Substrate stability in streams: effects of stream size, particle size, and rainfall on frequency of movement and burial of particles.

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ABSTRACT: Substrate stability in streams: effects of stream size, particle size, and rainfall on frequency of movement and burial of particles. Surface movement and burial of streambed particles are indicated in the literature as mechanisms by which floods disturb stream invertebrate assemblages. We designed an experiment to test whether stream size, rainfall, and particle size were important in the frequency of particle movement and burial. Five stream sites, from orders 1-4 and differing from each other in relation to substrate composition and presence of debris dams were studied. Labeled particles were placed in the streambed and checked every two months during one year. There was a statistically significant interaction among rainfall and particle size, indicating that the positive effect of rainfall was dependent on particle size. Also, there was a statistically significant positive effect of stream size, although of low magnitude when compared to the effects of rainfall. Frequency of burial was much lower than that of particle movements, except in the smallest stream site during the peak of the rainy season when 57% of the particles were buried to some degree. During periods of high rainfall several of the debris dams present in the smallest stream were broken, causing movements of particles located upstream and burial of particles in downstream areas. In a second survey one year after the end of the experiment, 67-100% of the particles were dislodged.

Key-words: bed stability, bedload transport, benthos, disturbance, Brazil.

RESUMO: Estabilidade de substrato em riachos: efeitos de tamanho do riacho, tamanho de pedra e chuva na frequência de movimento e enterramento de pedras. Rolagem e enterramento de pedras são indicados na literatura como mecanismos pelos quais enchentes perturbam comunidades de invertebrados em riachos. Nós usamos um experimento para avaliar a importância do tamanho do riacho, tamanho de pedras e chuvas na frequência de rolagem e enterramento de pedras. O experimento foi feito em cinco riachos, de ordens 1 a 4 e variando em composição do substrato e presença de pequenas cachoeiras formadas por deposição de detritos. Pedras marcadas foram colocadas no leito dos riachos e conferidas a cada dois meses durante um ano. Houve uma interação estatística significativa entre quantidade de chuva e tamanho de pedras, indicando que o efeito positivo de chuvas foi dependente do tamanho de pedra. Ainda, houve um efeito estatisticamente significativo de tamanho de riacho, embora de baixa magnitude quando comparado ao efeito de chuvas. A frequência de enterramento foi muito menor que o de rolagem, com exceção do menor riacho durante o pico da estação chuvosa, quando 57% das pedras foram pelo menos parcialmente enterradas. Durante períodos de chuvas intensas, diversas cachoeiras formadas por acumulação de detritos foram desfeitas, causando rolagem de pedras a montante e enterramento de pedras a jusante. Numa avaliação subsequente, após o término do experimento, 67-100% das pedras foram deslocadas num período de um ano.

Palavras-chave: estabilidade de substrato, rolagem de pedras, bentos, perturbações, Brasil.

Introduction

Disturbance caused by flood is an important process acting on benthic assemblages occurring in hard bottom running water systems (Resh et al., 1988; Townsend, 1989; Maltchik & Florín, 2002). After flood events, the abundance of organisms living on surface stones often decreases (Flecker & Feifarek, 1994; Uieda & Gajardo, 1996; Bispo et al., 2001). This decrease in abundance might be the result of passive detachment from the stone surface, active search for refuge, or even mortality (Dole-Olivier et al., 1997; Holomuzki & Biggs, 1999). The exact way in which floods depress organism abundance in streams is not fully understood, although turning and burying of particles are likely to be important mechanisms (Englund, 1991; Matthaei et al., 1999b, 2000; but see Bond & Downes, 2000).

Particle movements are affected by a number of factors including stone type, size, embedding, and position on the streambed (Downes et al., 1998; Matthaei et al., 1999a; 1999b). Thus, it is likely that particles differ in their suitability for organisms, depending on physical characteristics and position in the streambed. Douglas & Lake (1994) studied the relationship between species richness and stone area and found that small stones have lower species richness than large stones. Matthaei et al. (2000) found that after a flood event, abundance of species were higher on embedded stones than on those lying loose over the substratum. In both cases, the authors pointed to the high susceptibility to dislocation of small and loose stones during floods as the factor causing the decrease in species richness and abundance.

Across a catchment, channel morphology differs in several physical features (Church, 1996). Headwater streams usually have higher frequency of riffle-pool sequences than larger, downstream sites. Particle sizes in general are dependent on channel gradient, which in turn tend to decrease downstream. In seasonal environments, floods resulting from high rainfall events tend to last longer at downstream sites than at small streams, where the rise and fall of the water level can occur within a few hours. All these differences might result in different disturbance intensities for stream assemblages subjected to the same rainfall regime, but occurring in different places across a catchment.

Traditionally, assessment of proportions of particles of a given size that moved during a flood event has been made indirectly by calculating the critical force required to cause entrainment of each size (Cobb et al., 1992). Recently, river ecologists have assessed particle movements directly by observing the presence/absence of labeled particles in previously mapped places after a flood event (Death & Winterbourn, 1994; Townsend et al., 1997; Downes et al., 1998) or measuring the force needed to move stones (Downes et al., 1997). Burial and subsequent return to surface of particles can be inferred by monitoring partially buried chains and observing how many links were buried or remained on the surface after a flood (Matthaei et al., 1999b). A more costly method, but perhaps more realistic, to assess both movement and burial of particles, is the mapping of labeled stones and several subsequent visits to search for those missing.

In this study we tested the importance of stream size, rainfall, and stone size on the frequency of stone movement and burial in five streams located in the same catchment. Rainfall is used as a rough surrogate for spates, as direct measures of this last factor were not available. The assessment of movement and burial of particles was done directly, using painted stones.

Study sites

The study was carried out in the Carmo River catchment, at Parque Estadual Intervales (24°18'S, 48°25'W), São Paulo State, Brazil. The vegetation is tropical ombrophilous submontane-montane forest, commonly known as tropical rain forest (Mueller-Dombois & Ellenberg, 1974). The mean annual precipitation in the area is 2,040 mm (rain gauge located 20 km from the nearest stream site studied and subjected to the same precipitation regime of the studied catchment; 25 y record). Rainfall is unevenly distributed across two seasons: one wet (150-400 mm/mo) and warm (15-30 °C) from September through March and another dry (60-150 mm/mo) and cold (0-25 °C) from April to August. During the first year of the study, September 1999 through August 2000, 1,855 mm of precipitation were recorded. The months with highest total precipitation were February and March with 313 and 318 mm respectively. In the second year, 1,867 mm were recorded and the two rainiest months were September and December with 260 and 259 mm, respectively.

Experiments were performed in five sites comprising streams of first through fourth order. Physical characteristics of stream sites are presented in Tab. I. Studied stream sites 1-5 represent sites 1, 4, 6, 8, and 9 respectively in a previous study (Melo & Froehlich, 2001), where additional information on physical characteristics, invertebrate assemblages and a map are provided.

Table I: Physical characteristics of the five studied stream sites in Parque Estadual Intervales, Iporanga, Brazil.

	Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**
Stream order	1	2	3	4	4
Width (m)	0.5 - 1.0	2.5 - 3.5	3 - 4	9 - 11	9 - 11
Discharge in dry season (m^3/s)	0.0040	0.0414	0.0768	0.4934	0.6458
Drainage basin (km^2)	0.50	1.81	3.62	25.19	25.69
Streambed	sand, stones	stones, boulders	stones, boulders	stones, boulders	stones, boulders
Waterfalls	common	sparse	sparse	none	none

Materials and methods

Fieldwork

At each stream site, two sets of 15 stones were painted using automobile spray cans. The first set was composed of stones around 10 cm long (a-axis) and here are called small stones. The second set comprised stones around 18 cm long (a-axis) and are hereafter called large stones. We opted to use stones of 10 and 18 cm long as particles of these size classes are common in all five streams studied and have been used in studies of invertebrate diversity (Melo & Froehlich, 2001). Each stone was identified using a small plastic label attached to the stone using angling nylon line. As the shape and density of stones certainly affect movement frequency, we standardized stone type by selecting flat sedimentary stones (shales, siltstones, and sandstones), frequent in the five sites studied.

The painted stones were placed on the surface of the streambed in riffles. Specific places in the streambed were chosen according to the presence of particles of similar sizes. We did this in order to reduce the proportions of stones placed in unstable places, where particles of similar sizes would not settle in natural conditions. Although the artificial, human placement of stones on the streambed surface may have overestimated the frequency of movements due to the selection of unstable places, we have no reason to suspect that this varied across stream sites. We thus assume that although observed frequencies in our experiment may have overestimated frequencies of movements in natural conditions, the bias should be constant, making comparisons among sites within this study valid.

Stones were placed in rows perpendicular to the main flow. Rows were spaced at least 10 m from each other. In sites 1 and 2, each row comprised one small and one large stone, totaling 15 rows. In sites 3, 4, and 5, each row was composed of two stones of each size, except by the most downstream row that contained three stones of each size, totaling seven rows. Plastic strips tied to the surrounding vegetation were used to indicate the position of each row in the study reach.

The experiment was started in September 1999 and followed through one year. During the period, we visited each stream site every two months, recorded the movements and burial status of each stone, and replaced the dislodged and buried stones to their original position. Stones that remained in the original row were removed and then placed back in the same position to ensure that all stones were in the same condition of embedding (i.e. not embedded) for the next period. When necessary, stones were repainted.

We considered burial events independent of particle movements. Thus, we did not distinguish those burial events that occurred in original places from those that occurred after particle displacements.

In each visit, two people conducted searches over a 1-2 hour period. In cases in which a stone was not found, a new stone of the same size class was painted and replaced, but with a different label code. In subsequent visits, several previously lost stones were found. For these cases, we considered that the stone was completely buried and moved once during the original two-months period.

In the last bimonthly visit in August 2000, we also returned all stones to the original positions in order to assess how many stones moved from the original location in the following one-year.

Statistical analysis

We tested the importance of stream size, rainfall in the two-months period, and stone size on the number of stone movements using logistic regression. We used data of each stone subjected to the combination of the three independent variables. The analysis relied thus on 15 observations for each combination of the independent variables. As all 15 observations are subjected to the same combination of treatments, it is likely that our data are autocorrelated to some extent. We should thus interpret the experiment as a study case. Although we used the obtained p-values to interpret our results, readers should consider that significance of p-values is inflated to some ummeasured degree.

Stone size was treated as a categorical variable, while stream size and rainfall were treated as continuous variables. The largest distance between two streams sites was ca. 12 km and it is likely that some differences in rainfall may have occurred among studied streams. However, rainfall for each site was not available and thus we assume that rainfall was homogenous among sites and use a single value for all stream sites in a two-months period.

We fitted logistic models using two metrics of stream size, mean discharge during the driest period and drainage basin area. The same final model was selected using either metrics. We present results for the fitted model using mean discharge during the dryest period. Model selection was done using a hierarchical backward elimination approach (Kleinbaum, 1994), starting with the saturated model containing the interaction among the three explanatory variables. The procedure of model selection was done manually using a likelihood ratio test.

Number of burials was too low in most of the sites studied, precluding a reliable use of logistic regression. Data regarding small and large stones were pooled and are presented graphically.

Results

The main factor stream size and an interaction term among rainfall and stone size composed the simplest final model that still fitted the data for stone movements (Tab. II). More stone movements were observed in large streams than in small streams ($p = 0.007$; Fig. 1a). However, the magnitude of this difference was low when compared to the effects of rainfall (Fig. 1b). Small stones tended to move more than large stones, although this difference was dependent on the rainfall in the period (Figs 1b and 2). In periods of low rainfall, movements of small and large stones were similar, but tended to differ as rainfall increased (interaction term among rainfall and stone size, $p = 0.026$; Fig. 1b). The number of stone movements was strongly related to rainfall in the period (Fig. 1b).

Table II: Logistic regression model selected by hierarchic backward elimination procedure to test the effects of stream size, rainfall, and stone size on the frequency of stone movements. The selected model has residual deviance 627.852 on 895 degrees of freedom (df) and the null model (constant only) has deviance 771.206 on 899 df. The global hypothesis that all four explanatory variables are non-significant was rejected at $p < 0.001$ (deviance difference 143.354, chi-square distribution on 4 df). The factor stone size was dummy coded using large stone as reference (i.e. parameter estimate for large stone set to zero).

Parameter	**Estimate**	**S. E.**	**t-ratio**	**p**
Constant	-3.833	0.399	-9.614	<0.001
Rainfall (cm)	0.048	0.009	5.348	<0.001
Stone size (small)	-0.652	0.566	-1.152	0.249
Stream size (discharge m^3/s)	1.020	0.377	2.706	0.007
Rainfall x stone size (small)	0.029	0.013	2.230	0.026

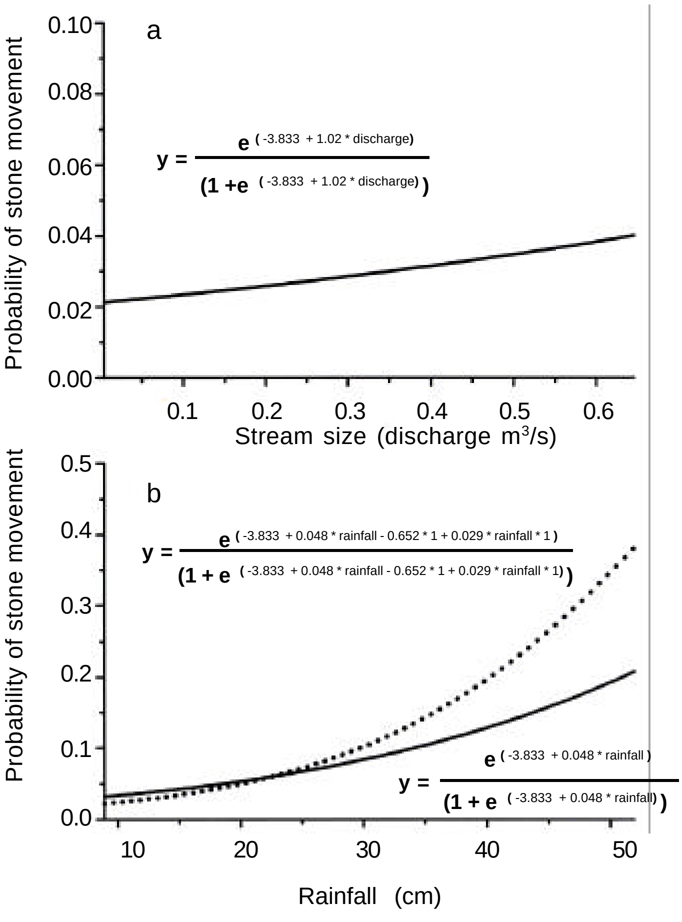

Figure 1. The relationship between the probability of stone movement and the significant factor stream size (a) and the interaction term among rainfall x stone size (b) of the logistic regression model. The dotted line in (b) indicates small stones and the solid line large stones. The fitted intervals of the factors are the ranges observed in the study. In (a) the fitted curve assumes that all but stream size parameters are zero and in (b) the opposite. Notice that y-axes are in different scales.

Frequencies of stone burial were generally low in the six periods studied (Fig. 3). Burial was rare at sites 2-5, but occurred at higher frequencies in site 1, particularly during January-February. Sediments covering stones in sites 2-5 were mainly gravel and pebbles. Covering material at site 1 was predominantly sand, derived from debris dams broken during high flow events.

On the second year of observation, 80-100% of the small and 67-93% of the large stones moved and/ or were buried (Fig. 4). In sites 1, 2, and 4 no small stone remained in place. The number of disturbed stones was lowest in site 5, but still high (80 and 67%, respectively for small and large stones).

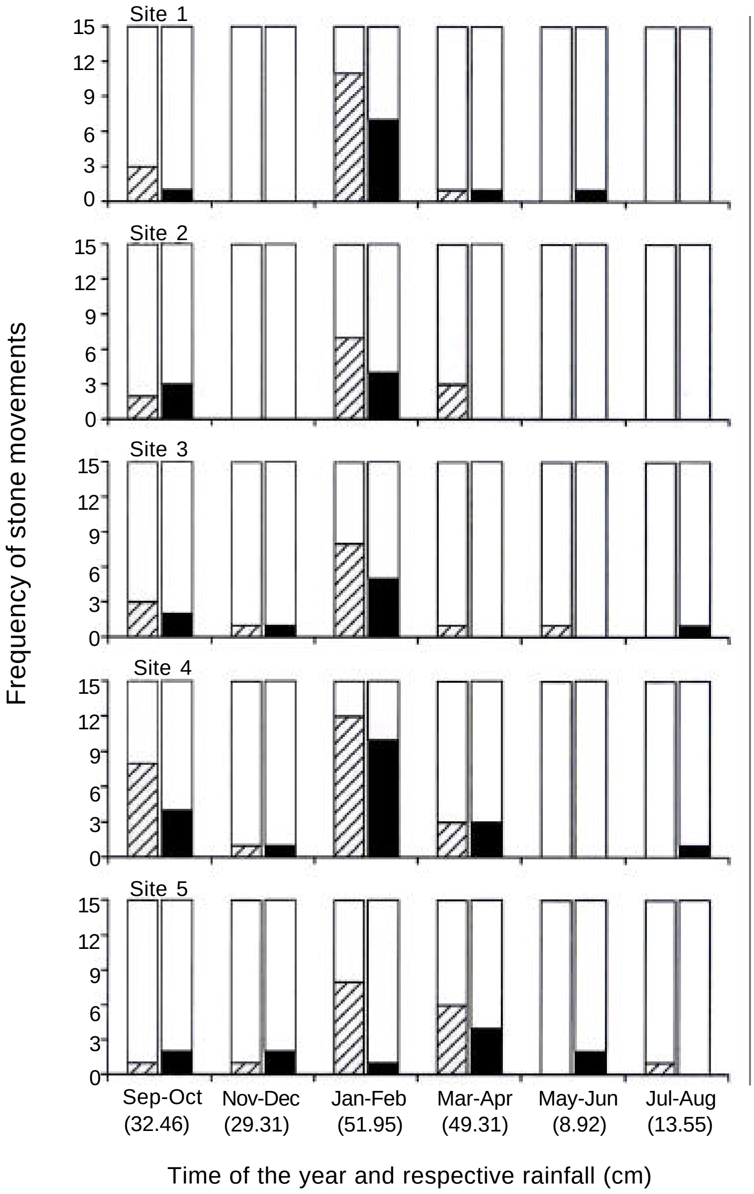

Figure 2: Frequency of stone movements during two-month intervals in five stream sites during the first year of the study. Hatched portion of bars indicate movements of small stones (around 10 cm) and black portions movements of large stones (around 18 cm). Hollow (white) portions of bars indicate stones that remained in place.

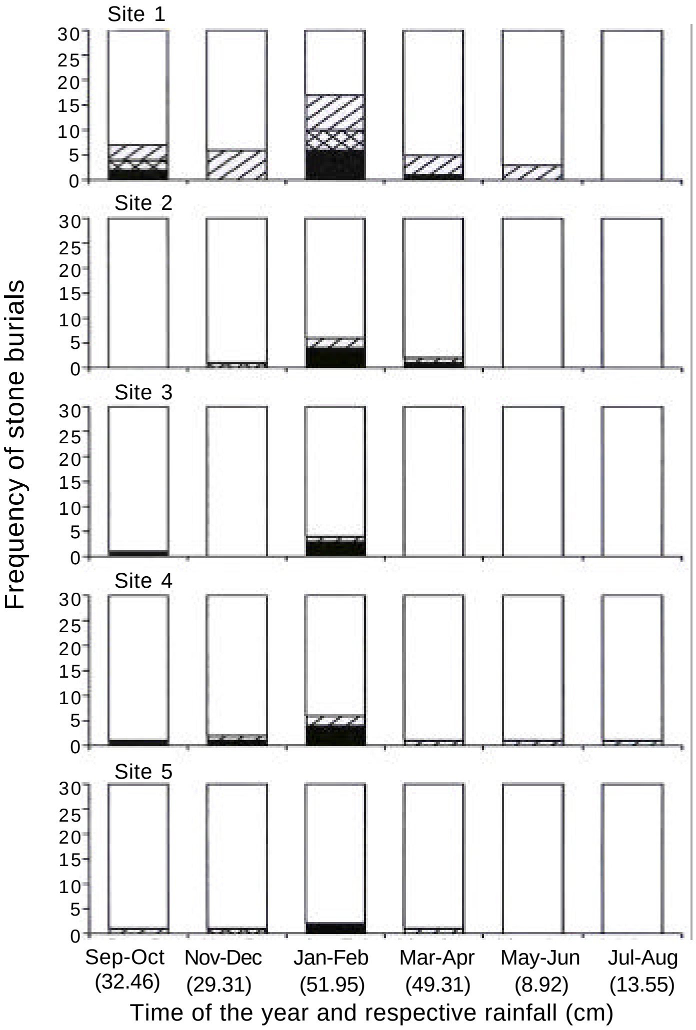

Figure 3: Frequency of stone burials in five stream sites during one year. Small and large stones pooled. Hatched, crosshatched, and black portions of bars indicate respectively 25-50, 51-75, and 76-100% of burial. Hollow (white) portions of bars indicate stones that remained entirely on the surface.

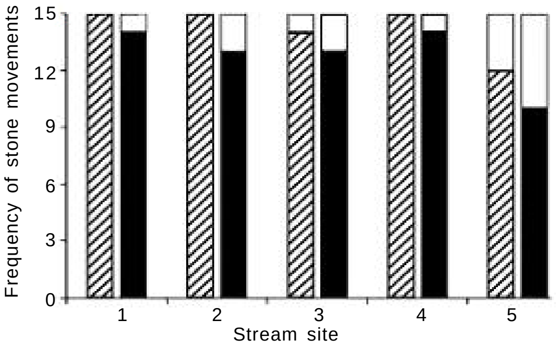

Figure 4: Frequency of stone movements during the second year of the study period. Hatched bars indicate movements of small stones and black bars movements of large stones. Hollow (white) portions of bars indicate stones that remained in place.

Discussion

Stone movements occurred with highest frequency during January-February in all stream sites, followed by the periods September-October and March-April. As would be expected, the period of most movements coincides with the peak of the rainy season, while the two others represent the start and the end of the rainy season in the studied area.

During periods of high rainfall, small stones moved more frequently than large stones, agreeing with previous results (Downes et al., 1998; Matthaei et al., 1999a). During periods of low rainfall movements of small and large stones were low and similar. Most of the stone movements during periods of low rainfall were restricted to short distances. Although we had not considered in our study the confounding effect of human-placing stones in the streambed (e.g. Downes et al., 1998), it is likely that most of the movements in periods of low rainfall were due to the placement of stones in unstable areas and thus independent of stone size.

Downes et al. (1998) found that disturbance levels were similar in third- and fourth-order streams during the dry-summer season. During winter, disturbance levels in upstream sites remained unchanged, but doubled in downstream sites. Based on results of Downes et al. (1998) we expected that the number of movements would increase downstream, at least during rainy periods. In fact, we found a statistically significant effect of stream size in our study. However, the magnitude of the effect was low (Fig. 1a). Also, the selected final model did not include an interaction term among stream size and rainfall, indicating that the effects of stream size on frequency of stone movement was constant over the year.

Frequency of burial was much higher at the smallest site than at the other four sites. The smallest stream contained several small debris dams formed by fallen trees and subsequent accumulations of twigs, leaves, and sand. We observed that the process of formation and the subsequent partial or total destruction of dams in this stream is very dynamic. After rupture of debris dams, stones located within 0-10 m upstream moved downstream. This occurred because of the increase in steepness and consequent movements of sand and gravel. In downstream areas ranging from 5 to 15 m long, stones were covered by sand and gravel derived from patches located in the eroded areas upstream of the ruptured dam. Hax & Golladay (1998) observed that debris dams increased the retention of wood debris, the main substrate used by invertebrates in a sandy stream. They argued that wood trapped by debris dams might be an important refuge, slowing the downstream transport of invertebrates during floods. While this might be true in some cases (Palmer et al., 1996), our data suggest that this statement is far from being a rule. Debris dams that acted as refuges for a particular flood, might act as a very unstable site during a later event when decaying key logs in the dam are no longer strong enough to withstand high flow.

Frequency of burial was low in stream sites 2-5 and in most of these cases stones were actually wedged by other stones. This is in agreement with previous findings that floods cause higher frequency of movements than of burial (Gintz et al., 1996). Nevertheless, burial was frequent in the first-order site, indicating that effects of flood disturbance might be site-dependent. Most recent studies of disturbance in streams have only taken in account stone movements as consequences of high flow events (Matthaei et al., 1997). Our data reinforce the suggestion of Matthaei et al. (1999b) that more attention should be paid by stream ecologists to burial of stones, which in some cases might be as important as stone movements.

On the second year of observation, we were not able to locate most of the disturbed stones because most of the paint coat had been scoured away. However, the plastic labels remained attached to the rocks, allowing us to assess at least whether stones remained in the original positions or were dislocated. For this entire one-year period, 95% of the small and 85% of the large stones were dislodged.

Our study indicates that disturbance of stones in streams is frequent. However, the causes of the disturbance might differ between sites differing in physical structure. In the small stream studied, perhaps most of the stone movements were caused by rupture of debris dams, while in the four large streams the main cause was likely the direct force of water during high flow. Also, physical differences among stream sites (i.e. the presence of debris dams) were a cause of frequent events of burial.

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