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Development of spatial pattern in large woody debris and debris dams in streams

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Abstract

The spatial distribution of large woody debris (LWD) in streams was evaluated using Neighbor *K* statistics, following extensive wood deposition from an ice storm in the eastern Adirondack Mountains (New York). Two years after wood deposition, we surveyed individual pieces of LWD in one stream and surveyed debris dam locations in eight streams within the ice storm area. To examine the linear pattern of debris dams within a stream, we used a one-dimensional version of Ripley's *K*, a second-order statistic that evaluates the spatial pattern of points within a landscape. Both aggregated and segregated (regularly spaced) distributions of wood were identified. Individual pieces of LWD were aggregated at spatial extents ranging from 0 to 40 m and were segregated at spatial extents ranging from 80 to 100 m. In two streams, we found that debris dams were segregated at distances ranging from 100 to 300 m relative to randomly chosen locations, but debris dams showed no significant spatial pattern in six other study streams. Previous studies of wood distribution in streams have not observed segregated distribution patterns. Spatial segregation of debris dams in the study area likely occurred in response to regularly spaced stream features or processes that allow movement of individual pieces of LWD toward more stable accumulation points. Neighbor *K* statistics can be used to identify and describe spatial pattern in large woody debris, and such patterns can be used to help evaluate and identify processes responsible for their generation.

Keywords: Spatial pattern; Woody debris; Debris dams; Stream geomorphology

1. Introduction

Large woody debris (LWD) and debris dams can both influence and are influenced by the physical characteristics of streams at a range of spatial scales (Nakamura and Swanson, 1994; Abbe and Montgomery, 1996; Piégay et al., 1999). Most previous investigations of the spatial arrangement of LWD and debris dams have examined processes associated with the formation, dynamics, and local spacing of debris dams (Bilby and Likens, 1980; Lienkaemper and Swanson, 1987; Van Sickle and Gregory, 1990; Gurnell et al., 2000). However, few studies have attempted to quantitatively characterize and statistically evaluate spatial patterns of wood distribution in streams (for an exception, see Wing et al., 1999). Scientists have explicitly recognized the importance of measuring and describing trends in spatial pattern in order to understand processes related to the for-

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mation of these patterns (Levin, 1992), and several previous studies have examined spatial distribution patterns of stream geomorphic units to evaluate stream processes (Lambert, 1997; Madej, 1999, 2001). In this paper, we evaluate spatial distributions of stream woody debris using Neighbor *K* statistics in an attempt to identify general patterns of wood redistribution within streams.

Woody debris has been shown to exert a strong influence on geomorphological processes in rivers and streams (Gregory and Davis, 1992; Abbe and Montgomery, 1996). Additionally, LWD and debris dams have been identified as providing beneficial habitat for many North American fishes (Bisson et al., 1987) and aquatic invertebrates (Wallace et al., 1995; Hilderbrand et al., 1997). Wood in streams also provides a point of accumulation for both autochthonous and allochthonous sources of carbon, thereby influencing energy flows and biogeochemical pathways within stream ecosystems (Raikow et al., 1995; Smock et al., 1989; Bilby and Likens, 1980).

Many factors influence the spatial arrangement of LWD and debris dams in streams, and a number of studies have described various processes responsible for wood accumulation in streams. For example, Nakamura and Swanson (1994) evaluated the distribution of LWD as a function of stream geomorphology and concluded that channel width and sinuosity are the primary factors that influence the distribution of storage sites for woody debris. Gregory and Davis (1992) made the general observation that debris dam spacing varies according to the type of forest vegetation, rates of wood decomposition, and the incidence of human activity. Other studies have reported finding both aggregated (clumped) and random spatial distributions of woody debris, depending on the presence of wood input and redistribution processes (Robison and Beschta, 1990; Richmond and Fausch, 1995; Keim et al., 2000).

Despite work conducted to characterize processes responsible for spatial distributions of stream woody debris, few studies have provided quantitative descriptions of LWD or debris dam spatial patterns. Two recent exceptions were an analysis of LWD spatial distribution in Oregon streams using two geostatistical measures (Wing et al., 1999), and a subsequent study applying a similar approach (Keim et al., 2000). These studies represent the only published applications of spatial pattern analysis techniques to quantitatively describe the arrangement of woody debris in streams, though several recent studies have evaluated the spatial distribution of other stream geomorphic features (Lambert, 1997; Madej, 1999, 2001).

2. Conceptual model

In this study, we propose a conceptual model for the development of spatial patterns of aggregation (points closer to one another than random) and segregation (points farther from one another than random) of woody debris in streams, then evaluate this model by examining the spatial pattern of woody debris and debris dam distributions in streams within a large region of extensive woody debris deposition from a major ice storm. This disturbance event provided us with a unique opportunity to evaluate the development of LWD spatial patterns, originating from a known date of wood input.

Previous studies have suggested that wood can become aggregated at specific locations along streams, and that wood is often responsible for the formation of regularly spaced geomorphological features, most notably pools (Montgomery et al., 1995). At the spatial scale of a stream reach ($\sim 10^3$ m), we propose that woody debris deposition from streamside forests will be initially distributed randomly (Wing et al., 1999). In order for wood within streams to be randomly distributed, woody debris deposition must have originated from streamside forests of consistent age and species composition, and these streamside forests must have been subject to a similar level of disturbance (e.g., fire, wind, ice storm, human).

According to our conceptual model, we propose that following the initial random distribution of individual pieces of LWD, fluvial processes rearrange these individual pieces into debris dams consisting of aggregations of LWD, smaller particulate organic material and particles ranging in size from silt to large boulders. These debris dam aggregations of individual pieces of LWD will continue to develop through time and will be distributed at regular intervals along a stream reach, corresponding to areas from which fluvial processes have removed LWD. The time scale at which aggregations of LWD develop will depend on fluvial transport, which is a function of flow intensity, piece length, and angle relative to flow direction (Lienkaemper and Swanson, 1987; Braudrick and Grant, 2000).

We further propose an additional level of spatial arrangement for LWD: debris dams—themselves aggregations of individual pieces of LWD—can become spatially arranged. Debris dams have been reported to accumulate along river bends (Nakamura and Swanson, 1994), which occur at regular intervals depending upon stream sinuosity. In our study area, most debris dams occur in association with large boulders, which have also been reported to demonstrate patterns of spatial aggregation (Lambert, 1997). Previous investigations have not examined the extent to which debris dams themselves are aggregated or occur at regular intervals within streams, therefore this is a major focus of our study.

3. Case study: debris dams and LWD from the 1998 ice storm

3.1. The 1998 ice storm and streamside tree damage

In January 1998, a severe ice storm damaged the canopy of forests throughout the NE US and SE Canada. Ice storms cause breakage of tree limbs and trunks and are responsible for deposition of woody debris on the forest floor (Hooper et al., 2001), including streams and associated riparian areas within those forests. The 1998 ice storm was notable for the large area of extensive damage, including four NE US states and two Canadian provinces. In New York alone, 18,100 km^2 were impacted by ice accumulations averaging 2.5 cm and reaching up to 3.3 cm (DeGaetano, 2000). Hooper et al. (2001) estimated that the woody debris deposited by the 1998 ice storm approached that of a large hurricane. Data collected in the eastern Adirondack Mountains of New York state indicated that, following the 1998 ice storm, the number and volume of LWD and debris dams within streams increased as a function of tree canopy damage (Kraft et al., 2002).

Tree canopy damage from the 1998 ice storm was patchy, and eight stream study reaches within forested areas were selected to represent a range of tree canopy damage. Within these reaches, the overall percentage of streamside trees with canopy damage ranged from 16% to 61% (Table 1), generally encompassing the entire range of tree canopy damage observed from the 1998 ice storm (Kraft et al., 2002). Although specific details of the age composition and disturbance history of streamside forests were not obtained, tree species composition was similar at all study sites and mean dbh (diameter at breast height) of trees did not differ significantly between study sites ($p = 0.69$) (Table 1). Based on the age of study area forests and our observations of the general absence of debris dams at locations without tree canopy damage from the 1998 ice storm, background woody debris inputs at our study sites were very low prior to the ice storm

Table 1
Characteristics of streamside forests associated with eight study streams

Stream[a]	Dominant riparian trees	Proportion damaged trees	Trees surveyed (no.)	Mean no. of trees per survey plot	Mean tree dbh (cm)
Black brook (A)	white pine, Am. beech, eastern hemlock	0.31	68	7.1	17.0
McNalley brook (B)	eastern hemlock	0.53	64	7.1	14.2
Rocky branch (C)	eastern hemlock, sugar maple, paper birch	0.51	81	11.6	18.3
Derby brook (D)	eastern hemlock, yellow birch	0.16	62	10.7	14.9
Spruce Mill brook (E)	eastern hemlock, yellow birch, sugar maple	0.34	107	12.2	17.1
Phelps brook (F)	sugar maple, Am. beech	0.42	76	6.9	18.8
Slide brook (G)	yellow birch, mountain maple, paper birch	0.27	71	7.6	15.6
Nichols brook (H)	eastern hemlock, sugar maple	0.61	122	8.5	16.3

[a] Letters in parentheses following stream names refer to locations shown in Fig. 1.

(Hedin et al., 1988). The degree of tree damage and subsequent woody debris deposition from the 1998 ice storm varied largely at the watershed scale (Rhoads et al., 2002), therefore we believe that woody debris deposition from this disturbance event initially resulted in a random distribution of woody debris within associated streams.

3.2. Study area characteristics

Stream study reaches were located in the Adirondack Mountains, a dome of predominantly Precambrian metamorphic rock located in northeastern New York (Fig. 1). All study streams ultimately drain northeast into Lake Champlain. In Fig. 1, the entire subwatershed upstream from the start of each survey reach is shown in gray; letters designate stream names: (A) Black Brook, (B) McNalley Brook, (C) Rocky Branch, (D) Derby Brook, (E) Spruce Mill Brook, (F) Phelps Brook, (G) Slide Brook, (H) Nichols Brook.

Surficial geology of the study region is dominated by metanorthorsite, mixed gneisses, syenitic metamorphic rocks, and leucogranitic/charnockitic gneiss. The entire Adirondack region was most recently scoured and further modified during the Wisconsin glaciation,

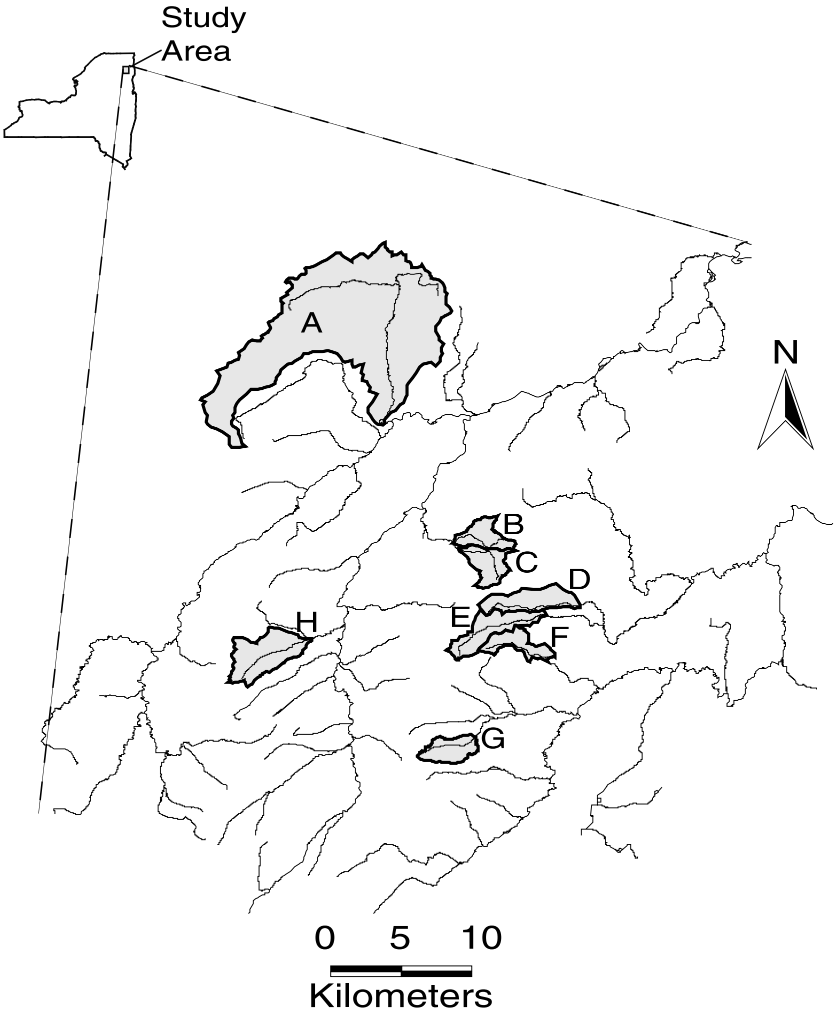

Fig. 1. Location map for the eight subwatersheds within which stream study reaches were located.

and soils are generally thin. The last glacier retreated between 15,000 and 8000 years ago, and the Adirondacks continue to rebound from glaciation at a rate of about 3 mm per year. Glacial erratics and glacial till are common in streambeds of this region. Streams are characterized by a peak flow following snowmelt in April or May, and base flow occurs in July and August with a slight recharge in fall.

Peak annual water flows at a US Geological Survey monitoring station (E Branch Au Sable River) located within 25 km of all study sites were relatively low between the time of the ice storm (January 1998) and initiation of our field surveys (July 2000). The peak annual flow during this interval was 4850 cfs, which ranked 18th out of 75 available years from which peak annual flows were available (water flow data available from 1925 to 2001; annual peak flows ranged from 2340 to 23,900 cfs).

This study was conducted in the eastern part of the Adirondack Mountains known as the "high peaks" region, where maximum elevations exceed 1600 m. Data were collected from eight tributary streams (Fig. 1). Stream morphology consisted of both pool–riffle and step-pool channel types, and boulders were the dominant pool-forming elements. Mean bankfull width for the eight streams was 8.5 m (S.D. = 3.1) and the mean watershed area for these streams was 24.2 km^2 (median = 9.1) (Table 2). Elevations of stream study reaches ranged from a minimum of 250 m to a maximum of 530 m, and stream gradients (calculated from 1:25,000 USGS topographic maps) ranged from 4.4% to 6.6% (Table 2). Weather stations near the study area receive a mean annual precipitation of 900 mm, a portion of which falls as snow (generally from December to March).

Most forests within the Adirondacks were first logged prior to 1900, and study streams are situated within second growth mixed hardwood–conifer forests ranging from approximately 20 to 80 years old. Dominant trees (tree species comprising >15% of the total trees surveyed) in riparian areas adjacent to stream reaches included: eastern hemlock (*Tsuga canadensis*), yellow birch (*Betula allegheniensis*), paper birch (*Betula papyrifera*), white pine (*Pinus strobus*), American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and mountain maple (*Acer spicatum*) (Table 1).

4. Methods

4.1. LWD and debris dam surveys

Along a 400-m reach of a second-order stream (Rocky Branch), the location of all wood 1 m in length and 10 cm in diameter was recorded in LWD surveys conducted during November 2000 and June 2001. This moderate gradient stream had a mean bankfull width of 8 m, and a substrate dominated by loose boulders and cobble. For each piece of LWD, we recorded its location relative to a permanent downstream landmark, length, width, orientation to flow, and whether or not the LWD was part of a debris dam. When an individual piece of LWD was located at an angle relative to the streambank, its midpoint was used to represent its stream location. Movement and recruitment of LWD within the study reach were also noted for all pieces of LWD.

In July and August 2000, an intensive survey was conducted in eight small streams within the ice storm-

Table 2
Characteristics of eight study streams

Stream[a]	Stream order	Mean width (m)	Watershed area (km^2)	Gradient (%)	Reach length (m)	Initial elevation (m)
Black brook (A)	3	13.4	128.7	4.4	850	370
McNalley brook (B)	2	6.1	6.6	6.1	900	335
Rocky branch (C)	2	8.0	7.4	6.6	700	385
Derby brook (D)	2	7.2	10.7	6.5	900	300
Spruce Mill brook (E)	1	9.0	11.1	6.0	1000	395
Phelps brook (F)	2	5.4	6.7	4.7	900	330
Slide brook (G)	2	8.8	7.0	6.0	1000	470
Nichols brook (H)	2	10.0	15.0	5.5	1000	250

[a] Letters in parentheses following stream names refer to locations shown in Fig. 1.

impacted region of the eastern Adirondacks to examine the frequency and association of debris dams with ice storm canopy damage in riparian areas (Kraft et al., 2002). We attempted to survey 1-km stream sections; however, logistical and physical constraints (e.g., stream access, stream length) limited survey reaches to 700 m to 1 km in length. Six of the eight stream reaches surveyed were second-order streams, one was a third-order stream and one was a large first-order stream (Table 2). Debris dam location, frequency, volume, position, and function were estimated for all debris dams within the stream study sections. Debris dam location was measured as the distance from a permanent downstream landmark. Bankfull width and wetted width were recorded every 50 m.

4.2. Neighbor K anaylsis

To examine the linear pattern of LWD and debris dams within stream reaches, we used a one-dimensional version of Ripley's K, a second-order statistic that evaluates the spatial pattern of points within a landscape (Ripley, 1977). Both LWD and debris dams were characterized as points or "events" distributed along a one-dimensional transect consisting of the stream reach. The distributions of LWD and debris dams were essentially one-dimensional, because the width of study streams was very small by comparison with reach lengths. Neighbor K analysis treats the distribution of an event as a spatial point process where the size of the individual events under consideration is negligible compared to the size of the study area (Ripley, 1981); therefore application of this statistical approach requires an assumption of one-dimensionality for our stream study systems.

The statistic used in our analysis evaluates the number of points within a series of distances centered at each point (e.g., LWD, debris dam) within a stream reach. The unbiased estimate of $K(t)$, the test statistic, was calculated as follows:

$$\hat{K}(t) = n^{-1} \sum_{i \neq j} \sum_{i \neq j} I_t(u_{ij}) \qquad (1)$$

where n is the number of points in the stream reach; u_{ij} is the distance between points i and j; $I_t(u)$, the counter variable, equals 1 if $u \leq t$ and equals 0 if $u > t$; and the summation is over all pairs of points not more than distance t apart. For a random arrangement of points in one dimension, $K(t) = 2t$; for clustered points, $K(t) > 2t$; and for segregated patterns, $K(t) < 2t$.

For the LWD and debris dam spatial point pattern analyses, $K(t)$ was calculated for all observed LWD or debris dams within a particular stream reach, then these values were compared with the distribution of 1000 Monte Carlo simulations of $K(t)$. For each Monte Carlo simulation of $K(t)$, simulated LWD or debris dam locations were randomly selected (without replacement) from within a stream-specific length of reach evaluated, and the number of LWD or debris dam locations was specified by the observed number of LWD or debris dams found within a particular stream reach.

We illustrate how this statistical measure was developed for a given sequence of point locations along a section of stream represented in Fig. 2. The lower part of the figure shows the point location for each debris dam as a vertical "stripe" along a 700-m reach of Rocky Branch Creek. Above this point pattern, the figure shows how the Ripley's K method sums the number of points (debris dams) at three example distances (t*1, t*2, and t*3) from 1 of 30 debris dams located along this stream, represented by an exaggerated vertical stripe at one point location (375 m). Summations at a similar range of distances (t) were then repeated for all 30 debris dams, allowing average values to be calculated at each distance by dividing the summation by the number of total debris dams. $K(t)$ is the representation of an average number of debris dams found at a particular distance (t). For the calculations in this manuscript, $K(t)$ was calculated for the observed point data (LWD and debris dams) using 5-m bins for distances ranging from 0 to 300 m,

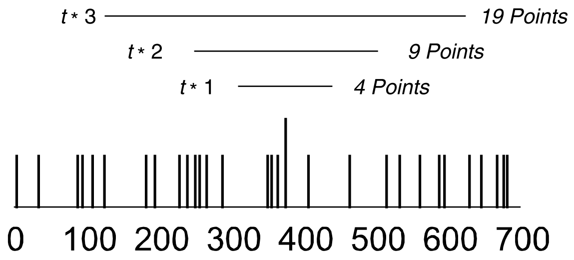

Fig. 2. Application of linear Ripley's K analysis to debris dam locations along Rocky Branch Creek.

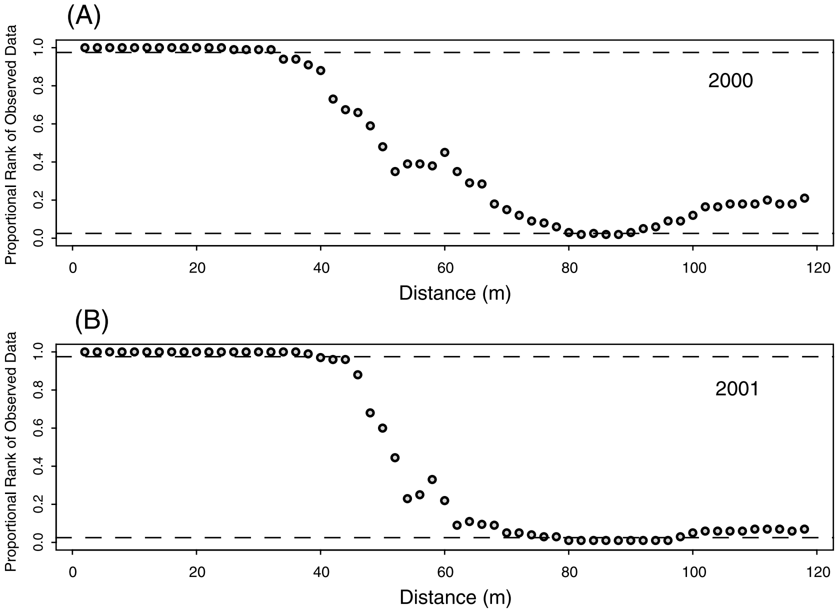

Fig. 3. Comparison of Rocky Branch Creek individual LWD spatial distributions in surveys conducted during 2000 and 2001.

thereby providing a measure of the average number of individual pieces of LWD or debris dams within 5-m distance intervals from any stream location containing another observed data point.

5. Results

Individual pieces of LWD were aggregated at spatial extents ranging from 0 to 35 m in 2000 and 0

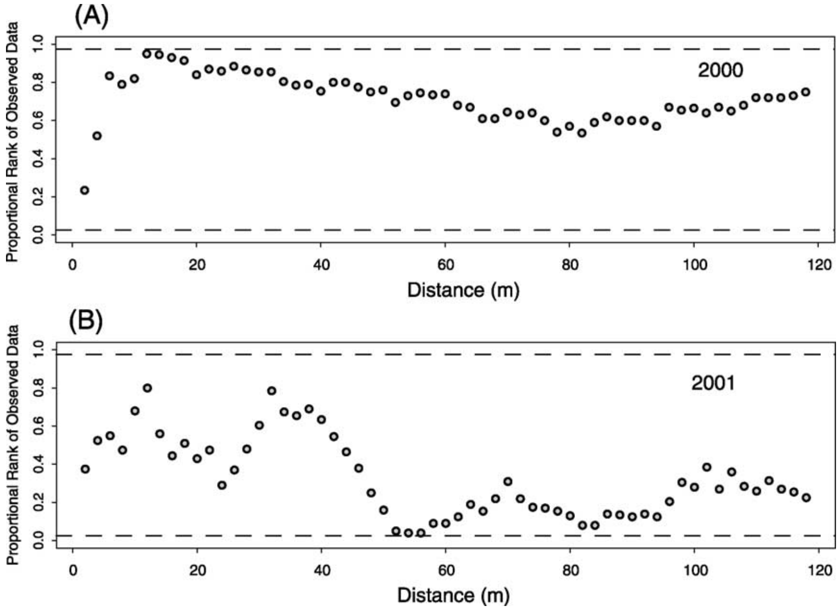

Fig. 4. Comparison of Rocky Branch Creek debris dam spatial distributions in surveys conducted during 2000 and 2001.

Table 3
Debris dam characteristics for study streams in the eastern Adirondack Mountains, New York

Stream	Total debris dam volume (m^3)	Number of dams	Dams per km	Spatial pattern
Black brook	25	9	11	random
McNalley brook	186	46	51	segregated
Rocky branch	123	30	43	random
Derby brook	21	13	14	random
Spruce Mill brook	70	29	29	random
Phelps brook	41	22	28	random
Slide brook	72	26	26	random
Nichols brook	115	34	34	segregated

to 40 m in 2001—and were segregated at spatial extents ranging from 80 to 90 m in 2000 and 76 to 98 m in 2001—in Rocky Branch Creek, the stream reach in which we evaluated both the distribution of individual pieces of LWD and debris dams in two consecutive years (Fig. 3). Fig. 3A shows the proportional rank of the observed number of LWD pieces at distances ranging from 0 to 120 m in Rocky Branch Creek in year 2000 by comparison with 1000 Monte Carlo simulations. Fig. 3B is the same as Fig. 3A, with data from the 2001 Rocky Branch Creek survey. Dashed horizontal lines in these figures show ranks at which values for observed data were >97.5% or < 2.5% of values for randomly simulated LWD distributions. These levels were used to determine significant aggregation or segregation.

Although we found no significant spatial pattern in debris dam distribution for Rocky Branch Creek, our analysis did show a trend toward the development of debris dam segregation at spatial scales ranging from 55 to 95 m in the 2001 survey, by comparison with the 2000 survey (Fig. 4). Fig. 4A shows the proportional rank of the observed number of debris dams at distances ranging from 0 to 120 m in Rocky Branch Creek in year 2000 by comparison with 1000 Monte Carlo simulations. Fig. 4B is the same as Fig. 4A, with data from the 2001 Rocky Branch Creek survey. Dashed horizontal lines show ranks at which values for observed data were >97.5% or < 2.5% of values for randomly simulated debris dam distributions.

Overall, the number of debris dams per kilometer within the eight study streams ranged from 9 to 46, with total volume of debris dams ranging from 21 to 186 m^3 (Table 3). Debris dams showed a significant segregated spatial pattern in two of the eight study streams (Table 3), with both of these streams showing significant segregation at distances between 200 and 250 m. In all other study streams, debris dams showed

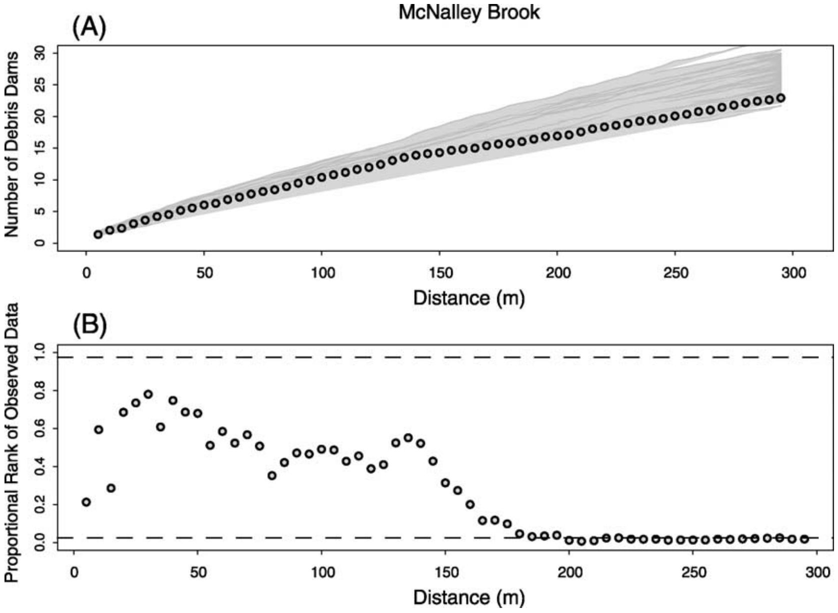

Fig. 5. Spatial distribution of McNalley Brook debris dams.

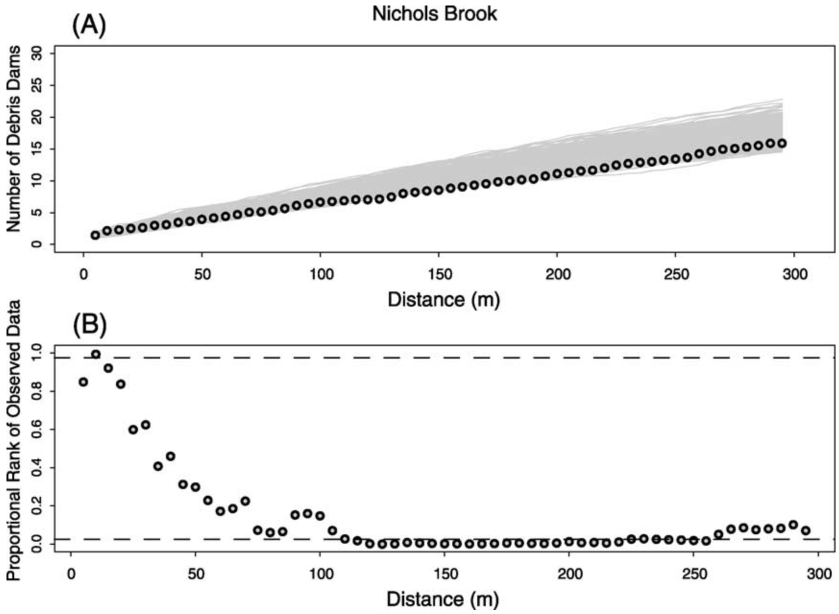

Fig. 6. Spatial distribution of Nichols Brook debris dams.

no significant aggregation or segregation. Debris dams were segregated (regularly spaced) at spatial scales ranging from 200 to 300 m in McNalley Brook relative to randomly chosen coordinates (Fig. 5), and were segregated at spatial scales ranging from 120 to 250 m in Nichols Brook (Fig. 6). In both Figs. 5A and 6A, circles show the observed average number of debris dams found at a given distance from any other debris dam within McNalley Brook and Nichols Brook, respectively, based on the one-dimensional version of Ripley's K statistic. Grey lines show the expected range of K based on 1000 Monte Carlo simulations of random debris dam locations. In both Figs. 5B and 6B, the proportional rank of the observed number of debris dams is shown by comparison with 1000 Monte Carlo simulations. Dashed horizontal lines show ranks at which values for observed data were >97.5% or <2.5% of values for randomly simulated debris dam distributions.

6. Discussion

In this paper, we have presented a statistical approach for evaluating the spatial pattern of LWD and debris dam distributions in order to help explain processes responsible for redistribution of woody debris within streams. By the time that we conducted our surveys, 18 months following a major wood deposition event, individual pieces of wood were significantly aggregated at spatial scales ranging from 0 to 35 m and showed a significant pattern of segregation at spatial extents >80 m.

In an attempt to evaluate stream processes, several previous studies have conducted a similar examination of spatial distribution patterns of stream geomorphic units (Lambert, 1997; Madej, 1999, 2001). These studies used Moran's I spatial autocorrelation coefficient (Legendre and Fortin, 1989) to identify spatial aggregations of boulders (Lambert, 1997) and identify the presence of regularity in streambed profiles (Madej, 1999, 2001). Wing et al. (1999) also used a similar semivariance approach to evaluate spatial pattern of stream LWD. We believe that the use of Moran's I to identify spatial pattern in continuous stream features is appropriate, yet it is not the most efficient statistic for evaluating stream features that can be characterized as points, such as LWD and boulders. For example, in Lambert's (1997) application of Moran's I to evaluate boulder distributions, boulder point locations were aggregated into reaches averaging 100 m in length. By contrast, Ripley's *K* evaluates an entire disaggregated point data set, increasing the amount of spatial information available for evaluation.

The strength of point pattern methods, such as Ripley's *K*, is in their ability to discriminate clustered patterns (e.g., points closer to one another than random) from random or regularly spaced (points farther from one another than random) distributions. Accurate pattern detection requires that the data be collected at a fine enough resolution (grain) to capture pattern, and across a large enough area (extent) for multiple replications of the pattern. In our evaluations of individual LWD distribution, these pieces of LWD could be effectively represented as points due to their small diameter relative to the length of the stream reach evaluated. In our evaluations of debris dam spatial pattern, the effective grain of our analyses was 3 m, which was the largest average linear dimension for debris dams in our study.

Given the large number of stream locations where no woody debris is generally observed, we recommend the use of spatial point pattern analysis techniques as more appropriate for evaluating wood distributions than variogram analysis (see O'Driscoll, 1998 for a similar recommendation for situations with many negative observations). Two previous studies have applied "first-order" point pattern analysis techniques to identify LWD spatial pattern (Wing et al., 1999; Keim et al., 2000). In both of these studies, they employed a "nearest neighbor" statistical approach that evaluated the relationship between a given piece of LWD and the nearest piece of LWD, thereby ignoring spatial relationships with LWD located at distances greater than the nearest neighbor. For example, if a 1000-m stream reach contained 11 pairs of LWD located 1 m apart and evenly spaced at 100-m intervals, the nearest neighbor analysis would identify an aggregated distribution pattern at 1-m intervals, but would not recognize the segregated distribution pattern at 100-m intervals. Ripley's *K* is a second-order point pattern analysis approach that accounts for spatial relationships between all points of interest, therefore would identify both aggregated and segregated distribution patterns in the example data set.

One of the nearest neighbor point pattern analysis studies found a random spatial distribution of LWD prior to an experimental addition of LWD, after which aggregated distributions of LWD were observed (Wing et al., 1999). In a subsequent study, Keim et al. (2000) also found aggregated wood distributions following experimental wood additions in three other streams deficient in coarse woody debris, though did not initially find random wood distributions in these streams. Neither study reported finding segregated LWD distributions.

Only one previously published application of Ripley's *K* has used this statistic in a one-dimensional analysis by evaluating spatial patterns in seabird distributions along line transects defined by the path of a ship (O'Driscoll, 1998). O'Driscoll's study presented additional modifications of the Ripley's *K* spatial pattern analysis approach that provided an ability to evaluate densities of observed points of interest, as well as correlations with other features measured along a line transect. Similar approaches could be usefully applied to evaluate the spatial distribution of a variety of stream geomorphic features.

Our results support a conceptual model in which stream LWD would have been distributed randomly within streams following batch deposition of wood from the 1998 ice storm, then LWD subsequently became aggregated in debris dams that were abundant within all study streams. In two of the eight study streams, these debris dams then subsequently exhibited a segregated spatial distribution pattern. Although few other studies have explicitly evaluated the spatial distribution of LWD, Madej's (1999) long-term evaluation of the spatial distribution of pool–riffle features in a northern California watershed provide some support for our contention that a random spatial pattern of LWD distribution is found after disturbance events provide large inputs of LWD. For example, according to observations from Upper Bridge Creek, regularly spaced bars were not found in 1986 and 1997 surveys because large inputs of LWD generated numerous, random irregularities in streambed topography (Madej, 1999).

Inputs of LWD can vary spatially along the length of a stream, and subsequent to entering a stream, wood can be redistributed by a variety of hydrological and physical processes (Lienkaemper and Swanson, 1987). At all spatial scales, the amount of LWD within a stream ecosystem represents a balance between wood inputs from the surrounding forest and losses due to decomposition and downstream movement (Harmon et al., 1986). Previous research has indicated that the distribution of woody debris changes with stream size, primarily due to changes in processes that influence wood movement. For example, Bisson et al. (1987) suggested that woody debris tends to be spaced at random intervals within small stream channels in which water discharge is insufficient to carry debris pieces downstream. Other studies have reported finding increased wood aggregation as stream size increases, primarily due to the increased ability of larger streams to transport wood (Robison and Beschta, 1990; Richmond and Fausch, 1995). The relatively modest flood events between the ice storm and our surveys provided enough capacity for redistributing wood into debris dams within our study streams. Whether larger flows will eventually produce spatial segregation of debris dams in all streams will continue to be evaluated.

Significant spatial aggregation of stream woody debris has been previously reported, but has seldom been quantified. Aggregated distributions are often visually apparent, as can be observed in figures provided within other studies (Robison and Beschta, 1990; Richmond and Fausch, 1995). Aggregated wood distribution patterns have also been qualitatively described by many investigators (Robison and Beschta, 1990; Nakamura and Swanson, 1994; Richmond and Fausch, 1995; Abbe and Montgomery, 1996; Harmon et al., 1986; Gurnell et al., 2000). These studies have generally described the types of stream locations at which wood accumulates but have not attempted to quantitatively evaluate or describe wood distribution patterns at a range of spatial scales.

By contrast with aggregated distribution patterns, segregated distribution patterns have never been reported from studies of LWD or debris dam dynamics. Segregated spatial patterns—which reflect the occurrence of regular intervals between individual pieces of LWD or debris dams—are more difficult to recognize than aggregated distributions. For example, in examining visual representations of wood distribution within our stream study reaches, the presence of a segregated spatial distribution pattern in two of these reaches was not easily recognized. In these streams, the Ripley's K spatial pattern analysis technique provided an ability to identify the presence of a regular spacing pattern at intervals ranging from 120 to 300 m. Based on our results, we speculate that regularly spaced intervals between LWD and debris dams have been present, but unrecognized, in other published studies of stream woody debris.

Segregated distribution patterns of LWD could potentially have been produced by regularly spaced stream features, such as channel bends or changes in channel width (Nakamura and Swanson, 1994). Segregation could also have been produced by the movement of individual pieces of LWD toward more stable accumulation points, thereby creating "gaps" in which woody debris was no longer present. We found evidence for wood redistribution in Rocky Branch, the stream that we surveyed for two consecutive years. In both years, a random distribution pattern of debris dams was observed at all spatial scales, but in the second year, we observed an increasing trend toward a segregated debris dam distribution at spatial scales >60 m (Fig. 4). Although we suspect that a segregated distribution pattern of debris dams is the most likely spatial pattern present in stream systems with "mature" distributions of wood (i.e., following movement and decomposition), we acknowledge the limitation of drawing broad conclusions from our short-term study.

In studies conducted in streams of the US Pacific Northwest, accumulations of woody debris generally result from the presence of large, stable pieces of LWD trapping smaller, mobile pieces of woody debris (Lienkaemper and Swanson, 1987). The dominant debris dam-forming element in streams within our study area were boulders; therefore, the segregated spatial pattern of debris dam spacing could potentially reflect underlying geological features responsible for the spatial arrangement of boulders (e.g., changes in gradient, pool–riffle spacing). Leopold et al. (1964) observed that in a Wyoming stream large boulders were only located in riffles, and these riffles were described (without statistical analysis) to have been regularly distributed. In a quantitative evaluation of boulder spatial distributions using Moran's I, Lambert (1997) found that boulders were aggregated, though not segregated, within streams. Unfortunately, we did not record the locations of boulders in our study, therefore cannot evaluate the relationship between boulder and debris dam spatial distributions.

7. Conclusions

The one-dimensional Ripley's *K* analysis presented in this study provided an ability to analyze the distribution and spacing of LWD and debris dams at a wide range of spatial scales, and identified both aggregated and segregated distributions of wood within streams. Previous studies of wood distribution in streams have not reported segregated distribution patterns, and in many cases these patterns have probably gone unrecognized. We suggest that spatial segregation of debris dams likely occurred in response to regularly spaced stream features or processes that allowed movement of individual pieces of LWD toward more stable accumulation points. Neighbor *K* statistics can be used to identify and describe spatial pattern in stream features represented as point locations, and such patterns can be used to help evaluate and identify processes responsible for the generation of observed patterns in stream geomorphology.

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