# Stream habitat hydraulics: interannual variability in three reaches of Catamaran Brook, New Brunswick

**Donna J. Giberson and Daniel Caissie**

**Abstract**: The hydraulic habitat of 12 sites in a small salmon stream in central New Brunswick was investigated between 1992 and 1995 to determine patterns of habitat (substrate) stability between and within reaches. Stability was evaluated by measuring particle size distribution in replicated erosional and depositional sites in each reach and calculating the proportion of the bed predicted to be in motion at given flood flows. Erosional (riffle) sites in all reaches showed significant differences (ANOVA, $p < 0.05$) in substrate particle sizes from year to year, movement of embedded sediment samplers, and high predicted bedload mevement, even in small spates. In contrast, depositional sites (flats, some runs) appeared stable, showing no significant year-to-year differences in particle sizes, no movement of embedded samplers, and no increase in predicted bedload movement until high flow. The impact of the flood on the streambed depends heavily on the particle size distribution present during the flood, resulting in different levels of substrate disturbance during equal-magnitude floods in different years. Certain sites (e.g., flats) may be able to serve as hydraulic refugia to stream fauna during some floods. It is clear that year-to-year variations in substrate stability must be considered when evaluating habitat stability for stream fauna.

**Résumé** : De 1992 à 1995, nous avons étudié l’habitat aquatique dans 12 secteurs d’une petite rivière à saumon du centre du Nouveau-Brunswick pour déterminer la stabilité de l’habitat (substrat) dans une même partie du cours d’eau et d’une partie à l’autre. Pour évaluer la stabilité du substrat, nous avons évalué la distribution granulométrique des particules de zones d’affouillement et d’alluvionnement délimitées en double dans chaque secteur, et nous avons calculé la proportion du lit qui devrait être mobile à divers débits de crue. Dans les zones d’affouillement (rapides) de tous les secteurs, le profil granulométrique du substrat présentait des différences significatives (ANOVA, $p < 0{,}05$) d’une année à l’autre, les échantillonneurs de sédiments enfouis au fond de l’eau se déplaçaient et les prévisions de la charge de fond donnaient des valeurs élevées et ce, même pour les périodes de faibles crues. Par contre, les zones d’alluvionnement (battures et certains rapides) semblaient stables, car le profil granulométrique ne présentait pas de différences significatives d’une année à l’autre, les échantillonneurs enfouis ne se sont pas déplacés et les prévisions n’ont pas indiqué de charge de fond accrue avant les grandes crues. L’effet de la crue sur le lit dépend beaucoup de la distribution granulométrique des particules durant la montée des eaux, ce qui se traduit par différents degrés de perturbation du substrat au cours de crues d’importance égale. Il se peut que la faune du cours d’eau se réfugie dans certaines zones (p. ex. les battures) durant certaines crues. Il apparaît clairement que les variations de stabilité observées d’une année à l’autre doivent être prises en considération dans l’évaluation de la stabilité de l’habitat occupé par la faune des cours d’eau.
[Traduit par la Rédaction]

## Introduction

The study of physical disturbance and consequent ecological community response is currently receiving a great deal of attention. In streams, floods are often thought to be the dominant disturbance parameter and may be the major factor determining benthic community structure (Resh et al. 1988). However, despite considerable study on the effects of floods on stream biota, there is still disagreement about whether, and how often, floods act as disturbance, at least in the context of flood predictability and disruption of ecosystem, community, or population structure (Resh et al. 1988; Cobb et al. 1992; Poff 1992). Flooding often causes dramatic reductions in benthic populations in streams (e.g., Gray and Fisher 1981; Scrimgeour and Winterbourn 1989; Cobb et al. 1992), but similar reductions have not been reported in all streams (e.g., Allen 1959; Giberson and Hall 1988) or even in all patches within a stream site (e.g., Lancaster and Hildrew 1993*a*, 1993*b*; Palmer et al. 1995; Robertson et al. 1995). Therefore, it has been suggested that floods do not disturb benthic communities unless they are strong enough to disturb bed materials (Poff 1992; Lancaster and Hildrew 1993*a*; Giberson and Cobb 1995).

It has not proven to be a simple matter to determine the stability of streambed materials at different flood levels. Various methods have been proposed to evaluate bed stability, including monitoring the movement of painted rocks (e.g., Death 1995; Death and Winterbourn 1995), use of qualitative indices of habitat stability (e.g., Eifert and Wesche 1982; Death and Winterbourn 1995), use of FST (fliesswasserstammtisch) hemispheres calibrated to move at known shear stresses (Lancaster

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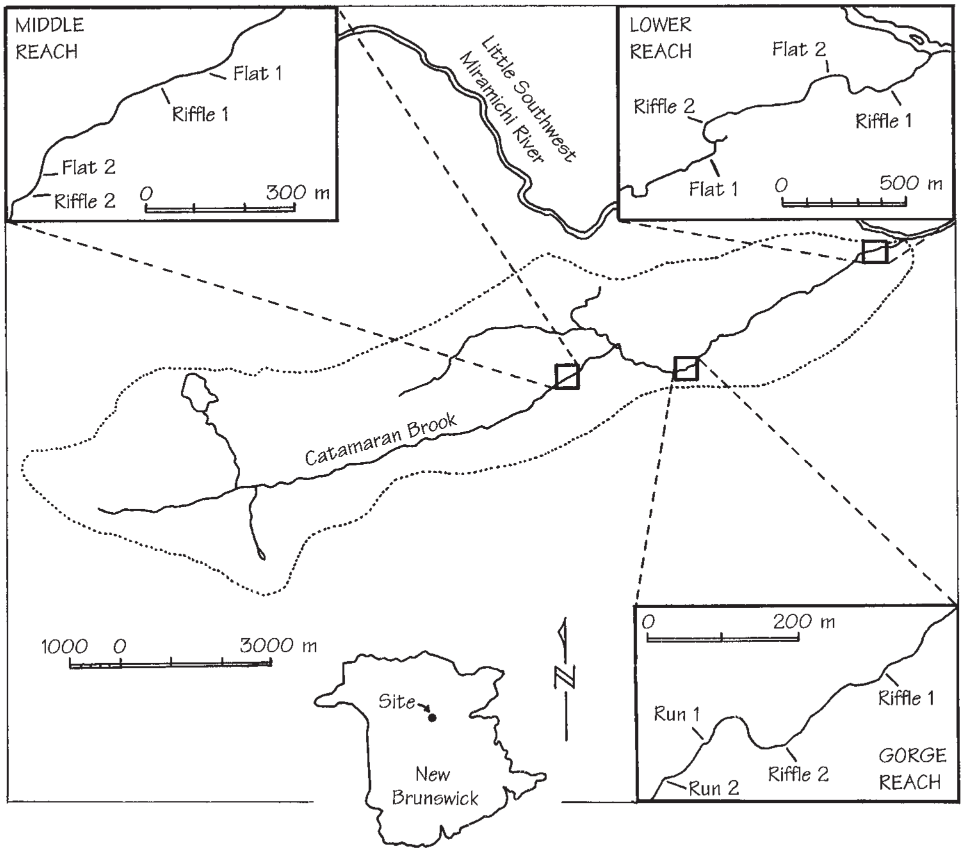
**Fig. 1.** Catamaran Brook, New Brunswick (46°52.7′N, 66°06.0′W), showing location of study reaches and sites.



and Hildrew 1993*a*, 1993*b*), and use of a calculated stream reach tractive force measurement to estimate average bed movement for a reach or site (Cobb et al. 1992; Muotka and Virtanen 1995). All of these methods have limitations, and attempts to correlate hydrologic and hydraulic variables with community structure have met with mixed success. Despite this, it is now clear that there are microhabitats within sites (Lancaster and Hildrew 1993*a*, 1993*b*) as well as adjoining macrohabitats (Palmer et al. 1995) that remain stable and can serve as refugia from hydraulic stress even at high flow. It is less clear, however, how such habitats are distributed along the length of a stream or how they may vary with respect to stability from year to year. The objective of this research was to determine bed stability in a number of erosional and depositional sites along the length of a small salmon stream in central New Brunswick, Canada, and to document any changes that might occur from year to year.

## Study site

Catamaran Brook is a third-order tributary of the Little Southwest Miramichi River in New Brunswick, Canada (46°52.7′N, 66°06.0′W; Fig. 1). Total stream length is about 25 km, with a drainage area of 50 km$^2$ of mixed coniferous hardwood forest. Climatic conditions in the basin have been continuously monitored since 1990 at a meteorological station located at midbasin. In addition, data on precipitation and air temperature have been collected from the nearby McGraw Brook Department of Natural Resources station since 1969. Annual precipitation ranges from 860 to 1365 mm, with a long-term average of 1142 mm (Cunjak et al. 1993). January has the coldest mean monthly temperature with a long-term mean of –11.8°C. July is the warmest month with a mean monthly temperature of 18.8°C. To monitor discharge, a hydrometric gauge was installed at midbasin in October 1989; in addition, a manual gauge at the mouth of the stream provides information on discharge at the mouth during the ice-free season, supplemented by prorated discharge data from the midbasin site. The mean annual flow in Catamaran Brook is 1.3 m$^3$/s or 754 mm of runoff. Other details on geochemistry, hydrology, other physical factors, and biota may be found in Cunjak et al. (1993).

Catamaran Brook is currently the focus of several multidisciplinary studies evaluating logging impacts on Atlantic salmon (*Salmo salar*) habitat and productivity. Four study reaches have been surveyed and characterized in the brook for long-term study, and sites representing replicated habitat types have been established in each reach (Fig. 1). Two habitat types representing fast flow (riffles) and slow to moderate flow (flats or runs) habitat in three reaches (middle, gorge, and lower) were monitored for this study. The middle reach (about halfway down the length of the stream) is characterized by a stream width of 6–8 m, riffle gradients of 2–2.3%, and riffle substrates of cobble and gravel. The gorge reach (downstream from the middle reach) runs through a bedrock outcrop area and is 6–8 m wide with riffle gradients around 2% and a primarily bedrock substrate with some gravel and cobble. The lower reach includes the lower 2 km of the stream and is 8–12 m

**Table 1.** Hydraulic parameters for each of the 12 study sites at Catamaran Brook.

| Site | *W* (m) | *D* (m) | *W*:*D* | *L* (m) | Cross-sectional area (m$^2$) | Wetted perimeter (m) | Hydraulic radius | Water slope (%) | $D_{50}$ range (cm) |
|---|---|---|---|---|---|---|---|---|---|
| MRi1 | 6.43 | 0.184 | 34.9 | 11.4 | 1.18 | 6.77 | 0.173 | 2.3 | 8–9 |
| MRi2 | 7.72 | 0.220 | 34.8 | 14.8 | 1.65 | 8.04 | 0.210 | 2.0 | 7.7–9.7 |
| MF1 | 8.16 | 0.395 | 20.7 | 17.6 | 3.26 | 8.36 | 0.385 | 0.05 | 3.0–3.7 |
| MF2 | 6.27 | 0.371 | 16.9 | 21.1 | 2.33 | 6.65 | 0.350 | 0.11 | 5.0–6.0 |
| GRi1 | 6.96 | 0.216 | 32.3 | 15.0 | 1.45 | 7.33 | 0.205 | 1.9 | 8.3–14 |
| GRi2 | 5.77 | 0.169 | 34.1 | 11.7 | 0.97 | 6.42 | 0.152 | 2.0 | 6.3–12 |
| GRu1 | 8.17 | 0.223 | 36.6 | 15.2 | 1.84 | 8.37 | 0.218 | 0.24 | 5.7–6.7 |
| GRu2 | 6.54 | 0.220 | 39.7 | 15.4 | 1.43 | 7.05 | 0.203 | 0.55 | 7.3–7.7 |
| LRi1 | 8.16 | 0.180 | 45.3 | 11.5 | 1.46 | 8.82 | 0.166 | 1.62 | 7–9 |
| LRi2 | 8.81 | 0.189 | 46.6 | 12.6 | 1.64 | 9.24 | 0.180 | 1.74 | 6.3–8.7 |
| LF1 | 8.84 | 0.285 | 31.0 | 14.1 | 2.52 | 9.04 | 0.278 | 0.11 | 2.7–3.7 |
| LF2 | 12.67 | 0.220 | 57.6 | 17.3 | 2.83 | 12.86 | 0.221 | 0.14 | 3–3.9 |

**Note**: All measurements represent summer low-flow conditions; ranges in median particle diameters ($D_{50}$) represent the ranges found between 1991 and 1995. *W*, mean width; *D*, mean depth; *L*, length. Slope was measured over the entire length of the site. Site key: M, middle reach; G, gorge reach; L, lower reach; Ri, riffle; F, flat; Ru, run.

wide with riffle gradients of 1.6–1.75% and riffle substrates of gravel, cobble, and boulder. Specific habitat details for each site are summarized in Table 1. The riffles were characterized as erosional (i.e., middle riffles 1 and 2, gorge riffles 1 and 2, and lower riffles 1 and 2) whereas the slower sites were characterized as depositional sites (i.e., middle flats 1 and 2, gorge runs 1 and 2, and lower flats 1 and 2).

## Methods

### Flood flow analysis

A flood frequency analysis allows determination of peak discharge for given recurrence intervals at gauged stream sites. Flood data used for such analyses may be the annual peak discharges or a partial duration series that considers all flows above an arbitrarily chosen flow truncation level. Catamaran Brook has been monitored for only 5 years, so data from the Renous River, a neighbouring stream with a 25-year record of flow (and similar hydrological conditions), were used in a regional analysis to extend the period of record (Caissie et al. 1992). Flood frequencies were determined by plotting annual peak floods against the recurrence interval and fitted to a Gumbel extreme value distribution, based on rank orders (Richards 1982).

Flow data were also analysed using a partial duration series approach (Richards 1982), where an arbitrary truncation flood level is chosen to provide more flood events for analysis. We chose a truncation level that would give an average of 3 flood events per year, resulting in analysis of flood peaks of 50–60% of the mean annual flood (Caissie and El-Jabi 1992). Duration and seasonal timing of all floods above the truncation level, and their flood volumes (total volume of water (cubic metres per second) above the truncation level), were recorded for each event.

Flow predictability was determined for Catamaran Brook following the method proposed by Colwell (1974) and applied to stream systems by Resh et al. (1988). Flood data (based on regional analysis of the Renous River) were cast into a frequency matrix (contingency table) where rows represented flood classes and columns were months (see Resh et al. 1988 for specific methods). "Uncertainty", in the statistical sense, may be calculated from the matrix. The predictability (*P*) is the reciprocal of the uncertainty and consists of two portions: constancy (*C*; the regularity of the environment) and contingency (*M*; whether the conditions vary in the same way from year to year). The predictability values may vary from 0 to 1, with a value of 1 indicating complete predictability.

### Bed stability

The tractive force, or bed shear stress, is the force being exerted on the bed by the water, and substrate particles will begin to move when the tractive force exceeds the frictional and gravitational forces holding them in place. The tractive force depends on the volume and weight of the water above the particle, as well as the slope. An average shear stress for a site can be obtained from the DuBoys equation for boundary shear (Baker and Ritter 1975):

$$(1)\qquad \tau = \gamma RS$$

where $\tau$ is the critical mean shear stress for initiating particle transport (kilograms per square metre), $\gamma$ is the specific weight of the fluid, *R* is the hydraulic radius (cross-sectional area/wetted perimeter), and *S* is the energy slope (or slope of the water surface if flow is uniform). Most streams transporting coarse bedload material have high width to depth ratios, so the depth of flow gives a close approximation of *R*, and unless a river is carrying very high suspended sediment loads, the specific weight of the fluid should approximate that of water, 1000 kg/m$^3$ (Baker and Ritter 1975; Newbury and Gaboury 1993). The assumption that depth approximated *R* was found to be valid in Catamaran Brook at low flow (Table 1). A further assumption of the method is that the water surface slope should be nearly parallel to the energy slope, i.e., that the flow be uniform. Given these assumptions, eq. 1 above can be rewritten as

$$(2)\qquad \tau\ (\text{kg/m}^2) = 1000\ \text{kg/m}^3 \cdot D \cdot S$$

where *D* is mean depth (metres) in the study site and *S* is the slope (metres per metre) of the water surface for the flows being investigated.

Mean depth and cross-sectional area were determined for at least five transects for each site at summer low flow, as well as at the truncation and bankfull flood levels. The bankfull flood stage was estimated to be about 5 m$^3$/s in the middle reach through flood frequency analysis and confirmed in 1997, when a flood of 5.7 m$^3$s was observed to be just above the banks in that reach. Slope of the water surface was measured for each site using a surveyer's level at summer low flows, at the truncation level, and at bankfull.

### Bed paving materials

Bed paving materials were sampled by the random selection "pebble-count" method, using a total of 100 particles in each site (Wolman 1954; Newbury and Gaboury 1993; Newbury 1996). In this method, the investigator measures the *x*, *y*, and *z* dimensions of particles encountered every few steps while walking through the stream site, taking care to sample the entire site equally. Samples were collected

**Fig. 2.** Annual hydrograph (discharge) for Catamaran Brook, 1990–1995, based on continuous data collected at a gauging station located in the middle reach. Asterisks indicate dates when rock measurements were collected.

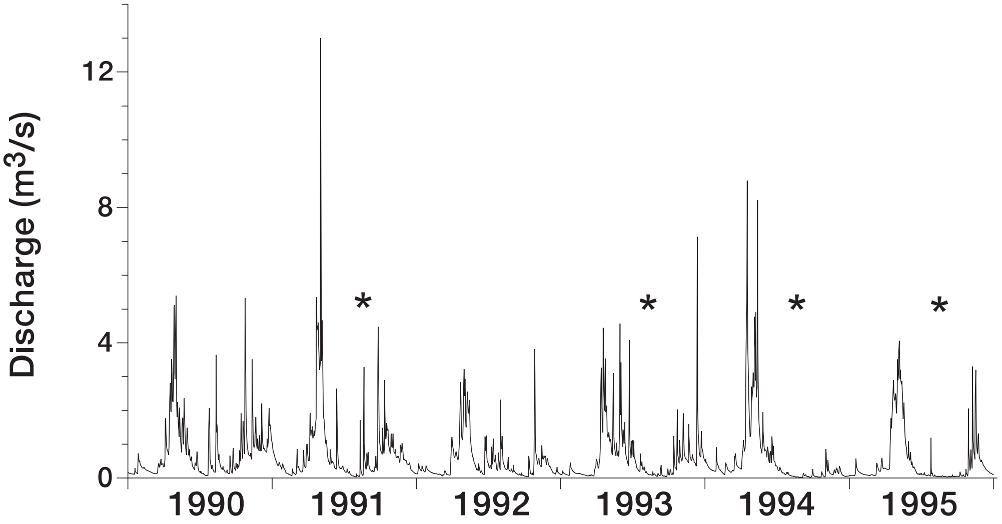
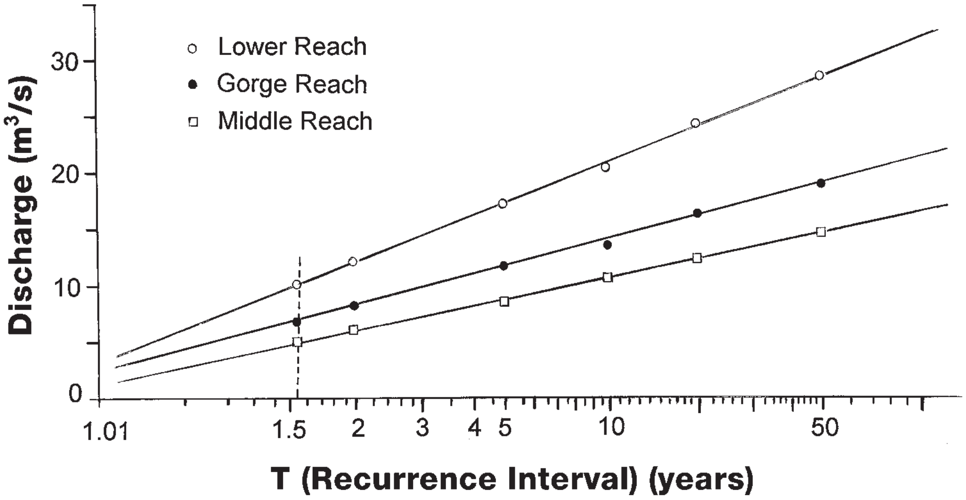


**Fig. 3.** Recurrence intervals for flood flows of various magnitudes for the three study reaches of Catamaran Brook based on prorated flows from the Renous River, New Brunswick. The broken line indicates bankfull conditions. Predictability analysis indicated an overall predictability (*P*) of 0.45, consisting of a constancy (*C*) of 0.25 and a contingency (*M*) of 0.20 (see text for explanation).



in mid-July in 1991 from the six riffle sites and in 1993, 1994, and 1995 from all 12 sites. In 1993, an additional series of samples were collected in each of lower riffles 1 and 2 to test the replicability of the pebble-count method.

The bed paving material measurements (*x*, *y*, *z*) were averaged for each particle and then the averages were ranked from largest to smallest and plotted as cumulative frequency distributions for each site and each year, following the methods in Newbury and Gaboury (1993). Particle sizes were compared among years and sites using ANOVA to determine whether particle size distributions varied from year to year. Median particle diameters ($D_{50}$) were determined from each of the plots for each year and each site.

For noncohesive bed materials (>5 mm in diameter), the size (centimetres) of rounded cobble that can be moved is approximately equal to the tractive force (kilograms per square metre) (Graf 1984). For example, a rounded particle with a mean diameter of 5 cm should be at the point of motion when the tractive force exceeds 5 kg/m$^2$. Site-scale (i.e., averaged over the entire site) tractive forces were calculated for each site and year and compared with the cumulative frequency distributions of the bed paving materials to determine the proportion of the bed materials predicted to move at each flow level.

## Results

### Flow analysis

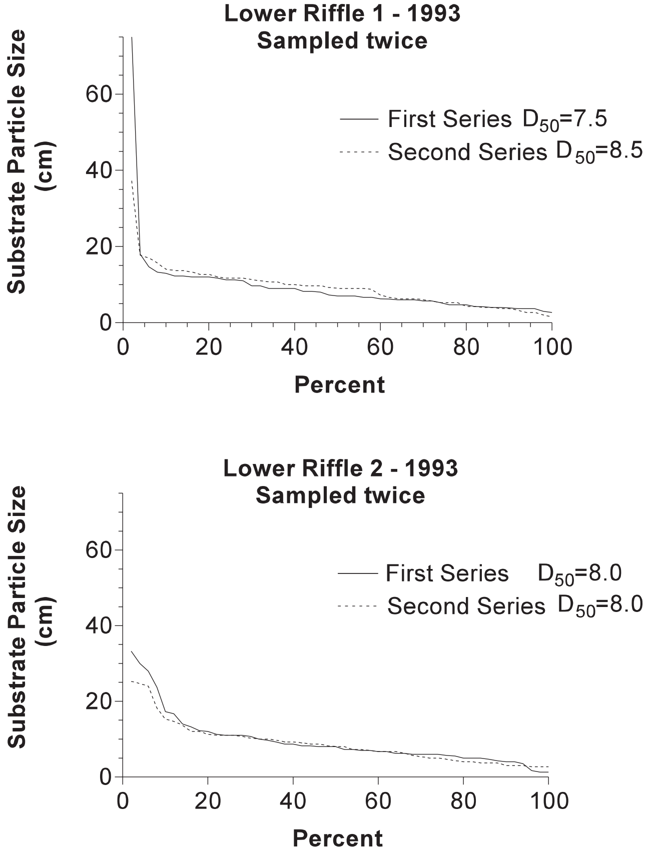
Peak flows in Catamaran Brook generally occur during snowmelt in the spring (Fig. 2), although flood events can occur at any time during the open-water (ice-free) season. Flood frequency analysis at Catamaran Brook indicated a bankfull discharge of 5 m$^3$/s at the gauging station (middle reach), 6.7 m$^3$/s at the gorge reach, and 10 m$^3$/s at the lower reach (Fig. 3). The truncation flow level (for the partial duration analysis) was 3.7 m$^3$/s at the gauging station at the middle reach, representing 58% of the mean annual flood and giving an average of 2.83 flood events per year (Table 2). In most years, two or three flood exceedances (i.e., flow above truncation level)

**Table 2.** Dates, durations, and flood volumes for flood exceedences (flows above truncation level of 3.7 $m^3/s$ at the gauging station) used for calculation of partial duration series analysis for Catamaran Brook, 1990–1995.

| Year | Dates of events | Duration (days) | Peak discharge ($m^3/s$) | Total flood volume ($m^3/s$) |
|---|---|---|---|---|
| 1990 | Apr. 26–29 | 3 | 5.11 | 2.19 |
| | Apr. 30–May 3 | 3 | 5.39 | 1.64 |
| | Oct. 23–26 | 3 | 5.32 | 1.54 |
| Total | | 9 | | 5.37 |
| 1991 | Apr. 21–29 | 8 | 5.35 | 6.01 |
| | May 2–6 | 4 | 13.00 | 16.16 |
| | May 6–8 | 2 | 4.66 | 0.77 |
| | Sept. 25–27 | 2 | 4.47 | 0.43 |
| Total | | 16 | | 22.40 |
| 1992 | Oct. 25–27 | 2 | 3.82 | 0.01 |
| Total | | 2 | | 0.01 |
| 1993 | Apr. 17–19 | 2 | 4.44 | 0.28 |
| | May 29–31 | 2 | 4.57 | 0.27 |
| | June 22–24 | 2 | 4.08 | 0.05 |
| | Dec. 11–13 | 2 | 7.13 | 2.38 |
| Total | | 8 | | 2.98 |
| 1994 | Apr. 14–20 | 6 | 8.79 | 9.72 |
| | May 5–8 | 3 | 4.77 | 0.89 |
| | May 8–10 | 2 | 4.92 | 0.78 |
| | May 11–15 | 2 | 8.21 | 4.63 |
| Total | | 13 | | 16.00 |
| 1995 | May 6–7 | 2 | 4.06 | 0.40 |
| Total | | 2 | | 0.40 |

**Note**: The peak discharge is the absolute value for the maximum discharge for a given event, while the flood volume refers to the volume above the truncation level. Bankful discharge for this station is 5 $m^3/s$.

**Fig. 4.** Test for replicability of the substrate measuring technique. First and second series refer to consecutive, and completely separate, sampling of the same study riffles on the same day in 1993.



occurred during spring, but in 1992, no spring flood exceedance occurred, and in 1993, flooding persisted to the end of June. The peak event in 1991 (May 2–6) (Table 2; Fig. 2) has been estimated to have a return period of 40 years. Predictability analysis of Catamaran Brook yielded a predictability value of 0.45, indicating moderate predictability of flows (Fig. 3).

## Bed stability

Particle diameter frequency distributions showed no significant differences in repetitive sampling in an individual site (Fig. 4), indicating that the particle measuring technique is replicable. Some differences were seen in the presence of the largest substrate particles (boulders) which were relatively rare and which could easily be missed during random sampling.

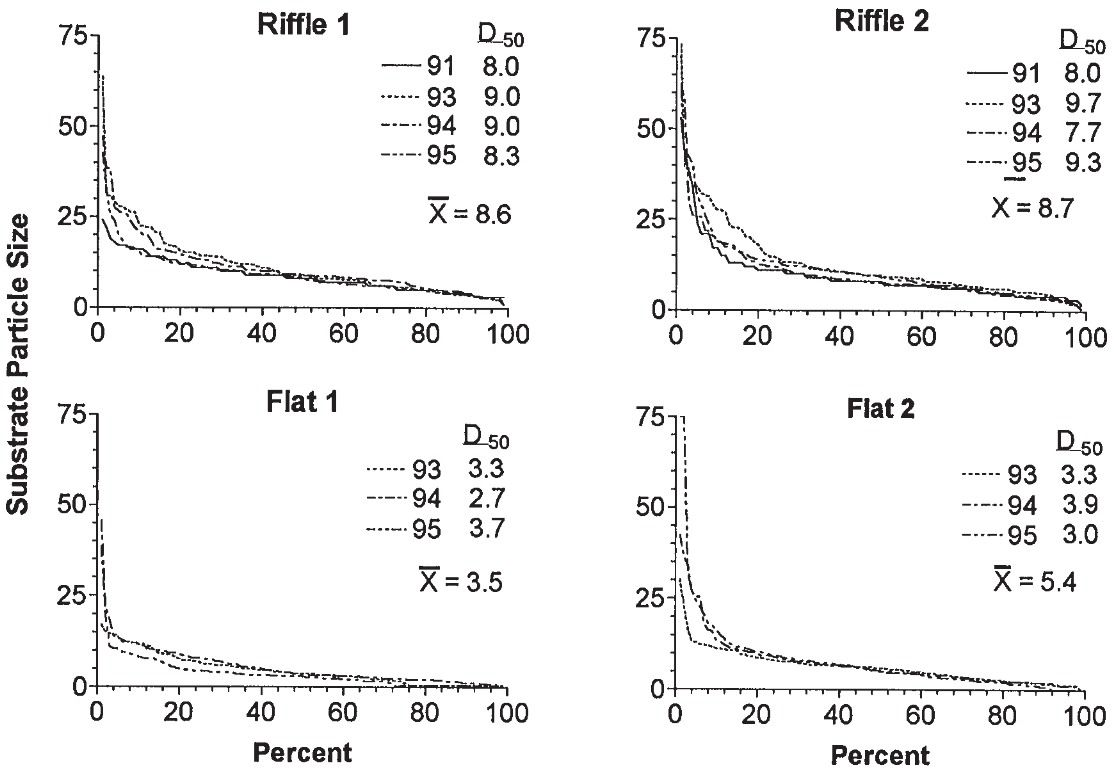
Median particle diameters were generally about twice as large in the riffles (6.3–14 cm) as in the flats (2.7–6.0 cm), and substrates in the erosional riffle sites showed a greater range in particle sizes than in the depositional sites (Fig. 5). Bed paving materials in the gorge sites (Figs. 5C and 5D), however, were quite different from those in the middle and lower reaches (Figs. 5A and 5B) due to a high percentage of hardpan bedrock in these sites. Median particle diameters (riffles) of loose (nonbedrock) substrate materials were highest in the gorge reach, followed by the middle and the lower reaches (Fig. 5). Slopes (which have an effect on substrate movement) were highest in the gorge and middle reaches, followed by the lower reach (Table 3).

In the middle and lower reaches, the plotted particle size distributions were similar from year to year in the depositional sites (flats) (Figs. 5A and 5B), suggesting either that there was little substrate movement or that the same particle sizes were deposited each year. In contrast, measured rock sizes varied significantly (ANOVA, $p < 0.05$) between years in the erosional (riffle) sites, particularly in the larger size-classes of substrate (Figs. 5A and 5B), indicating that these sites experience considerable substrate movement from year to year.

In the gorge reach, the substrate patterns were complicated by the presence of bedrock, so separate analyses were conducted based on including the bedrock material in the pebble count and on counting only the overlying loose substrate material. Proportions of the bed made up of exposed bedrock substrate varied significantly from year to year in all the gorge sites (ANOVA, $p < 0.05$; Fig. 5C); however, particle sizes of the loose substrate materials (overlying the bedrock) were only significantly different among years in the gorge riffles (Fig. 5D). The gorge runs showed greater range of substrate sizes than did the flats in the middle and lower reaches, but year-to-year differences in rock sizes were not significant (ANOVA, $p = 0.13$; Fig. 5).

**Fig. 5.** Among-year variability in substrate particle size distributions for the four study sites in each of the three study reaches at Catamaran Brook, 1991–1995. Note that no samples were collected in 1992 or in the flats or runs in 1991. $D_{50}$ is median particle diameter (cm).

(A) Middle Reach



(B) Lower Reach

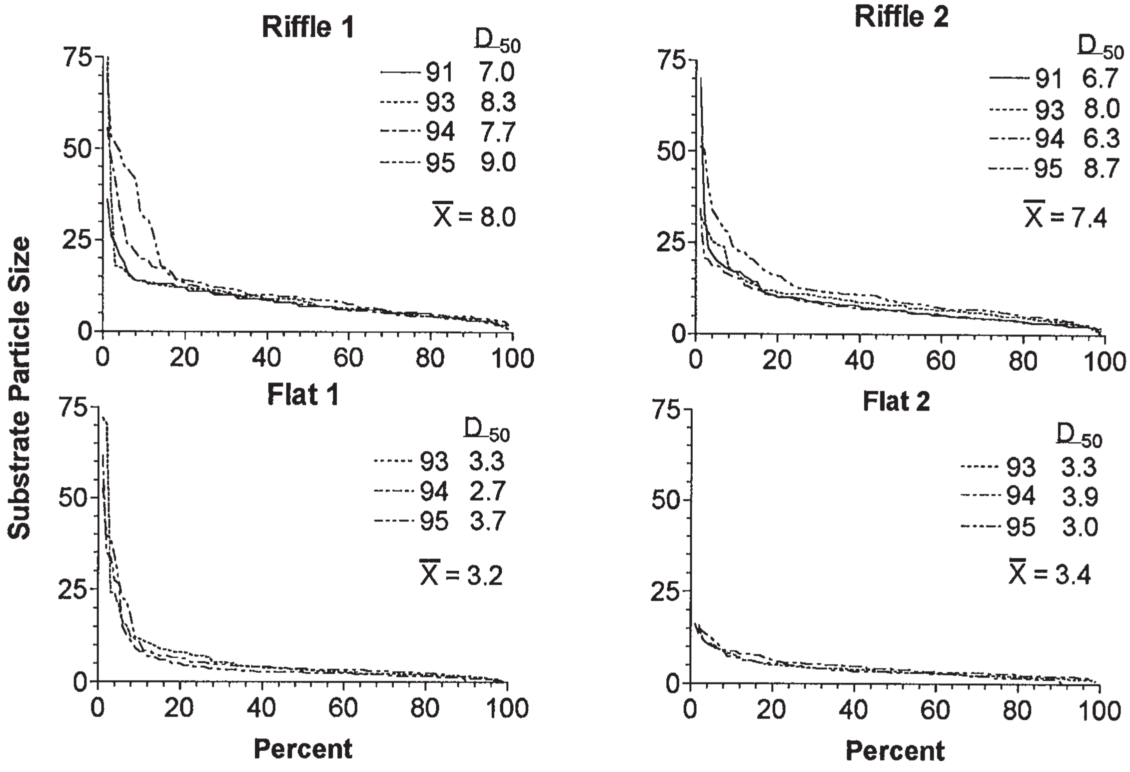
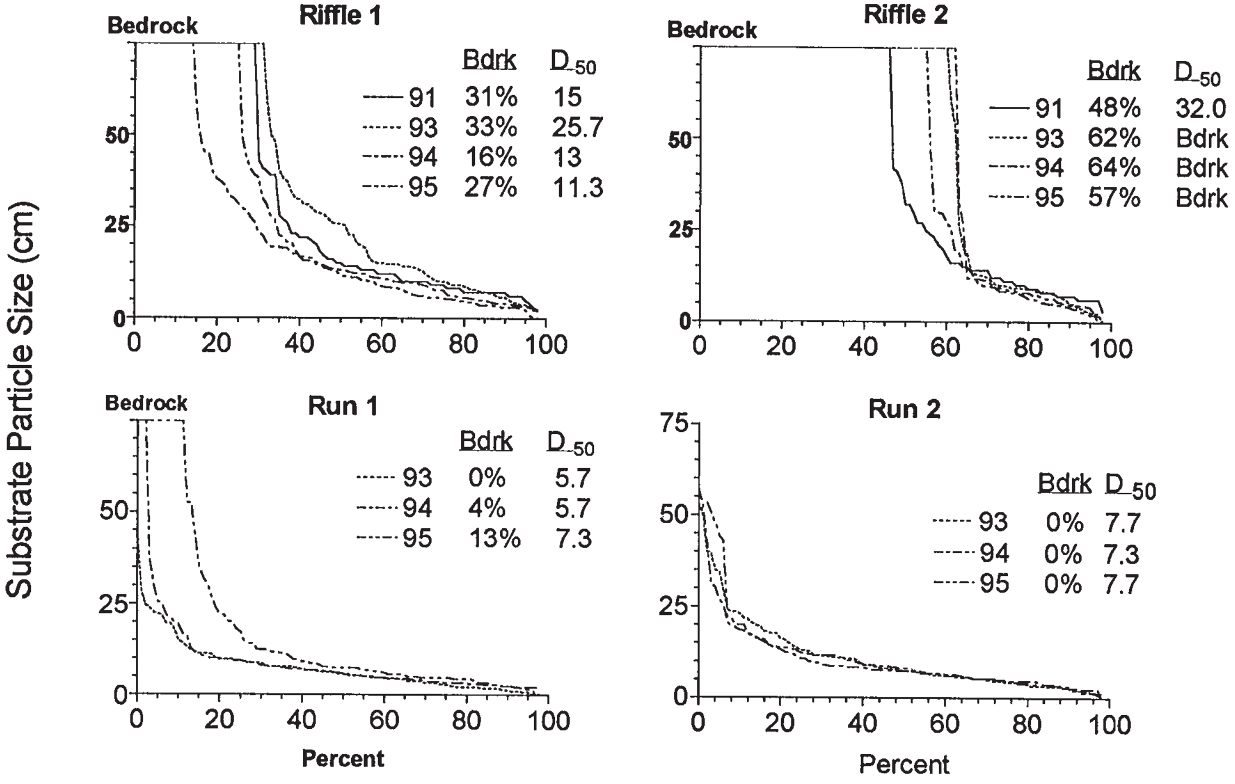


**Fig. 5** (*concluded*).

(C) Gorge, including bedrock



(D) Gorge, excluding bedrock

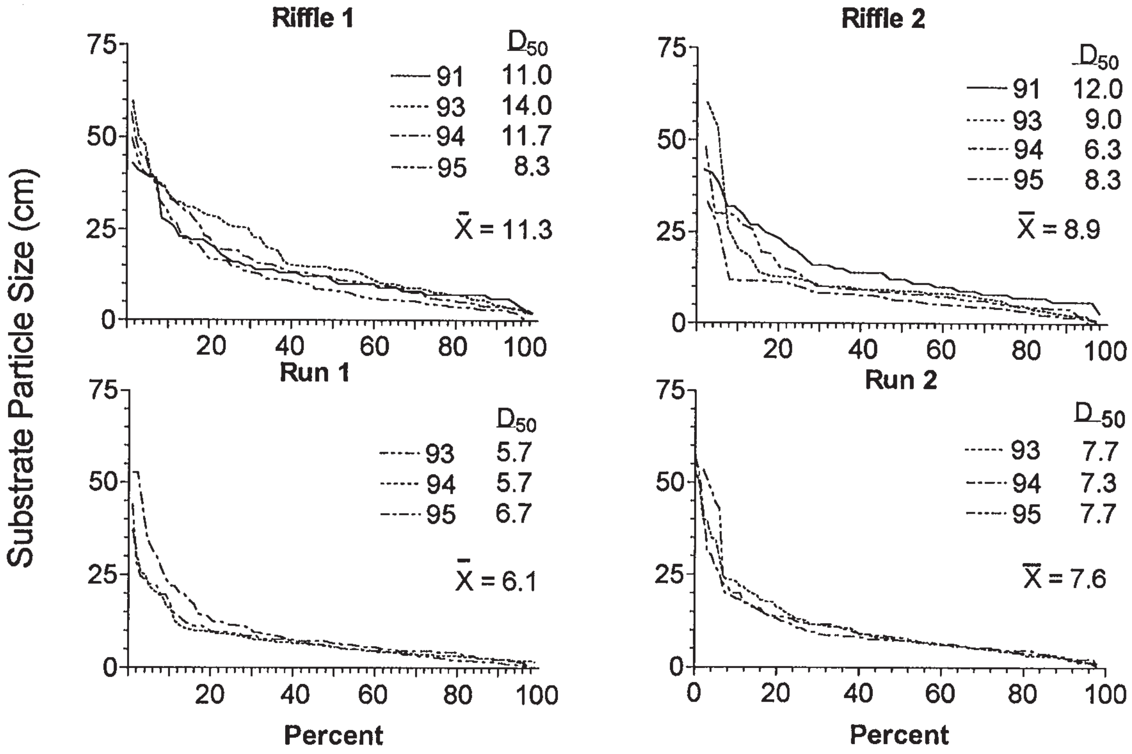


**Table 3.** Average tractive force acting on bed materials in 12 sites in Catamaran Brook at three flow levels (based on DuBoys equation; see text for explanation).

| | Summer flow | | | Truncation level | | | Bankfull flow | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | $D$ | $S$ | $\tau$ | $D$ | $S$ | $\tau$ | $D$ | $S$ | $\tau$ |
| MRi1 | 0.184 | 2.28 | 4.2 | 0.473 | 1.4 | 6.9 | 0.553 | 1.60 | 8.8 |
| MRi2 | 0.222 | 1.99 | 4.4 | 0.439 | 1.22 | 5.4 | 0.519 | 1.40 | 7.3 |
| MF1 | 0.395 | 0.05 | 0.2 | 0.727 | 0.057 | 0.4 | 0.807 | 0.31 | 2.5 |
| MF2 | 0.371 | 0.11 | 0.4 | 0.580 | 0.22 | 1.3 | 0.660 | 0.61 | 4.0 |
| GRi1 | 0.216 | 1.89 | 4.1 | 0.568 | 1.30 | 7.4 | 0.658 | 1.29 | 8.5 |
| GRi2 | 0.169 | 2.02 | 3.4 | 0.430 | 2.21 | 9.5 | 0.520 | 2.40 | 12.5 |
| GRu1 | 0.223 | 0.24 | 0.5 | 0.396 | 0.875 | 3.5 | 0.486 | 0.92 | 4.5 |
| Gru2 | 0.220 | 0.55 | 1.2 | 0.398 | 0.812 | 3.2 | 0.488 | 0.88 | 4.3 |
| LRi1 | 0.180 | 1.62 | 2.9 | 0.546 | 1.19 | 6.5 | 0.616 | 1.04 | 6.4 |
| LRi2 | 0.189 | 1.74 | 3.2 | 0.669 | 1.30 | 8.7 | 0.769 | 1.05 | 8.1 |
| LF1 | 0.285 | 0.11 | 0.31 | 0.778 | 0.12 | 0.9 | 0.848 | 0.45 | 3.8 |
| LF2 | 0.224 | 0.14 | 0.31 | 0.567 | 0.17 | 1.0 | 0.667 | 0.54 | 3.6 |

**Note**: $D$, mean depth (m) for each flow level; $S$, slope of water surface (%); $\tau$, tractive force (kg/m$^2$). Site key: M, middle reach; G, gorge reach; L, lower reach; Ri, riffle; F, flat; Ru, run.

Proportions of large substrate particles (>15 cm in diameter) were generally lower in riffle sites in 1991 and 1994 than in other study years (Fig. 5), corresponding to years with at least two successive high-volume events (Table 2). This pattern suggests that years with successive large floods may scour bed materials in the riffles, reducing the relative size of the bed materials.

The slope of the water surface changed as flow increased in a site, generally "flattening out" in riffles and becoming steeper in the flats and runs (Table 3). However, because depth increased with increased flow, tractive force also increased at high flow in all sites, even when slopes remained fairly constant (Table 3). The percentage of the bed materials predicted to be in motion at each flow level was determined by comparing the theoretical particle size in motion at different flows with the particle size distributions for each year (Fig. 6). Because of the variation in substrate size distributions from year to year, this percentage also varied from year to year, particularly for the riffles (Fig. 6).

All the riffles apparently experienced more substrate movement than the flats, with large increases in substrate movement predicted even at truncation-level events that occur, on average, about three times per year (Fig. 6). Similar increases in predicted bed movement in the flats did not occur until higher flow (bankfull stage; Fig. 6), suggesting that flats are more stable in small spates than riffles. The different riffles were variable in their substrate stability, even within a reach (Fig. 6).

## Discussion

The use of tractive force calculations to determine streambed stability must be viewed with some caution, since this method gives an average estimate for an entire site and does not take small microhabitat characteristics into consideration. However, interannual differences in measured particle sizes in Catamaran Brook generally supported the results from the tractive force measurements, suggesting that this measure can be used to compare different sites within the same system. In other words, the sites with the highest tractive force values showed the greatest among-year changes in particle size distribution, and those with low values showed little or no change.

The observed differences in particle size distribution in Catamaran Brook could have related to sample bias, to particles being scoured from a site during high flow, or to particles being redeposited in the site. The pebble-count sampling method gave replicable results in the two study riffles evaluated, so we believe that the observed patterns reflect stream processes that redistribute substrate materials. At least part of the between-year variation probably relates to large particles being scoured from the riffles during successive high-volume flood events, since there were lower proportions of large particles in most sites following repeated large floods. In the sites (e.g., the flats) where little or no between-year changes were seen in particle size distributions, it is impossible to say whether there was little substrate movement (as predicted at truncation-level floods by the tractive force calculations) or whether equivalent-sized particles were simply deposited on top of old materials during the flood. Other concurrent studies within the Catamaran Brook sites may give a clue to this pattern. Although we did not compare tractive force measurements with painted rock movements, small substrate-filled baskets (10 × 10 × 20 cm) were embedded into the substrates at the all the study sites by other researchers to measure accumulations of fine sediments (R. Cunjak, Department of Fisheries and Oceans, Maritime Region, Moncton, N.B., personal communication). These baskets move as much as several metres downstream from one year to the next in the riffle sites, but are apparently undisturbed from year to year in flats and runs, neither moving nor being covered by sediments (R. Cunjak, personal communication).

The tractive force calculation related well to other hydrological measurements taken concurrently in Catamaran Brook, providing a good relative measure of stability among sites in the one stream. However, it is not clear how accurately tractive force values reflect actual bed movement in a stream. Studies of bedload movement have occupied engineers for more than a century (see Carson and Griffiths 1987 for examples), and these studies have shown the DuBoys equation for boundary shear to be a good predictor of particle movement (Lane 1955;

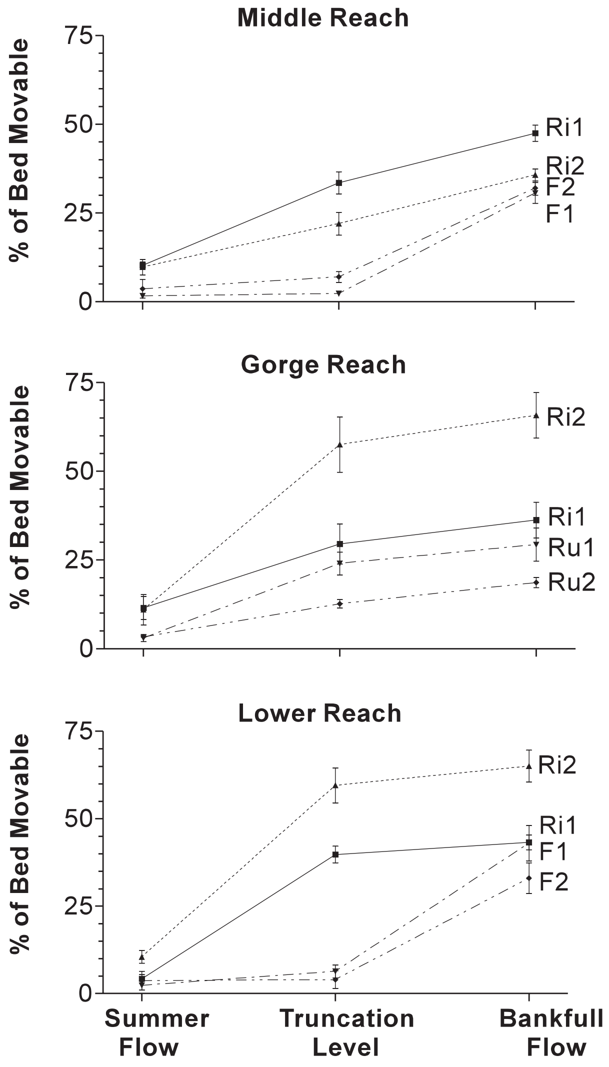
Baker and Ritter 1975; Carson and Griffiths 1987). However, Baker and Ritter (1975) indicated that the DuBoys equation may overestimate particle movment in extremely wide and shallow rivers and underestimate movement in very deep channels. Hallisey and Belt (1996) proposed a series of characteristics of streams that showed a good fit to the tractive force model, based on a study of 123 Idaho streams. They suggested that streams with coarse gravel substrates ($D_{50}$ = 4.8 cm), high percentages of fine particles ( 30%), moderate slopes ( 2.8%), moderate width to depth ratios ($W$:$D$ = 16.9), and mean widths of  7 m gave good agreement with the model. Streams where the model underestimated movement (i.e., movement was initiated earlier than predicted) had larger, cobble substrates ($D_{50}$ = 12.1 cm), low gradients (1.7%), high $W$:$D$ (36.9), low percentages of fine particles (11.3%), and stream widths of >17 m. Streams where the model overestimated movement had finer substrates ($D_{50}$ = 3.6 cm), steep gradients (5.5%), moderate $W$:$D$ (16.5), and relatively narrow stream widths (5.4 m). The Catamaran Brook stream sites showed good agreement with Baker and Ritter's (1975) characteristics but were intermediate to those that fitted Hallisey and Belt's (1996) "good fit" characteristics and those that underestimated movement. Therefore, the tractive force model may provide slight underestimates of particle movement in the Catamaran riffle sites during high flow.

Tractive force measurements have also been shown to correlate with biological data. Cobb et al. (1992) and Muotka and Virtanen (1995) found that tractive force values were good predictors of biotic responses to floods (for aquatic insects and mosses, respectively) in a variety of stream sites. However, Death and Winterbourn (1994) found that tractive force calculations did not correspond to movement of painted stones placed on the streambed in several New Zealand streams. Note, however, that Death and Winterbourn (1994) did not consider the differences in slope at varying flows when they calculated tractive force, so their comparisons may not be valid.

The variability in particle sizes among years has important implications for studies of stream stability and biotic responses, especially in sites where the interannual variability is high, such as riffles. Substrate stability measurements are rarely collected for more than one year, even though they may be compared with biotic data from several years. High interannual variability (especially in riffle sites) could lead to poor correlations between bed stability measurements and biotic responses, if the bed stability was not measured every year during a study. For example, we predicted substrate movement of >80% in gorge riffle 1 for a 5-year flood in 1994, compared with only 53% during an equivalent-sized flood in 1991. This pattern related to the size distribution of substrate materials present during the flood year, which depends on complex interactions between site slope and the flood conditions of the preceding year.

The pattern of substrate stability in different habitats during floods supports the conclusions from other recent intensive studies showing the presence of "hydraulic refugia" within sites and reaches (Lancaster and Hildrew 1993*a*, 1993*b*). Since particles that are larger than the calculated tractive force for a given reach should remain stable, there should still be patches within most riffle sites that remain stable during floods. Sites that show little substrate movement during spates may also act as hydraulic refugia. Such sites could retain their existing fauna, and even collect drifting fauna, during floods and act as sources of colonists for recolonization following floods (e.g., Giberson and Hall 1988; Palmer et al. 1995, 1996).

**Fig. 6.** Average proportion of substrate predicted to be in motion at given flows at Catamaran Brook based on tractive force calculations and substrate particle distributions for each site. Error bars are standard errors, but are based on values obtained following arcsine transformation. Site key: Ri, riffle; F, flat; Ru, run.



Resh et al. (1988) suggested that floods were not a disturbance if they were predictable, due to the ability of organisms to adapt over time to predictable events. Catamaran Brook showed low to moderate statistical flow predictability overall (sensu Resh et al. 1988), but certain sites were highly predictable with respect to substrate size from year to year whereas other sites were variable. These data show that not only is flow predictability a poor indicator of habitat predictability in streams, but that the substrate movement varies inconsistently with flow from year to year. Evidently, streams are highly dynamic systems that can change radically from year to year, particularly in certain sites. Measurements of bed stability, for example using tractive force calculations along with regular measurement of substrate particles, should be collected each year that biotic comparisons are being made. These measures can give a reasonable estimate of habitat variability and provide a framework for evaluating relative bed stability.

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