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Hydraulic dispersion and reach-averaged velocity as indicators of enhanced organic matter transport in small Puget Lowland streams across an urban gradient

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With 8 figures and 3 tables

Abstract: Organic matter transport and retention were evaluated in 14 small streams representing a range of riparian vegetation disturbance and watershed development levels in the Puget Lowland of western Washington. To determine relative transport and retention, diamond-shaped acetate strips of similar size and density to leaves were released in riffles during low-flow conditions. Simultaneous dissolved tracer releases were used to measure hydraulic characteristics of each reach. Both reach-averaged velocity and hydraulic dispersion predicted median leaf-surrogate material travel distance ($R^2 = 0.87$, $p < 0.001$) and characterized transport and retention over longer reach lengths than in traditional organic matter release experiments. Relative organic matter transport distance increased as the pool/riffle ratio decreased, reach-averaged velocity increased, and dispersion increased. Because urban development affects hydraulic characteristics, urbanization enhances organic matter transport in small streams, reducing the retention of organic matter available for biotic processes.

Key words: organic matter, transport, retention, stream, urban, disturbance, dispersion.

Introduction

Terrestrial organic matter represents an important source of energy and nutrients in many small streams (Vannote et al. 1980, Triska et al. 1984), and availability affects overall ecosystem structure and function (Wallace et al. 1997). Once organic matter reaches streams, various biotic and abiotic processes transport and decompose the materials (Webster et al. 2000). Riparian vegetation type determines the amount of litterfall reaching streams (Bray & Gorham 1964, Gregory et al. 1987, Bilby & Bisson 1992) and also affects the physical hydraulic structure by influencing the channel complexity of small streams (reviewed in Tabacchi et al. 2000). The physical complexity, in turn, affects the retention of leaves and other organic matter (Bilby & Likens 1980). Lower retentiveness decreases storage and availability of organic matter that may support macroinvertebrates relying on detritus as food or shelter (Laasonen et al. 1998). Organic matter transport thus regulates energy exchanges in streams.

Factors that affect relative leaf retention include stream order and discharge (Young et al. 1978, Jones & Smock 1991, Snaddon et al. 1992, Larrañaga et al. 2003, Pretty & Dobson 2004), channel gradient (Larrañaga et al. 2003), channel depth (Speaker et al. 1984), substrate texture (Speaker et al. 1984, Webster

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et al. 1994, Oelbermann & Gordon 2000, Mathooko et al. 2001, Larrañaga et al. 2003), and elements of channel complexity such as the pool/riffle (P/R) ratio (Lamberti et al. 1989, Muotka & Laasonen 2002, Brookshire & Dwire 2003).

Watershed-scale urbanization directly and indirectly affects a variety of processes that influence organic matter availability in small streams, including hydrology, geomorphology, and riparian vegetation characteristics. Increased impervious surface area and enhanced hydraulic connectivity accelerate the transport of stormwater from land surfaces to streams, increasing peak discharge and storm flow frequency (Booth 1991, Booth et al. 2002, Konrad et al. 2005). At high levels of impervious surfaces, frequent high-flow pulses occur in response to even low-intensity rain events (Burges et al. 1998, Konrad & Booth 2002). Traditional stormwater and flood-control practices also directly reduce channel complexity through channel straightening and removal of woody debris, practices that destabilize stream channels (Booth et al. 2002).

Urbanization has altered the composition of riparian forests. Historically, large conifers dominated many riparian areas in the Puget Lowland, but short-lived deciduous species, especially red alder (*Alnus rubra*), or shrubs and herbaceous vegetation now dominate many river valleys (Collins & Montgomery 2002). As the dead wood produced by large conifers is removed or eventually decomposes, the current riparian forest cannot replace this material. The loss of in-channel wood results in reduced channel complexity. Streams with simplified channel geomorphology have fewer sites where particulate organic matter can accumulate, decreasing organic matter retention and enhancing transport (Bilby & Likens 1980).

Previous studies of organic matter transport have introduced material into streams and documented downstream progress. Released materials have included both leaves and surrogate materials that are highly visible yet possess the relative transport characteristics of natural organic matter. Leaves of tree species native to a site (Oelbermann & Gordon 2000, Larrañaga et al. 2003) are problematic in that they cannot be easily distinguished from natural material (e.g., Muotka & Laasonen 2002). To reduce this problem, many studies have employed either leaves that can be easily distinguished from those naturally input to the study stream (e.g., painted or dyed natural leaves [Jones & Smock 1991, Chergui et al. 1993, Mathooko et al. 2001, Pretty & Dobson 2004], non-native leaves [Ehrman & Lamberti 1992, Brookshire & Dwire 2003]) or artificial materials (e.g., flagging tape [Bilby 1981], plastic strips [Speaker et al. 1988, Webster et al. 1994, Wallace et al. 1995, Richardson & Maxcy 1997, Díez et al. 2000, Larrañaga et al. 2003], or Rite in the Rain™ paper [Brookshire & Dwire 2003]).

Experimental design of these studies varied widely. The numbers of surrogate material pieces released to characterize a given stream reach range from 20 (Pretty & Dobson 2004) to over 1,000 (Muotka & Laasonen 2002, Larrañaga et al. 2003). Time between release and collection generally has ranged from 1 minute (Pretty & Dobson 2004) to three hours (Díez et al. 2000, Muotka & Laasonen 2002, Larrañaga et al. 2003), although a few studies have used time periods of months between release and collection (Bilby & Likens 1980). Despite the variation in materials and time between release and recovery, the frequency with which this technique has been employed indicates its overall effectiveness.

A parallel approach commonly has been used to assess the movement of dissolved materials through streams or to characterize patterns of water movement (Roberts et al. 2007). Addition of solutes to stream water to trace the movement of the material downstream has indicated that hydraulic characteristics of the channel, such as reach-averaged velocity and dispersion, are primary determinants of the movement of dissolved materials. Reach-averaged velocity represents the cumulative velocity over multiple pool/riffle units, determined from the travel time of a solute between two points of known distance along a stream. Hydraulic dispersion refers to the spread of solute as water parcels travel downstream. These two hydraulic attributes are related to various hydrologic and morphologic channel characteristics. Wilcock et al. (1999) found longitudinal dispersion was positively related to stream discharge and velocity. They also documented the effects of aquatic macrophytes on the velocity structure, which also resulted in differences in dispersion. Koussis & Rodríguez-Mirasol (1998) found longitudinal dispersion varied with stream depth, width, wetted cross section, and channel slope. However, the relationship between hydraulic characteristics of a stream reach and leaf transport and retention has not been evaluated.

The objectives of this study were to evaluate relative organic matter transport by streams across watershed- and local-scale disturbance gradients using surrogate leaf materials, and to evaluate whether transport was related to two hydraulic characteristics, reach-averaged velocity and hydraulic dispersion.

Methods

Study area description

Hundreds of small streams flow through the Puget Lowland ecoregion of western Washington, bounded to the west by the Olympic Mountains and to the east by the Cascade Range. The lowland was formed during repeated glaciations that produced plateaus of glacial till and outwash deposits generally ranging from 50 m to 150 m above sea level. The Green and Gold Mountains on the Kitsap Peninsula rise to 540 m above sea level and consist of a combination of volcanic bedrock and upland deposits of glacial till. Streams generally trend north–south as a result of glacial fluting and typically exhibit a pool/riffle morphology. Annual precipitation varies from 800 to 1300 mm across the study area.

Widespread timber harvesting occurred in the Puget Lowland in the late 1800s and early 1900s, followed by increasing residential and commercial development from the early 1900s to present. The eastern shore of Puget Sound developed early in this succession, due to economic activity in Seattle and Tacoma (Fig. 1). Between 1980 and 2005, however, the population of Kitsap County, on the western shore of Puget Sound, increased by 63 % (Washington State Office of Financial Management 2006), although the absolute level of development is still considerably lower than in the Seattle-Tacoma area. Riparian vegetation disturbance patterns reflect these spatial and temporal patterns of human activity, with riparian disturbance on the Kitsap Peninsula more recent and less extensive compared with the Seattle-Tacoma area.

Study site selection

Study sites were selected using a stratified-random approach based on local riparian vegetation disturbance level. Small streams with watershed areas between 4 and 24 km^2 were identified using a 30-m digital elevation model. In each watershed, primary stream centerlines were refined using orthophotos and segmented at 100-m intervals. Only accessible points, defined as those within 1 km of a road or trail, were retained.

Each stream segment was assigned to an initial local riparian vegetation disturbance class based on qualitative field observations supplemented by orthophoto interpretation. Four disturbance categories were recognized. Reference vegetation (REF) was defined by the presence of mature conifer-dominated and mixed riparian forests. While not pristine, these areas

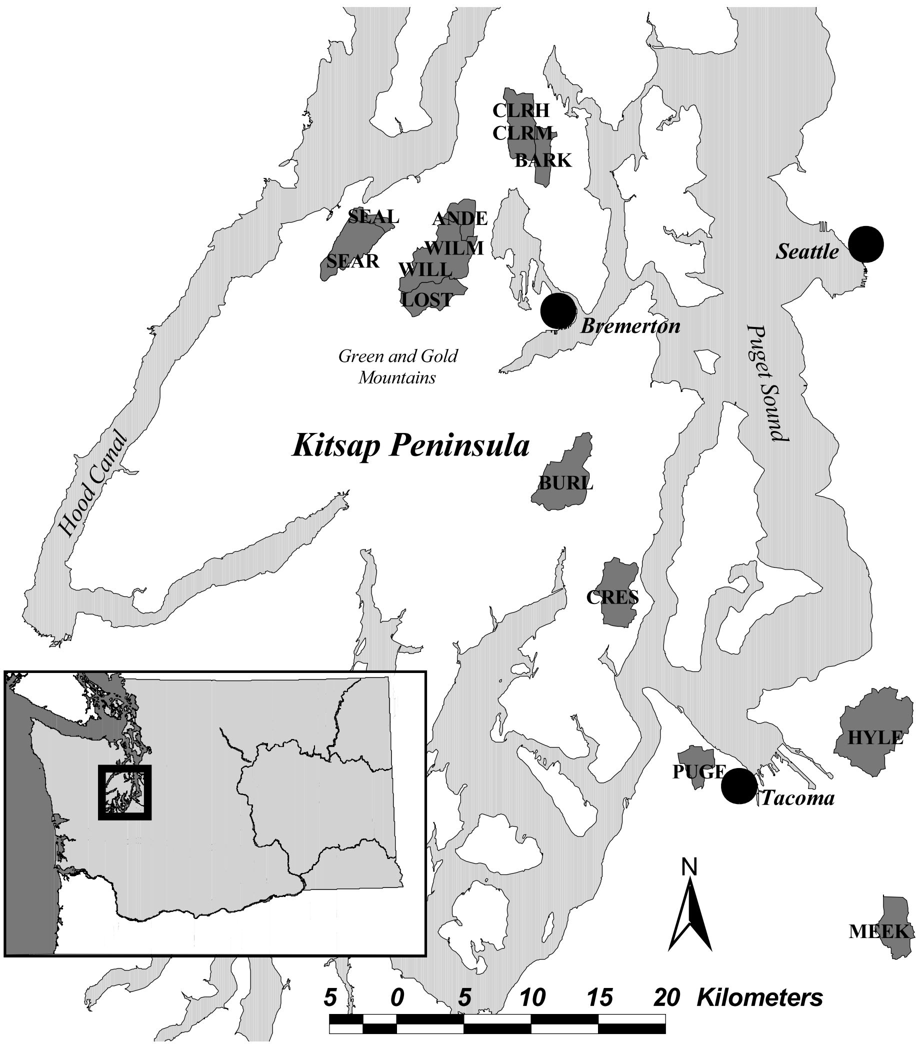

Fig. 1. Study site locations.

represented the lowest level of human disturbance existing in the study area. Low-disturbance sites (LOW) were defined by mature, deciduous-dominated vegetation with a few conifers. Medium-disturbance sites (MED) included a range of vegetation characteristics, from very young natural vegetation to residential landscaping to restoration sites with native vegetation plantings. High-disturbance sites (HIGH) generally lacked overstory trees and herbaceous vegetation dominated. Ten sites were identified randomly within each class. Property owners were contacted to request initial access to the locations; if permission to monitor that reach was not given, the site was removed from consideration. This process enabled us to identify four sites within each initially defined disturbance level.

Categorical riparian vegetation disturbance levels were subsequently corrected based on more intensive field data of vegetation at the selected study sites, as described in Roberts (2007). The final study design included four sites within each disturbance class, but one medium- and one high-disturbance site subsequently were discontinued due to persistent vandalism.

Although study sites were selected on the basis of local riparian vegetation disturbance, the study sites also reflected a range of watershed development levels that indirectly affect hydraulic characteristics, channel geomorphology, and, potentially, organic matter transport within the streams. Therefore, both watershed-scale development and local-scale riparian vegetation disturbance level were compared with transport metrics.

Watershed land cover characteristics were determined from a 1998 LandSat Thematic Mapper image (Hill et al. 2003). Total impervious area (TIA) was estimated from the land cover analysis using previously developed relationships for the Puget Lowland between land cover and percent TIA (Dinicola 1990) and sites were categorized as high, medium, or low development based on TIA. Local channel slope was determined from USGS quadrangle maps.

Field methods

Discharge was determined using the velocity-area method (Marsh-McBirney® velocity meter) once during summer low-flow conditions. These flows also are typical of autumn non-storm conditions, when highest litterfall inputs occur (Roberts 2007). Measurements were taken at riffles, and station velocity (V_{sta}) was determined as the average velocity at the cross-section.

The channel morphology, defined as the relative cumulative length of pools and riffles in a 100-m study reach, was determined during summer low-flow conditions. Pools were defined as water features with subcritical flow characteristics where waves propagate upstream, and riffles as supercritical reaches where waves do not propagate upstream. Most studies quantify pool/riffle (P/R) ratios using the relative lengths of pools and riffles in a reach during low-flow conditions. This approach assumes that low-flow conditions reflect other ecologically meaningful conditions and that relative length accurately represents pool and riffle area. These assumptions were assessed by repeating the pool/riffle surveys during high spring discharges and by comparing P/R ratio derived from length with those based on area. For a subset of eight streams, two in each vegetation disturbance category, spring and summer pool and riffle areas were quantified for four randomly selected pools and four randomly selected riffles.

The number of wood jams per 100-m reach was tabulated as an additional indicator of relative reach complexity. Jams were defined as containing at least three pieces of wood (minimum size 10-cm diameter and 1-m length) within the wetted margin.

Reach-averaged velocity was determined using a pulse release of saturated salt solution at the top of a riffle (Hubbard et al. 1982). Reach lengths for hydraulic characterization varied with P/R structure, ranging from 14 m to 108 m based on the hydraulics and geomorphology at each site. Measured reach lengths at some sites were shortened due to sluggish velocities or a change in geomorphology. For example, the release at WILL used a reach length of 34 m due to the low flow velocity (0.004 m s^{-1}) and consequent very long travel time (4.9 h). Reach length at CRES was decreased because of a wood constriction near the upstream end of the reach that would have affected surrogate leaf travel. Salt tracer release locations were shifted to the nearest upstream riffle of the modified study reach to achieve rapid mixing of the solute. Measurement locations also were shifted to the nearest downstream riffle. At least two pool-and-riffle sequences, and generally five to nine such units, were included in each study reach.

Enough salt solution was released to be easily detectable above background levels, but peak conductivities did not exceed 1000 μmhos cm^{-1} at the release location or 400 μmhos cm^{-1} at the bottom of the reach. A Hanna Instruments (model HI-9033) conductivity meter, calibrated to a solution of 100 μmhos cm^{-1} and self-compensating for temperature, recorded conductivity at a point downstream from the salt release. Conductivity was recorded until in situ values approached background levels.

Estimating reach-averaged velocity and hydraulic dispersion

Reach-averaged velocity was determined from the travel time of the tracer concentration center of mass from the release point to the conductivity recorder. Hydraulic dispersion, also called mechanical or longitudinal dispersion, was determined from the time-varying tracer concentration. Dispersion results from velocity variations within the stream, and it includes the effects of vertical velocity variations together with turbulent mixing.

Dispersion is analogous to molecular diffusion and is represented using a form of Fick's first law. In cases where dispersion in one dimension is of primary interest, such as in streams, the longitudinal dispersion coefficient characterizes mixing, which increases as the velocity distribution becomes more complex.

The one-dimensional mass transport equation

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = D_L \frac{\partial^2 C}{\partial x^2}$$

can be solved for solute concentration (C) resulting from an instantaneous tracer release:

$$C = \left[\frac{M}{2A\sqrt{\pi D_L t}}\right] e^{\frac{-(x-Ut)^2}{4D_L t}}$$

where m is total solute mass, A is the stream cross-sectional area, M is the dispersion coefficient, x is longitudinal distance, U is reach-averaged velocity determined from the tracer study, and t is time. The form of the equation is Gaussian with respect to location but not strictly with time, since time is retained in the denominator. When using conductivity, solute mass is not easily measured in the field but can be estimated based on the maximum concentration (C_{max}) observed and the time from the release:

$$C_{max}(t) = \frac{M}{2A\sqrt{\pi D_L t}} \quad .$$

Therefore, the reach-averaged velocity and dispersion coefficient, the two quantities of interest in tracer studies, can be found from the simultaneous solution of the two equations using a best fit to the concentration data. Microsoft Excel® Goal Seek was used to minimize the root-mean-square error between the estimated and measured reach conductivity.

Surrogate leaf travel distance

Relative transport and retention of leaf litter were determined using surrogate leaf materials. A small-scale trial compared the relative transport of a variety of materials with that of red alder leaves to select the best material. Materials included yellow- and orange-colored acetate, red alder leaves colored with permanent marker, white cotton cloth, yellow fabric, heavy pink polyethylene, medium orange polyethylene, and orange coated nylon. Materials were cut into diamond or leaf shapes approximately the same size as red alder leaves. These preliminary tests indicated that the acetate pieces most closely represented the transport behavior of the alder leaves and were easy to relocate in the stream.

To determine leaf transport distance, 50 orange, diamond-shaped acetate surrogate leaves, approximately 7.8 cm × 7.8 cm × 0.16-mm thick and weighing 1.2 g, were released at the head of a riffle for each experimental run. We observed that surrogate leaves released at summer low-flow conditions rapidly caught on obstacles and no appreciable movement occurred after several minutes. As a result, distance traveled was recorded for each surrogate leaf within one hour of release.

For the surrogate leaf materials, the median distance traveled was used as a measure of central tendency, because the distances were not normally distributed. The interquartile range, or the difference between the 25th and 75th percentile distances, was used to characterize the spread in the travel distance of the surrogate materials. Skewness was calculated as an indication of the degree of asymmetry in the distribution. Previous studies (Speaker et al. 1988, Larrañaga et al. 2003) estimated mean travel distance by fitting a first-order decay relationship then calculating mean distance as the inverse of the decay coefficient (k):

$$N(x) = N_o e^{-kx}$$

where N(x) is the number of leaves passing a distance x from the release and N_o is the total number of materials released. However, while much of the variability was described by these relationships ($R^2 = 0.55$ to 0.97), the few leaves that traveled the farthest heavily influenced the mean travel distance. Therefore, we used median distance.

Statistical analyses

Relationships among transport parameters and channel hydraulic characteristics were based on linear regression, while ANOVA and Student's t-tests were used to compare hydraulics and leaf transport characteristics among watershed and local riparian disturbance classes. The Tukey test was used for multiple comparisons. For all tests, $\alpha \leq 0.05$ was used to determine significance.

Results

Site characteristics

Developed land (high- and low-density developed, and bare ground) ranged from 5 % to 18 % of the watershed areas for sites with REF or LOW riparian vegetation disturbance, while sites with MED or HIGH riparian vegetation disturbance levels had 20 % to 63 % developed land (Roberts 2007). Forest cover (conifer, mixed, and deciduous forest classes) ranged from 30 % to 45 % for the less-disturbed riparian vegetation sites, but only 5 % to 32 % for the more disturbed sites. Local riparian vegetation disturbance level was related to total impervious area (TIA) (ANOVA, p = 0.044 for four treatments with BURL), as found for other areas of the Puget Lowland (Morley & Karr 2002). Table 1 summarizes site characteristics.

The BURL watershed exhibited a local groundwater anomaly with much higher discharge than would be expected on the basis of tributary area. The summer unit discharge at BURL was four times the next highest value and an order of magnitude greater than that at some of the study reaches, indicating a much different hydrologic regime at this site. No data were available to anticipate or quantify this effect a priori. Because the site represented an anomaly in many of our analyses, statistical parameters do not include BURL except where noted.

Discharge was low but considerably variable among sites. While summer baseflow was greater in the three watersheds with the greatest TIA (ANOVA, p = 0.034), the regression relationship was not significant (p = 0.119). However, discharge per unit area (Q/A) increased with increasing TIA and the relationship was significant (p = 0.034). Table 2 summarizes regression relationships for continuous variables.

The cross-sectional station velocity calculated from the discharge measurement was greater than the solute-derived reach-averaged velocity at most sites, since discharge measurements generally were conducted within fast-moving riffles. The reach-averaged velocity represented the net effect of riffle and pool velocities in the study reaches. Channel slope was related to station velocity and median transport distance but was not related to reach-averaged velocity, summer pool/riffle (P/R) ratio, or watershed characteristics.

Table 1. Organic matter transport study site characteristics. Land cover is presented as percent developed land (DEV) and percent forest cover (FOR), with the remainder consisting of shrubby vegetation, as described in Roberts (2007). Total impervious area (TIA) was estimated from land cover relationships. Watershed (WS) development level is categorized as low (L, TIA ≤ 7.3 %), medium (M, 7.9 < TIA < 10.2 %), or high (H, TIA ≥ 19.2 %). Riparian vegetation disturbance refers to levels documented in Roberts (2007). A is watershed area, Q is discharge, and Q/A is the unit discharge normalized by watershed area. Slope was determined from USGS quadrangle maps. V_{sta} refers to the instantaneous station velocity derived from discharge measurements. P/R is the pool/riffle ratio, presented as both feature length ratios ($m\ m^{-1}$) and feature area ratios ($m^2\ m^{-2}$). LWD is large woody debris. U is the reach-averaged velocity and D is the hydraulic dispersion determined from the tracer study. Surrogate release distances are presented as the median (X_{med}) and the interquartile range (IQR), or spread between the 25th and 75th percentile travel distances. Positive skewness indicates that the average travel distance exceeds the median.

	Watershed					Local		Discharge			Summer Pool/Riffle			Tracer Study		Surrogate Release		
Station	A (km^2)	DEV (%)	FOR (%)	TIA (%)	WS development	Riparian Vegetation	Slope (%)	Q ($m^3\ s^{-1}$)	Q/A ($m^3\ s^{-1}\ km^{-2}$)	V_{sta} ($m\ s^{-1}$)	P/R ($m\ m^{-1}$)	P/R ($m^2\ m^{-2}$)	LWD Jams	U ($m\ s^{-1}$)	D ($m^2\ s^{-1}$)	X_{med} (m)	Interquartile Range (m)	Skewness
ANDE	4.2	18	44	7.3	L	REF	2.1	0.001	0.0002	0.09	1.0	1.6	2	0.03	0.038	0.5	0.9	0.3
LOST	7.3	2	37	4.2	L	REF	1.7	0.012	0.0017	0.08	1.2	1.3	0	0.08	0.135	1.4	1.1	2.1
SEAR	10.3	5	45	4.3	L	REF	1.6	0.002	0.0002	0.02	1.1		0	0.01	0.023	0.8	0.6	1.5
WILM	15.8	9	45	5.2	L	REF	1.3	0.003	0.0002	0.06	1.2	0.9	3	0.02	0.062	1.2	1.4	2.3
BURL	14.6	18	30	7.9	M	LOW	1.3	0.270	0.0185	0.41	0.5	0.6	6	0.52	0.443	17.1	5.4	0.0
CRES	11.2	9	48	5.0	L	LOW	1.1	0.023	0.0021	0.15	1.4		5	0.01	0.014	1.2	0.5	0.8
SEAL	12.7	5	44	4.4	L	LOW	1.9	0.019	0.0015	0.30	1.1		0	0.08	0.143	1.0	1.0	2.3
WILL	6.4	8	39	5.3	L	LOW	1.9	0.001	0.0001	0.11	1.5		4	0.004	0.003	0.1	0.0	4.7
BARK	4.9	20	32	8.8	M	MED	0.8	0.019	0.0039	0.15	0.4	0.4	2	0.13	0.356	3.7	0.6	0.3
CLRM	9.7	23	30	10.2	M	MED	0.4	0.013	0.0014	0.07	0.7		0	0.13	0.074	1.5	0.5	1.4
PUGE	5.0	60	5	29.5	H	MED	4.5	0.024	0.0047	0.21	0.2	0.2	0	0.28	0.465	7.9	7.7	1.2
CLRH	8.7	23	32	9.6	M	HIGH	0.4	0.009	0.0011	0.11	2.6	3.0	0	0.09	0.132	1.2	0.8	–0.3
HYLE	18.8	40	20	19.2	H	HIGH	1.7	0.067	0.0036	0.27	0.2	0.2	0	0.37	0.359	6.9	3.4	1.9
MEEK	14.8	44	8	22.4	H	HIGH	0.3	0.010	0.0007	0.08	+		0	0.05	0.042	0.3	0.3	1.3

+ Study reach had no riffles

Table 2. Regression relationships (R^2) among watershed development, local riparian vegetation disturbance, geomorphology, hydraulics, and surrogate leaf transport characteristics. Bold italicized values are significant. See Table 1 for abbreviations.

	A (km^2)	DEV (%)	FOR (%)	TIA (%)	Q ($m^3\ s^{-1}$)	Q/A ($m^3\ s^{-1}\ km^{-2}$)	Slope	V_{sta} ($m\ s^{-1}$)	Summer P/R ($m\ m^{-1}$)	Summer P/R ($m^2\ m^{-2}$)	Spring P/R ($m\ m^{-1}$)	U ($m\ s^{-1}$)	D ($m^2\ s^{-1}$)	X_{med} (m)	IQR (m)
A (km^2)	1.000	0.005	0.007	0.011	0.234	0.011	0.111	0.052	0.003	0.037	0.058	0.043	0.009	0.002	0.005
DEV (%)		1.000	***0.871***	***0.973***	0.205	***0.349***	0.120	0.100	0.251	0.185	0.050	***0.487***	***0.408***	***0.500***	***0.517***
FOR (%)			1.000	***0.916***	0.160	0.304	0.060	0.065	0.256	0.219	0.041	***0.425***	***0.367***	***0.384***	***0.381***
TIA (%)				1.000	0.206	***0.348***	0.159	0.108	0.295	0.246	0.096	***0.479***	***0.404***	***0.503***	***0.560***
Q ($m^3\ s^{-1}$)					1.000	***0.492***	0.021	***0.532***	0.253	0.279	0.108	***0.734***	***0.415***	***0.554***	0.203
Q/A ($m^3\ s^{-1}\ km^{-2}$)						1.000	0.191	***0.408***	***0.395***	***0.460***	0.091	***0.660***	***0.861***	***0.805***	***0.504***
Slope							1.000	***0.393***	0.225	0.262	***0.345***	0.165	0.261	***0.350***	***0.682***
V_{sta} ($m\ s^{-1}$)								1.000	0.130	***0.343***	0.099	***0.423***	***0.389***	***0.347***	0.220
Summer P/R ($m\ m^{-1}$)									1.000	***0.933***	***0.741***	***0.791+***	***0.820+***	***0.473***	0.288
Summer P/R ($m^2\ m^{-2}$)										1.000	***0.755***	***0.346***	***0.459***	***0.517***	0.291
Spring P/R ($m\ m^{-1}$)											1.000	0.124	0.090	0.208	0.209
U ($m\ s^{-1}$)												1.000	***0.755***	***0.866***	***0.553***
D ($m^2\ s^{-1}$)													1.000	***0.872***	***0.610***
X_{med} (m)														1.000	***0.764***
IQR (m)															1.000

+ Values ignore CLRH. With station CLRH, regressions still significant but R^2 values decline to 0.388 for U and 0.392 for D

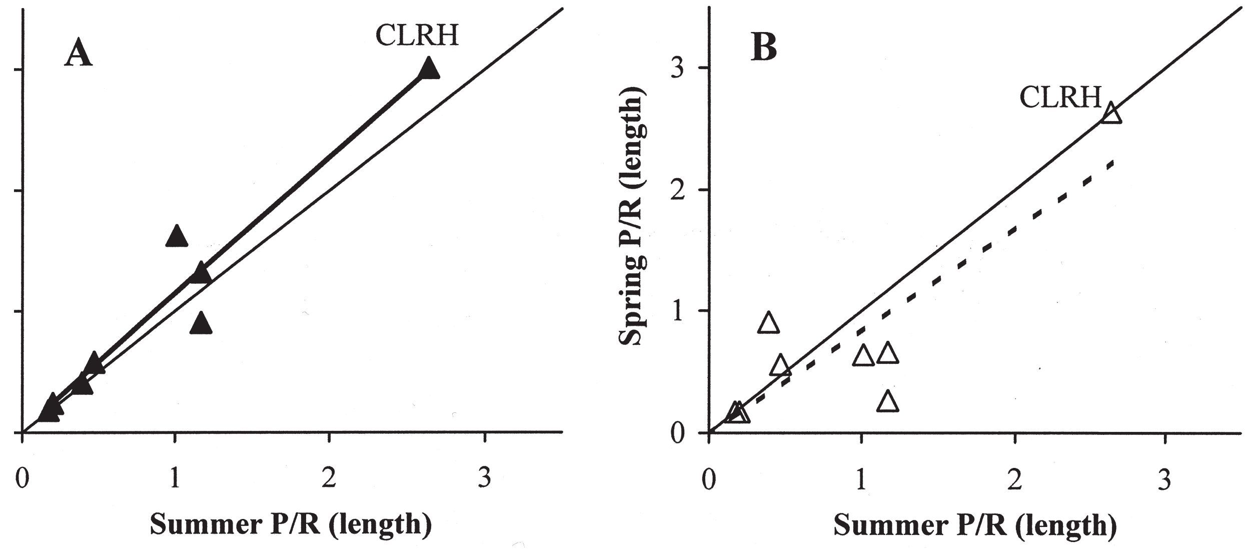

Fig. 2. (**A**) Pool/riffle (P/R) ratio for summer low discharge, comparing values derived from area with those based on length (R^2 = 0.93, p < 0.001); and (**B**) Pool/riffle ratio based on length measurements, comparing values for moderate spring discharge and summer low discharge conditions (R^2 = 0.74, p < 0.005). The thin, continuous line in each panel represents a 1:1 relationship between the regressed variables.

The number of wood jams tended to be greater in the REF and LOW-disturbance sites as compared with the MED- and HIGH-disturbance sites, although the difference was not significant (ANOVA for four treatments, p = 0.069; t-test for two treatments, REF+LOW and MED+HIGH, p = 0.056). However, only one of the MED- and HIGH-disturbance sites had any wood jams at all. Because of the lack of wood in the relatively short reaches used in this study, P/R ratio was considered a more appropriate metric for comparing channel complexity among the study reaches.

Pool/riffle ratio definitions

For summer low-flow conditions, the P/R ratio calculated from relative length was an appropriate proxy for total feature area (Fig. 2a). Summer P/R based on length was not significantly different than P/R based on area (paired t-test, p = 0.361) and the slope of the plotted data was not significantly different than 1. The regression relationship was significant (p < 0.001 with CLRH and p = 0.006 without CLRH). CLRH had a somewhat different morphology than the other study streams and distinguishing between pools and riffles was difficult. While the study reach exhibited some pool/riffle structure, the low gradient of the valley resulted in very slow-moving water, and areas that may have been riffles during other flow regimes exhibited subcritical flow more typically associated with pools during low flow. Thus, the use of subcritical flow as a determinant of the feature type likely resulted in a higher proportion of pools at this site than the other study reaches. Because no significant difference was found in the two approaches to characterize P/R ratios, the additional field effort necessary to determine pool and riffle areas was not warranted for the study streams.

Summer and spring P/R ratio were related (Fig. 2b), but only when station CLRH was included (paired t-test, p = 0.005). However, the difference between summer P/R and spring P/R was not significant with or without CLRH (paired t-test, p = 0.360 and p = 0.365, respectively). The proportion of pools was lower during moderate spring discharges for three locations, likely due to the more rapid loss of shallow-water areas (riffles) than deep-water areas (pools) with declining flow. These results suggest the need to establish P/R ratios at flow rates of interest to a particular study, since extrapolation to other flow conditions may not be justified. Since the purpose of the present study was to evaluate relative leaf retention during summer conditions, the summer P/R ratio based on relative feature length is used for the remainder of the analyses.

Dissolved tracer studies

At the low flows that most sites exhibited during tracer releases, reach-averaged velocity and dispersion rates were variable but both were positively related to discharge (Fig. 3a). One site (BURL) dominated both re-

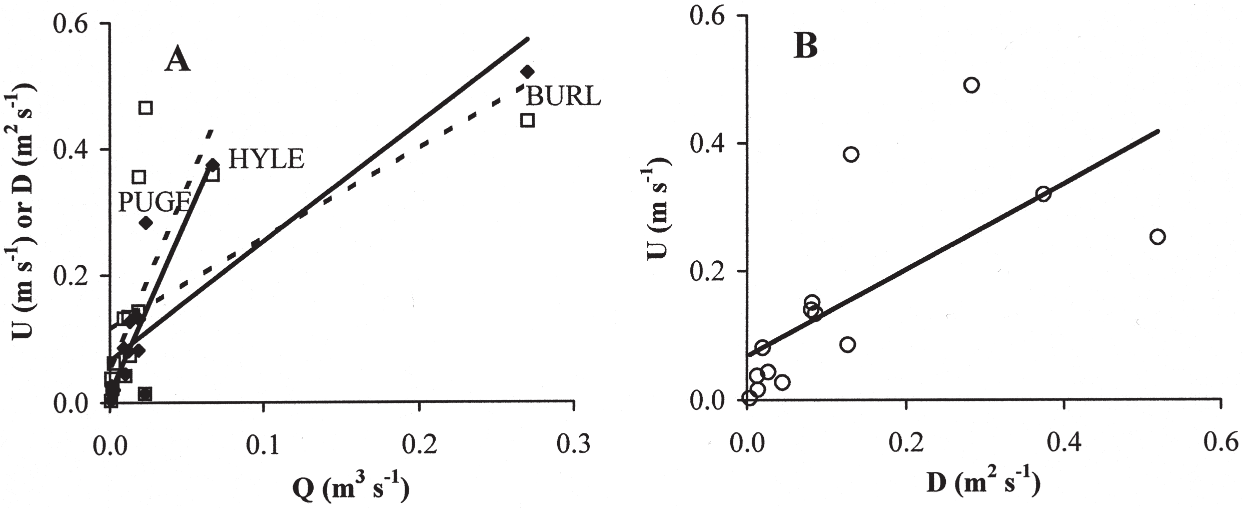

Fig. 3. **(A)** Reach-averaged velocity (U, diamonds and solid line) and longitudinal dispersion coefficients (D, open squares and dashed line) as a function of stream discharge (Q) with and without BURL (without BURL: $R^2 = 0.73$ and $p < 0.001$ for reach-averaged velocity and $R^2 = 0.42$ and $p = 0.017$ for dispersion; with BURL: $R^2 = 0.71$ and $p < 0.001$ for reach-averaged velocity and $R^2 = 0.36$ and $p = 0.021$ for dispersion); and **(B)** relationship between reach-averaged velocity (U) and dispersion (D) ($R^2 = 0.76$, $p < 0.001$).

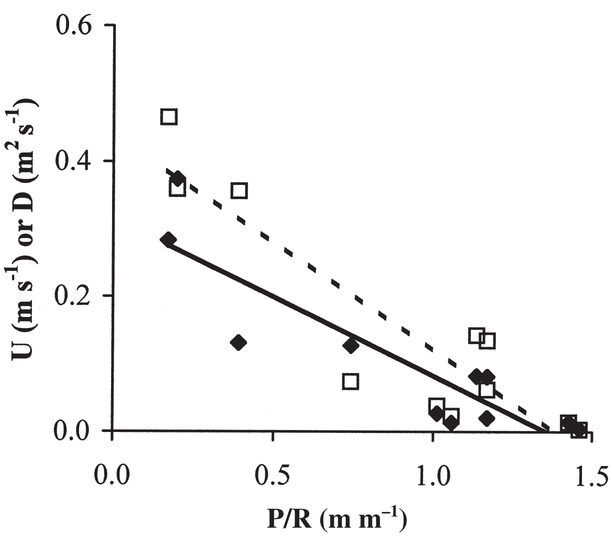

Fig. 4. Reach-averaged velocity (U, diamonds and solid line) and dispersion (D, open squares and dashed line) as a function of pool/riffle (P/R) ratio. ($R^2 = 0.79$ and $p < 0.001$ for reach-averaged velocity; $R^2 = 0.82$ and $p < 0.001$ for dispersion)

gression relationships. Without the data from BURL, both relationships were still highly significant and described more of the variation than those with BURL included ($R^2 = 0.73$, $p < 0.001$ for reach-averaged velocity and $R^2 = 0.42$, $p = 0.017$ for dispersion). Reach-averaged velocity increased with dispersion (Fig. 3b) and the regression was significant ($p < 0.001$).

As the proportion of pools increased, the reach-averaged velocity decreased (Fig. 4). The reach-averaged velocity was well described by the pool/riffle ratio ($R^2 = 0.79$, $p < 0.001$ without CLRH or BURL), as was dispersion ($R^2 = 0.82$, $p < 0.001$ without CLRH or BURL) and both relationships were significant. CLRH was removed from this analysis because of the unusual P/R structure, as described above.

Surrogate leaf transport and retention

At the low flows under which our releases were conducted, a few surrogate leaves traveled much longer distances than the bulk of the leaves, but 50 % of the surrogates were retained within 1.4 m of the release across all study locations and the mean of the site median travel distances was 3.2 m. Ninety percent of all surrogates released in the various stream reaches were retained within 11.3 m and only 4 of the 14 stations had a median travel distance > 2 m. As a result of the short transport distances, conditions near the release locations strongly affected retention and transport of the surrogate leaves. However, short transport distances are indicative of actual conditions during this flow regime.

Both dispersion and reach-averaged velocity described well the median distance traveled by the surrogate leaves (Fig. 5). Station BARK was the exception, where the travel distance was controlled by wood in the stream close to the release location rather than by dispersion or reach-averaged velocity. Station BURL

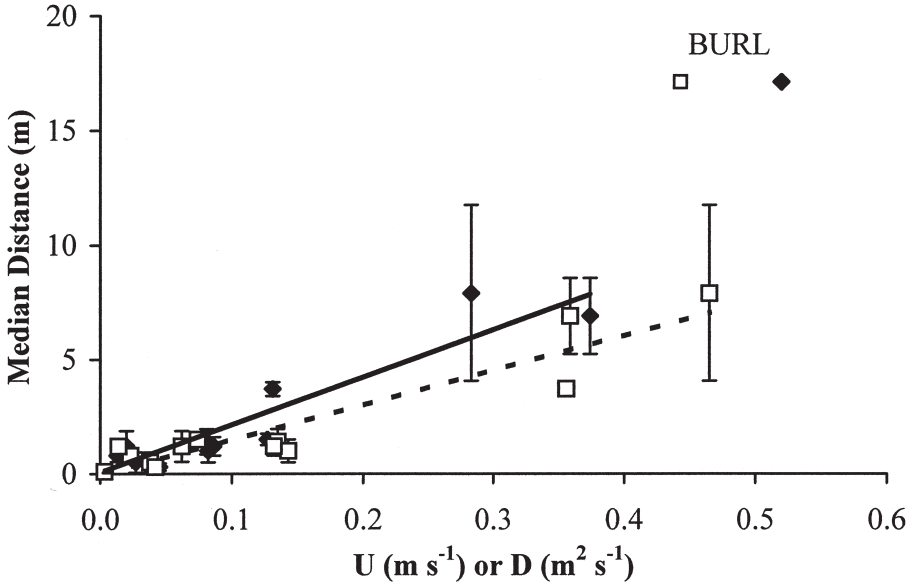

Fig. 5. Median travel distance for surrogate leaves as a function of reach-averaged velocity (U, diamonds and solid line) and dispersion (D, open squares and dashed line). (R^2 = 0.87 and $p < 0.001$ for both reach-averaged velocity and dispersion.) Bars represent the interquartile range. Station BURL was removed from the analysis because a wood-induced constriction produced local conditions not representative of the reach as a whole.

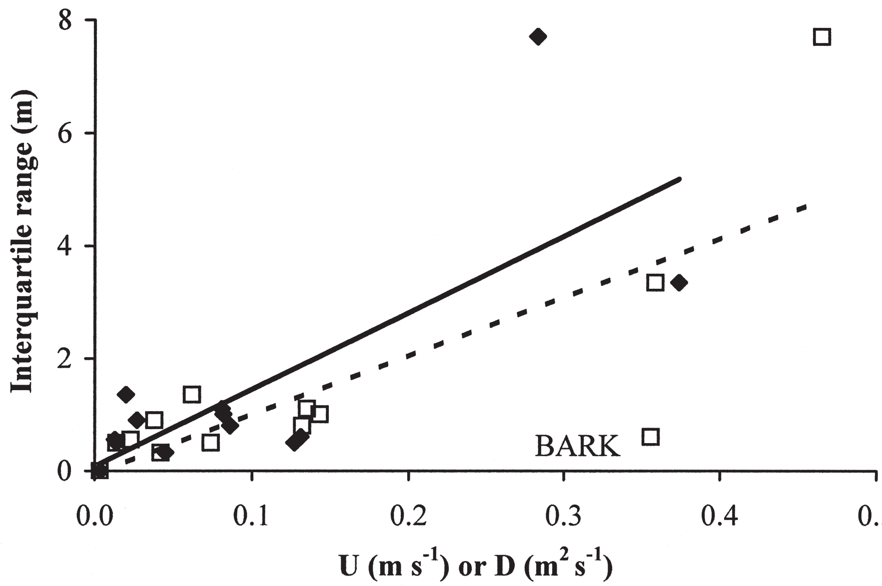

Fig. 6. Interquartile ranges of distance traveled by surrogate leaves as a function of reach-averaged velocity (U, diamonds and solid line) and dispersion (D, open squares and dashed line). (R^2 = 0.55 and p = 0.004 for reach-averaged velocity; R^2 = 0.61 and p = 0.002 for dispersion)

was removed from the relationship between distance and hydraulic characteristics because a wood-induced constriction of the channel at the point of release produced very high velocities, local conditions that were not representative of the reach. More of the variability in travel distance was described by reach-averaged velocity and dispersion (R^2 = 0.87 for both) than discharge although an increase in median travel distance with discharge was observed (R^2 = 0.55), as has been found in previous investigations (Jones & Smock 1991, Snaddon et al. 1992, Larrañaga et al. 2003, Pretty & Dobson 2004).

The interquartile range of surrogate material travel distances increased with both reach-averaged velocity (R^2 = 0.55) and dispersion (R^2 = 0.61), and the relationships were highly significant (p = 0.004 and p = 0.002, respectively) (Fig. 6). The interquartile range was significantly related to normalized discharge (R^2 = 0.50, p = 0.007) but not discharge (p = 0.122).

The travel distances exhibited positive skew for nearly all locations, and the median travel distance was lower than the mean. Notably, BURL, with the higher flows, approached a normal distribution and CLRH exhibited a slight negative skew. Skewness

Table 3. Relationships among watershed development, local riparian vegetation disturbance, geomorphology, hydraulics, and surrogate leaf transport characteristics categories (ANOVA p-values). Asterisks indicate significant differences. See Table 1 for abbreviations.

Parameter	TIA (≤ 10.2 %, > 10.2 %)	Watershed Development (LOW, MED, HIGH)	Watershed Development (LOW, MED+HIGH)	Riparian Vegetation Disturbance Level (REF, LOW, MED, HIGH)	Riparian Vegetation Disturbance Level (REF+LOW, MED+HIGH)
Watershed Development (LOW, MED, HIGH)	< 0.001*	–			
Watershed Development (LOW, MED+HIGH)	0.004*	–	–		
Riparian Vegetation Disturbance Level (REF, LOW, MED, HIGH)	0.044* +	–	–	–	
Riparian Vegetation Disturbance Level (REF+LOW, MED+HIGH)	0.004*	–	–	–	–
X_{med}	0.003*	0.038*	0.047*	0.235	0.047*
P/R	0.010*	0.041*	0.199	0.484	0.199
Q	0.034*	0.106	0.125	0.361	0.125
Slope	0.426	0.180	0.662	0.677	0.702
U	0.009*	0.016*	0.016*	0.158	0.016*
D	0.007*	0.064	0.028*	0.133	0.028*

+ Includes BURL. Without BURL, p = 0.059.

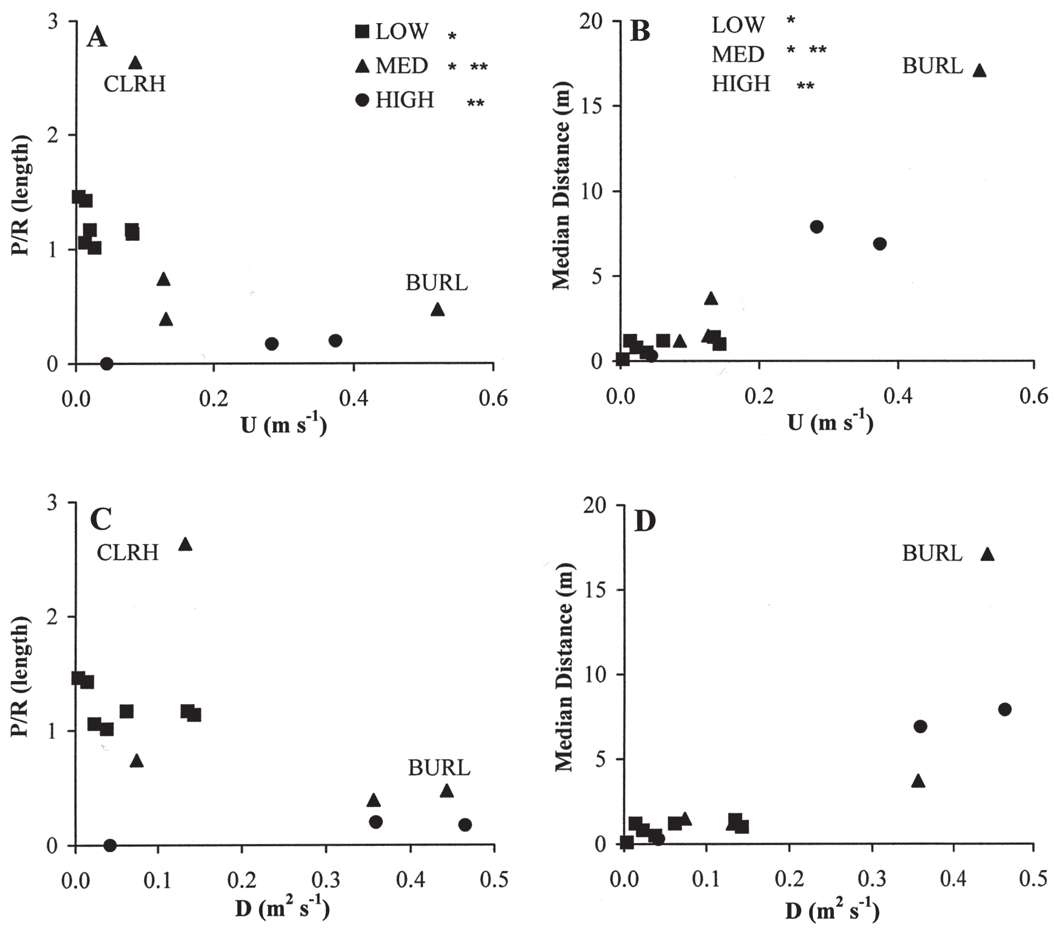

Fig. 7. Pool/riffle (P/R) ratio and surrogate leaf transport distance as a function of reach-averaged velocity (U) and dispersion (D) by watershed development level (low, medium, and high development). Asterisks indicate differences that are not statistically significant.

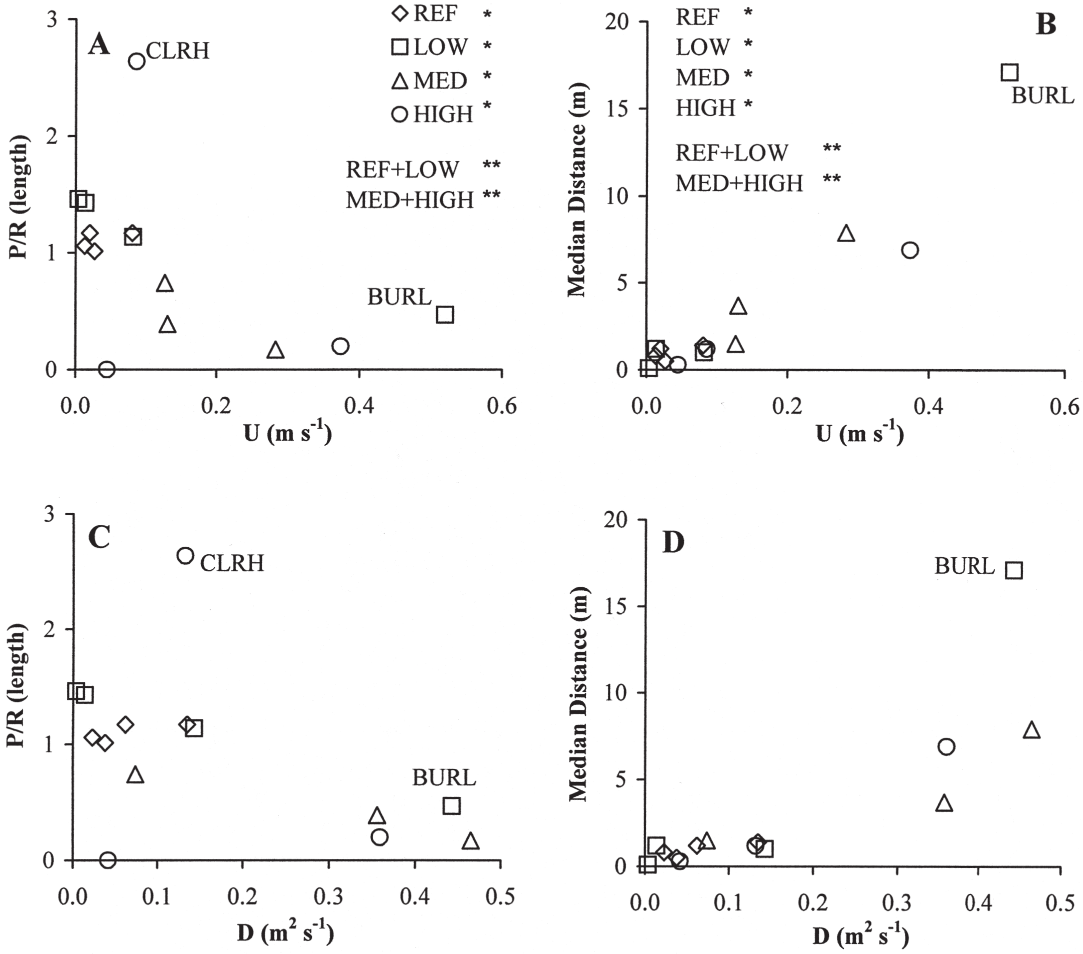

Fig. 8. Pool/riffle (P/R) ratio and surrogate leaf transport distance as a function of reach-averaged velocity (U) and dispersion (D) by riparian vegetation disturbance level (reference, low-, medium- and high-disturbance). Asterisks indicate differences that are not statistically significant.

decreased with increasing discharge, station velocity, reach-averaged velocity, and dispersion, but the relationships were not significant.

Relationships among watershed development, riparian vegetation disturbance levels, and transport metrics

Relationships among the watershed- and local-scale parameters were complex (Table 3). Watershed total impervious area and local riparian vegetation were related (including BURL) (ANOVA, $p = 0.044$). A significant relationship also was noted with the disturbance categories combined into two classes (REF+LOW and MED+HIGH, ANOVA, $p = 0.004$). This grouping was performed post priori, but is appropriate because it distinguishes mature vegetation (reference and low disturbance) from young or non-existent vegetation (medium and high disturbance). Discharge was significantly higher among the three most developed watersheds (> 19 % TIA) than those with ≤ 10.2 % TIA (ANOVA, $p = 0.034$) although the linear relationship was not significant ($p = 0.119$).

Grouping the sites by impervious cover (≤ 10.2 % and > 10.2 %), the P/R ratio was lower for the watersheds in the higher TIA category. However, pool/riffle ratio was not related to discharge ($p = 0.080$), nor did it reflect local riparian vegetation disturbance. Local geomorphology exhibited variability that was not fully explained by either watershed- or local-scale conditions.

Study reach hydraulic parameters were related to some, but not all, watershed-scale and local geomorphology metrics (Table 2). While P/R ratio was not related to discharge, it strongly influenced both reach-averaged velocity ($R^2 = 0.79$, $p < 0.001$) and dispersion

($R^2 = 0.82$, $p < 0.001$). Similarly, reach-averaged velocity and dispersion also varied with TIA ($R^2 = 0.48$ and 0.40, respectively) although discharge did not.

Stream channel and hydraulic properties reflected the patterns of watershed development (Fig. 7). Watersheds with low levels of development had higher stream pool/riffle ratios than watersheds with high development levels (ANOVA, p = 0.041), but the medium-development watersheds could not be distinguished from low- or high-development watersheds. As the proportion of pools increased, reach-averaged velocity and dispersion decreased. Low-development watersheds also produced lower median travel distances for surrogate leaves (ANOVA, p = 0.038) than high-development watersheds, reflecting the lower reach-averaged velocity and dispersion in low-development watersheds. Therefore, the effects of watershed development on hydraulic and channel complexity affected surrogate leaf retention, and stream reaches in low-development watersheds retained leaves closer to the release location than those within high-development watersheds.

Stream channel and hydraulic patterns, however, were not clear with respect to riparian vegetation disturbance level. Less-disturbed vegetation sites (REF and LOW in Fig. 8) exhibited lower surrogate transport distance, reach-averaged velocity, and dispersion than more-disturbed sites. However, the P/R ratio was not distinguishable among vegetation disturbance levels for either four categories (REF, LOW, MED, HIGH; p = 0.484) or grouped categories that distinguish mature and young vegetation (REF+LOW, MED+HIGH; p = 0.199). The median transport distance, reach-averaged velocity, and dispersion only varied significantly when classes were collapsed into two. The median travel distance was significantly higher in sites with MED- and HIGH-disturbance riparian vegetation disturbance levels (2.7 m) as compared with sites with REF and LOW-disturbance levels (1.1 m) (p = 0.047), but the difference was not distinguishable among the four categories due to lower statistical power. While riparian vegetation influenced some hydraulic and transport parameters, statistical power limited further comparisons.

Discussion

Small streams generally are very effective at retaining organic matter. The streams in this study were highly retentive at low flows, but level of development, channel complexity, and hydraulic characteristics clearly influenced surrogate leaf transport. Median transport distance decreased as pools increased and reach-averaged velocity decreased. Streams with lower pool/riffle ratios and higher velocities, characteristics that increased hydraulic dispersion, also produced greater travel distance and less retention.

Leaf transport reflects both watershed development and local riparian vegetation

Watershed development and local riparian vegetation disturbance level were related, with more mature conifer vegetation associated with watersheds of low development. Watershed development and local riparian vegetation influenced local channel hydraulics and watershed development also influenced geomorphology. Because these affect organic matter retention, both watershed development and riparian vegetation disturbance can affect organic matter processes with cascading effects on ecological functions. For example, removing stream complexity elements reduces organic matter retention (Bilby & Likens 1980, Bilby 1981), and eliminating organic matter inputs strongly affects aquatic communities and nutrient regimes (Wallace et al. 1997, Webster et al. 2000).

Low-development watersheds had lower median transport distances than high-development watersheds, but discharge was a confounding factor since high-development watersheds also had the highest discharges (beyond the BURL flow anomaly). Factors that may have contributed to the higher discharge at these sites include differences in headwater geology and drinking water supply source. However, discharge was not the best predictor of leaf transport distances. Instead, hydraulic properties, and to a lesser degree channel morphology, were better related to leaf transport and these characteristics were related to overall watershed development.

Local-scale riparian vegetation disturbance also was related to leaf litter retention; median surrogate travel distances were lower for reference and low-disturbance vegetation sites than for medium- and high-disturbance vegetation sites. Even at very low flows, when streams are highly retentive and leaf travel distances are small, the differences were statistically significant.

The effects of urbanization on hydrology and geomorphology, coupled with the loss of mature native riparian vegetation, destabilize stream channels and contribute to a loss of in-channel structural complexity as development increases (Booth et al. 2002). These changes in turn affect the transport and retention of organic matter. Stream reaches with more disturbed vegetation and more developed watersheds produce greater water velocities, which reduce organic matter retention and increase transport distance compared to stream reaches with less riparian disturbance and watershed development. Higher velocities and lower pool/riffle ratios, associated with more disturbed riparian vegetation and higher watershed development, increase hydraulic dispersion as well. The significant differences in leaf transport distances found during low flows are likely to be magnified at higher discharges, which are more frequent in developed watersheds, further amplifying enhanced transport.

Hydraulic characteristics describe ecological processes

The hydraulic parameters reach-averaged velocity and dispersion characterized leaf litter retention on a reach scale. Organic matter transport increased with increasing discharge, but discharge explained less of the variability in median travel distance than did reach-averaged velocity and dispersion. Surrogate transport increased as reach-averaged velocity and hydraulic dispersion increased. Our results suggest that hydraulic dispersion may be an especially meaningful parameter for ecological studies, because the velocity variations that control dispersion also reflect channel complexity, and channel complexity influences material transport and retention. Neither parameter has been used extensively in stream ecology studies, but our results suggest that hydraulic parameters such as these may be useful indicators of various transport processes in streams. Insofar as transport and storage of organic matter and nutrients in stream ecosystems are fundamental ecological processes related to biotic function and productivity, further evaluation of the linkages between hydraulic characteristics and ecological processes in streams is warranted. Both tracer-derived parameters are easily determined from field experiments that may be conducted at flow conditions of interest to ecological studies.

One advantage of using hydraulic characteristics, like reach-averaged velocity and dispersion, is that simple field experiments can characterize longer reach lengths than traditional organic matter surrogate release experiments. In this study, the tracer study reach length was selected to encompass multiple pool/riffle units. Even longer reaches may be evaluated using these methods as long as the tracer concentration is discernible above background levels. Evaluating longer reaches reduces the confounding effect of unusual local conditions, such as occurred in this study at BURL where a wood constriction enhanced water velocity at the leaf release site, transporting surrogate materials farther than if the leaves had been released within a more typical riffle. These hydraulic parameters also provide an objective measure of channel complexity, whereas determination of complexity using traditional channel survey methods often is observer dependent, making comparisons among study results difficult (Scholz & Booth 2001).

This study was conducted during low-flow conditions, which occur in the Pacific Northwest in late summer and early autumn and coincide with peak litterfall inputs (Roberts 2007). Further study is needed before extrapolating to higher flow conditions. Complexity elements that retain organic matter during low flows may be submerged and less effective at high flows. However, the simplification of channel form, increased runoff rate, and reduction in wood jams associated with increased urbanization and riparian disturbance would suggest that the differences in organic matter transport we observed are likely to persist, and possibly become greater, at higher flow. This hypothesis could be evaluated by characterizing reach-averaged velocity and dispersion at a variety of stream flows across a gradient of urban development or other disturbance levels.

Restoration plans should include organic matter retention and related variables

Leaf litter provides critical support of trophic processes in stream ecosystems (Cummins 1974, Wallace et al. 1997). Leaf litter availability may decline through a number of pathways, including decreased inputs, enhanced decomposition rates (Roberts 2007), and enhanced transport. Urbanization potentially affects each of these pathways, such that leaf litter availability can be limited in urban streams.

The results of this study demonstrate that the effects of urbanization enhance organic matter transport in small streams, which in turn reduces the organic matter available for biotic processes. Decreased organic matter availability in streams has not been considered widely as one of the potential effects of urbanization and thus rarely has been directly addressed in restoration efforts. Despite some prior recognition (e.g., Muotka & Laasonen 2002) of this need, organic matter retention is rarely a stated objective of stream restoration plans. Whether intended or not, however, many restoration efforts probably do enhance organic matter input and retention, with typical measures such as planting native vegetation and placing in-stream structures both having the potential to increase channel complexity and organic matter retention. Better evaluation of the value of these efforts for organic material transport and related ecological processes could be easily assessed using our methods, particularly by measuring hydraulic parameters before and after restoration.

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