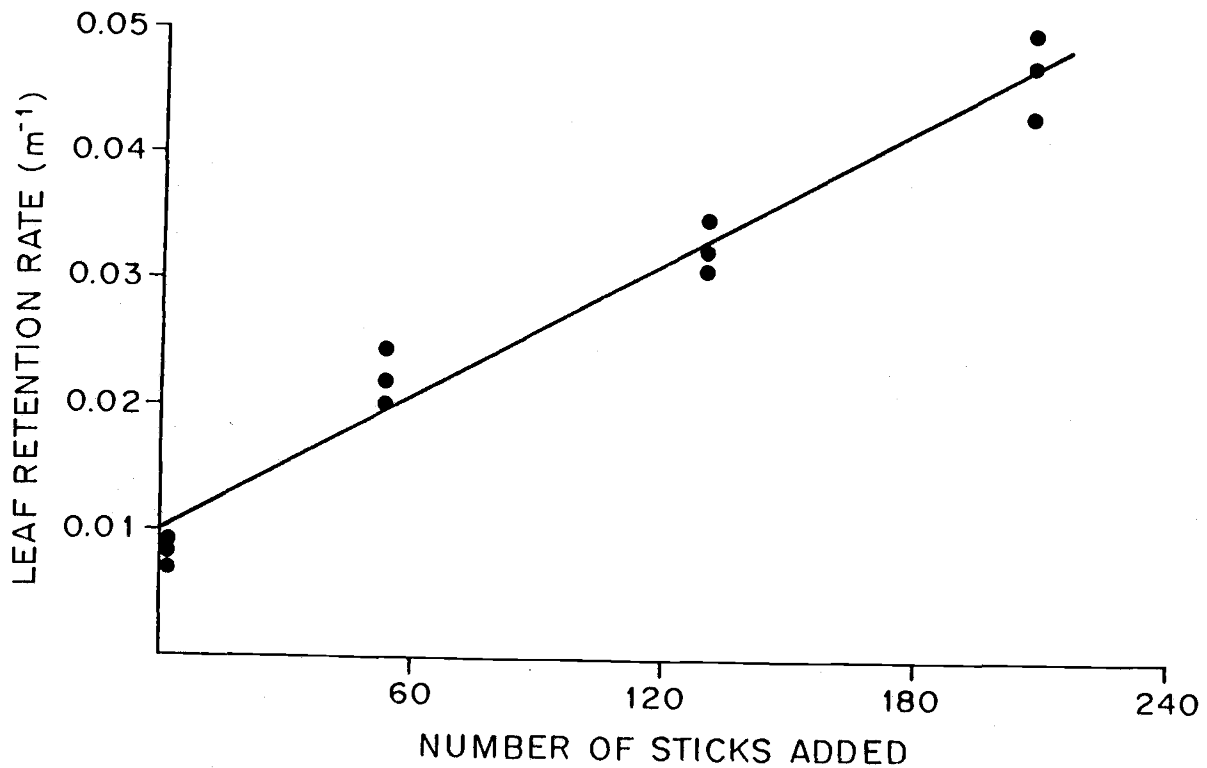

Figure 19. Leaf retention rate versus the number of sticks added to a cleared, 20-m section of Lookout Creek.

In natural streams, sticks in riffles were one of the most important leaf retention features, retaining 30.2% of the leaves that were introduced (Table 9). In pools, sticks occupied only 0.2% of the area but retained 4.5% of the leaves. By comparison, all inorganic substrates combined (sand through bedrock) occupied 73.7% of the total streambed in riffles but retained only 43.3% of the leaves Inorganic substrates in pool covered 19.7% of the streambed and retained only 6.2% of the leaves.

Leaf retention relative to the area of stream habitats was highest along the stream margin. The ratio of the percent of the total number of leaves retained in a habitat to the percent of area occupied by that habitat was 4.42 for stream margins, 0.99 in riffles, 0.58 in pools, and 0.06 in backwaters (Table 9). Higher retention along stream margins is probably due to reduced water depth and velocity near the edge of the channel. Lower relative retention in pools and backwaters may have resulted from the reduced probability of leaves in transport entering these habitats.

Retention features in pools and backwaters generally had lower trapping efficiencies than corresponding retention features in riffles (Fig 14). This may have been a result of differences in the number of leaves entering riffles, pools, and backwaters, which was not directly measured, rather than differences in the efficiency of these areas in trapping leaves that had entered them. In a riffle, not all of the leaves in transport are available to be retained by each retention feature; but the flow is turbulent and leaves tend to be distributed across the width of the riffle, making it likely that a large por-

Table 9. The percent of the total number of retained leaves that were caught on a retention feature and the relative area of retention features within reaches.

Retention Feature		Coniferous		Deciduous		Open		All Sites	
		Leaves Retained (%)	Area (%)	Leaves Retained (%)	Area (%)	Leaves Retained (%)	Area (%)	Leaves Retained (%)	Area (%)
Riffle	Gravel	1.9	11.7	2.6	6.1	2.9	4.8	2.4	7.9
	Cobble	23.9	27.4	18.0	25.9	26.2	25.4	23.1	26.3
	Sm. Boulder	16.3	24.5	10.9	21.2	10.4	24.2	12.9	23.5
	Lg. Boulder	5.1	10.0	2.1	14.5	6.5	23.6	4.8	15.7.
	Bedrock	0.0	0.2	0.1	0.4	0.1	0.5	0.1	0.3
	Sticks	33.7	1.3	32.3	0.5	24.3	0.2	30.2	0.7
	Wood	1.3	1.7	0.2	0.8	1.3	0.1	1.0	0.9
	Total	82.2	76.8	66.2	69.4	71.7	78.8	74.5	75.3
Pool	Sand	0.0	1.7	0.1	1.6	0.0	2.5	0.1	1.9
	Gravel	0.9	7.5	0.3	8.1	0.2	3.4	0.5	6.3
	Cobble	1.8	4.6	3.6	6.8	1.6	4.2	2.2	5.0
	Sm. Boulder	1.7	2.1	1.4	6.0	1.1	2.4	1.4	3.2
	Lg. Boulder	2.0	3.0	2.6	1.8	1.5	3.0	2.0	2.7
	Bedrock	0.0	0.2	0.0	0.4	0.0	1.1	0.0	0.6
	Sticks	3.5	0.3	9.1	0.3	2.6	0.1	4.5	0.2
	Wood	1.6	1.6	1.8	0.8	0.0	0.0	1.3	0.8
	Total	11.5	21.0	18.9	25.8	7.0	16.7	12.0	20.7
Backwater		0.3	1.0	0.0	1.8	0.0	2.4	0.1	1.7
Stream Margin		3.3	1.9	9.0	2.3	12.2	1.7	8.4	1.9

tion of the leaves in transport will be available to each retention feature. The number of leaves in transport in pools was generally lower than the number of leaves in transport in riffles, and very few leaves were carried into backwaters. Pools that span the entire channel width had the same number of leaves passing through them as riffles, but these types of pools made up only a fraction of the total pool area in the study reaches. Pools behind boulders or logs and pools that were laterally displaced from the main flow had fewer leaves entering them than riffles.

To examine differences in leaf availability to the different habitats, discharges were measured in a riffle that spanned the entire channel width, a pool that was laterally displaced from the main flow, and a backwater. Fluorescein dye was dripped into the stream at a constant rate 40 to 42 m above the sampling locations and the concentration of dye in the riffle, pool and backwater was monitored. After 30 minutes the dye introduction was terminated and the decline in dye concentration was measured. Dye reached the riffle about 1.2 minutes after dripping began and dye concentration began to level off after 5 minutes (Fig. 20). Dye concentrations in the riffle were undetectable 5 minutes after the input was stopped. Dye concentrations in the pool began to level off after 14 minutes and there was no dye in the pool 9 minutes after the upstream dye input was terminated. The backwater took 24 minutes to reach peak concentration and had not evacuated all of the dye 22 minutes after the dye input had been stopped. When dye input was terminated, all three habitats contained a known amount of thoroughly mixed dye and the discharge of the

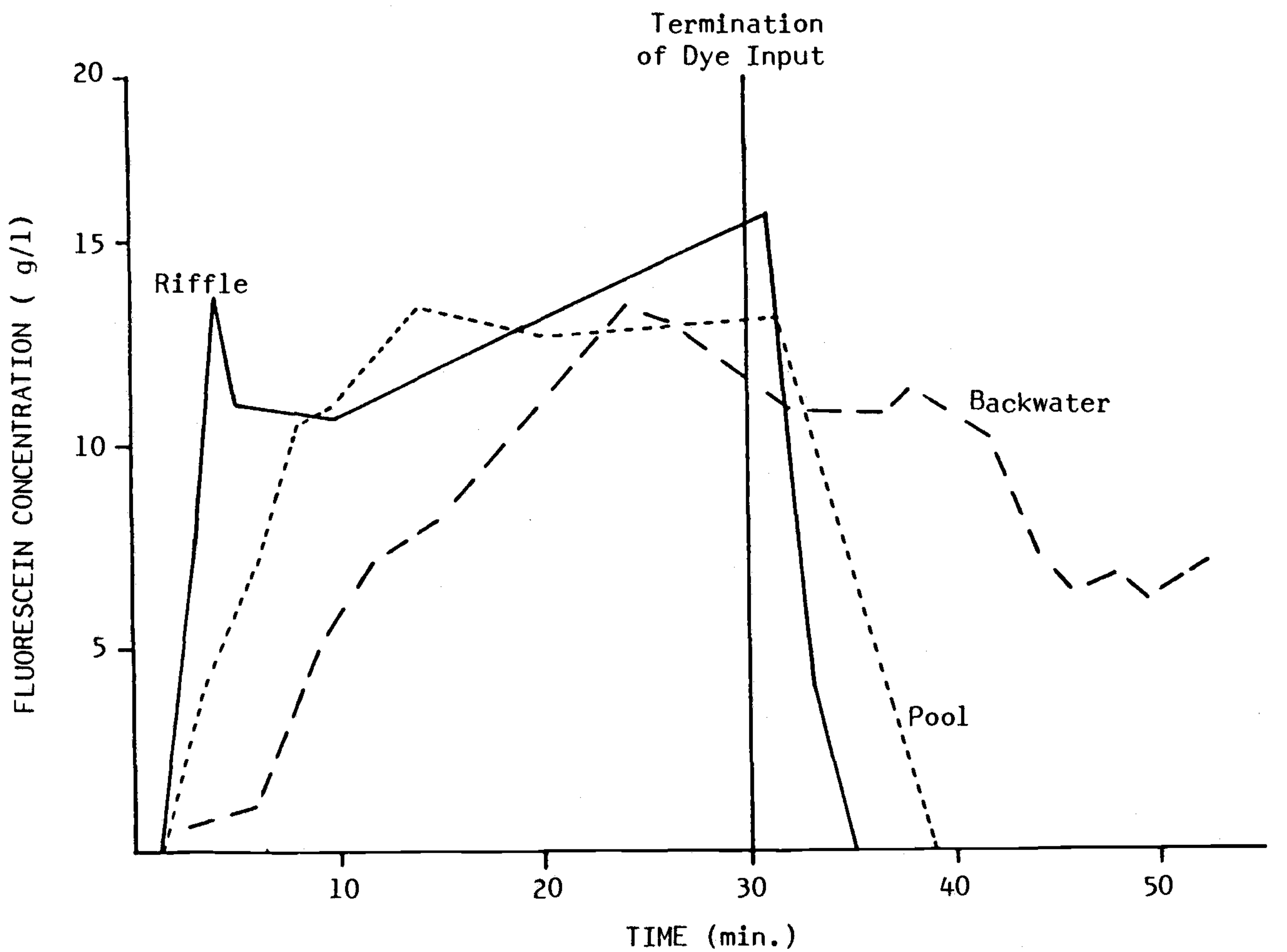

Figure 20. Fluorescein concentration versus time in a riffle, pool, and backwater. Dye was dripped into the stream at a constant rate 40 to 42 m upstream from the sampling locations. After 30 minutes the dye input was terminated.

pool and backwater were calculated from the descending portions of the curves of dye concentration vs time as:

$$Q = \frac{M}{\int_0^\infty c\, dt}$$

where: Q = discharge.

M = amount of dye in the habitat after the riffle had emptied at 35 minutes.

c = dye concentration in the habitat.

t = time that had elapsed since the riffle had cleared at 35 minutes.

If leaves in transport entered the pool and backwater at about the same rate that water from a mid-channel riffle entered these areas, then approximately 3.5% of the leaves in transport in the riffle entered the pool and 0.05% entered the backwater.

The portion of leaves entering different pools and backwaters will vary depending on flow conditions and the position of these areas relative to the main flow. It can be as high as 100% in pools that span the entire channel width, and this experiment indicates that it can be much less than 1 % in backwaters at low flow. When differences in the availability of leaves in transport to different areas in the stream are taken into consideration, pools may be more efficient at retaining leaves at low flows than riffles, and backwaters probably retain nearly all leaves that enter them.

Effects of Riparian Vegetation on Leaf Retention

Riparian vegetation influenced channel morphology and leaf retention primarily through its effects on the formation of large organic debris dams. Leaf retention rates were significantly (ANOVA) higher in streams with coniferous ($\overline{x}$=0.185 m^{-1}, p<0.01) and deciduous ($\overline{x}$=0.159 m-1, p<0.01) trees in the riparian zone than streams with riparian zones dominated by herbs and shrubs (x=0.040 m-1)(Table 10). There was no significant difference in leaf retention rates between study sites with coniferous and deciduous riparian zones. Mann 2, a high gradient (24.4%), first-order channel, was not used in this comparison. The channel was a series of small, steep falls and plunge pools, with very high retention occurring at the top of the falls and in the plunge pools.

Debris dams were more abundant in study reaches with coniferous and deciduous riparian zones than in streams with open riparian zones, influencing 37%, 10% and 0% of the active channel respectively (Table 10). The absence of debris accumulations in streams with open riparian zones was a major factor in the lower leaf retention rates in these streams. There were no statistically significant differences (ANOVA, p>0.35) in the relative abundance of riffles and pools between sites with different riparian zones and also no difference (ANOVA, p>0.32) in 1/R between sites.

There were no significant differences (ANOVA) in the percent of gravels, cobbles, small boulders and large boulders between sites with different types of riparian zones, however, sites with open riparian zones tended to have a larger median substrate particle size than sites with deciduous or coniferous riparian zones (148 mm, 136 mm and 107 mm respectively) (Fig. 21). Open sites also tended to have a higher percentage of substrate in the boulder size classes (45.5%) than deciduous (38.9%) and coniferous sites (27.0%)(Table 11).

Table 10. Leaf retention rates and physical parameters affecting retention in study reaches with different riparian zones. Debris dam influence is expressed as the percent of reach length affected by large organic debris. 1/R is the reciprocal of the hydraulic radius.

	Stream	Number of Reaches Studied	Total length Studied (m)	Discharge (m^3/s)	Debris Dam Influence (% of length)	1/R (m/m^2)	LRR (m^{-1})
CONIFEROUS							
	Mack Cr.	4	170	0.042	29.0	12.9	0.187
	Lookout Cr.	1	50	0.137	8.0	11.0	0.079
	Grasshopper Cr.	1	24	0.065	100.0	12.4	0.155
	Cougar Cr.	1	30	0.065	0.0	9.5	0.100
	Shorter Cr.-Control	1	46	0.023	69.6	13.1	0.204
	Fritz Cr.	1	50	0.022	14.0	16.7	0.383
			$\bar{X}$ =	0.059	36.8	12.6	0.185
			sd =	0.043	39.6	2.4	0.109
DECIDUOUS							
	Quartz Cr.	2	115	0.050	22.0	9.4	0.192
	Wycoff Cr.	1	50	0.026	0.0	17.6	0.169
	Cougar Cr.	1	50	0.114	2.0		0.148
	S.F. Hagan Cr.	4	200		15.0		0.125
			$\bar{X}$ =	0.063	9.8	13.5	0.159
			sd =	0.045	10.5	5.8	0.029
OPEN							
	Grasshopper Cr.	2	100	0.073	0.0	7.9	0.025
	Rbro.-Quartz Cr.	1	50	0.073	0.0	6.8	0.017
	Mann Cr.	1	50	0.107	0.0	9.6	0.056
	Mack Cr.	1	50	0.084	0.0	13.4	0.060
			$\bar{X}$ =	0.084	0.0	9.4	0.040
			sd =	0.016		2.9	0.022

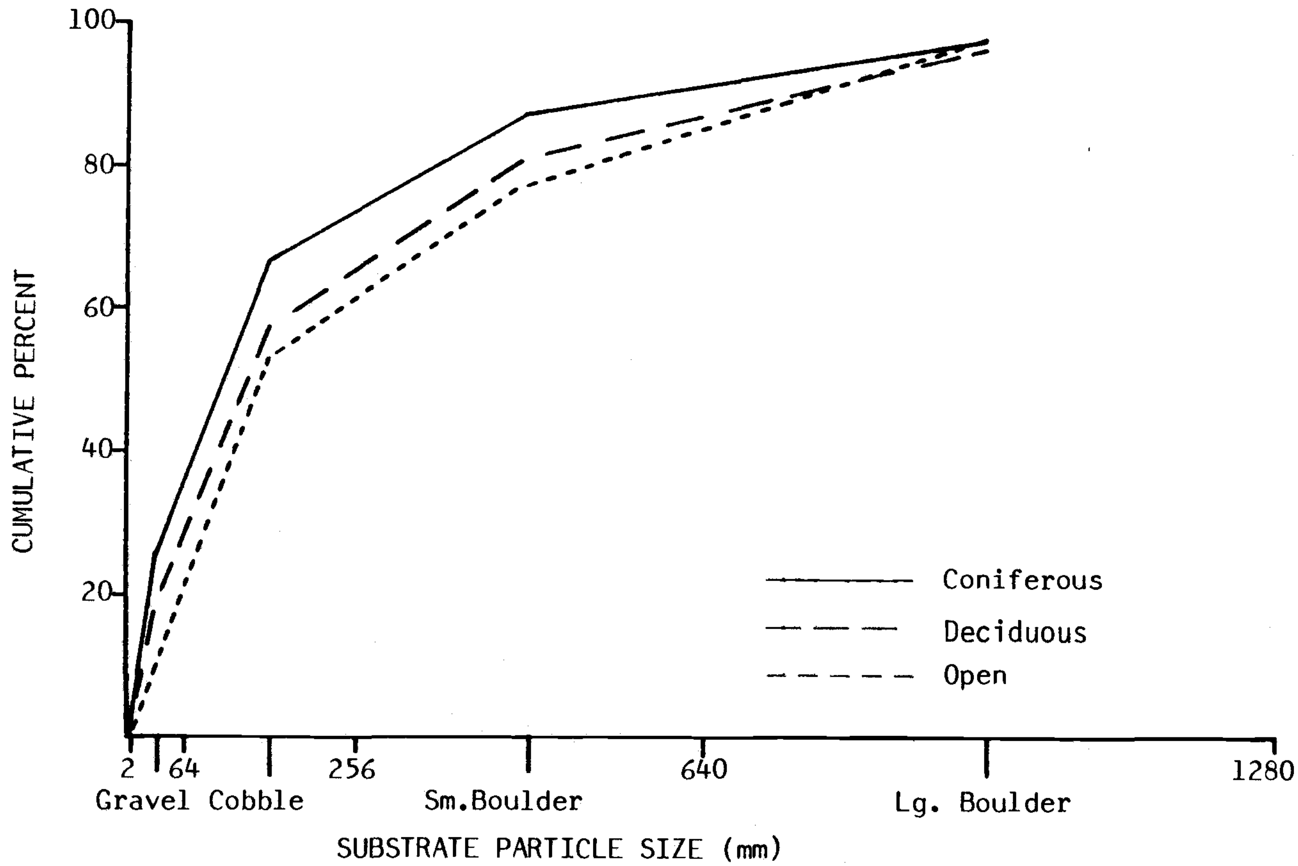

Figure 21. Substrate particle size distribution in streams with old-growth coniferous, deciduous, and open riparian zones.

Table 11. Summary of stream habitat and substrate composition in streams with different types of riparian vegetation.

Site	Number of Reaches	Total Length (m)	Riffle (%)	Pool & Bkwtr. (%)	Sand (%)	Gravel (%)	Cobble (%)	Small Boulder (%)	Large Boulder (%)	Bedrock (%)	Wood (%)
Coniferous											
Mack	4	170	71.1	28.9	1.3	25.8	34.8	22.9	11.5	2.1	1.4
Lookout	1	50	87.1	12.9	0.0	19.1	42.6	33.0	3.5	0.0	0.9
Grasshopper	1	24	62.3	37.7	10.6	64.5	21.3	2.1	0.7	0.0	0.0
Cougar	1	30	80.9	19.1	4.2	12.6	49.0	23.8	10.5	0.0	0.0
		$\bar{x}$ =	75.4	24.7	4.0	30.5	36.9	20.5	6.6	0.5	0.6
		sd =	10.9	10.9	4.7	23.3	11.9	13.1	5.3	1.1	0.7
Deciduous											
Quartz	2	115	53.2	46.8	0.8	33.6	27.7	17.1	17.5	1.6	0.3
Cougar	1	50	85.1	14.1	2.0	2.8	34.1	31.9	24.0	0.0	1.6
Wycoff	1	50	70.7	29.3	0.0	18.2	53.2	23.4	2.6	0.0	0.0
		$\bar{x}$ =	69.9	30.1	0.9	18.2	38.3	24.1	14.7	0.5	0.6
		sd =	16.4	16.4	1.0	15.4	13.3	7.4	11.0	0.9	0.9
Open											
Grasshopper	2	100	61.3	38.7	2.9	26.5	28.3	19.1	18.4	4.4	0.3
Rbro Quartz	1	50	71.8	28.2	0.0	8.6	27.9	32.1	31.4	0.0	0.0
Mann	1	50	63.5	36.5	3.5	27.9	39.6	20.9	8.1	0.0	0.0
Mack	1	50	82.0	18.0	0.9	24.6	21.6	23.7	28.4	0.0	0.9
		$\bar{x}$ =	69.7	30.4	1.8	21.9	29.4	24.0	21.5	1.1	0.3
		sd =	9.4	9.4	1.6	9.0	7.5	5.8	10.6	2.2	0.4

DISCUSSION

Leaf Retention and Reach Residence Time

The lack of correlation between LRR and reach residence time is a result of differences in the relative importance of various stream features in determining reach residence time and leaf retention. Leaf retention depended primarily on the frequency of large organic debris dams, 1/R, the abundance of sticks, and pool area. Reach residence time was largely a function of pool volume and the frequency of large organic debris dams. Greater pool area and debris dam frequency resulted in higher leaf retention and reach residence time, however, leaf retention was much more sensitive to debris dam frequency and less sensitive to pool area than reach residence time. The abundance of sticks and 1/R were also important in the retention of leaves but did not play a major role in determining reach residence time. Leaf retention was very dependent on 1/R in reaches without debris dams (Fig. 12, p. 42) but, while 1/R may have been important in determining reach residence time in some reaches, it was not correlated with residence time when all reaches were considered (r^2=0.10).

There are three major sources of resistance to flow in streams (Leopold et al. 1964). Internal distortion resistance is caused by large channel features, such as bars and bends that set up eddies and secondary circulations. This form of resistance is important in low gradient streams and rivers with complex channel configurations, but is not a major source of resistance in small mountain streams. Spill resistance occurs locally as moving water encounters an obstruction or falls and the velocity abruptly decreases. Skin resistance is a function of flow velocity and the roughness of the streambed, and is a major impediment to flow in small, high gradient streams with large substrates.

Spill resistance accounted for much of the resistance to flow in the high gradient mountain streams in this study, because many of the larger pools were at the base of small falls where depressions in the streambed had been scoured during high flows. However, skin resistance may also have been important in determining residence time in some reaches. In Wycoff 1 (Q = 0.026 m3/s), stream residence time (18.6 minutes) was considerably higher than would be expected by pool volume (23.0%) alone. Along with Fritz 1, which had the highest reach residence time of all sites, Wycoff 1 had a very high 1/R and low average depth, indicating potentially high skin resistance to flow. This may have contributed to the higher than predicted residence times in these reaches.

Leaf Retention Model

Though the use of only one type of particle limits extrapolation of the results of this study to other types of particles, soaked ginkgo leaves are similar to many organic particles in streams. Ginkgo leaves are transported and retained in a manner similar to several common riparian leaves and the retention of wetted leaves and dry leaves are similar under some conditions (Young et al. 1978, and this study). When debris dams and other leaf retention features that are found near the surface of the stream (sticks, overhanging vegetation and roots from terrestrial vegetation) are not abundant, transport distances of dry leaves may be much greater than the distances observed for soaked leaves here. However, most leaves that enter a stream naturally are wetted to some degree, either from rainfall while on the tree or from soil moisture and rain while on the ground, and few, if any, leaves will enter the stream as dessicated as the ginkgo leaves used in this study were prior to soaking.

Fine particulate organic matter (FPOM, less than 1 mm in diameter) derived from foliage and wood typically has a density of 1.4 to 1.8 g/cm3 in streams and most FPOM from pool sediments has a density greater than 1.8 g/cm^3 (Sollins et al. 1985). This FPOM may be transported lower in the water column and be more likely to contact the streambed and be retained than neutrally bouyant particles. Average travel distances of these particles will probably be less than those observed for ginkgo leaves. Coarse particulate organic matter (CPOM, greater than 1 mm in diameter) and FPOM that enters the stream from the terrestrial environment through lateral movement must move through the stream margin. This material probably will also be retained more rapidly than leaves, small branches and twigs that enter the main flow directly via litterfall.

Effects of Stream Size on Retention

The frequency or relative area of most major retention features decline as stream size increases (Table 12). Large organic debris dams are one of the most important retention features in small wooded

Table 12. Frequency, overall importance and trapping mechanisms of several major retention features in streams.

Feature	Particle Size Trapped	Relative Trapping Efficiency	Frequency of Occurrence	Overall Importance	Effects
Large Organic Debris Dams	CPOM FPOM	Very High	High in wooded headwater streams, decreasing as stream size increases.	Very high in wooded headwater streams to none in large rivers.	1) Obstructs flow 2) Increases 1/R 3) Traps sticks 4) Creates pools and backwaters
Sticks	CPOM	Very High	High in wooded headwater streams, decreasing as stream size increases.	High in wooded headwater streams to very low in large rivers.	1) Provides obstruction
Backwaters	CPOM FPOM	High	Low and decreasing as stream size increases.	High in headwater streams to very low in rivers.	1) Low current velocity 2) Infrequent flushing 3) Storage of direct allochthonous inputs
Pools	CPOM FPOM	High to Moderate	High to Low	High to Low	1) Low current velocity 2) Size of obstructions present may affect retention
Riffles	CPOM FPOM	Moderate to Low	High	High to Moderate	1) Substrate provides obstruction to flow 2) Retentiveness largely determined by 1/R
Vegetation	CPOM FPOM	High to Moderate	Moderate to Low	High to Low	1) Provides obstruction 2) May reduce current velocity

streams, but in the H.J. Andrews Experimental Ecological Reserve, debris dam frequency declines from about 17/km in a third-order stream (Mack Creek) to 2 to 3/km in a fourth-order stream (Lookout Creek), and debris dams that span the channel are minor features in most fifth-order and larger streams in this area (G.W. Lienkaemper, USFS Research Laboratory, Corvallis, Oregon, unpublished data). This decline in the importance of large wood in large streams and rivers has been exaggerated by the removal of debris from nearly all major rivers for navigational purposes (Sedell et al. 1982). Similarly, the relative area of sticks and the ratio of wetted perimeter to cross-sectional area of flow in riffles (1/R) are lower in larger streams. Increases in retention resulting from increases in pool area and the amount of in-stream aquatic vegetation are probably small relative to the changes that reduce retention as streams get larger. Minshall et al. (1983) observed a large reduction in retention of organic matter as stream size increased from first- to seventh-order in four drainages in different parts of the United States, indicating that the net effect of increasing stream size is lower retention. They expressed reach retention as the ratio of benthic particulate organic carbon to particulate organic carbon in transport times depth.

As debris dam frequency decreases and riffles become the dominant channel feature in many intermediate-sized mountain streams and rivers, the relative importance of 1/R in total retention may be greatly increased. The channel roughness coefficient (n) in the Manning equation theoretically would provide an excellent measure of the physical heterogeneity or roughness of a stream reach; however, the Manning equation was developed for artificial channels with uniform flow, beds that are parallel to the water surface, and reaches with constant depth, area and hydraulic radius (Barnes 1967). These assumptions are not applicable in high gradient mountain streams with cascading, turbulent flows. The ratio of the wetted perimeter to the cross-sectional area of flow (1/R) is directly proportional to the probability of a neutrally bouyant particle in transport coming into contact with the stream bed. The relationship between 1/R and the probability of a particle contacting the streambed can be used to evaluate the influence of stream size (width and depth) and substrate heterogeneity on the retention of organic matter in transport in riffles.

The probability of a particle in transport being retained (P_r) is equal to the product of the probability of the particle contacting an obstruction (P_c) and the probability of the particle becoming trapped once it comes into contact with the obstruction (Pt):

$$P_r = P_c \times Pt \qquad \text{(Equation 3)}$$

Assuming that there is an equal probability of a neutrally bouyant, spherical particle occupying any position in the water column in a turbulent flow, the probability of contact with the streambed is:

$$P_c = (P/A)Y \qquad \text{(Equation 4)}$$

where: P = Wetted Perimeter

A = Cross-sectional Area

Y = Particle Diameter

If the channel is assumed to be approximately rectangular in cross-section, then:

$$P/A = ((W+2D)/WD)B$$

where: W = Stream Width

D = Water Depth

B = Bed Form Index (=P/W)

or:

$$P/A = ((1/D)+(2/W))B \qquad \text{(Equation 5)}$$

Substituting Equation 5 into Equation 4 gives:

$$P_c = ((1/D)+(2/W))(B)(Y) = ((Y/D)+(2Y/W))B \qquad \text{(Equation 6)}$$

If Y=0.05 m for ginkgo leaves and the mean value of B=1.12 (sd=0.038) from sites in this study are used in Equation 6, the resulting relationship shows that the probability of a particle contacting the streambed is dependent on water depth and changes little as stream width changes (Fig. 22). The solid line shows the relationship between P_c and depth as stream size increases from a small, first-order stream (W=1 m, D=0.05 m) to a stream with a width of 18 m and an average depth of 0.9 m. P_c decreases very quickly with increasing depth and at a depth of 30 cm, commonly encountered in third- and fourth-order streams, P_c=0.2. If P_t remains fairly constant as stream size increases, the probability of a particle being retained on the streambed decreases with increasing depth. Changes in bed form index (B) will modify this relationship somewhat, but changes over the range observed in the 17 sites where B was measured (B=1.07 to 1.19) will have a small affect on P_c. Further analysis using V-notched channels of varying steepness and semi-circular channels showed that changes in channel cross-sectional geometry shifted the

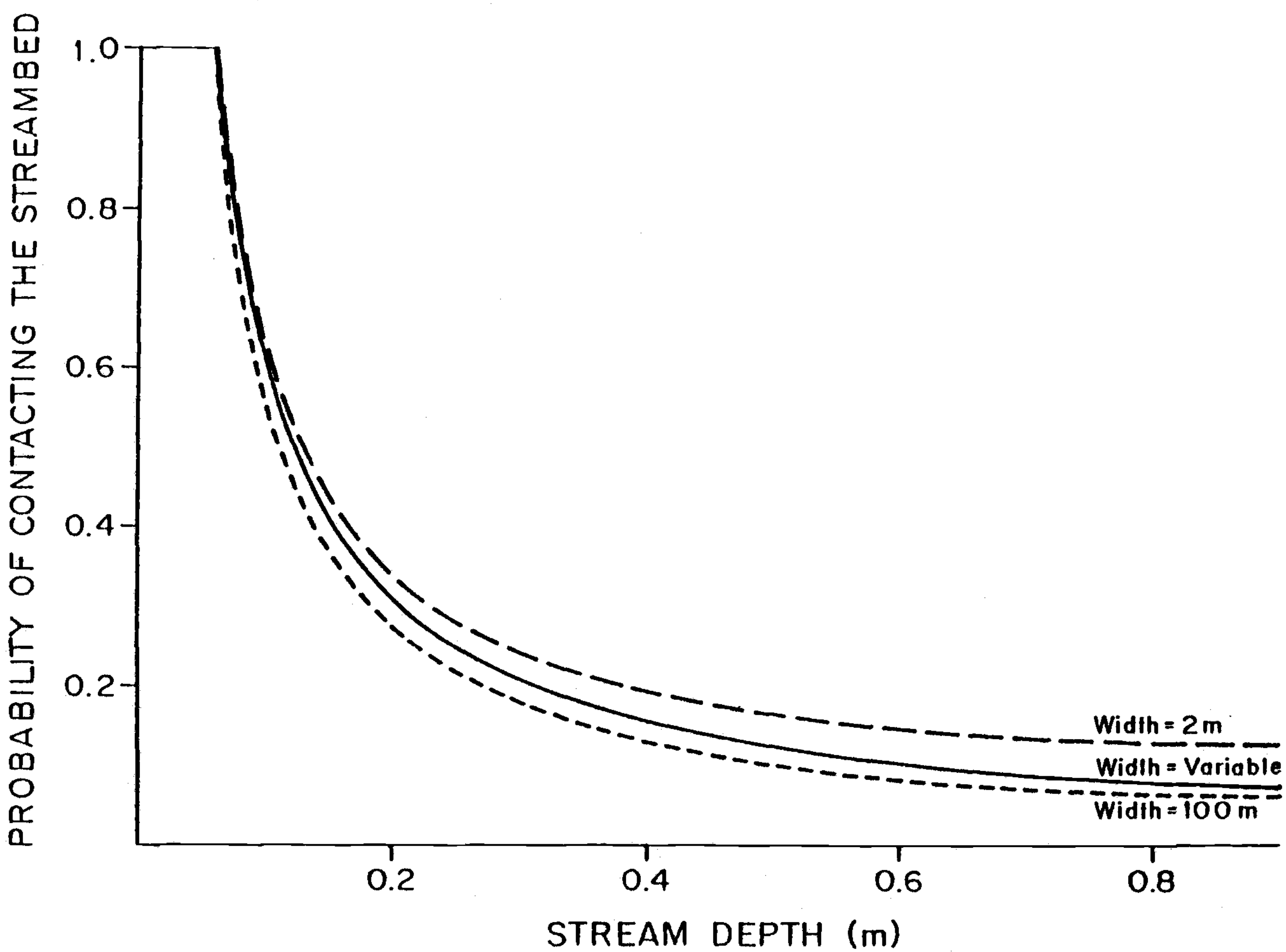

Figure 22. The effect of stream depth on the probability of a neutrally bouyant, spherical (diameter=0.05 m) particle contacting the streambed in a 2-m wide stream, a 100-m wide stream, and in a stream where width increases continuously with depth (solid line).

position of the curve only slightly and did not significantly alter the relationships shown in Figure 22.

The assumption that a spherical, neutrally bouyant particle has an equal probability of occupying any given position in the water column in a turbulent riffle is probably valid for small to medium sized, steep, mountain streams. Increases in specific gravity over the range found for organic particles in streams are probably overridden by current velocity and turbulence in these streams. As channel gradient decreases and current velocity and turbulence are reduced, there is a greater likelihood that a particle with a greater specific gravity will be in the lower portion of the water column and P_c will be higher.

Using the same assumptions, a relationship between 1/R and water depth can be generated from:

$$1/R = P/A = ((W+2D)/(WD))B \qquad \text{(Equation 7)}$$

Since 1/R is a hyperbolic function of water depth, it is likely that the relationship between 1/R and stream discharge is also hyperbolic. Therefore, leaf retention in a reach will decrease rapidly as discharge increases above summer base flow (high 1/R) and decline much more slowly as discharge continues to increase (e.g. Fig. 13A, page 43). The exact shape of this curve depends on how 1/R changes with increasing flow. In broad, flat channels 1/R and leaf retention decrease more rapidly with increasing discharge than in more constricted, notched channels.

When 1/R values generated from equation 7 are used with the measured relationship between leaf retention rate and 1/R in reaches without debris dams (Equation 2, page 41), a relationship between LRR and water depth can be generated (Fig. 23). LRR drops from 0.825 to 0.030 as depth increases from 5 to 15 cm. As depth increases beyond 15 cm, LRR decreases much more slowly. Average travel distances and 90% retention distances increase rapidly up to depths of about 30 cm, after which the increase is more gradual (Fig. 23). Average riffle depths in the study sites were less than 20 cm and LRRs ranged from 0.017 to 0.241 m^{-1} in sections without debris dams. All of these sites fall into the range where small changes in riffle depths have a major effect on LRR and retention distance (Fig. 23). If other major retention features are not present the model predicts that in streams larger than the second- and third-order streams studied here, LRR is low and decreases slowly moving down the drainage.

As stream size increases, there is a rapid decline in the frequency and size of most major retention features, relative to the size of the stream channel. Large organic debris dams are dominant features of first- to third-order streams in forested reaches but are usually restricted to bars and stream margins in larger streams and rivers. Retention in riffles decreases rapidly as stream size increases. Sticks in riffles, an important CPOM retention feature in first- to third-order streams, are much less important in larger streams because the area of sticks relative to the cross-sectional area of flow is much smaller. This reduction in retention features potentially results in a rapid decline in retention with increasing

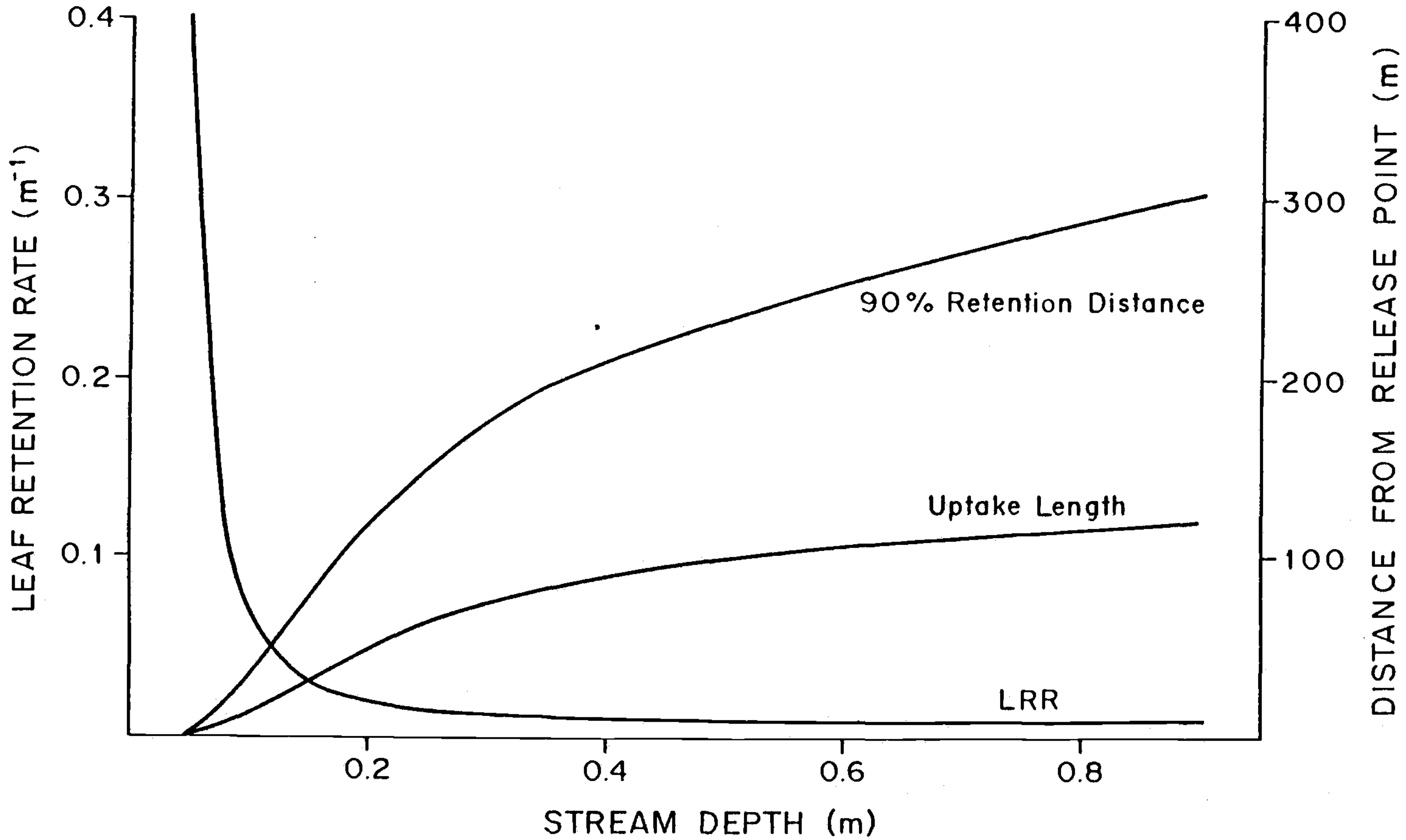

Figure 23. The effect of stream depth on leaf retention rate and retention distance.

stream size. Retention by debris dams is probably low once the stream is large enough to float most of the large organic debris that enters it every few years. At this point streams shift from being primarily retentive of organic matter, at least during periods of low flow, to exporting most of the organic matter that enters them.

Effects of Riparian Vegetation on Retention

The riparian vegetation of a stream affects the retention and storage of organic matter in the stream through its influence on:

1) the quantity and timing of organic inputs,

2) stream channel structure.

Vegetation in the riparian zone often accounts for more than 90% of the organic inputs in woodland streams (Cummins 1975). In undisturbed watersheds in the Cascade Mountains of the Pacific Northwest, the dominant riparian species are typically conifers. At Mack Creek, litterfall inputs from a mature conifer stand were fairly evenly distributed throughout the year with somewhat more material entering the stream between August and January (Dr. S.V. Gregory, Dept. Fisheries and Wildlife, Oregon State University, unpublished data)(Fig. 24). In Quartz Creek, litterfall inputs from a 35-year-old red alder stand, primarily leaves and small branches, were highest in September, October and November and were greater than at Mack Creek in almost all months. In Grasshopper Creek, litterfall inputs from a predominantly herb and shrub riparian zone were much lower than at Mack Creek and Quartz Creek. Both the old-growth conifer and deciduous sites receive large amounts of inputs in the summer and early autumn when flows are

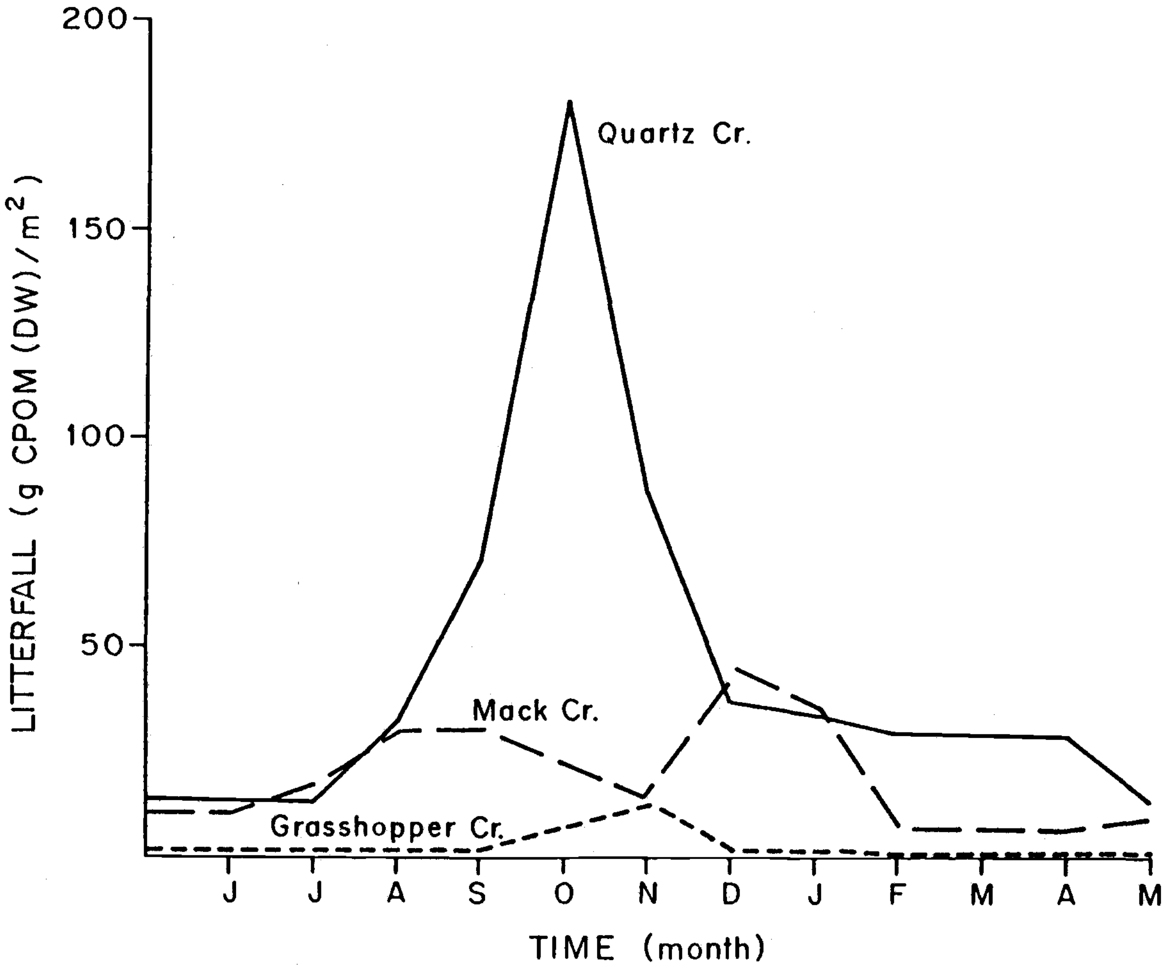

Figure 24. Monthly litterfall inputs at the intensively studied riparian sites; Mack Creek (coniferous), Quartz Creek (Blue R.)(deciduous), and Grasshopper Creek (open), June 1982 to May 1983.

usually quite low and retention is high. Most of the material entering these streams at this time is probably retained in a relatively short distance. The material that is retained remains on site and is processed at least until flows increase in November and December. A smaller but still significant portion of the organic matter entering these streams in the winter and spring is retained.

Riparian vegetation also influences the size distribution of organic matter that enters the stream. Streams with old-growth conifer riparian zones receive large quantities of needles and woody material, ranging in size from very large bole material to fine twigs. Wood that is too large to be transported by the stream is retained in place until discharge increases enough to dislodge and transport it downstream. Smaller pieces of wood and needles may be transported immediately after entering the stream. Streams with riparian zones dominated by deciduous trees receive large quantities of leaves from August through March. Though abscission is typically complete by mid-November, leaves enter the stream from the side slopes and stream banks throughout the winter. Organic inputs in these streams are dominated by leaves and leaf fragments (20-200mm) and woody material ranging in size from small branches to fine twigs. Large wood is much less common than in old-growth conifer streams.

Riparian vegetation affects retention through its influence on channel structure in several ways. If large trees are present and the stream is not large enough to float the bole material that enters the channel, large organic debris will be a major structural feature of the channel. If the stream is large enough to float at least some of this material short distances, large organic debris dams that span the channel may form (Swanson et al. 1976). These debris dams are areas of very high retention. They obstruct the flow, store sediment and create side channels, which tend to increase 1/R and retention. Debris dams also enhance retention by decreasing the effective gradient of the stream by creating a stepped longitudinal profile, which increases spill resistance to flow. Large trees in the riparian zone also provide resistance to bank cutting and aid in the formation of pools and backwaters, which retain large amounts of organic matter. In addition to large trees, streamside shrubs that extend into the flow and the exposed roots of terrestrial vegetation enhance retention by removing organic matter from transport.

Retention may also be affected by the influence of watershed vegetation on peak streamflows and annual water yield. Removal of vegetation from the watershed can increase annual water yield (Harr 1976, Harr et al. 1979) and increase some stormflows (Harr et al. 1975, Harr and McCorison 1979, Harr et al. 1979). Retention rate is sensitive to stream discharge (Fig. 13, 23) and may be reduced if watershed management practices cause increases in annual water yield or stormflows.

DETRITUS STORAGE

RESULTS

Detrital standing crops tended to be highest at the coniferous site, Mack Creek, intermediate at the deciduous site, Quartz Creek, and lowest at the open site, Grasshopper Creek, in both the summer and winter (Tables 13, 14, Appendix D). Differences in total detritus, CPOM, and FPOM storage between sites, habitats (riffles, pools, and backwaters) and substrates (gravels and cobbles) were tested using a nonparametric rank test (Quade test)(Conover 1971). In the summer of 1982, total detritus standing crops in all habitats were significantly greater ($p<0.005$) in Mack Creek and Quartz Creek than in Grasshopper Creek. There was no significant difference between Mack Creek and Quartz Creek. Both of these streams also stored more of each size fraction of detritus, than Grasshopper Creek ($p<0.05$) but were not significantly different from each other. In the winter of 1983, total detritus and FPOM standing crops over all habitats were higher ($p<0.06$) in Mack Creek than in Quartz Creek and Grasshopper Creek. There were no significant differences in CPOM storage at the three sites in either season.

Backwater areas stored more detritus than all other habitats except for debris pools in all three streams in the summer (Table 13). Pools along the stream margin generally had higher standing crops of detritus than pools in the main flow. Detrital standing crops were generally lowest in riffles, although these differences were not always significant. In the summer of 1982, standing crops of detritus

Table 13. Standing crops of benthic detritus by particle size group and habitat from streams with coniferous, deciduous and open riparian zones in August, 1982.

		Detritus (g AFWD)/m^2					
Site	Habitat	CPOM (>1mm)	FPOM (1mm–0.7μm)	UPOM (53μm–0.7μm)	Total	sd	n
Coniferous							
Mack	Riffle Bedrock	2.7	8.8	3.7	11.5	5.4	5
	Riffle Cobble	12.8	47.1	10.4	60.0	69.9	5
	Riffle Gravel	26.3	140.1	48.3	166.4	164.8	5
	Pool Cobble	236.3	139.0	17.8	375.4	295.7	5
	Pool Gravel	44.1	222.9	66.0	267.0	176.6	4
	Stream Margin	140.4	406.6	123.7	546.9	387.8	10
	Debris Pool	1566.9	897.9	83.7	2464.5	2273.5	4
	Backwater	2730.9	1423.2	280.5	4154.1	3810.1	5
Deciduous							
Quartz	Riffle Bedrock	0.9	3.6	2.3	4.5	0.2	2
	Riffle Cobble	11.8	16.8	8.0	28.6	17.4	5
	Riffle Gravel	72.9	83.4	38.2	156.3	118.7	5
	Pool Cobble	51.6	75.3	26.1	126.8	61.5	5
	Pool Gravel	128.9	397.4	131.3	526.3	480.6	5
	Stream Margin	79.8	469.7	251.5	549.5	282.5	10
	Backwater	1494.3	682.5	179.7	2176.8	2822.3	5
Open							
Grass-hopper	Riffle Bedrock	1.5	13.4	2.9	15.0	12.9	5
	Riffle Cobble	3.3	13.9	7.0	17.2	11.6	5
	Riffle Gravel	41.3	62.1	31.3	103.5	83.4	5
	Pool Cobble	25.3	35.8	13.8	61.0	25.1	5
	Pool Gravel	23.2	123.3	43.5	146.5	119.7	5
	Stream Margin	47.6	348.0	88.4	395.6	173.6	10
	Backwater	118.4	335.7	118.5	454.2	293.6	5

Table 14. Standing crops of benthic detritus by particle size group and habitat from streams with coniferous, deciduous and open riparian zones in March, 1983.

		Detritus (g AFWD)/m^2					
Site	Habitat	CPOM (>1mm)	FPOM (1mm-0.7μm)	UPOM (53μm-0.7μm)	Total	sd	n
Coniferous							
Mack	Riffle Bedrock	1.9	5.3	3.4	7.1	2.5	5
	Riffle Cobble	19.5	33.5	14.3	53.0	61.2	5
	Riffle Gravel	102.5	259.1	88.0	361.7	341.8	5
	Pool Cobble	128.5	60.8	22.8	189.1	245.7	5
	Pool Gravel	468.1	703.1	206.2	1171.2	491.5	5
	Stream Margin	641.8	876.6	265.6	1518.4	1509.8	5
	Backwater	1294.0	1259.1	440.6	2553.0	1788.4	5
	Debris Pool	3009.0	1176.7	269.0	4185.6	5036.8	5
Deciduous							
Quartz	Riffle Cobble	10.1	18.9	10.3	29.7	24.8	5
	Riffle Gravel	26.5	201.4	95.4	227.8	65.3	5
	Pool Cobble	51.2	14.1	7.1	75.0	105.7	5
	Pool Gravel	67.5	196.2	82.3	263.7	96.1	5
	Stream Margin	986.3	374.4	149.1	1360.7	1868.9	5
	Backwater	1364.5	788.5	240.8	2152.9	1431.7	6
Open							
Grass-	Riffle Cobble	3.5	13.5	7.7	17.1	9.4	5
Hopper	Riffle Gravel	29.0	185.4	102.7	214.5	157.9	5
	Pool Cobble	24.3	57.3	27.1	81.6	34.5	5
	Pool Gravel	41.1	122.0	48.3	163.1	77.9	5
	Stream Margin	78.7	255.3	124.7	334.1	73.5	5
	Backwater	1248.2	721.7	126.5	1969.9	2982.6	5

were significantly higher in backwaters ($p<0.05$) and in pools along the stream margin ($p<0.10$) than in all other habitats. Detritus storage in debris pools was not significantly different than in backwaters in Mack Creek. Detrital standing crops were lower on bedrock in riffles ($p<0.05$) and in cobbles in riffles ($p<0.10$) than in any other habitat. The same pattern was observed for CPOM and FPOM storage in these habitats. There were no significant differences in amounts of total detritus, CPOM or FPOM in different habitats in the winter.

In riffles, there was more CPOM (Quade test, $p<0.10$) and total detritus ($p<0.10$) stored per unit area in gravels than in cobbles in the summer (Table 15). In the winter, total detritus, CPOM and FPOM standing crops in gravels and cobbles in riffles were not significantly different. No significant difference was found between detritus standing crops in gravels and cobbles in pools in either season.

The total amount of detritus stored in equal distances of stream in the summer of 1982 was more than three times higher at Mack Creek and Quartz Creek than at Grasshopper Creek (Table 16). CPOM, FPOM and total detritus stored in 100-m reaches of Quartz Creek and Mack Creek were about the same. Even though Mack Creek had somewhat higher detritus concentrations in most habitats, slightly more detritus was stored in Quartz Creek because of the larger stream area. Both of these streams had nearly ten times more CPOM and twice as much FPOM as Grasshopper Creek. Some of these differences result from the smaller allochthonous inputs at Grasshopper Creek, but much of the difference is probably due to lower retention of available material at Grass-

Table 15. p-values for Quade tests of differences between means of standing crops of detritus by stream habitat. The data from all three sites has been grouped.

TOTAL DETRITUS

	Riffle Bedrock	Riffle Cobble	Riffle Gravel	Pool Cobble	Pool Gravel	Stream Margin
Riffle Bedrock	-					
Riffle Cobble	ns	-				
Riffle Gravel	0.05	0.10	-			
Pool Cobble	0.05	0.05	ns	-		
Pool Gravel	0.01	0.01	ns	ns	-	
Stream Margin	0.005	0.001	0.05	0.05	0.10	-
Backwater	0.005	0.005	0.005	0.01	0.05	ns

CPOM

	Riffle Bedrock	Riffle Cobble	Riffle Gravel	Pool Cobble	Pool Gravel	Stream Margin
Riffle Bedrock	-					
Riffle Cobble	ns	-				
Riffle Gravel	0.01	0.10	-			
Pool Cobble	0.005	0.01	ns	-		
Pool Gravel	0.005	0.05	ns	ns	-	
Stream Margin	0.001	0.005	ns	ns	ns	-
Backwater	0.0005	0.0005	0.005	0.05	0.05	0.05

FPOM

	Riffle Bedrock	Riffle Cobble	Riffle Gravel	Pool Cobble	Pool Gravel	Stream Margin
Riffle Bedrock	-					
Riffle Cobble	ns	-				
Riffle Gravel	0.10	ns	-			
Pool Cobble	ns	ns	ns	-		
Pool Gravel	0.05	0.06	ns	ns	-	
Stream Margin	0.01	0.05	ns	0.06	ns	-
Backwater	0.005	0.05	0.07	0.05	ns	ns

hopper Creek. Gravel bars, cobble bars, and pools associated with large organic debris dams were major detritus storage sites in Mack Creek and Quartz Creek but rarely occurred at Grasshopper Creek.

Differences in the form of allochthonous inputs and detritus retention patterns are reflected in the relative amounts of CPOM and FPOM stored in each stream (Table 16). In Mack Creek, where there were large inputs of woody material, about the same amounts of coarse and fine organic matter were stored in the summer (CPOM/FPOM=1.11). In Quartz Creek, which received large inputs of alder leaves and small branches and twigs in the summer and fall, there was slightly more FPOM than CPOM in storage (CPOM/FPOM=0.86). In Grasshopper Creek, where allochthonous inputs were much lower, there was about four times as much FPOM as CPOM (CPOM/FPOM=0.26).

In the summer, cobbles in pools had a higher percentage of CPOM relative to the total amount of detritus in storage than all other habitats except backwaters (Quade Test, $p<0.10$)(Table 17). Backwaters stored a higher percentage of CPOM than pools along the stream margin, gravels in pools and bedrock in riffles ($p<0.04$). There was no significant difference in the percentage of CPOM in storage in the other habitat-substrate groups ($p>0.10$). Debris pools had about the same CPOM-FPOM composition as backwaters in Mack Creek.

Quartz Creek had a higher percentage of CPOM in storage over all habitats than Mack Creek and Grasshopper Creek in the summer ($p<0.05$). There was no difference in the percentage of CPOM in storage at Mack Creek and Grasshopper Creek ($p>0.10$). CPOM comprised 17 to 49% of the total detritus in a habitat in Mack Creek, 16 to 46% in Quartz Creek

Table 16. Benthic detritus in 100-m reaches of streams with different riparian zones in August 1982.

Stream	Riparian Type	Area (m^2)	Benthic CPOM	Benthic FPOM	Total Benthic POM	Total Benthic POM	CPOM/ FPOM
			($g\ AFDW/m^2$)			($g\ AFDW/100m$)	
Mack Creek	Coniferous	324	215	194	409	132,629	1.11
Quartz Cr.	Deciduous	414	157	184	341	141,057	0.86
Grasshopper Cr.	Open	337	23	90	113	38,082	0.26

and 10 to 38% in Grasshopper Creek. There were no differences in the percentage of CPOM stored in the habitats or at the three sites in the winter ($p>0.10$)(Table 17).

At Mack Creek, a higher percentage of CPOM was stored in the winter than in the summer in gravels in riffles (Quade test, $p<0.10$) and in gravels in pools ($p<0.10$). In Quartz Creek there was a higher percentage of CPOM in gravels in riffles ($p<0.05$) in the summer than in the winter and the percentage of CPOM in pools along the stream margin was higher in the winter ($p<0.05$). There was also a higher percentage of CPOM in pools along the stream margin ($p<0.03$) in the winter than in the summer at Grasshopper Creek.

Detritus Storage in Artificial Substrates

In the inorganic substrates placed in trays, detritus standing crops in riffles increased for the first 12 to 28 days then levelled off or decreased in all but one of the treatments (Fig. 25). At all three sites, maximum standing crops in all sizes of artificial substrates were in the range found in natural stream cobbles and were less than detritus standing crops found in natural stream gravels.

In riffles, detritus was trapped at rates ranging from 0.5 to 3.1 g AFDW/m^2/day in detritus free gravels and cobbles during the first two weeks (Table 18). In Mack Creek, the amount of detritus in small and large gravel increased for 28 days before declining during the final 14 days of the experiment. Detritus standing crops in cobbles remained constant after two weeks. At Quartz Creek, detritus accumu-

Table 17. Relative amounts of coarse, fine and ultra-fine benthic organic matter in different stream habitats.

SUMMER

Current-Substrate	CPOM (%) (> 1 mm)			FPOM (%) (1 mm - 0.7µm)			UPOM (%) (53µm - 0.7µm)		
	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper
Riffle Bedrock	19.0	19.0	10.3	80.9	81.0	89.7	36.8	50.9	30.4
Riffle Gravel	19.3	41.3	28.2	80.8	58.8	71.8	22.2	27.5	36.3
Riffle Cobble	23.5	39.5	20.4	76.5	60.6	79.6	29.7	28.3	45.3
Pool Gravel	17.0	31.2	18.4	83.1	68.8	81.6	21.0	24.4	28.3
Pool Cobble	48.6	43.3	37.5	51.3	56.6	63.6	6.6	20.1	25.4
Stream Margin	26.4	16.4	11.5	73.7	83.8	88.6	18.9	40.1	24.9
Backwater	44.2	45.6	20.4	55.9	54.4	79.5	7.5	17.3	27.6
Debris Pool	41.5			58.7			11.6		

WINTER

Current-Substrate	CPOM (%) (> 1 mm)			FPOM (%) (1 mm - 0.7µm)			UPOM (%) (53 m - 0.7µm)		
	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper
Riffle Bedrock	24.4			75.6			49.1		
Riffle Gravel	31.8	12.4	16.8	68.3	87.6	83.3	24.4	42.2	44.6
Riffle Cobble	33.3	39.0	21.7	66.7	61.0	78.3	38.8	34.6	47.9
Pool Gravel	41.2	22.7	23.1	58.7	77.2	76.9	17.5	33.9	32.1
Pool Cobble	56.0	48.5	34.4	43.8	51.5	65.6	21.3	32.3	28.2
Stream Margin	26.3	41.2	23.4	73.8	58.8	76.6	26.2	27.4	37.1
Backwater	42.3	57.0	38.4	57.6	43.2	61.6	22.2	12.8	16.8
Debris Pool	55.8			44.2			12.6		

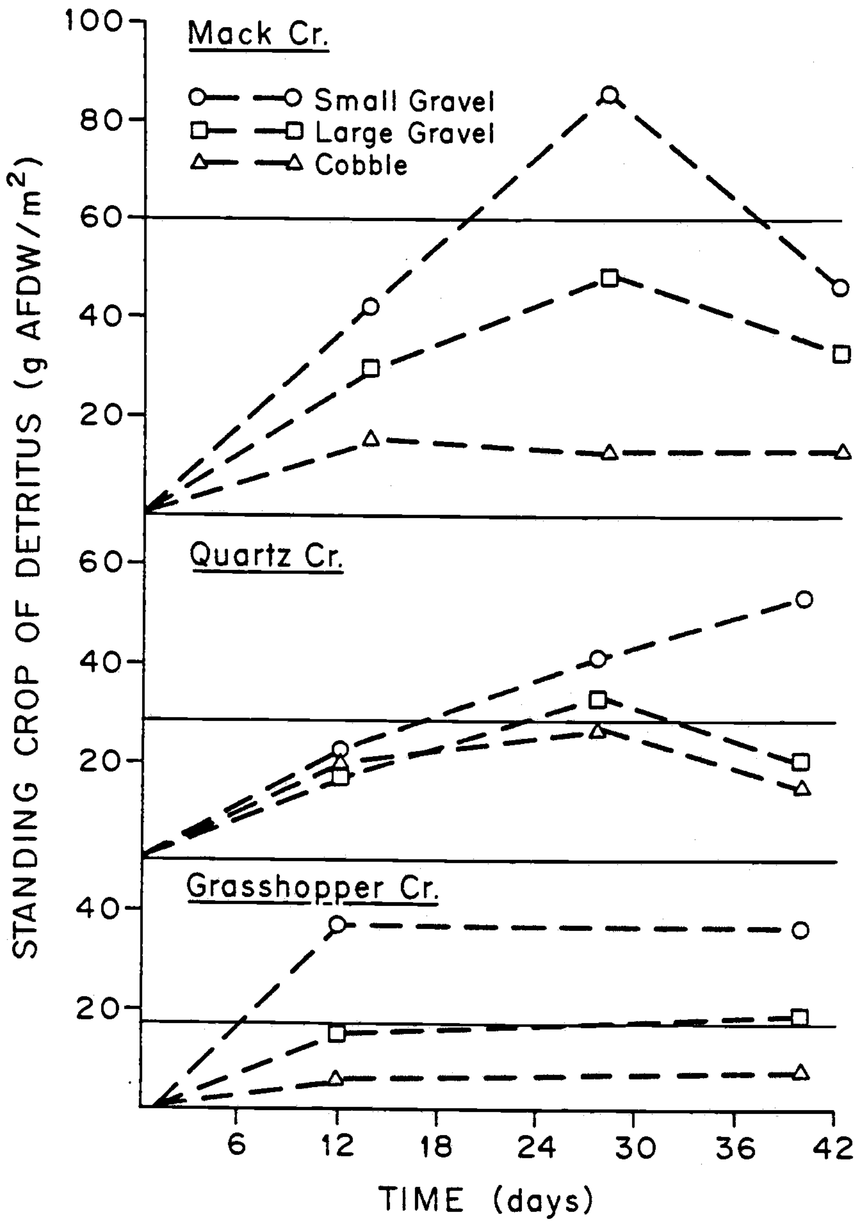

Figure 25. Standing crop of detritus in inorganic substrates placed in riffles at Mack Creek, Quartz Creek, and Grasshopper Creek.

Table 18. Rates of accumulation of detritus (g AFDW/M^2/day) in trays filled with different size inorganic substrates from July to October 1983.

RIFFLES

Substrate	MACK			QUARTZ			GRASSHOPPER	
	0-14 Days	14-28 Days	28-42 Days	0-12 Days	12-28 Days	28-40 Days	0-12 Days	12-40 Days
Small Gravel	3.1	3.1	1.1	1.8	1.5	1.4	3.1	0.9
Large Gravel	2.2	1.7	0.8	1.5	1.2	0.5	1.3	0.5
Cobble	1.2	0.5	0.3	1.7	1.0	0.4	0.5	0.2

POOLS

Substrate	MACK				QUARTZ			GRASSHOPPER			
	0-17 Days	17-31 Days	31-42 Days	42-95 Days	0-17 Days	17-29 Days	29-95 Days	0-17 Days	17-29 Days	29-40 Days	40-95 Days
Small Gravel	11.9	8.3	5.1	6.5	5.4	5.1	3.4	14.3	17.9	3.0	5.3
Large Gravel	13.3	7.4	5.5	6.7	11.8	12.4	3.9	10.8	8.6	2.3	10.8
Cobble	10.5	6.1	4.7	4.8	19.5	16.9	5.9	10.3	5.9	1.8	9.2

lated at a relatively constant rate for 28 days and declined over the last 14 days in large gravels and cobbles. In the small gravel substrate, detritus was trapped at a rate of about 1.4 g AFDW/m^2/day for the entire 42 days. Near maximum detritus levels were reached after 12 days in all three substrates in Grasshopper Creek. These levels were maintained for the duration of the experiment.

Large gravel substrates in riffles in Mack Creek contained more detritus than the same substrates in Quartz Creek on all three sampling dates (Table 19). Grasshopper Creek stored the least amount of detritus in large gravels. Quartz Creek stored the most detritus in cobbles, Mack Creek was intermediate and again Grasshopper Creek contained the least amount of detritus. There was no trend in detritus storage in small gravels at the three sites. Few of the differences were statistically significant because of the high variance associate with many of the standing crops. After 12 days, small gravels in Quartz Creek had stored significantly less detritus than small gravels in Mack Creek (t-test, $p<0.05$) or Grasshopper Creek ($p<0.05$), and large gravels in Mack Creek contained significantly more detritus than large gravels in Grasshopper Creek ($p<0.05$). No significant differences were found after the first 12 days.

During the first two weeks, rates of detritus accumulation in pools were higher and more variable than in riffles, ranging from 5.4 to 19.5 g AFDW/m^2/day (Table 19). In Mack Creek, detritus accumulated at a rate of more than 10 g AFDW/m^2/day in all substrates for the first 17 days, remained relatively constant for the next 25 days and then increased at between 4.9 and 7.7 g AFDW/m^2/day for the next 53

Table 19. Standing crops of benthic detritus (g AFDW/m^2) in trays filled with different size inorganic substrates from July to October 1983.

	RIFFLES								
	Small Gravel			Large Gravel			Cobble		
Time (days)	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper
12-14	43.6	22.1	37.5	30.1	17.8	15.7	16.1	20.5	5.9
28	85.9	26.3		48.6	38.2		48.2	27.8	
40-42	47.3	54.2	36.7	33.6	21.0	19.6	14.3	16.1	8.1

	POOLS								
	Small Gravel			Large Gravel			Cobble		
Time (days)	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper	Mack	Quartz	Grass-hopper
17	202.2	91.9	243.6	226.6	200.5	183.6	177.6	331.0	174.9
29-31	257.7	148.9	518.8	230.4	360.7	249.3	189.6	489.6	172.4
40-42	213.0		121.5	229.2		90.9	196.2		73.5
94-95	616.2	325.7	498.7	637.7	372.8	1012.9	457.2	562.9	865.0

days (Fig. 26). In Quartz Creek, detritus accumulated at a rate of 11.8 to 19.5 g AFDW/m^2/day for the first 29 days in the two larger substrates. CPOM made up 70-83% of the material stored during this period. Detritus continued to accumulate over the next 66 days, but at a much slower rate (0.2-1.1 g AFDW/m2/day). Detritus accumulated much more gradually in the small gravel substrates, but continued at a relatively constant rate (~3.4 g AFDW/m2/day) for the entire 95 days. There was a decline in the amount of detritus stored in all substrates between the 29th and 40th days of the experiment in Grasshopper Creek. Both before and after this decrease detritus accumulated at between 7.0 and 17.9 g AFDW/m2/day. The levelling off or decline and subsequent increase in the amount of detritus could have been caused by scouring of surface detritus or by differences in detritus accumulation rates at different locations within the same pool.

The type of pool in which artificial substrates were placed played a major role in determining the rate of accumulation and the total standing crop of detritus. In Mack Creek, the artificial substrates were placed in a pool below a debris dam and the detrital standing crops after 95 days were higher than those found in natural gravels and cobbles in pools not associated with debris dams (Fig. 26). In Quartz Creek, artificial substrates were put in a large pool that was not associated with large organic debris, and standing crops were in the range found in natural gravels in pools. The artificial cobbles substrates contained more leaves and had much higher detrital standing crops than the natural pool-cobble areas that were sampled. In Grasshopper Creek, the artificial substrates were put in a pool

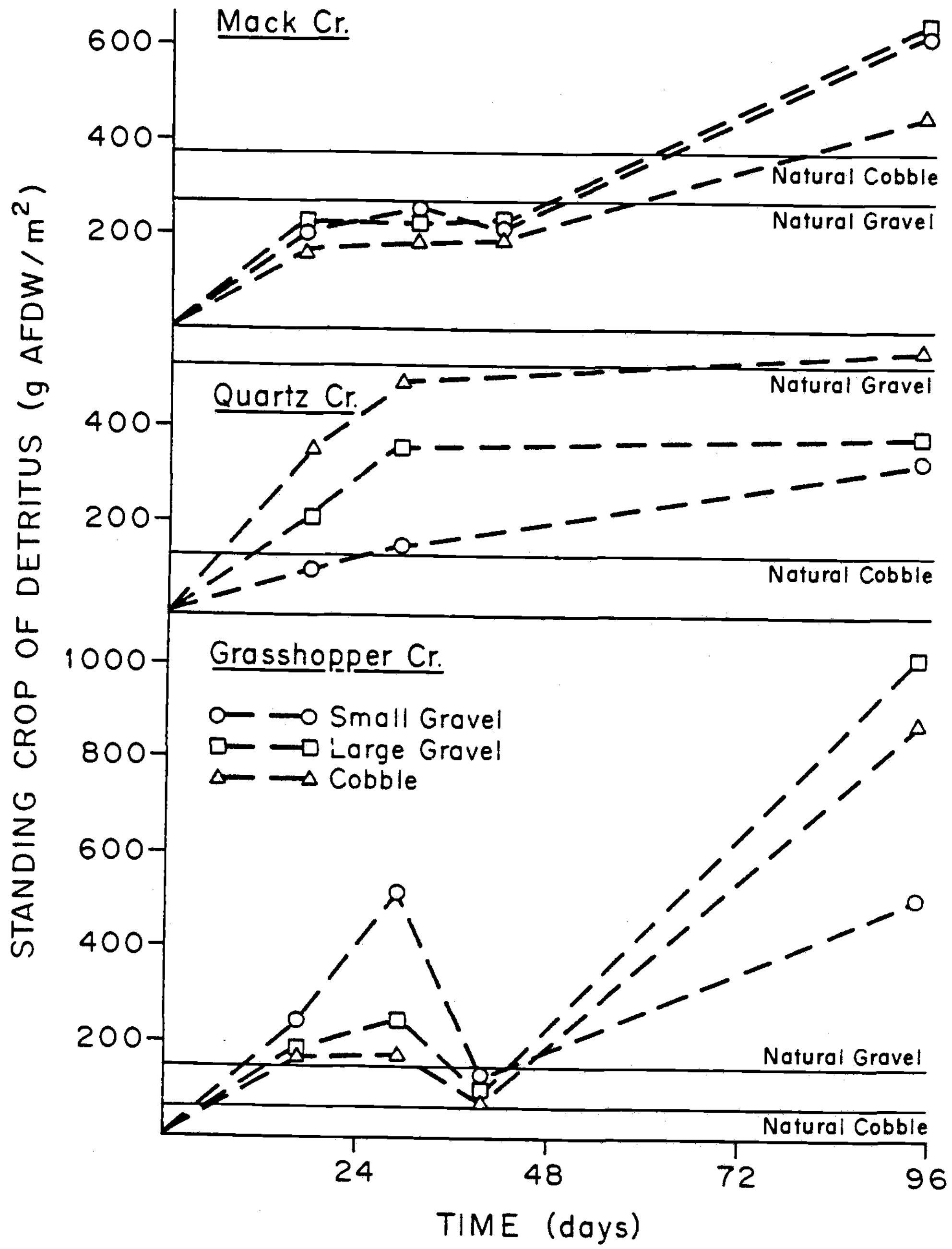

Figure 26. Standing crop of detritus in inorganic substrates in trays placed in pools at Mack Creek, Quartz Creek and Grasshopper Creek.

that was laterally displaced from the main flow. As streamflow increased, large amounts of detritus were carried into and deposited in the pool. At even higher flows, current was funnelled through the pool, possibly scouring surface accumulations of detritus. This may have occurred between July 27 and August 7 and caused the observed decrease in detritus standing crops.

Detritus standing crops in the artificial substrates in pools was significantly higher ($p<0.004$; Wilcoxon Signed Rank Test) than in riffles for all sites on all dates (Table 19). Maximum riffle accumulation for the three substrates were between 16-86 g AFDW/m^2 in Mack Creek, 28-54 g AFDW/m^2 in Quartz Creek and 8-38 g AFDW/m^2 in Grasshopper Creek. Maximum standing crops in pools over the first 42 days of the experiment ranged from 196-258 g AFDW/m^2 in Mack Creek, 149-490 g AFDW/m^2 in Quartz Creek and 174-519 g AFDW/m^2 in Grasshopper Creek.

Substrate size influenced storage of FPOM in riffles but did not have an effect on CPOM storage in riffles or CPOM and FPOM storage in pools. In riffles, more FPOM was stored in small gravels than in large gravels (t-test, $p<0.05$) and both of these substrates stored more FPOM than cobbles ($p<0.05$) at all sites on all sampling dates.

DISCUSSION

The standing crop of benthic detritus in a stream reach is a function of the amount of organic matter available for storage, retention characteristics of the reach, and timing and frequency of flows that export or redistribute detritus. The amount of organic matter available for storage is regulated largely by processes occurring in the riparian zone. In forested reaches, riparian vegetation is the primary source of organic matter and the type of riparian vegetation present is a major determinant of the timing of inputs. In streams with little riparian vegetation and open canopies, in-stream primary production may be the main source of detritus and the timing of detrital inputs will be related to scouring events or seasonal die-offs of the algal and macrophyte communities (Minshall 1980).

Retention of POM depends on stream discharge and physical characteristics of the particle and the stream reach. Retention is enhanced by the presence of large organic debris in the stream channel. Streams with coniferous or deciduous trees in their riparian zones had higher litterfall inputs, higher leaf retention rates, and higher standing crops of benthic detritus than streams with open riparian zones. In streams with forested riparian zones, leaf retention and detrital standing crops were approximately four times higher than in streams with open riparian zones. This implies that the marked particle release method for experimental measurement of retention accurately reflects long term POM storage as well as short term retention in some streams.

The distribution of aquatic habitats within a stream reach influences the amount of detritus stored in the reach. Backwaters and pools associated with large organic debris store more detritus than other habitats and the least amount of detritus is stored in riffles. Debris-associated pools, backwaters, and cobbles in pools tend to have a higher ratio of CPOM to FPOM in storage than other habitats, and gravels in riffles tend to accumulate a larger proportion of FPOM than other habitats.

Detrital storage patterns were consistent with ginkgo leaf retention patterns for all stream features except backwaters. Large organic debris dams increased leaf retention rates and pools associated with large organic debris had high standing crops of detritus. Trapping efficiencies in pools are probably higher than in riffles, and pools tended to store more detritus and have a higher ratio of CPOM to FPOM than riffles. Pools along the stream margin had higher trapping efficiencies and stored more detritus than main-channel pools. Backwaters had the highest detrital standing crops but the lowest leaf trapping efficiencies. Leaf trapping efficiency is not a good indicator of detrital standing crops in backwaters because of differences between routes of entry of organic matter into backwaters and other habitats and differences in the frequency of flushing of backwaters, pools and riffles. Backwaters are not efficient at trapping material that is in transport in the main channel because of the low rate of exchange between backwaters and the main flow. However, backwaters accumulate POM that enters them directly from the terrestrial environment and they are depositional areas during receding flows. Large amounts of POM enter forested reaches via litterfall and lateral movement down the side slopes. A portion of the litterfall enters backwaters directly and is stored until the backwater is scoured. All of the POM entering the stream via lateral movement moves across stream margins and may enter backwaters.

The relationship between removal of POM from transport (retention) and flushing of POM from a storage location is an important determinant of the standing crop of detritus in a habitat at any point in time. The rapid flow through riffles prevents the build up of POM on the surface sediments and reduces the storage capacity of these areas relative to pools and backwaters. This was reflected in the asymptotic standing crops of detritus in the artificial substrates in riffles after 12 to 28 days. Detritus continued to accumulate in the artificial substrates in pools for over 90 days but was significantly affected by flushing at higher flows in Grasshopper Creek (Fig. 26). Backwaters are generally not affected by small changes in flow and they tend to store large amounts of detritus much of the year. Debris pools are similar to backwaters because they are often shielded from scour during small changes in flow and they tend to accumulate large standing crops of detritus.

Relative abundance and distribution of habitats differed greatly at summer and winter flows. Riffles were the dominant stream habitat at the higher winter flows and many areas that were depositional in the summer (pools and backwaters) became erosional. As the channel expanded laterally, depositional zones were located further from the central axis of the stream. This redistribution of habitats did not, however, result in a significant change in the amount of detritus stored in each habitat between seasons.

The pattern of storage of detritus in a stream affects the invertebrate community of the stream (Hynes 1963, Egglishaw 1964, Cummins 1972). Aquatic macroinvertebrates are strongly linked to their food source, and the amount and distribution of detritus in the stream is an important determinant of macroinvertebrate abundance and distribution (Cummins 1972, Anderson and Cummins 1979). Backwaters, debris pools and pools along the stream margin tend to store more detritus, particularly CPOM, than other habitats and support large populations of shredding and detritus collecting insects (M.S. Moore, Dept. of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon, unpublished data, R. Weissmann, Dept. of Entomology, Oregon State University, Corvallis, Oregon, unpublished data). The length of time that POM is stored in a particular location affects the availability of detritus to stream organisms. Colonization by fungi and bacteria begins immediately upon entry to the stream, but utilization by macroinvertebrates requires microbial conditioning for periods ranging from a few days for alder leaves, to several months for conifer needles, to a year or more for some wood (Kaushik and Hynes 1971, Petersen and Cummins 1974, Suberkropp et al. 1975, Sedell et al. 1975, Anderson and Cummins 1979). Organic matter that is exported from a reach before it is adequately conditioned is not available as food for macroinvertebrates in the reach.

SUMMARY

Transport distances and retention locations of wetted ginkgo leaves released into reaches of second- and third-order mountain streams were used to measure reach retention characteristics and the relative importance of major in-stream features. Leaf retention rates (LRR) were calculated using a negative exponential model (Young et al. 1978).

Leaf retention rates ranged from 0.017 to 0.383 m^{-1} and were influenced by the amount of large organic debris in the channel and the ratio of the wetted perimeter of the channel to the cross-sectional area of flow in riffles (1/R). LRRs were approximately twice as high in channels with large organic debris present as in channels with no large organic debris. Streams flowing through coniferous and deciduous stands had significantly higher LRRs than streams with herb-shrub riparian zones, primarily because of large organic debris in the channel. LRR increased exponentially with increasing relative channel roughness (1/R) in riffles, indicating that leaf retention is dependent on water depth in riffles. Leaf retention and 1/R were greatly reduced at higher stream discharges. This may result in much lower retention of CPOM as stream size increases. Average travel distances (S_W=1/LRR)(Newbold et al. 1981) of leaves in transport were very short, ranging from 2.6 to 58.8 m.

Leaf retention rates were influenced by the effects of riparian vegetation on stream channel structure. Streams flowing through coniferous and deciduous stands had significantly higher LRRs than streams flowing through recent clear-cuts.

The length of time required for evacuation of 90% of the dye released in a reach (reach residence time) was strongly correlated with pool volume in the reach. Reach residence time was not correlated with LRR over the range of residence times most commonly encountered in this study.

Sticks trapped ginkgo leaves more efficiently than all sizes of inorganic substrates, large wood and aquatic vegetation. Trapping efficiencies of all features other than sticks were not significantly different. The introduction of boulders, sticks and large pieces of wood to cleared stream reaches resulted in increased leaf retention in the reaches. The increase in retention was directly proportional to the amount of boulders, sticks or wood added.

More leaves per unit area were retained along the stream margin than in any other aquatic habitat. Riffles retained more leaves per unit area than pools, and pools retained more than backwaters. This comparison of the relative trapping efficiency of the different habitats is biased by the assumption that leaves in transport are equally available to all parts of the stream.

Standing crops of CPOM, FPOM and total detritus were higher in Mack Creek and Quartz Creek than in Grasshopper Creek in the summer of 1982. Detrital standing crops were not different in Mack Creek and Quartz Creek. In the winter, the standing crops of FPOM and total detritus were higher at Mack Creek than at Quartz Creek and Grasshopper Creek. There was no significant difference in detrital standing crops in Quartz Creek and Grasshopper Creek. There was no difference between the amount of detritus stored at a site in the summer and winter.

In the summer, backwaters stored more detritus than all other habitats except debris pools. Pools along the stream margin tended to store more detritus than pools in the main flow and standing crops of detritus were generally lowest in riffles, although these differences were not always significant. The same general pattern of detritus storage was found in the winter but none of the differences between habitats were significant. There was no difference in the amount of detritus stored in a habitat in the summer and winter at all sites.

The total amount of detritus stored in equal distances of stream in the summer was more than three times higher at Mack Creek and Quartz Creek than at Grasshopper Creek. The ratios of CPOM to FPOM in storage in the reaches were 1.11 in Mack Creek, 0.86 in Quartz Creek and 0.26 in Grasshopper Creek.

In the summer, cobbles in pools had a higher percentage of CPOM relative to the total amount of detritus in storage than all other habitats except backwaters. Backwaters stored a higher percentage of CPOM than pools along the stream margin, gravels in pools and bedrock in riffles. There was no significant difference in the percentage of CPOM in storage in the other habitat-substrate groups.

Quartz Creek had a higher percentage of CPOM in storage overall habitats than Mack Creek and Grasshopper Creek in the summer. There was no difference in the percentage of CPOM in storage at Mack Creek and Grasshopper Creek. There was no difference in the percentage of CPOM stored in the habitats or at the three sites in the winter.

Artificial substrates in pools had higher rates of accumulation of detritus and higher standing crops of detritus than artificial substrates in riffles. Detritus continued to accumulate for 95 days in pools but detrital standing crops levelled off after 12 to 28 days in riffles. In riffles, maximum standing crops of detritus were in the range found in natural stream cobbles and were less than detrital standing crops found in natural stream gravels. The type of pool that the artificial substrates were placed in played a major role in determining the rate of accumulation and the total standing crop of detritus. In Mack Creek and Grasshopper Creek, standing crops of detritus were higher than those found in natural substrates in pools not associated with large organic debris. In Quartz Creek, detrital standing crops were in the range found in natural gravels in pools. Artificial substrate size influenced storage of FPOM in riffles but did not have an affect on CPOM storage in riffles or CPOM and FPOM storage in pools. In riffles, more FPOM was stored in small gravels than in large gravels and both of these substrates stored more FPOM than cobbles.

Leaf retention rates of stream reaches and the leaf trapping efficiencies of individual retention features reflected patterns of detritus standing crops in the three intensively studied streams. In reaches with forested riparian zones, leaf retention rates and detrital standing crops were approximately four times higher than in a stream with an open riparian zone. Large organic debris dams increased leaf retention rates and pools associated with debris dams had high standing crops of detritus. Backwaters had low trapping efficiencies for leaves because of the low rate of exchange of POM between the main flow and backwaters. The high standing crops of detritus found in backwaters resulted from storage of POM entering these areas directly from the terrestrial environment, deposition during receeding flows, and low frequency of flushing of these habitats.

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APPENDICES

APPENDIX A. Dye concentration versus time curves (all reaches).

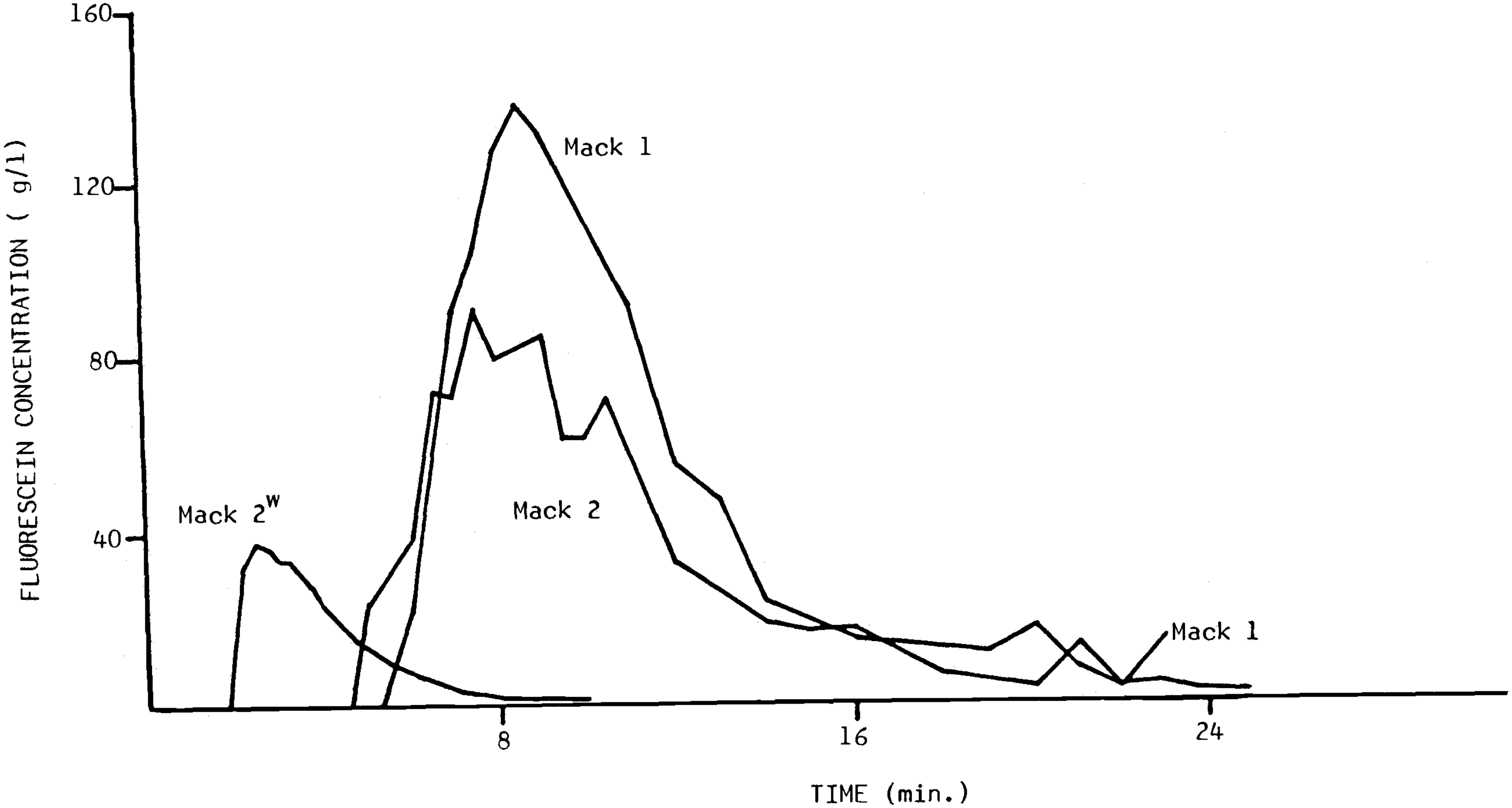

Figure A1. Dye concentration versus time in the old-growth reaches of Mack Creek.

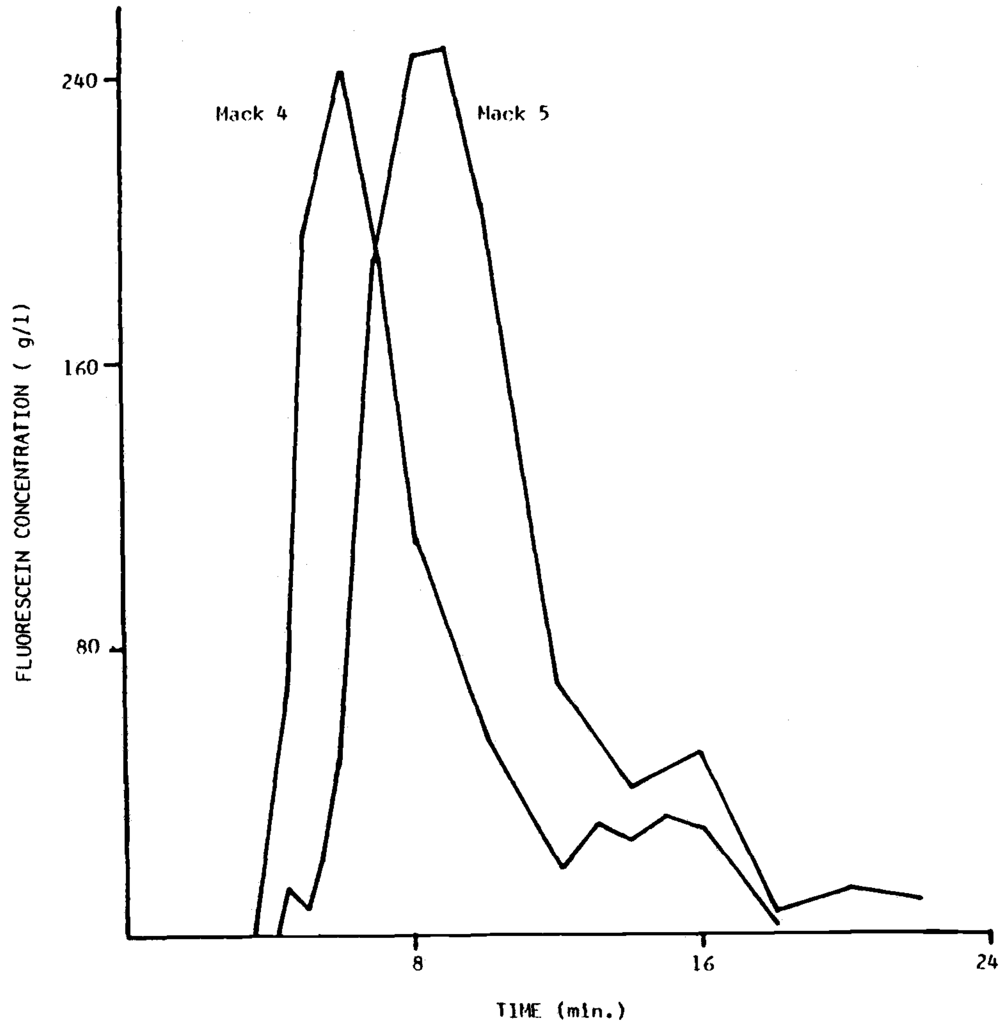

Figure A2. Dye concentration versus time in old-growth reaches of Mack Creek.

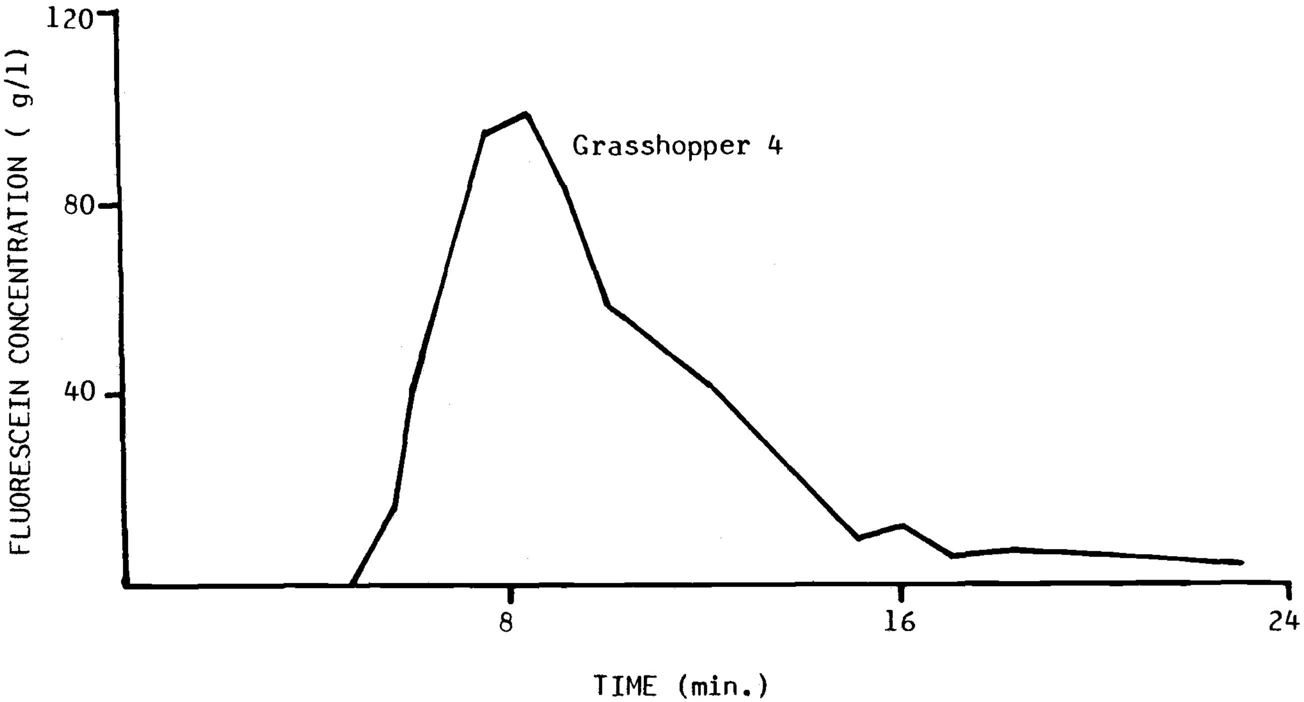

Figure A3. Dye concentration versus time in an old-growth reach of Grasshopper Creek.

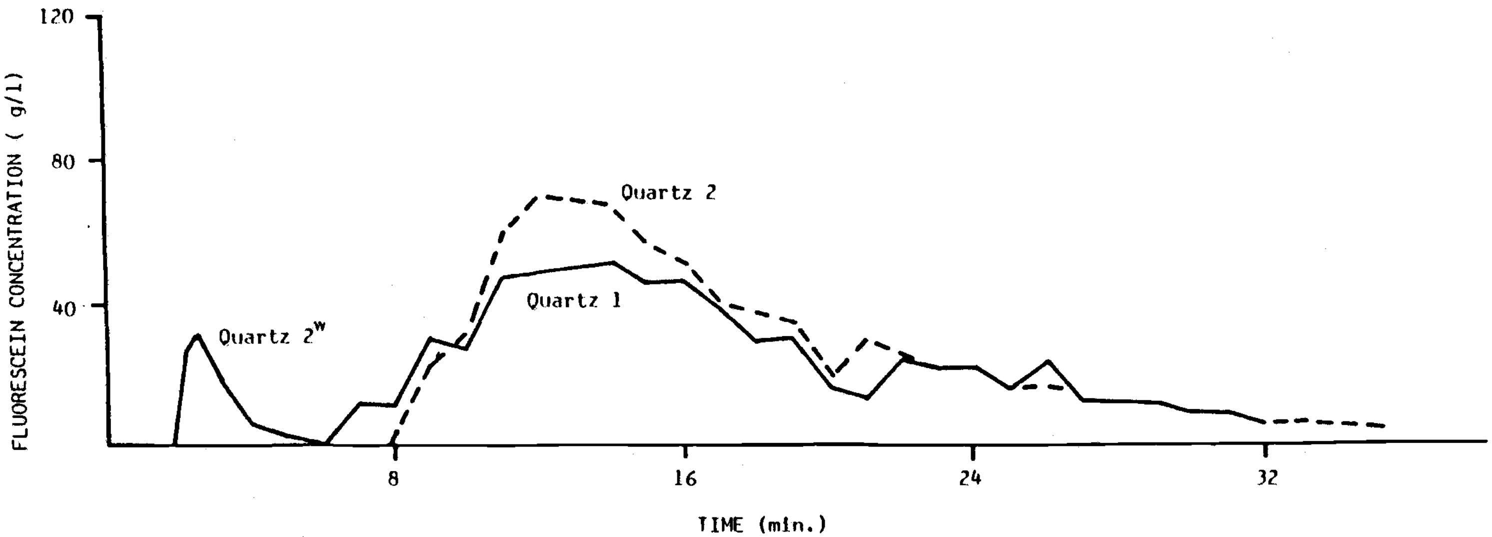

Figure A4. Dye concentration versus time in reaches of Quartz Creek (Blue R.).

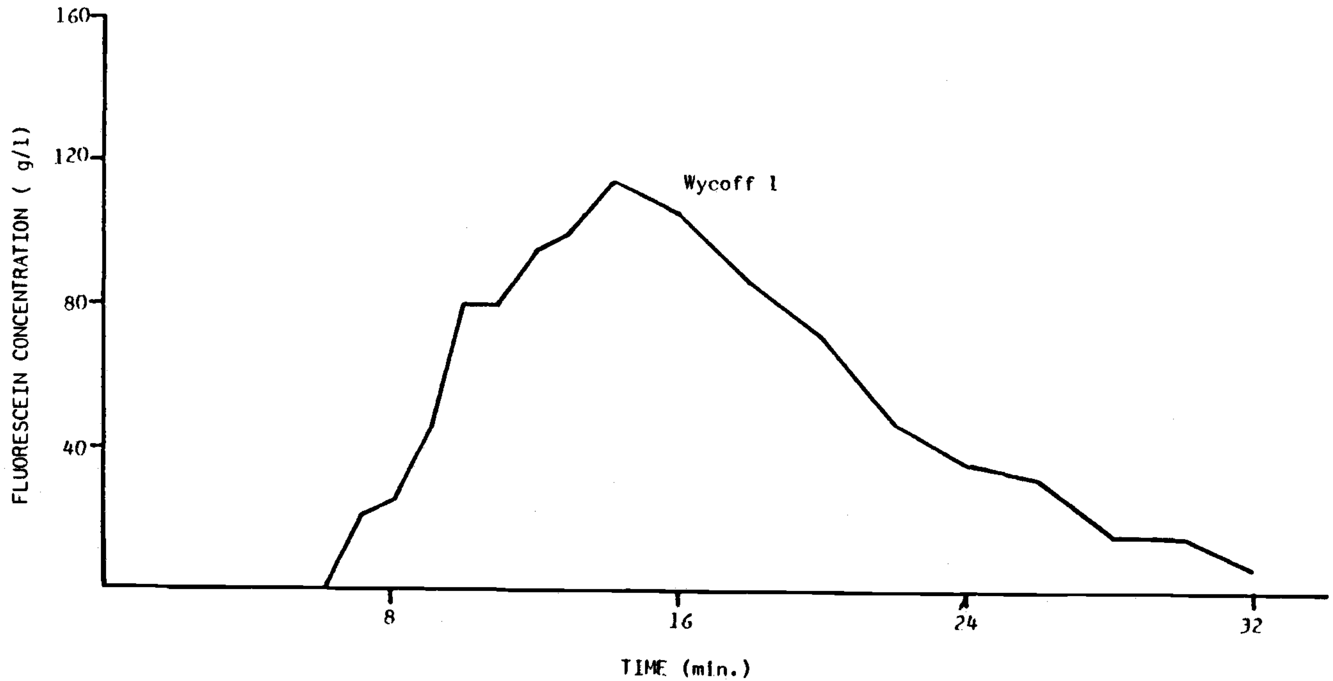

Figure A5. Dye concentration versus time in Wycoff Creek.

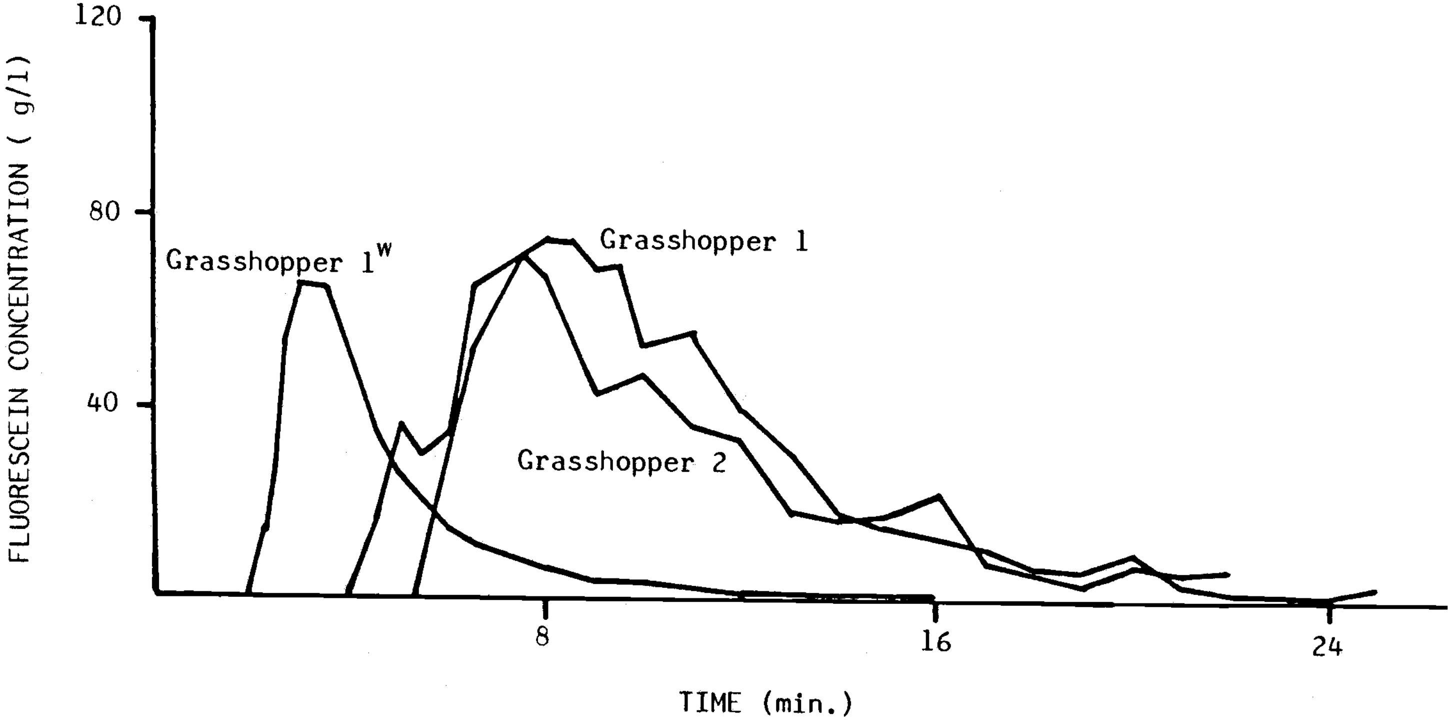

Figure A6. Dye concentration versus time in recently clear-cut reaches of Grasshopper Creek.

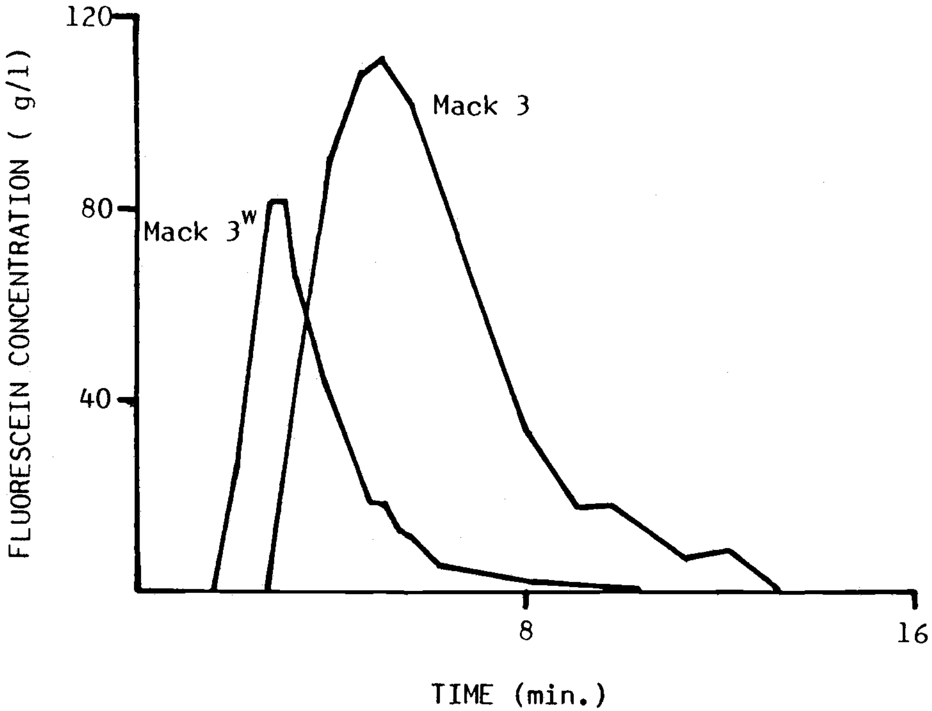

Figure A7. Dye concentration versus time in a recently clear-cut reach of Mack Creek.

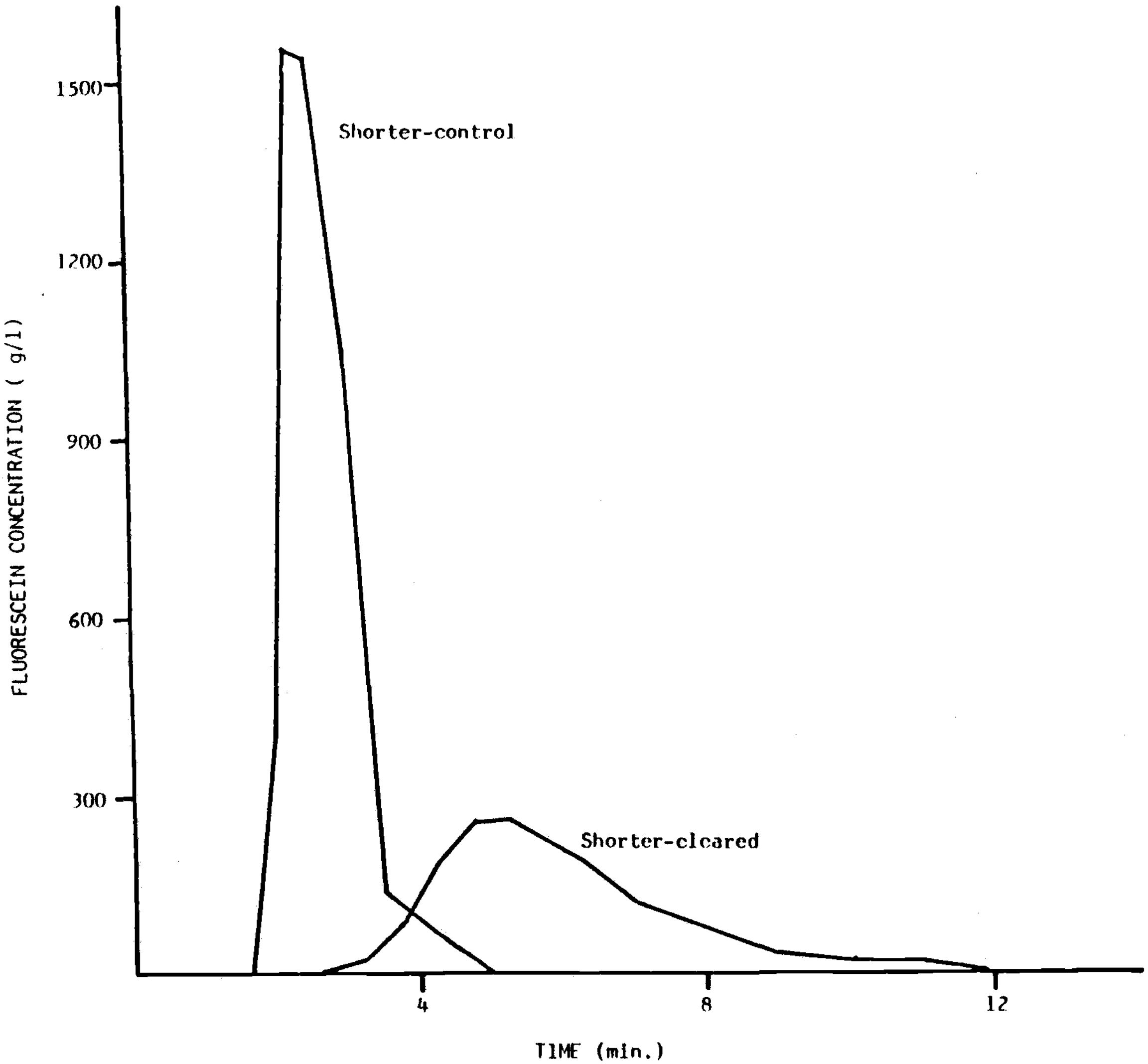

Figure A8. Dye concentration versus time in two reaches of Shorter Creek.

APPENDIX B.

Table B1. Physical parameters and retentino characteristics of study reaches.

Riparian Vegetation	Site	Stream Order	Stand Age (yrs)	Reach Length (m)	Gradient (%)	Dis-charge (m^3/s)	Debris Dam Influence (% of Length)	Relative Riffle Area (%)	Relative Pool and Backwater Area (%)	Relative Pool Volume (%)	Reach Residence Time (min)	Riffle 1/R (m/m^2)	LRR (m^{-1})
Coniferous	Mack 1	3	450	50	7.0	0.041	12	73.0	26.7	28.1	20.0	12.5	0.134
	Mack 2	3	450	50	11.0	0.061	38	72.4	27.6	28.1	16.3	9.2	0.159
	Mack 4	3	450	20	6.0	0.037	66	68.5	31.5		13.2	12.5	0.165
	Mack 5	3	450	50	10.0	0.027	0	70.4	29.3		14.9	17.4	0.288
	Lookout 1	3	450	50	7.4	0.137	18	87.1	12.9	18.5	8.9	11.0	0.079
	Grasshopper 4	3	450	50	12.0	0.065	100	62.3	37.7		13.7	12.4	0.155
	Cougar 2	3	300	30	6.0	0.065		80.9	18.8			9.5	0.100
	Fritz 1	2	450	50	14.6	0.022	14	51.5	48.5	52.5	40.0	16.7	0.383
	Mann 3[a]	3	300	50	6.0	0.017	0	71.3	28.7		6.6	11.3	0.021
	Shorter control	2	450	46		0.023	70				3.2	13.1	0.204
	Mack 2[w]	3	450	50	11.0	0.353	38				6.0		0.034
Deciduous	Quartz 1	3	35	50	5.5	0.053	30	60.4	39.3	45.4	29.4	7.6	0.281
	Quartz 2	3	35	65	4.8	0.047	14	46.0	54.0			11.3	0.102
	Wycoff 1	3	24	50	11.6	0.026	0	70.7	29.3	23.0	24.6	17.6	0.148
	Cougar 1	3	34	50	5.8	0.114	2	85.1	13.4		9.0		0.169
	S.F. Hagan 1	3	110	50	5.0	0.040	12				8.5		0.146
	S.F. Hagan 2	3	110	50	5.0	0.043	4				10.1		0.077
	S.F. Hagan 3	3	110	50	5.0	0.029	0				11.9		0.082
	S.F. Hagan 4	3	110	50	6.0	0.040	44				10.2		0.196
	Simmons 1	3	32	50	2.0	0.138	0	78.6	21.4		4.2	10.5	0.030
	Quartz 2[w]	3	35	65	4.8	0.820	14			12.0		5.4	0.030
Open	Grasshopper 1	3	8	50	5.2	0.073	0	60.3	39.7	43.1	20.9	7.1	0.024
	Grasshopper 2	3	8	50	9.6	0.072	0	62.3	37.7	42.3	20.0	8.6	0.025
	Mann 1	3	10	50	12.4	0.107	0	63.5	36.55	19.0	10.0	9.6	0.056
	Rbro-Quartz 1	3	10	50	5.0	0.073	0	71.8	28.4	31.4	12.9	6.8	0.017
	Mack 3	3	20	50	9.2	0.084	0	82.0	18.0	17.1	8.8	13.4	0.060
	Mann 2	2	10	50	24.4	0.072	0	65.8	34.7	41.2	25.2	13.5	0.145
	Grasshopper 1[w]	3	8	50	5.2	0.208	0				9.2	6.8	0.021
	Mack 3[w]	3	20	50	9.2	0.221	0				7.2	6.1	0.031

[a] Recent debris torrent through channel.
[w] Leaves released in the winter (higher flows).

APPENDIX C. Leaf retention curves (all reaches).

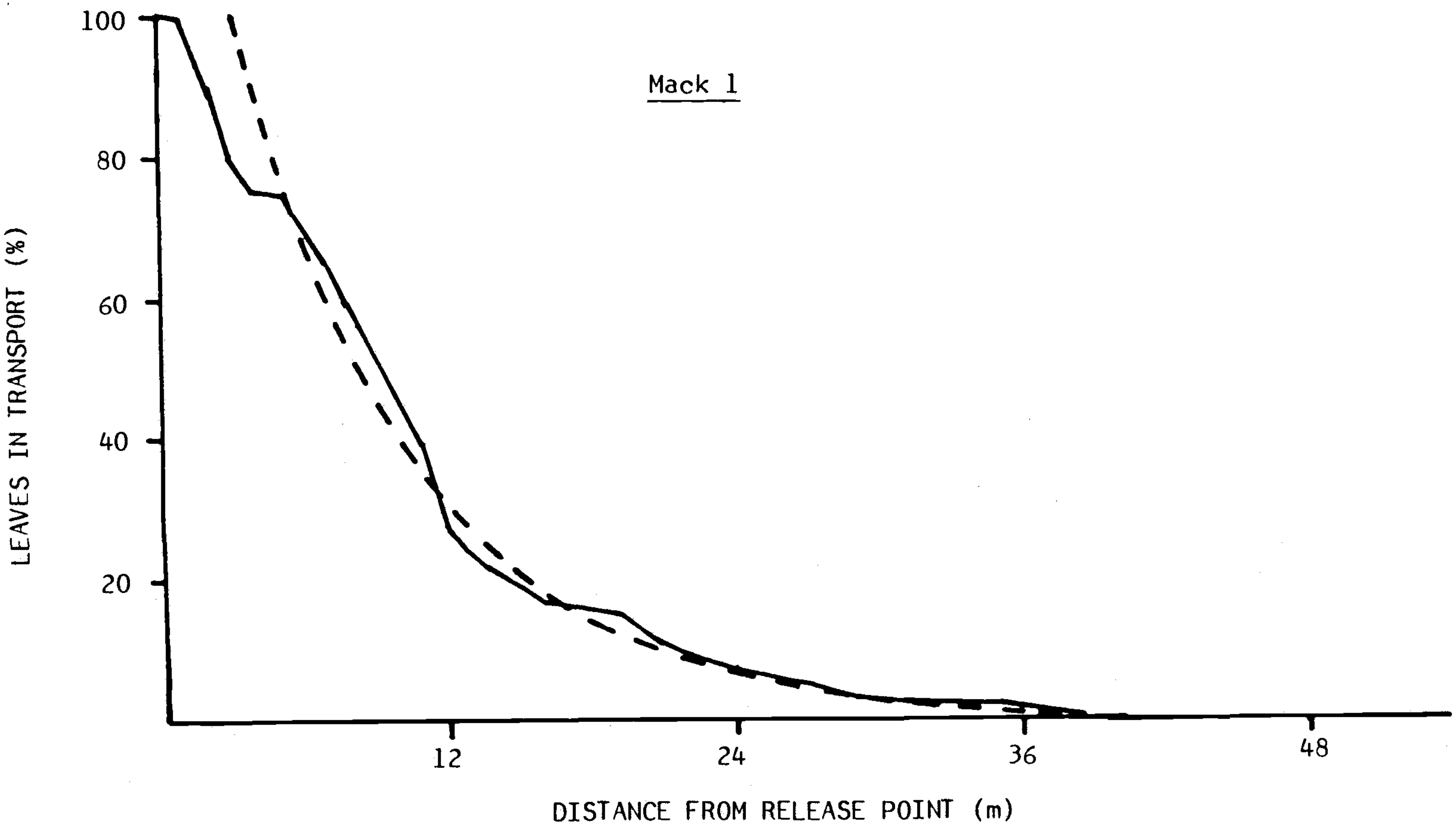

Figure C1. Leaf retention curve for reach Mack 1.

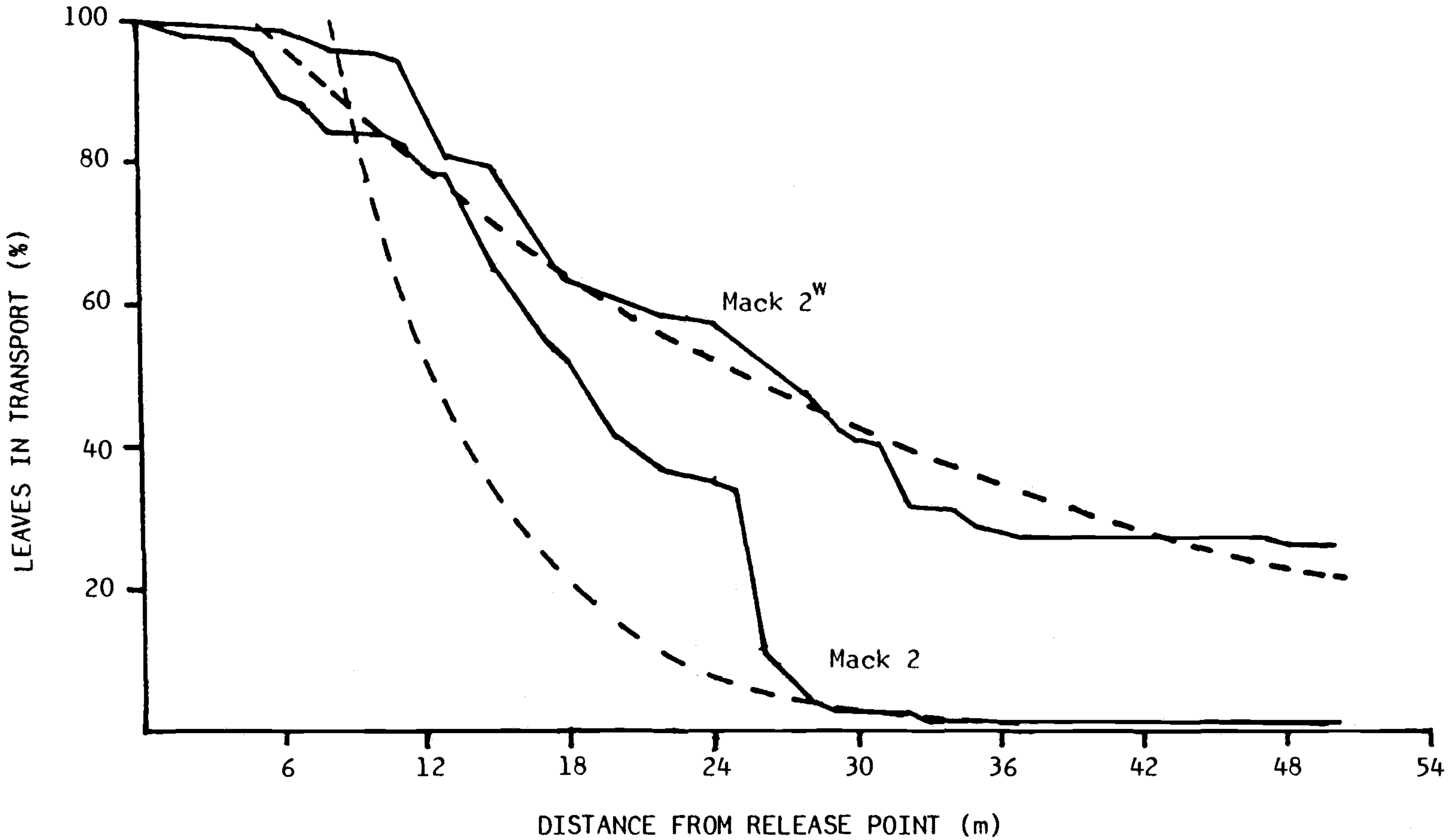

Figure C2. Leaf retention curve for reach Mack 2. ^{W} denotes winter leaf release.

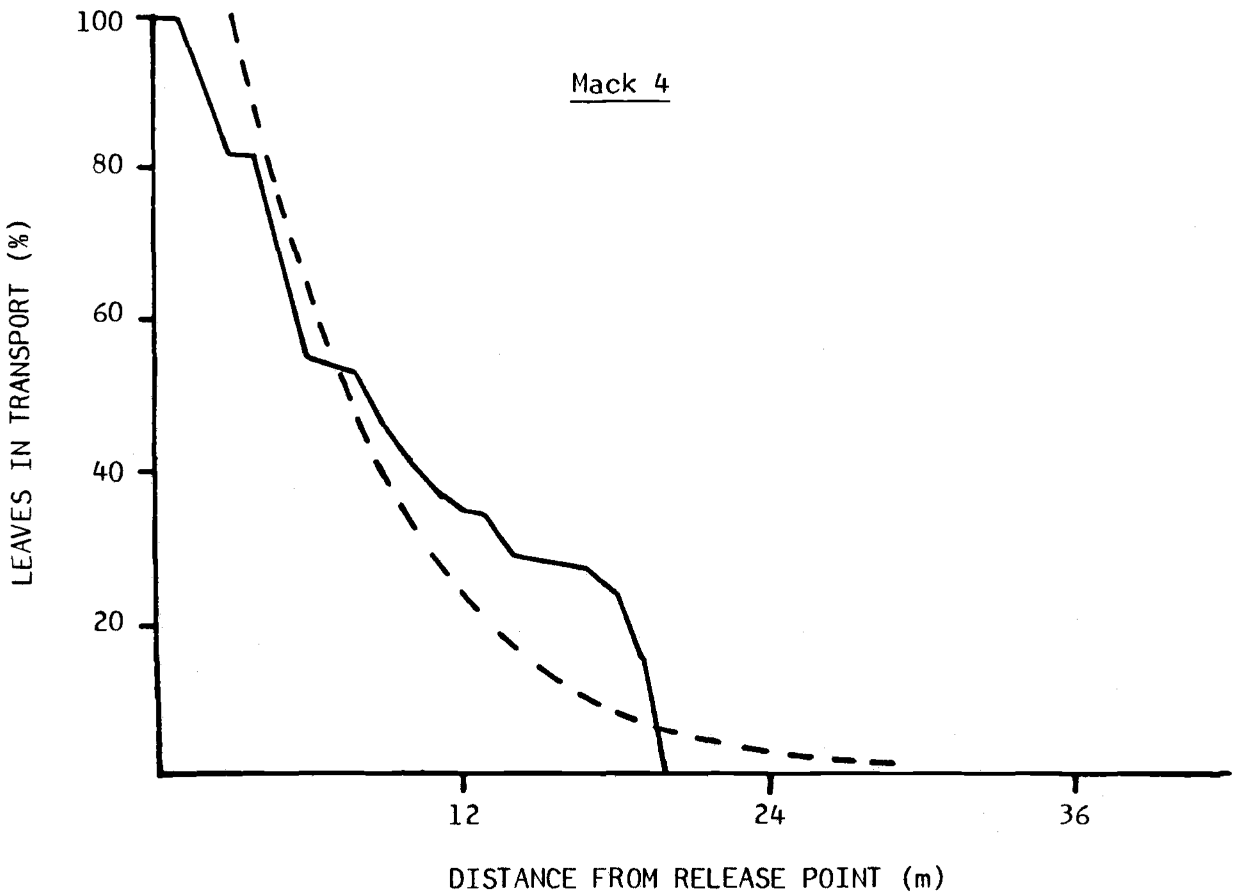

Figure C3. Leaf retention curve for reach Mack 4.

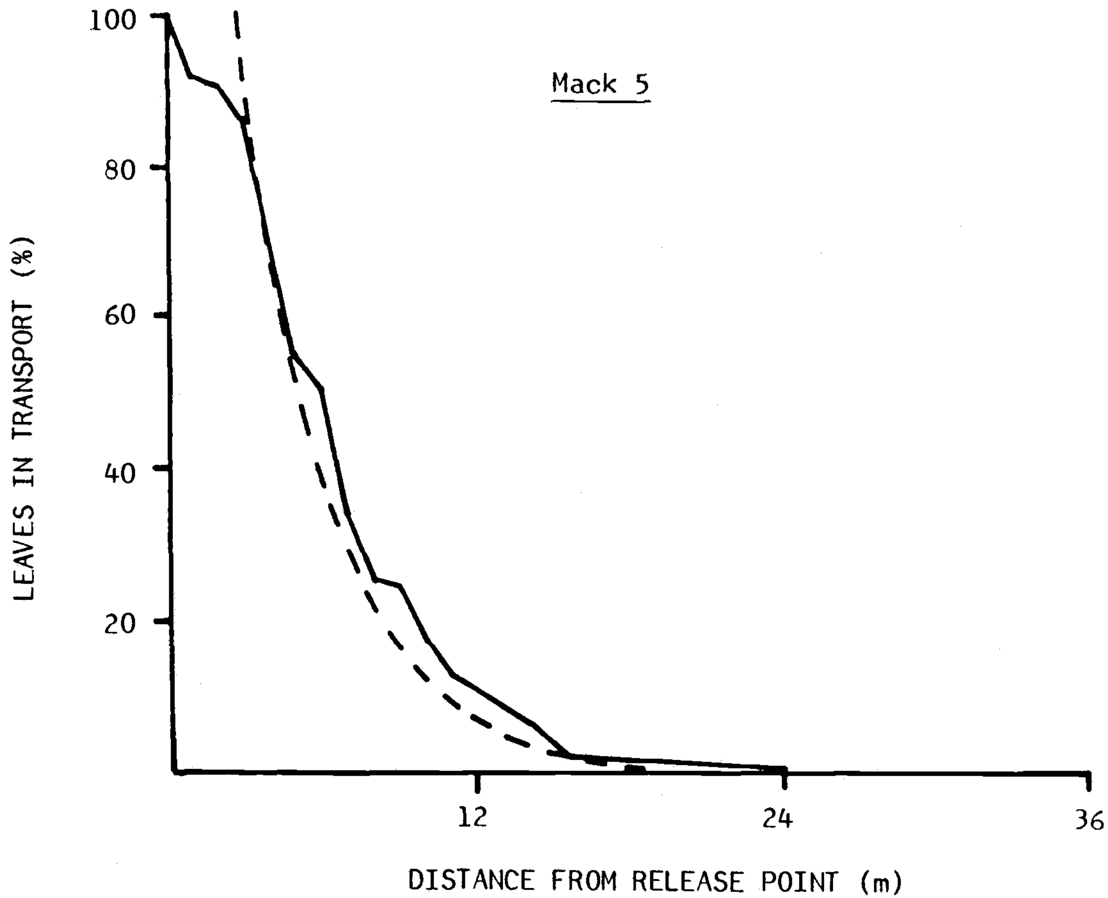

Figure C4. Leaf retention curve for reach Mack 5.

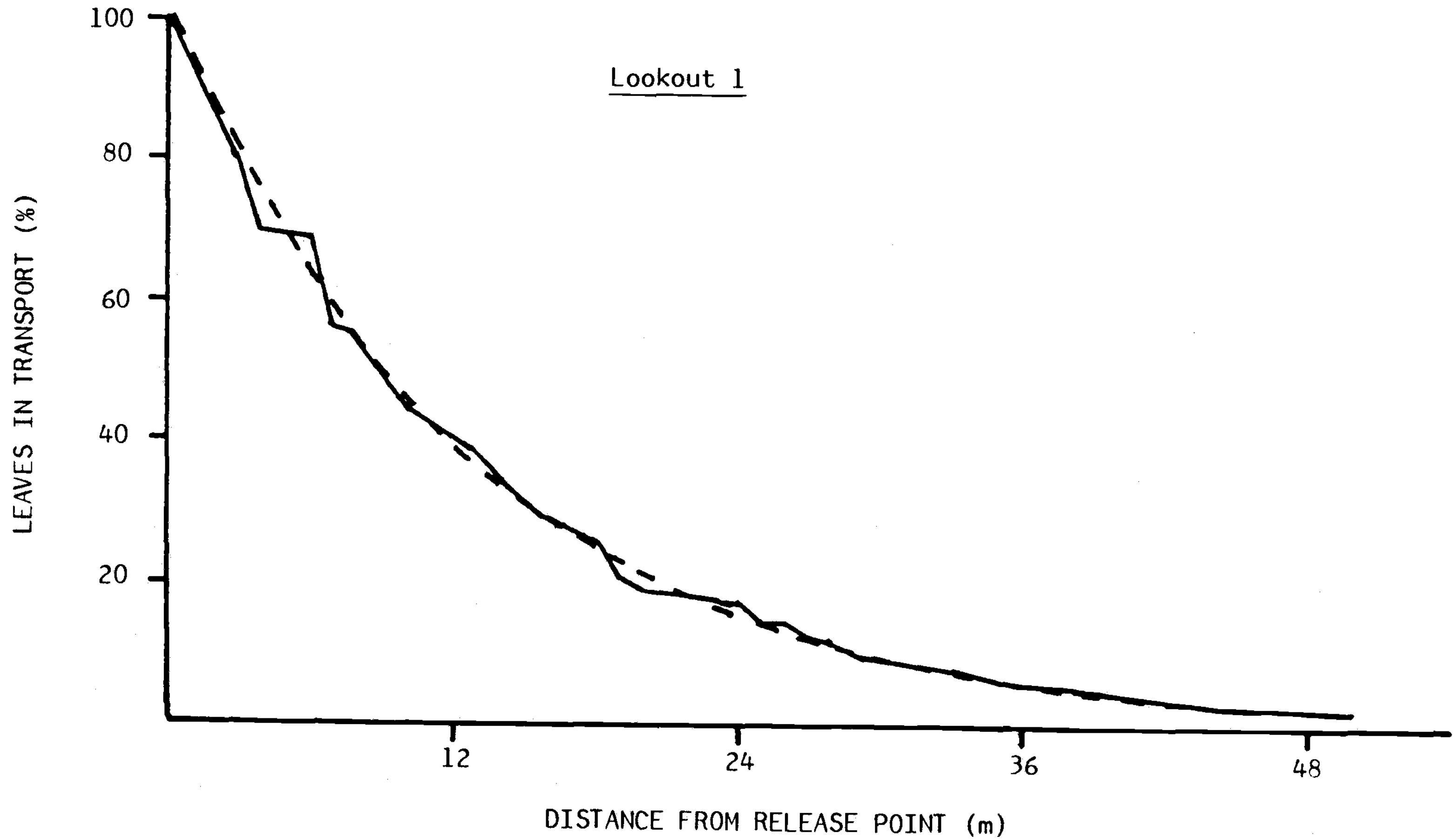

Figure C5. Leaf retention curve for reach Lookout 1.

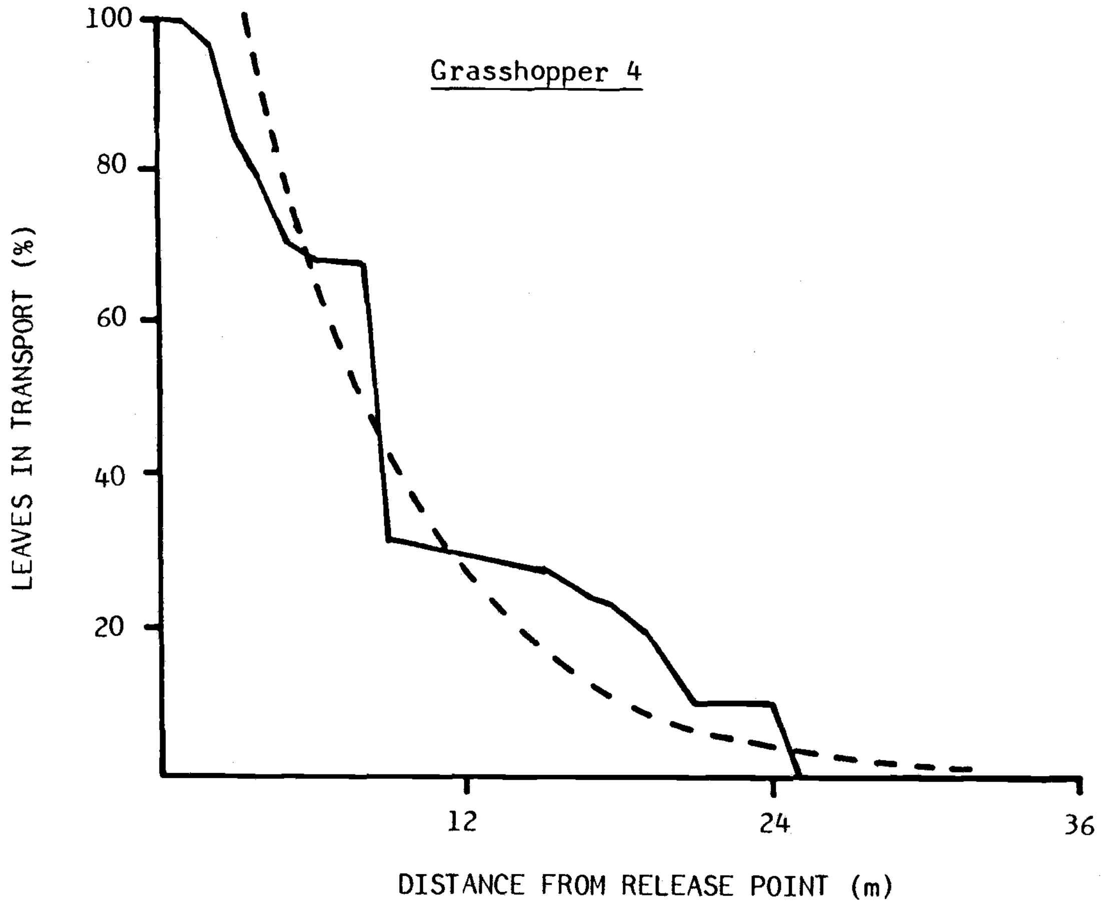

Figure C6. Leaf retention curve for reach Grasshopper 4.

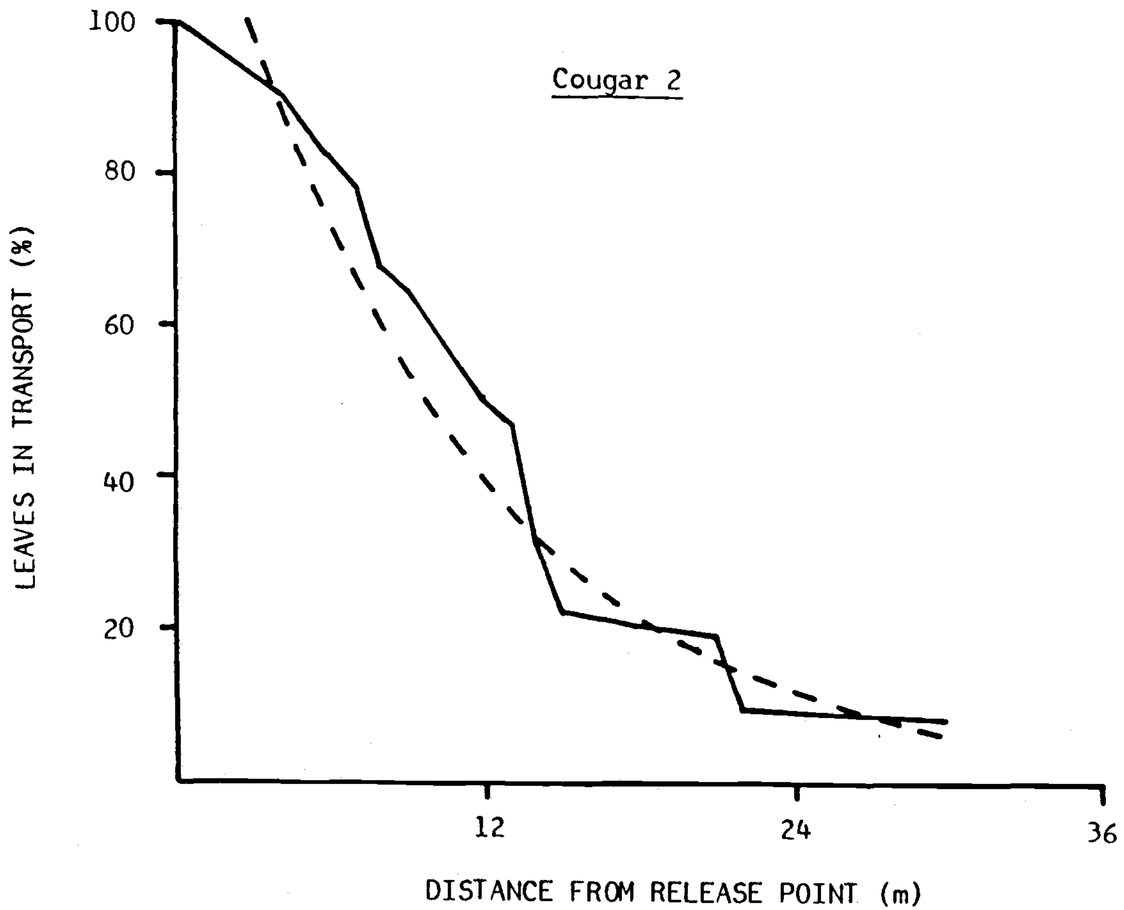

Figure C7. Leaf retention curve for reach Cougar 2.

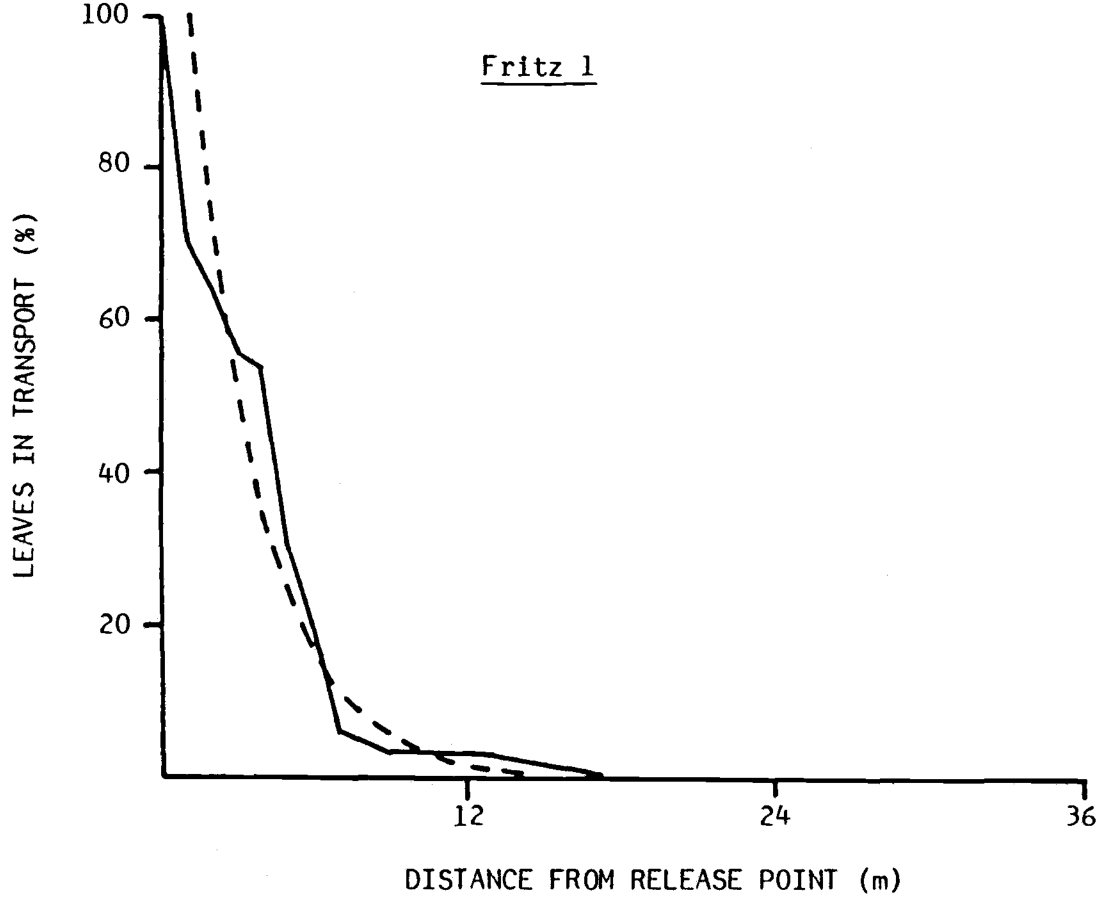

Figure C8. Leaf retention curve for reach Fritz 1.

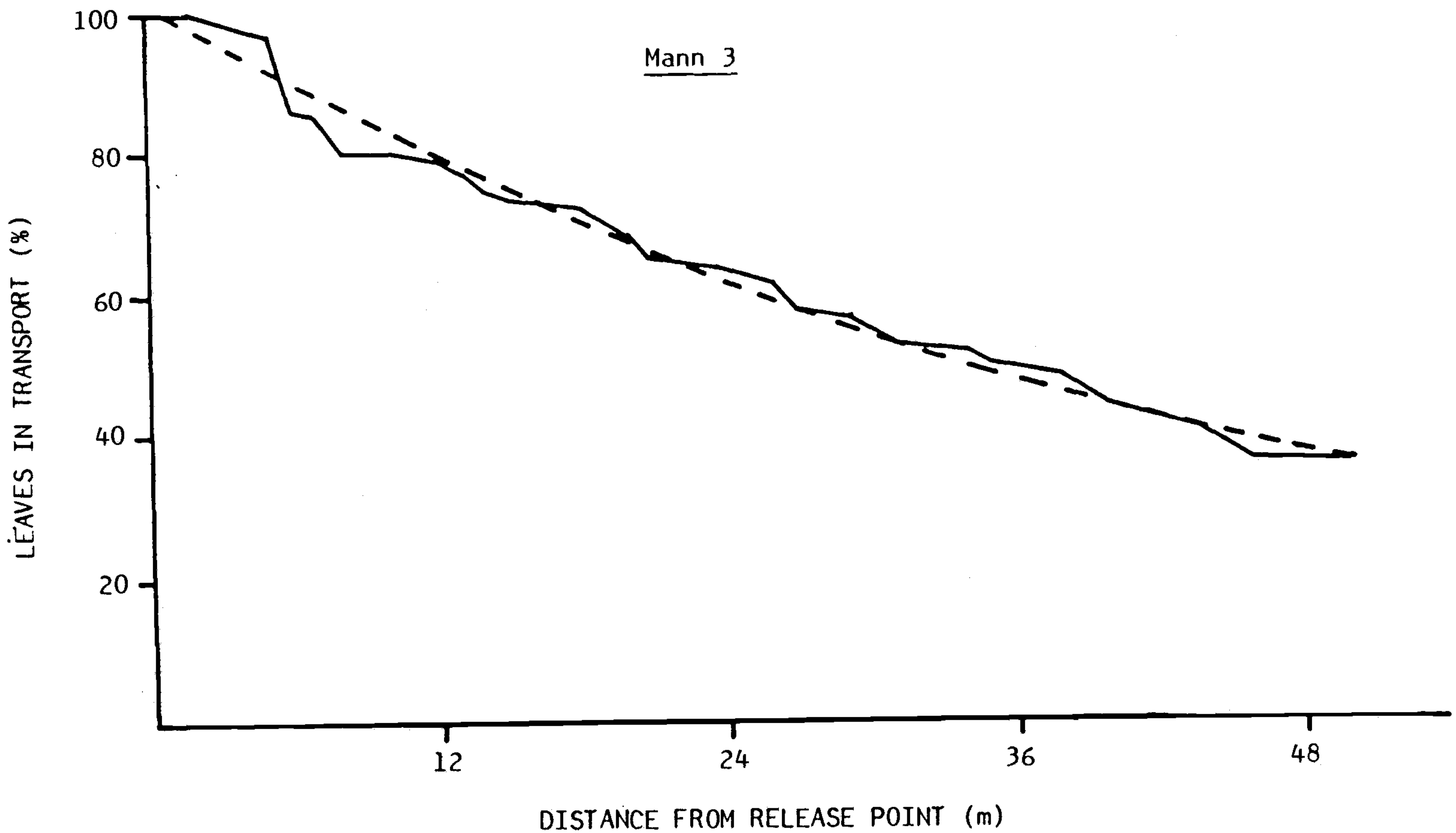

Figure C9. Leaf retention curve for reach Mann 3.

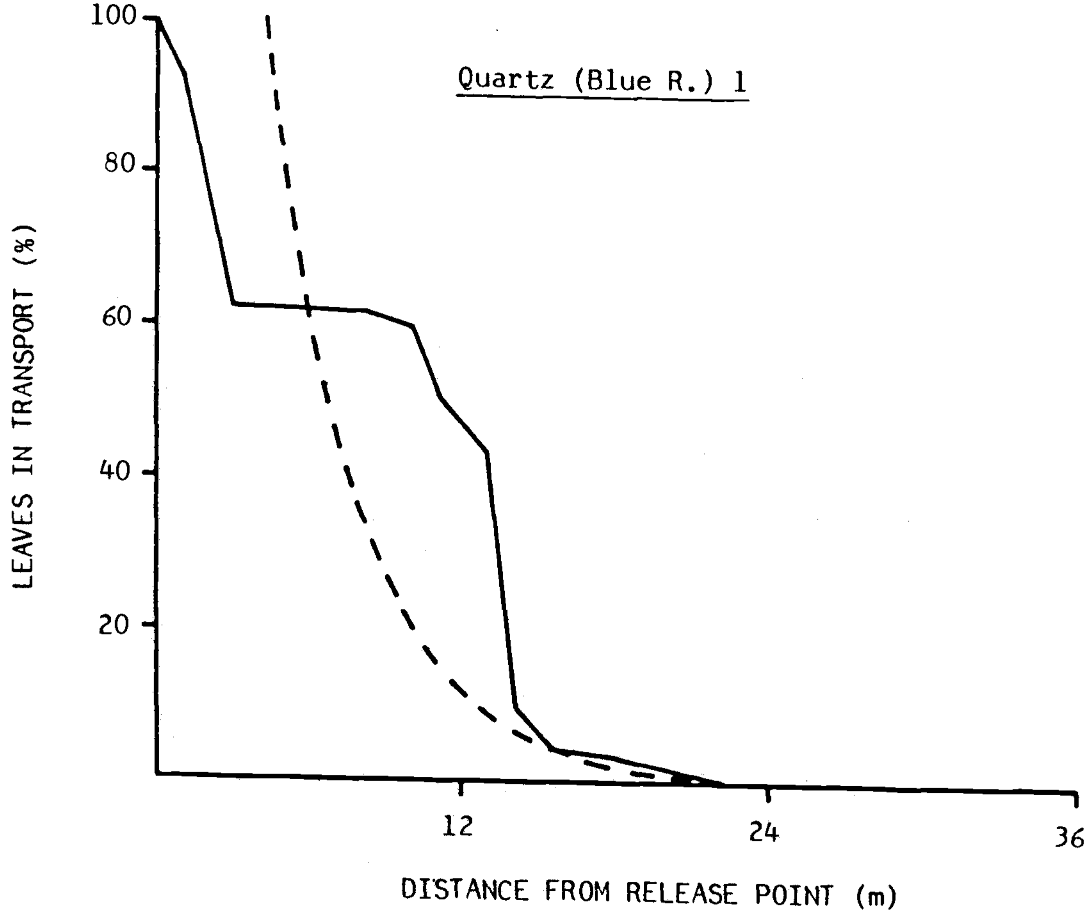

Figure C10. Leaf retention curve for reach Quartz (Blue R.) 1.

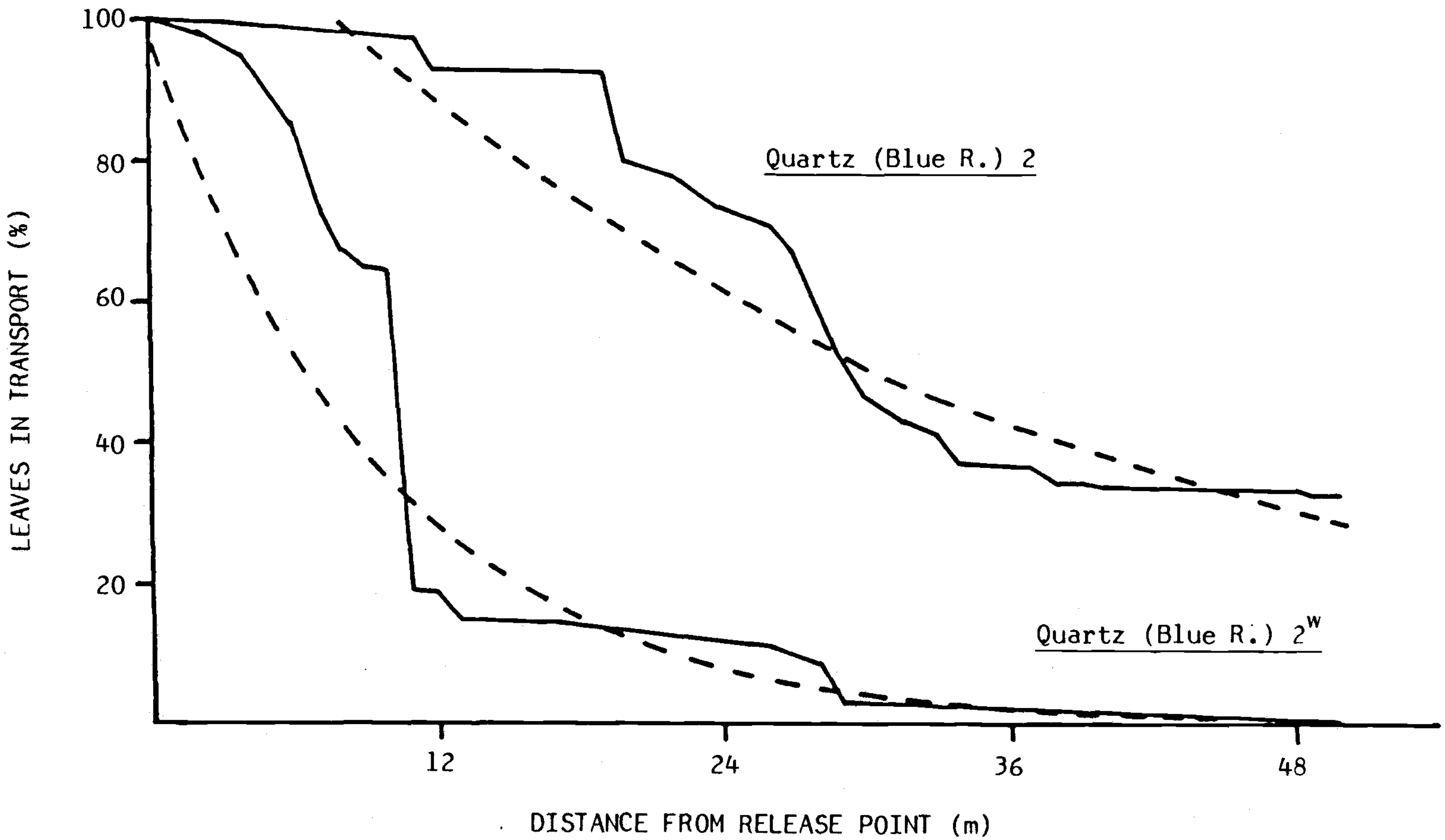

Figure C11. Leaf retention curve for reach Quartz (Blue R.) 2. [w] denotes winter leaf release.

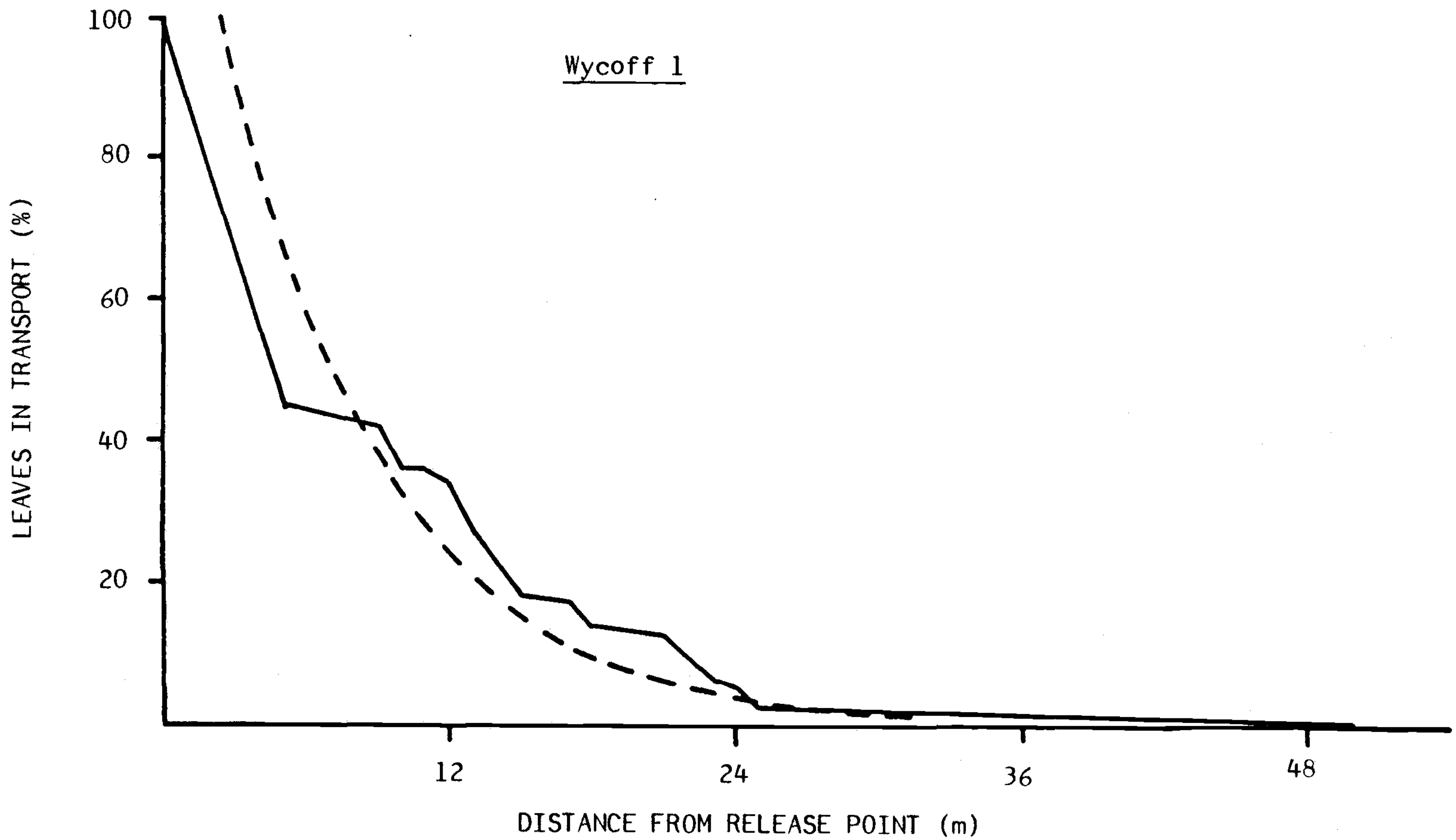

Figure C12. Leaf retention curve for reach Wycoff 1.

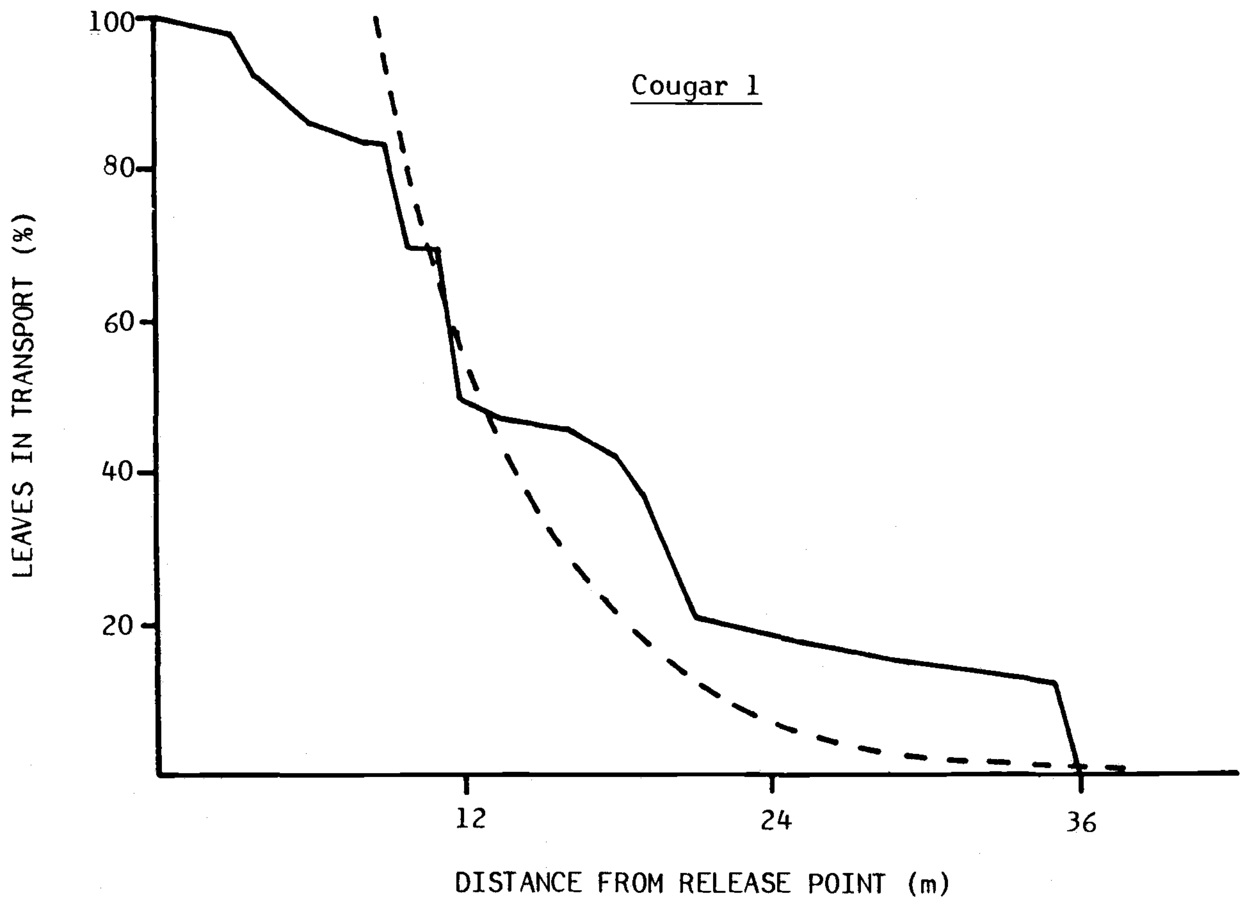

Figure C13. Leaf retention curve for reach Cougar 1.

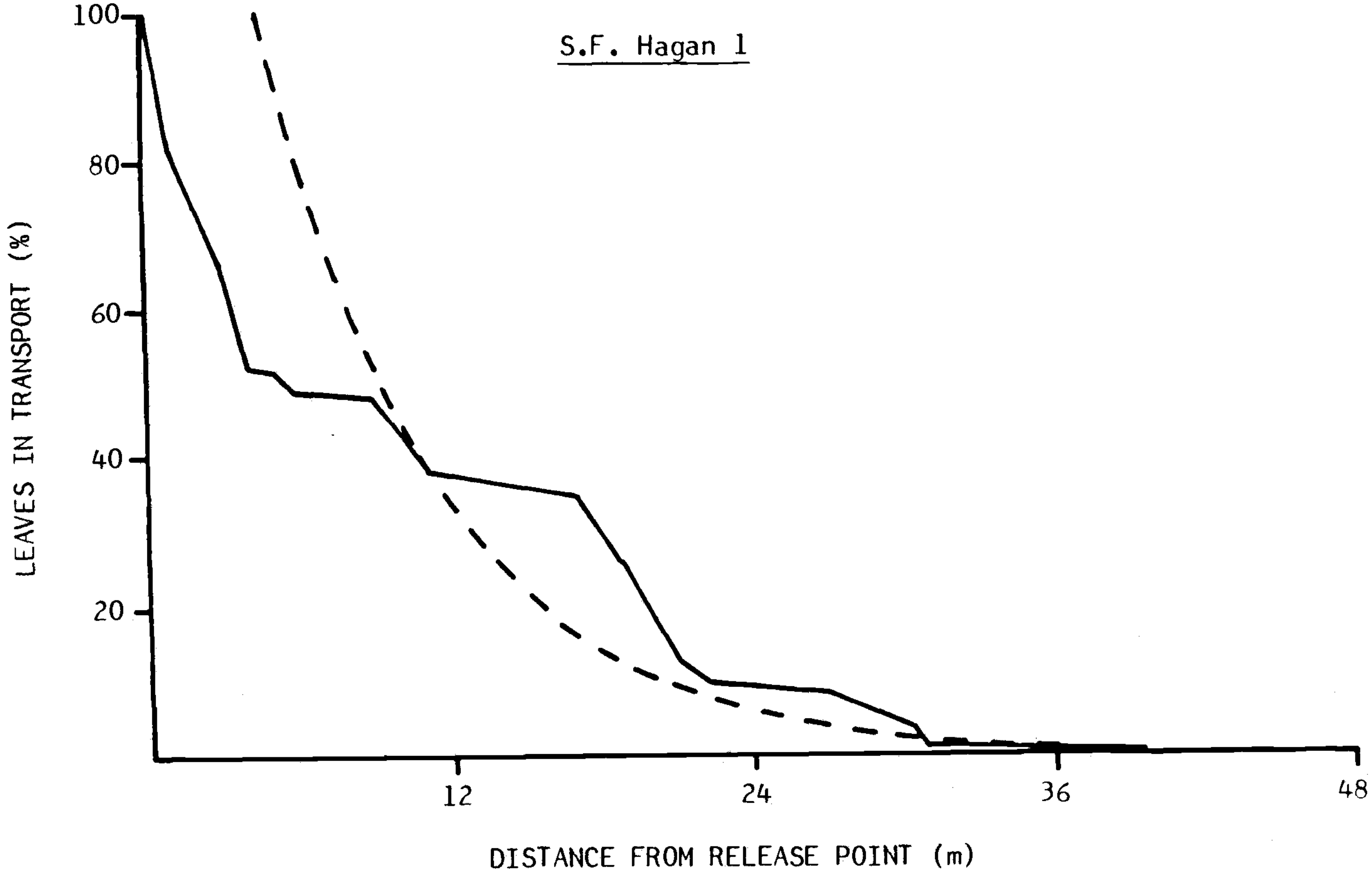

Figure C14. Leaf retention curve for reach S.F. Hagan 1.

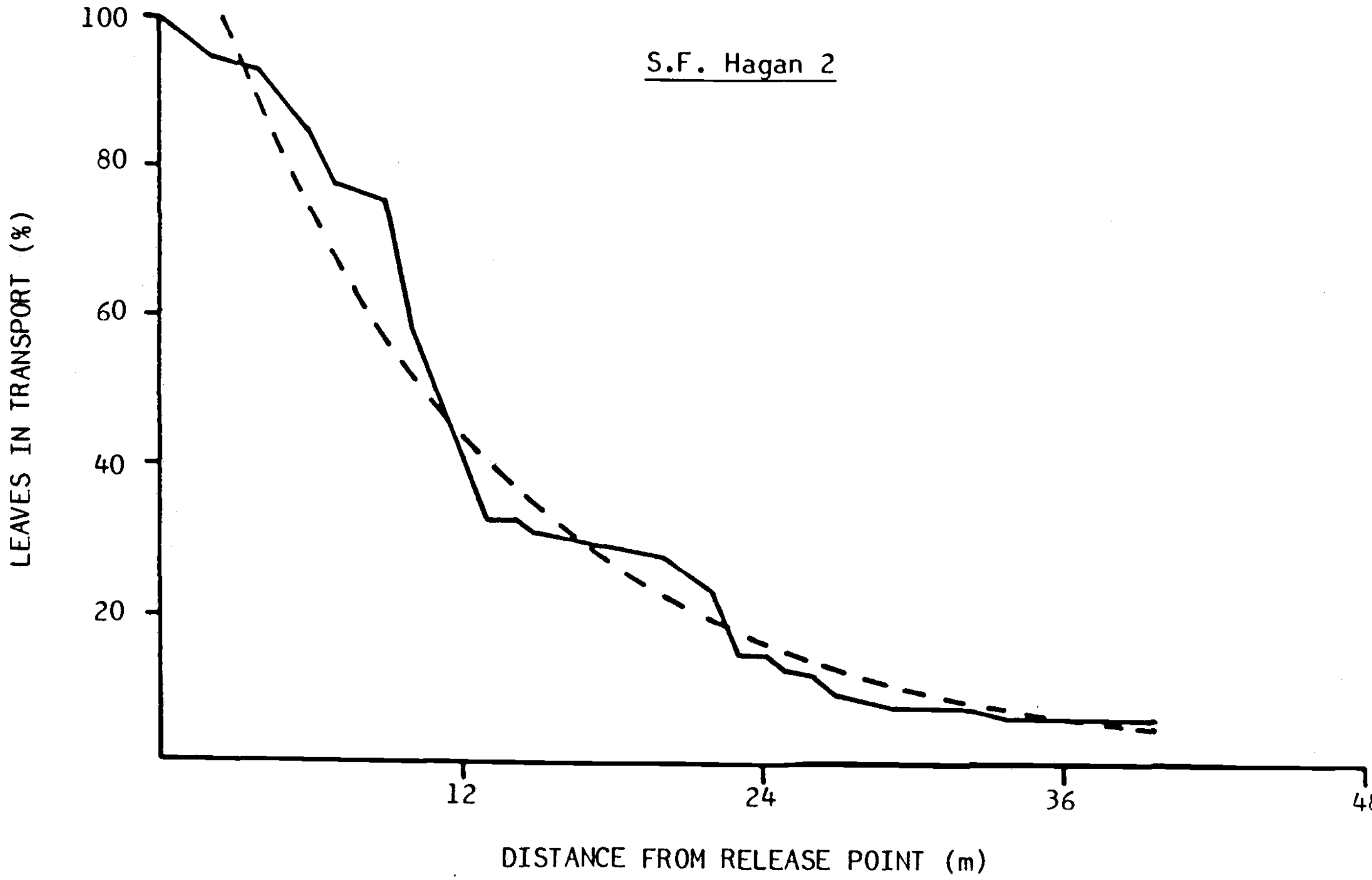

Figure C15. Leaf retention curve for reach S.F. Hagan 2.

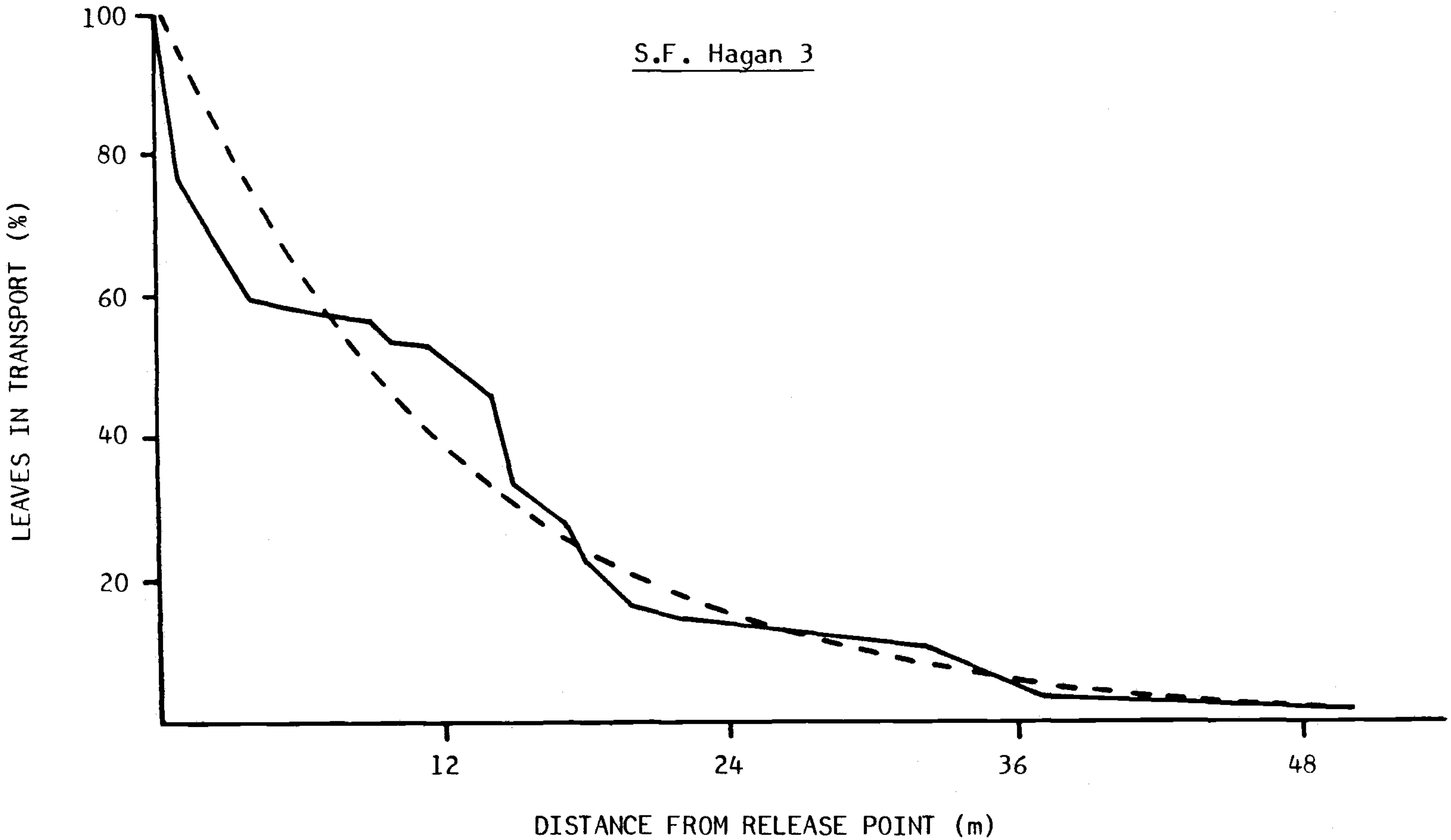

Figure C16. Leaf retention curve for reach S.F. Hagan 3.

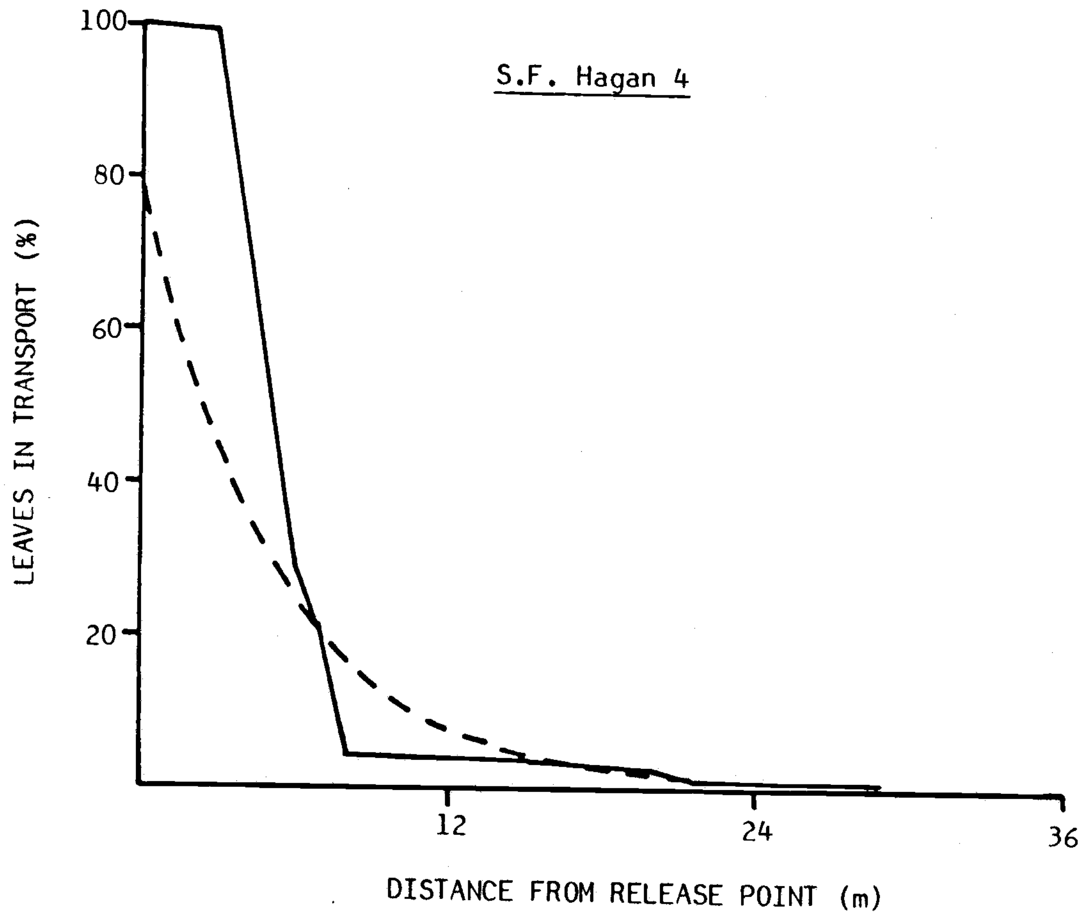

Figure C17. Leaf retention curve for reach S.F. Hagan 4.

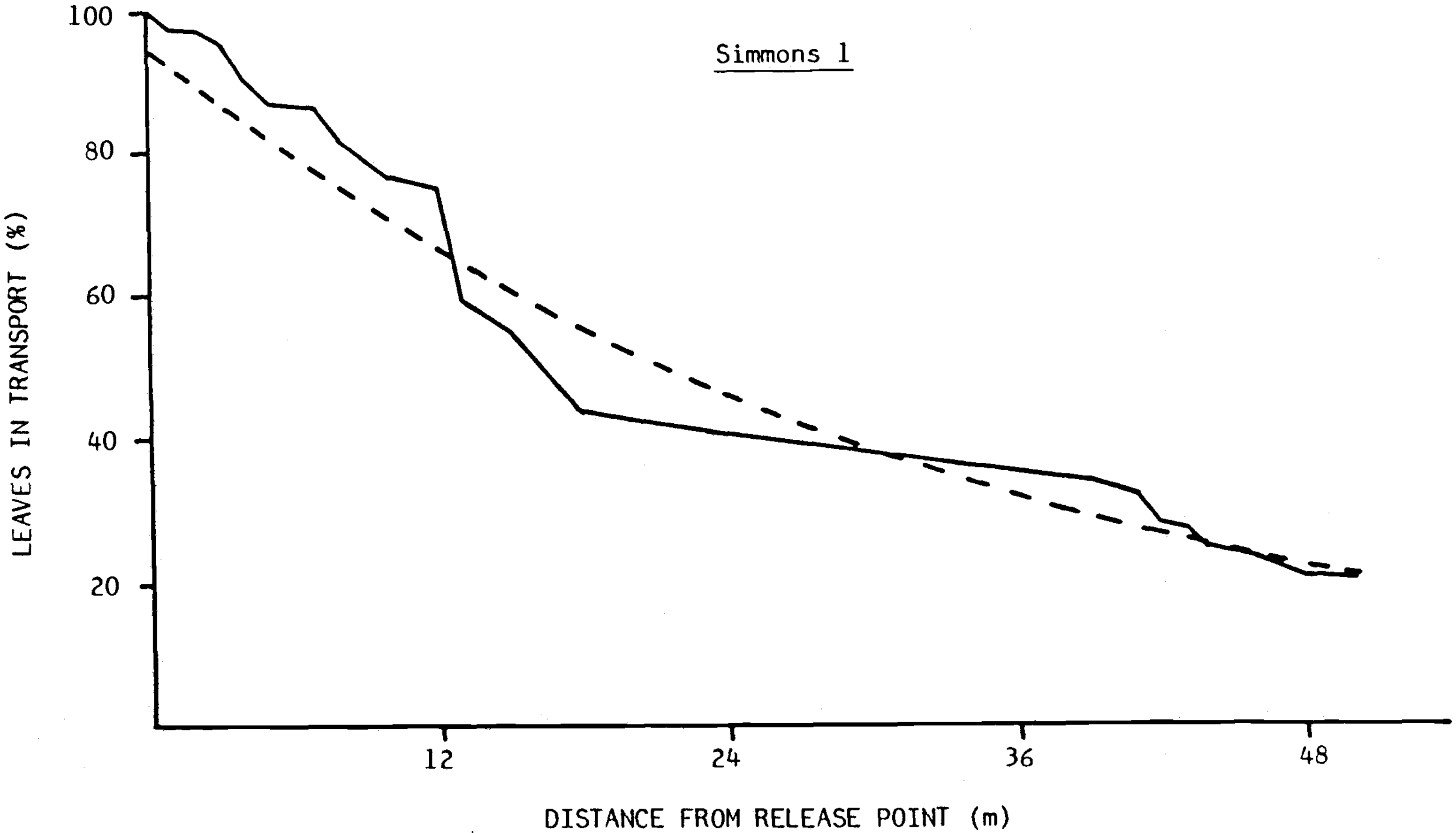

Figure C18. Leaf retention curve for reach Simmons 1.

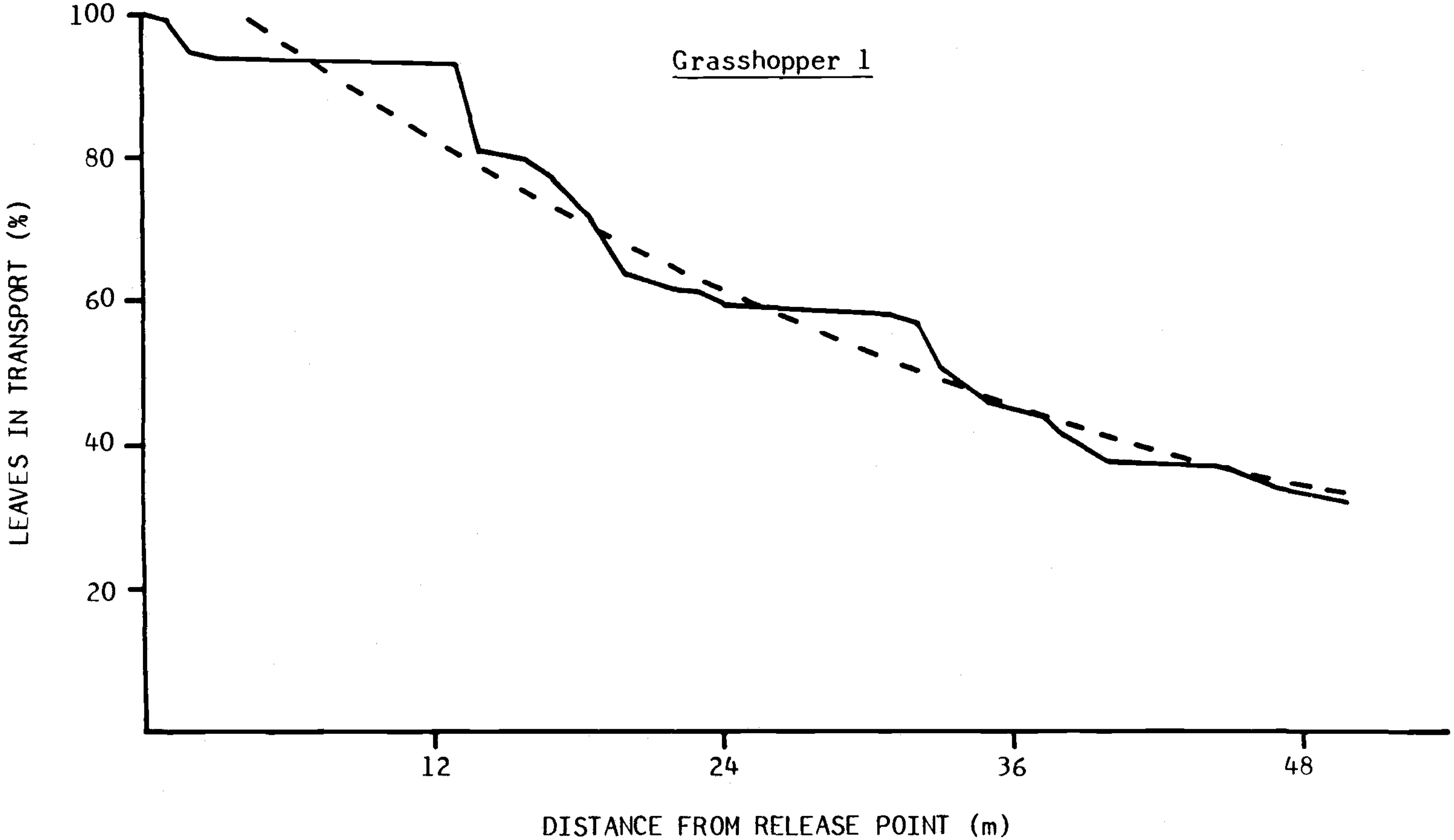

Figure C19. Leaf retention curve for reach Grasshopper 1.

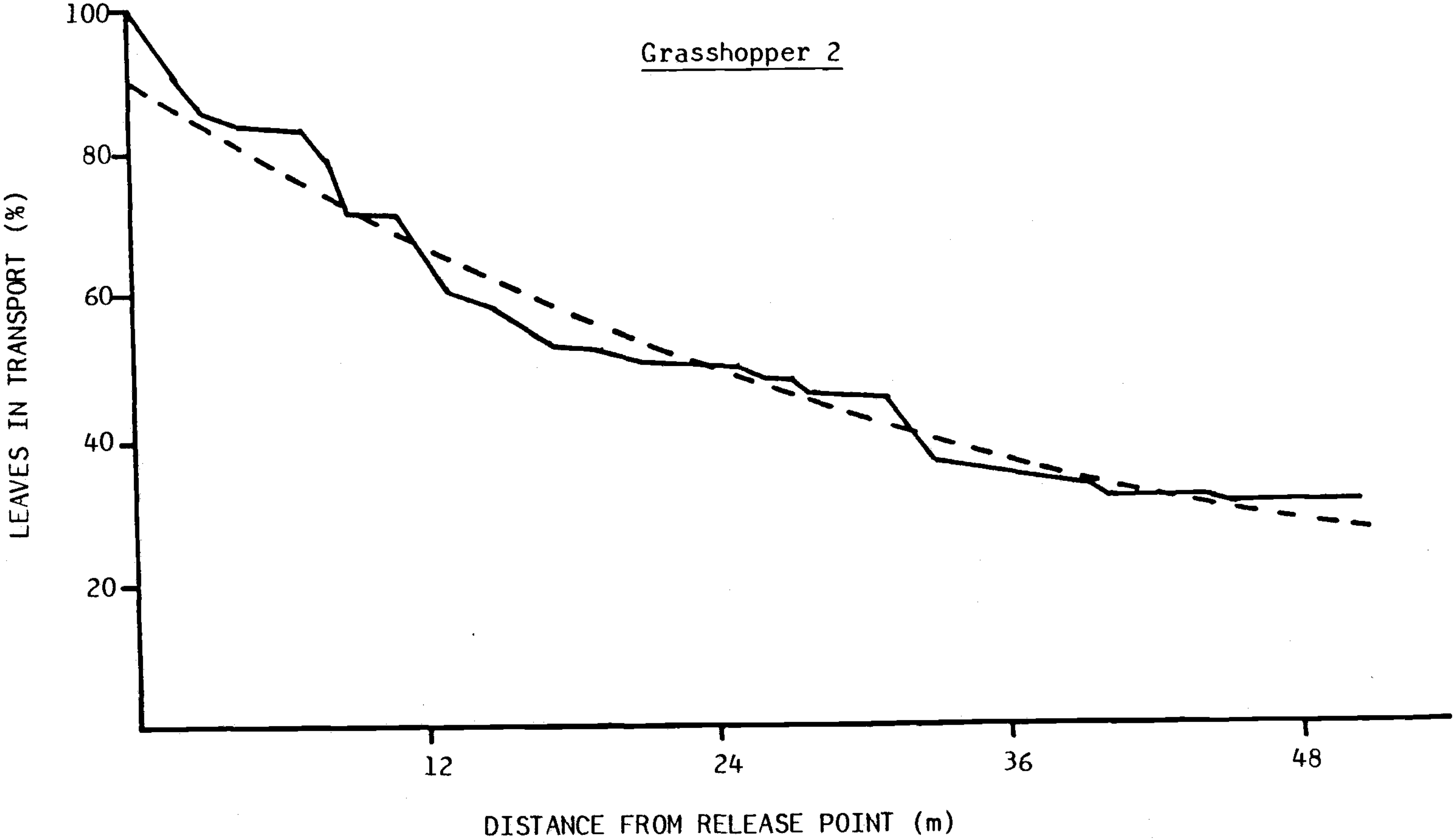

Figure C20. Leaf retention curve for reach Grasshopper 2.

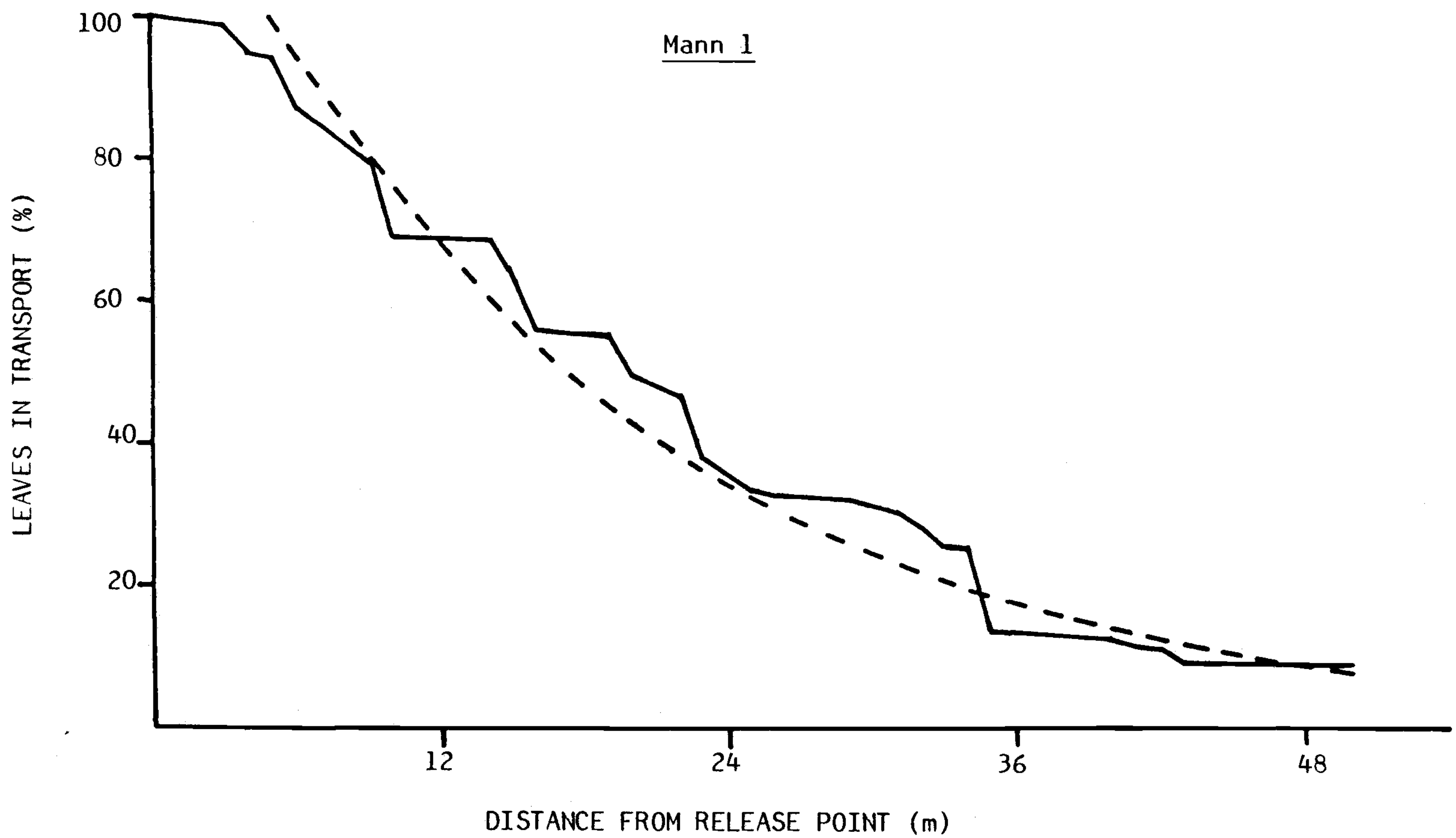

Figure C21. Leaf retention curve for reach Mann 1.

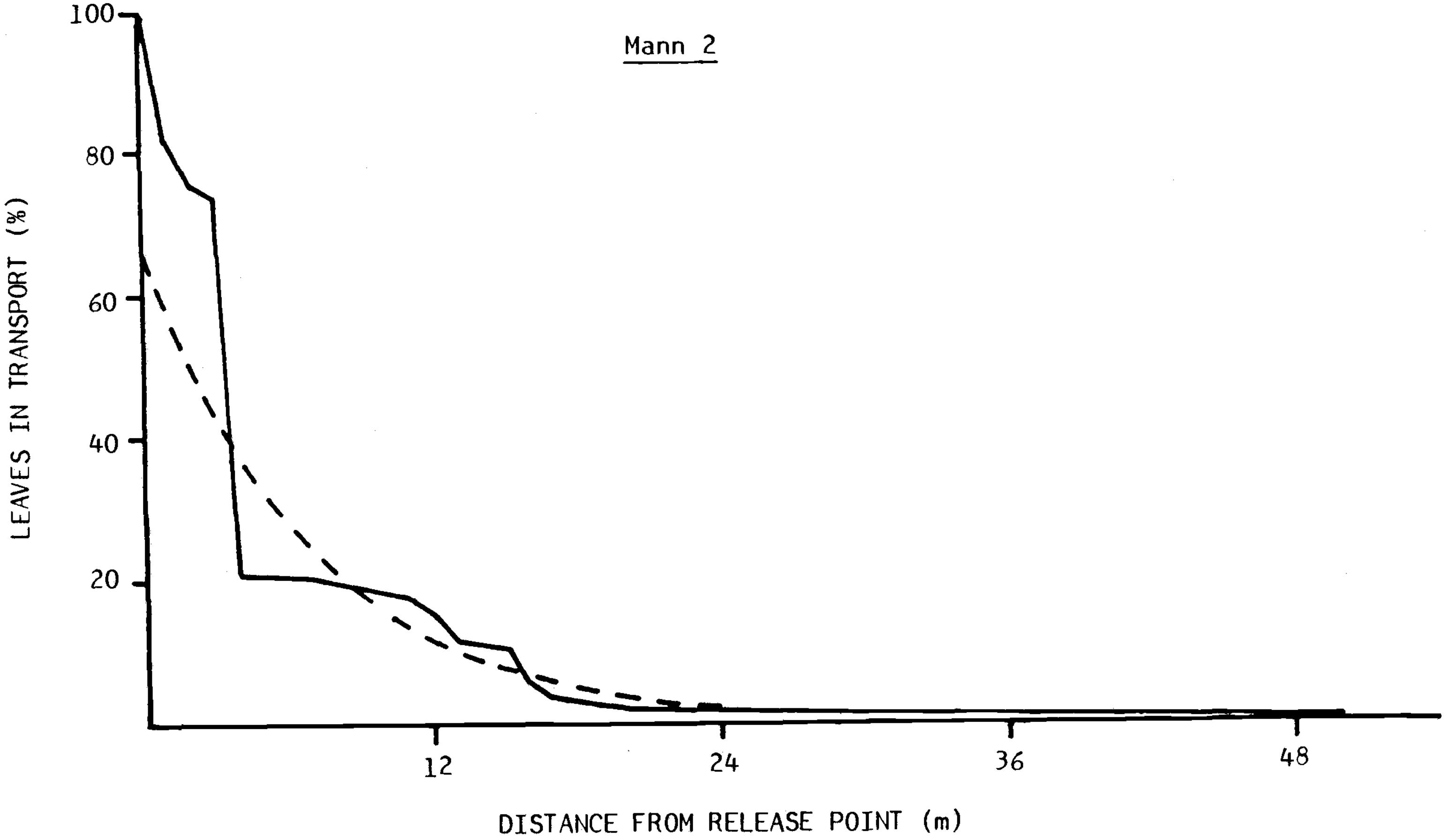

Figure C22. Leaf retention curve for reach Mann 2.

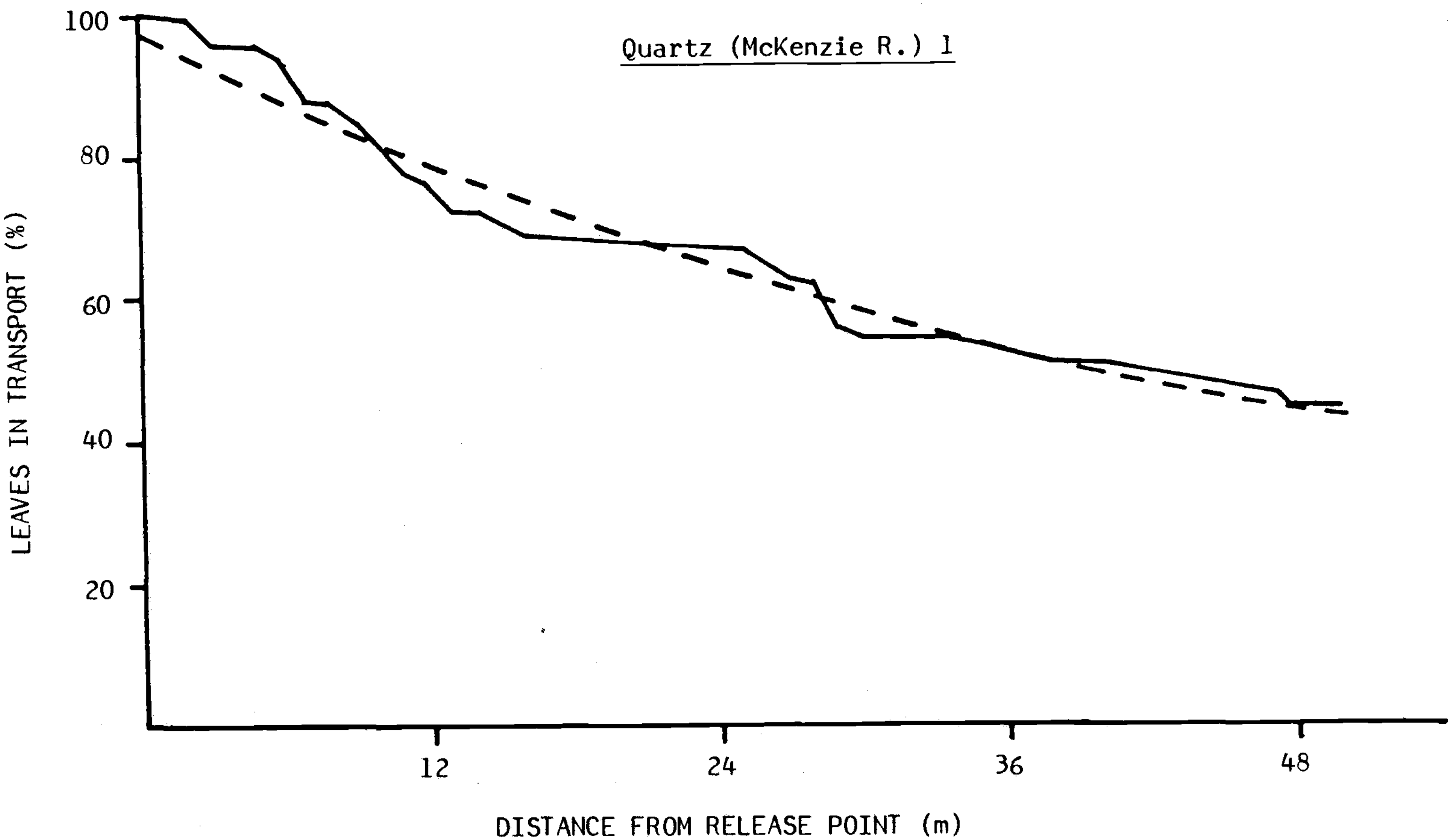

Figure C23. Leaf retention curve for reach Quartz (McKenzie R.) 1.

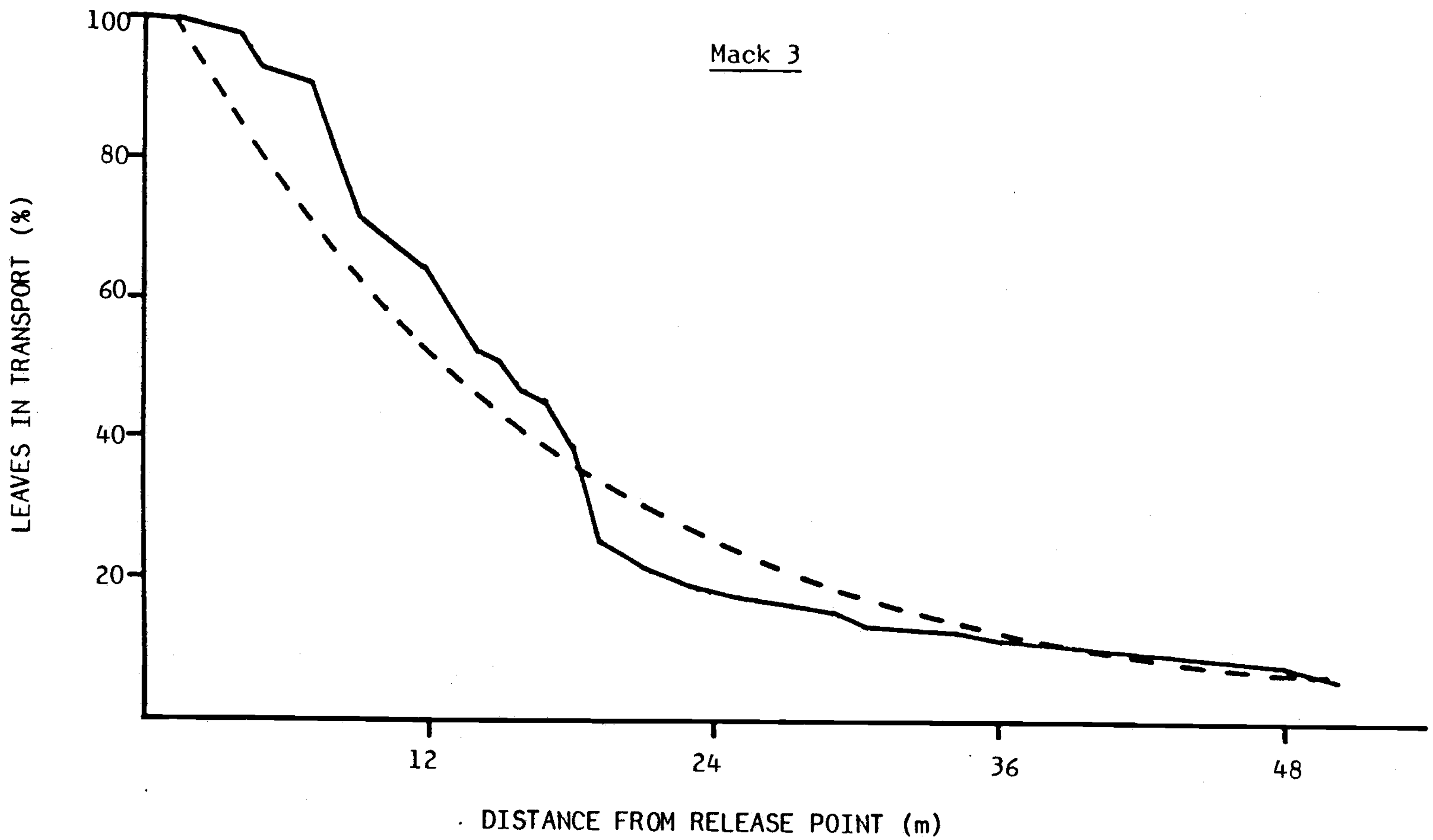

Figure C24. Leaf retention curve for reach Mack 3.

APPENDIX D.

Table D1. Standing crop of detritus by particle size in Mack Creek, Quartz Creek and Grasshopper Creek in summer of 1982.

	Pool Cobble			Pool Gravel			Margin Pool			Backwater			Debris Pool		
Particle Size (mm)	$\overline{X}$	sd	n	$\overline{X}$	sd	n	$\overline{X}$	sd	n	$\overline{X}$	sd	n	$\overline{X}$	sd	n
Mack Creek															
16	105.7	147.7	5	0.0	-	4	0.0	-	10	648.7	922.2	5	476.6	953.3	4
4	93.8	142.2		3.6	6.9		51.8	70.2		1684.2	1685.2		815.7	1027.6	
1	36.8	30.8		40.5	28.8		88.6	57.2		398.0	341.2		274.6	280.0	
0.25	27.0	17.0		45.7	33.1		102.3	73.3		526.3	480.4		33.1	332.8	
0.106	35.9	42.7		59.2	35.7		87.6	57.0		263.0	231.0		162.4	126.8	
0.053	58.3	64.1		52.0	23.0		93.0	42.0		353.3	283.9		318.5	305.2	
0.035	6.8	3.5		26.5	24.5		58.8	74.3		80.8	95.5		30.2	31.2	
0.010	7.7	7.3		32.7	30.8		53.9	48.3		163.3	205.4		44.0	55.3	
0.0007	3.3	3.1		6.9	8.5		11.0	9.3		36.4	56.0		9.6	6.1	
Total	375.4	295.7		267.0	176.6		548.9	480.4		4154.1	3810.1		2464.5	2273.5	
Quartz Creek															
16	22.2	26.8	5	44.1	85.0	5	0.0	-	10	354.6	699.1	5	No Sample		
4	10.7	7.4		16.9	12.9		12.8	10.4		808.3	1274.4				
1	18.7	13.4		67.9	62.7		67.0	33.5		331.4	369.7				
0.25	15.7	10.5		136.6	165.6		73.4	24.3		245.2	240.6				
0.106	19.2	16.4		54.0	56.6		79.4	38.4		133.6	97.0				
0.053	14.3	9.9		75.5	84.4		65.5	24.9		124.0	88.9				
0.035	8.4	6.6		44.8	49.6		43.3	36.6		61.0	44.2				
0.010	13.0	10.3		65.5	73.0		163.5	157.4		105.3	68.9				
0.0007	4.6	2.2		21.0	23.7		44.6	90.0		13.4	8.3				
Total	126.8	61.5		526.3	480.6		440.1	117.4		2176.8	2822.3				
Grasshopper Creek															
16	6.4	14.3	5	0.0	-	5	0.0	-	10	0.0	-	5	No Sample		
4	13.1	27.7		0.6	0.8		6.9	9.2		53.0	104.8				
1	5.7	4.4		22.6	15.6		40.7	36.0		65.5	61.7				
0.25	7.9	5.5		39.0	37.4		118.0	73.2		93.1	47.6				
0.106	7.8	6.6		20.8	14.5		93.4	53.9		76.4	38.7				
0.053	6.3	4.4		20.0	17.7		48.3	19.5		47.8	30.3				
0.035	4.5	2.8		13.9	12.1		26.6	15.7		32.1	28.4				
0.010	7.1	5.5		22.7	19.9		54.0	24.8		77.1	70.6				
0.0007	262	1.8		7.0	6.2		7.7	2.8		9.3	4.5				
Total	61.0	25.1		146.5	119.7		435.55	109.5		454.2	293.6				

Table D2. Standing crop of detritus by particle size in Mack Creek, Quartz Creek and Grasshopper Creek in summer of 1982.

Particle Size	Riffle Cobble			Riffle Gravel			Riffle Bedrock		
	$\overline{X}$	sd	n	$\overline{X}$	sd	n	$\overline{X}$	sd	n
Mack Creek									
16	0.0	-	5	0.0	-	5	0.0	-	5
4	1.8	1.3		5.7	4.5		1.2	1.8	
1	11.0	16.2		20.6	19.0		1.5	1.2	
0.25	10.2	15.2		22.8	20.4		1.8	1.3	
0.106	10.5	13.7		23.3	15.9		1.2	0.8	
0.053	16.0	23.6		45.7	48.3		2.0	0.5	
0.035	5.8	6.6		14.9	19.4		1.2	0.1	
0.010	2.7	1.2		26.5	44.4		1.0	0.5	
0.0007	1.9	1.4		6.9	10.1		1.5	0.5	
Total	60.0	69.9		166.4	164.8		11.5	5.4	
Quartz Creek									
16	5.1	8.0	5	0.0	-	5	0.0	-	2
4	2.7	2.3		27.6	26.7		0.0	-	
1	4.0	4.0		45.2	50.0		0.9	0.2	
0.25	2.7	2.2		21.7	18.0		0.6	0.2	
0.106	2.5	2.2		9.3	6.1		0.2	0.1	
0.053	3.7	2.0		14.3	8.5		0.6	0.1	
0.035	2.6	2.5		8.9	4.3		0.5	0.1	
0.010	4.0	3.3		21.7	8.6		0.7	0.0	
0.0007	1.3	0.2		7.6	6.9		1.1	0.4	
Total	28.6	17.4		156.3	118.7		4.5	0.2	
Grasshopper Creek									
6	0.0	-	5	0.0	-	5	0.0	-	5
4	1.0	1.1		8.8	15.8		0.0	0.1	
1	2.3	1.2		32.6	50.1		1.5	1.5	
0.25	2.5	2.2		1.6	8.3		5.2	5.7	
0.106	2.1	1.9		9.4	6.2		3.1	3.0	
0.053	2.3	1.5		9.8	6.3		2.2	2.0	
0.035	2.0	1.3		9.4	5.8		0.9	0.6	
0.010	3.5	2.3		14.5	8.5		1.3	1.0	
0.0007	1.5	1.1		7.2	6.6		0.7	0.7	
Total	17.2	11.6		103.5	83.4		15.0	12.9	

Table D3. Standing crop of detritus by particle size in Mack Creek, Quartz Creek and Grasshopper Creek in winter of 1983.

Particle Size (mm)	Riffle Cobble			Riffle Gravel			Riffle Bedrock		
	$\bar{X}$	sd	n	$\bar{X}$	sd	n	$\bar{X}$	sd	n
Mack Creek									
16	0.0	-	5	0.0	-	5	0.0	-	5
4	5.4	8.5		24.2	10.3		0.0	-	
1	14.1	19.6		78.3	71.4		1.9	1.5	
0.25	9.1	12.3		79.0	95.1		1.1	0.5	
0.106	5.2	6.9		49.1	53.8		0.5	0.3	
0.053	4.9	5.9		43.0	41.1		0.3	0.2	
0.035	2.5	2.2		24.4	18.9		0.3	0.1	
0.010	2.0	2.2		35.2	38.4		0.3	0.2	
0.0007	9.8	6.8		28.4	19.4		2.8	0.6	
Total	53.0	61.2		361.7	341.8		7.1	2.5	
Quartz Creek									
16	0.0	-	5	0.0	-	5	0.0	-	1
4	3.6	4.0		2.9	3.1		0.0	-	
1	6.5	4.3		23.6	11.5		0.7	-	
0.25	5.5	6.3		30.5	17.2		0.6	-	
0.106	1.7	1.3		41.6	17.8		0.3	-	
0.053	1.4	1.2		33.9	10.9		0.3	-	
0.035	0.9	0.6		17.6	4.3		0.4	-	
0.010	1.6	1.5		41.2	16.0		1.4	-	
0.0007	7.8	8.4		36.6	8.0		5.4	-	
Total	29.2	24.8		227.8	65.3		9.1	-	
Grasshopper Creek									
16	0.0	-	5	0.0	0.0	5	No Sample		
4	0.5	0.7		2.1	2.2				
1	3.0	2.0		26.9	19.4				
0.25	2.4	1.4		28.2	14.3				
0.106	1.7	1.1		26.8	27.7				
0.053	1.7	1.2		27.7	29.2				
0.035	1.2	1.1		20.2	15.7				
0.010	2.0	2.1		24.1	13.7				
0.0007	4.5	1.9		58.4	71.5				
Total	17.1	9.4		214.5	157.9				

Table D4. Standing crop of detritus by particle size in Mack Creek, Quartz Creek and Grasshopper Creek in winter 1983.

Particle Size (mm)	Pool Cobble $\overline{X}$	Pool Cobble sd	Pool Cobble n	Pool Gravel $\overline{X}$	Pool Gravel sd	Pool Gravel n	Margin Pool $\overline{X}$	Margin Pool sd	Margin Pool n	Backwater $\overline{X}$	Backwater sd	Backwater n	Debris Pool $\overline{X}$	Debris Pool sd	Debris Pool n
Mack Creek															
16	56.6	126.5	5	176.4	394.4	5	44.5	99.5	5	128.6	287.6	5	850.8	1568.0	5
4	28.7	39.2		96.1	82.4		284.5	498.5		752.4	888.9		1368.4	1706.1	
1	43.2	49.1		195.6	80.5		312.8	269.5		413.0	300.6		771.8	852.2	
0.25	21.2	24.5		242.1	168.9		317.8	259.8		399.4	266.1		512.0	536.1	
0.106	9.0	10.4		142.8	111.4		170.7	131.7		233.5	121.8		231.2	182.0	
0.053	7.8	8.7		112.0	83.1		122.5	89.9		185.6	95.2		164.5	118.5	
0.035	5.2	6.0		58.9	29.7		70.4	41.3		72.0	49.8		77.4	78.9	
0.010	3.4	3.5		81.0	66.6		118.2	90.0		220.2	151.0		104.5	64.3	
0.0007	14.2	15.6		66.3	47.3		77.0	58.0		148.4	82.2		87.1	60.7	
Total	189.1	245.7		1171.2	491.5		1518.4	1509.8		2553.0	1788.4		4185.6	5036.8	
Quartz Creek															
16	51.2	114.1	5	0.0	-	5	351.0	784.9	5	602.3	1238.9	6	No Sample		
4	2.5	3.1		13.4	13.2		495.5	782.2		436.7	274.6				
1	7.4	9.5		54.1	39.1		139.8	170.3		325.5	195.4				
0.25	3.0	4.1		55.5	31.3		103.5	88.8		303.4	291.4				
0.106	2.0	2.9		32.3	13.0		69.6	47.0		149.9	135.3				
0.053	2.0	3.1		26.1	7.7		52.2	16.8		94.4	77.1				
0.035	1.4	1.3		12.5	2.0		29.4	9.2		40.3	31.2				
0.010	2.1	3.2		37.3	22.7		74.3	22.1		137.6	167.6				
0.0007	3.6	2.2		32.5	10.6		49.9	23.1		62.9	42.8				
Total	75.0	105.7		263.7	96.1		1360.7	1868.9		2152.9	1431.7				
Grasshopper Creek															
16	0.0	-	5	0.0	-	8	0.0	-	8	148.7	332.6	5	No Sample		
4	8.7	6.3		15.8	27.8		28.5	25.9		311.9	547.2				
1	15.6	14.8		25.3	20.3		50.2	23.4		787.6	1463.4				
0.25	9.8	6.3		24.0	12.8		39.7	13.9		270.3	283.0				
0.106	11.0	7.4		24.1	12.2		44.7	13.3		200.0	203.9				
0.053	9.4	8.0		25.6	15.2		46.2	16.0		124.9	114.9				
0.035	6.9	8.1		9.2	5.4		29.8	15.4		28.4	18.5				
0.010	6.7	9.2		10.3	7.3		30.1	22.3		24.7	17.2				
0.0007	13.5	12.2		28.8	12.4		64.8	18.0		73.4	47.1				
Total	81.6	34.5		163.1	77.9		334.1	73.5		1969.9	2982.6				