Ice storm impacts on woody debris and debris dam formation in northeastern U.S. streams

Clifford E. Kraft, Rebecca L. Schneider, and Dana R. Warren

Abstract: In January 1998, an ice storm damaged forests in northeastern United States and eastern Canada, causing coarse woody debris (CWD) deposition in riparian areas and associated streams. During 1999 and 2000, tree canopy damage, stream physical habitat, and wood deposition were evaluated within 51 first-, second-, and third-order streams located within five eastern Adirondack Mountain watersheds (New York, U.S.A.). In first- through third-order streams, the number and volume of stream debris dams increased in response to streamside trees with canopy damage. Tree canopy damage was not a significant predictor for individual pieces of stream CWD but was correlated with CWD >10 cm in diameter in third-order, but not first-order, streams. At debris dam locations, bankfull width was greater and stream substrates consisted of increased fines. Woody debris resulting from the 1998 ice storm was not associated with increased pool formation; instead, boulders and rocky substrate were the dominant pool-forming elements. CWD length in first-order streams generally exceeded bankfull width, but in third-order streams, CWD length was shorter than bankfull width and therefore was subject to greater transport and accumulation into debris dams. Our results indicate that ice storm disturbances can increase wood inputs to first- through third-order forested stream ecosystems.

Résumé : En janvier 1998, une tempête de glace a endommagé les forêts du Nord-est des États-Unis et de l’Est du Canada, ce qui a entraîné une chute de débris ligneux grossiers (CWD) dans les zones ripariennes et les cours d’eau associés. En 1999 et en 2000, nous avons évalué les dommages à la canopée de la forêt, les habitats physiques des cours d’eau et la chute de bois dans 51 cours d’eau de premier, second et troisième ordres, dans 5 bassins versants des monts Adirondack (New York, États-Unis). Dans les cours d’eau d’ordre 1 à 3, il y avait une relation entre le nombre et le volume des barrages formés par l’accumulation de débris et l’importance des dommages à la canopée. Le dommage à la canopée n’était pas une variable explicative significative de la présence de pièces individuelles de CWD, mais il y avait une corrélation entre le dommage et la présence de CWD de diamètre >10 cm dans les cours d’eau de troisième ordre, mais pas dans ceux de premier ordre. Aux points de barrage, la largeur du cours d’eau à pleins bords était plus grande et le substrat contenait plus de particules fines. Les débris apportés par la tempête de glace de 1998 n’étaient pas associés avec la formation accrue de profonds; ce sont les blocs et les substrats rocheux qui constituaient les éléments principaux de formation de profonds. La longueur des CWD dans les cours d’eau de premier ordre dépassait généralement la largeur à pleins bords du lit, mais elle était inférieure à la largeur du lit dans les cours d’eau de troisième ordre, ce qui causait plus de déplacement des débris et leur accumulation en barrages. Nos résultats démontrent que les tempêtes de glace peuvent accroître l’apport de bois dans les écosystèmes des cours d’eau forestiers de premier à troisième ordre.

[Traduit par la Rédaction]

Introduction

Wood recruitment to streams is an important link between terrestrial and aquatic systems, and it has become increasingly clear that wood inputs into streams are primarily episodic (Benda et al. 1998). Models simulating woody debris recruitment following catastrophic events have indicated that massive influxes of new material occur during the first 50 years following disturbances, instead of a slow and steady accumulation of wood (Bragg 2000). Field studies have demonstrated that disturbances such as fire (Young 1994; Benda et al. 1998), wind (Lienkaemper and Swanson 1987), and intense storms (Gregory 1992; Dolloff et al. 1994) increase wood inputs into streams.

Coarse woody debris (CWD, defined as woody material >1 cm in diameter and 10 cm long) and debris dams influence both abiotic and biotic factors of stream ecosystems by providing habitat for fish and invertebrates (Bisson et al. 1987; Wallace et al. 1995) and by influencing pool formation and sediment transport (Keller and Swanson 1979; Bilby and Likens 1980). Wood in streams also serves as a point of retention for allochthonous material at the base of stream food webs (Bilby and Likens 1980; Raikow et al. 1995), and the geomorphology of rivers and streams is influenced by woody debris and debris dams (Bilby 1984; Triska 1984; Abbe and Montgomery 1996).

Although disturbances such as avalanches, debris flows, windstorms, fires, and floods have been recognized as important sources of woody debris in rivers and streams (Keller and Swanson 1979; Bisson et al. 1987; Young 1994), ice

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storms have not been widely recognized as a source of wood for aquatic systems. Ice or glaze storms occur when rain falls into the cooler lower atmosphere and then freezes on contact with substrates (Lemon 1961). Ice storms often cause tree canopy branches to break, producing significant increases in the amount of woody debris deposited on the forest floor (Rebertus et al. 1997; Hooper et al. 2001). Streams in forested areas may be particularly affected by wood deposition in that tree canopy damage from ice storms is often more severe in lowlands and valleys (Rebertus et al. 1997).

In January 1998, a severe ice storm extensively damaged the canopy of many northeastern U.S. and eastern Canadian forests, causing deposition of CWD in riparian areas and associated streams. Woody biomass deposited on the forest floor during the 1998 ice storm was the greatest ever reported for an ice storm (Hooper et al. 2001). In New York, ice accumulations were estimated to have ranged from 2.0 to 3.3 cm (DeGaetano 2000). As has been reported from other ice storms (Bruederle and Stearns 1985; Seischab et al. 1993; Mou and Warrillow 2000), tree canopy damage from the 1998 ice storm was patchy, varied by elevation and aspect, and was greatest near streams (Rhoads et al. 2002).

Although factors responsible for woody debris inputs to streams of the U.S. Pacific Northwest have been extensively examined (e.g., Benda et al. 1998), few comprehensive evaluations of woody debris recruitment have been conducted in other geographic regions. This research effort evaluated the impact of the 1998 ice storm on woody debris accumulation in streams of the eastern Adirondack Mountains. Because of the widespread spatial extent of this disturbance event, we were able to compare CWD accumulation in first-, second-, and third-order streams within watersheds that sustained varying degrees of ice storm damage. In this study, we report that tree canopy damage from the 1998 ice storm resulted in increased CWD, particularly in the form of debris dams, in northeastern U.S. first-, second-, and third-order streams.

Materials and methods

Field data collection

From June through September 1999, 43 first- and third-order stream reaches with varying ice storm effects and geomorphic character were surveyed within five large watersheds in the eastern Adirondack Mountains (New York). Thin soils, steep slopes, and glacial till over igneous and metamorphic bedrock are typical geomorphic features in these watersheds. Floods occur regularly in late April or early May, following spring snowmelt.

Study sites were organized into 11 subwatersheds, each comprised of a third-order stream (n = 11) and three associated first-order streams (with one exception involving only two first-order streams; n = 32) located upstream from the third-order study site. Stream order was assigned using U.S. Geological Survey 1 : 24 000 topographic quadrangles and the Strahler (1963) classification system. All study sites included a forested riparian zone at least 30 m wide. To encompass a complete set of stream geomorphic features, first-order study reaches were 60 m long and third-order stream study reaches were 300 m long (both greater than 10 times mean bankfull width).

Tree canopy damage was assessed within eight 25-m^2 streamside plots located adjacent to each stream study reach, extending from the stream bank to 5 m inland. Streamside plots were evenly distributed and located along alternate sides of the stream. For third-order sites, four additional interior plots were located 10–15 m from the stream bank. Diameter at breast height (dbh) and extent of canopy damage were assessed for each tree >2 cm dbh within each plot. Tree canopy damage was assessed using a breakage index (e.g., extent of missing canopy) with six categories: “no broken branches”, “twigs broken”, “ <1/3 of canopy missing”, “1/3–2/3 canopy missing”, “>2/3 canopy missing”, and “trunk snapped between ground and canopy (100% canopy loss)”. The first two categories were designated as undamaged; all other tree canopy damage categories were designated as damaged. For 1999 analyses, the proportion of tree canopy damage within a plot was determined by calculating the proportion of damaged to undamaged trees for all trees evaluated.

Within each 1999 study reach, stream physical habitat characteristics were measured at regular intervals using transects placed perpendicular to stream flow (Platts et al. 1983). For first-order study sites, 12 transects were located at 5-m intervals along the stream bank; for third-order study sites, 30 transects were placed at 10-m intervals. When a debris dam (defined as an accumulation of CWD greater than 1 m long in any dimension, aggregated through fluvial processes) was intersected by a transect, the length and diameter of the largest single intersected piece of wood was recorded and the debris dam volume was estimated. Debris dams were evaluated only the first time if intersected by two transects. For single pieces of intersected woody debris, the length, diameter at the point of intersection, and maximum diameter were recorded. For a single piece, or the key structural piece in a debris dam, age (e.g., “old”, exhibiting signs of decay, therefore likely originating before the 1998 ice storm, or “new”, likely originating after the ice storm) was also characterized.

At each transect location within a given stream study reach, bankfull width, water depth, and substrate composition were assessed. Bankfull width was delineated according to Simonson et al. (1994). Water depth was measured at three equally spaced points across the stream within the wetted perimeter. Substrate composition was evaluated by visually estimating the proportion of the three dominant substrate sizes (Cummins 1962) intersected along each transect (Simonson et al. 1994). Within each reach, we measured the maximum pool depth and length of every riffle and pool. Pool-forming elements were also designated by assigning one of the following categories: woody debris (log, tree, root, stump, or brush), channel meander, rubble or gravel, boulder or bedrock, stream channel (designated when the pool-forming element could not be determined), stream bank, human object (culvert, bridge, etc.), and beaver dam (adapted from Platts et al. 1983). Gradient was determined for an entire reach using a level and stadia rod.

In July and August 2000, a more comprehensive survey was conducted to more precisely quantify the frequency and association of debris dams with ice storm canopy damage. Eight stream reaches approximately 1 km long, not surveyed in the previous field season, were selected for this survey. Six of the reaches surveyed were second-order, one was first-order, and one was third-order. Instead of recording only those debris dams intersected by transects, as in the 1999 surveys, the 2000 surveys evaluated every debris dam encountered. Debris dam volume, channel position, and function were estimated for all debris dams within each stream reach. Single pieces of CWD were not evaluated, and all debris dams consisted of CWD accumulations. Bankfull width and wetted width were recorded every 50 m. Tree canopy damage was estimated at 100-m intervals within 10 alternating 50-m^2 streamside plots located adjacent to the stream bank (plots extended 10 m along the stream bank). Tree dbh was recorded for trees >5 cm dbh, and canopy damage was evaluated using a reduced set of three inclusive damage categories: “not damaged” designated undamaged trees and “<50% canopy missing” and “>50% canopy missing” designated trees damaged by the ice storm. The proportion of canopy damage was determined from all plots within a stream section, and total debris dam volume was summed for each stream section.

Data analysis

Linear models were developed to determine the association between streamside tree canopy damage and dependent variables associated with CWD in streams. All statistical analyses were conducted using Systat (version 8.0). For analyses of debris dam volume, data were log-transformed to eliminate skewness within residuals. To avoid pseudoreplication, mean values for substrate composition and bankfull width were used as the dependent variable for analyses comparing debris dam effects among reaches.

The 1999 estimate of debris dam volume per stream reach was the summed volume of dams intersected by transects; debris dam number per stream reach was the sum of intersected debris dams. Because the number and spacing of transects differed at first- and third-order stream study sites, 1999 data could not be used to make direct comparisons between debris dam number and volume at first- and third-order sites. As a result, the data from these first- and third-order streams were analyzed using separate linear models. In 2000, follow-up surveys were established to specifically examine the impact of ice storm related tree canopy damage on stream debris dams at a greater spatial scale (1 linear km).

Results

All streams in the study area were of a relatively high gradient (average of 6.5, 5.7, and 2.8%, respectively, for first-, second-, and third-order streams; Tables 1, 2), with cobble as the dominant substrate and a pool–cascade dominated flow. Boulders were the dominant pool-forming elements (78% of total), with debris dams accounting for only a small proportion (5%). Mean bankfull width for first- through third-order streams was 4.8, 8.5, and 11.7 m, respectively (Tables 1, 2).

Based on 1999 field data, a significant proportion of the variation in number of transects intersecting debris dams was accounted for by the proportion of riparian trees with canopy damage in third-order, but not first-order, streams (Fig. 1). A significant proportion of the variation in total debris dam volume within a stream reach was also accounted for by the proportion of riparian trees with canopy damage in first- and third-order streams (Fig. 2). Although the number of stream transects at which individual pieces of CWD were intersected was not generally related to tree canopy damage for first- ($N = 32$, $R^2 = 0.06$, $p > 0.18$) and third-order ($N = 11$, $R^2 = 0.13$, $p > 0.27$) streams, we found that tree canopy damage accounted for a significant proportion of variation in the number of transects with CWD >10 cm diameter in third-order ($N = 11$, $R^2 = 0.38$, $p < 0.05$), but not first-order ($N = 32$, $R^2 = 0.03$, $p > 0.31$), streams. Tree canopy damage also accounted for a significant proportion of variation in the number of transects with recently deposited individual pieces of CWD showing no decay (categorized as “new”), all widths included, in third-order ($N = 11$, $R^2 = 0.52$, $p < 0.02$), but not first-order ($N = 32$, $R^2 = 0.05$, $p > 0.19$), streams. (Given that these latter two analyses were developed a posteriori, after we observed a lack of significance in the analysis of the relationship between canopy damage and all individual pieces of intersected CWD, we report the values from a priori tests but allow readers to draw their own conclusions regarding the significance of these results.)

In 1999 surveys, the maximum diameter of all trees surveyed in plots associated with stream study reaches was a significant predictor of the maximum diameter of the largest piece of woody debris found in debris dams at third-order sites ($R^2 = 0.55$, $p < 0.01$) but was not significant for first-order study sites ($R^2 = 0.01$, $p = 0.95$). CWD length in first-order streams generally exceeded bankfull width, whereas CWD length in third-order streams was generally shorter than bankfull width (Fig. 3). Mean CWD length in first-order streams (5.1 m, standard deviation (SD) = 4.1) was significantly shorter than in third-order streams (7.0 m, SD = 5.7; two-sample t test, $p < 0.01$).

A linear model including site location and the presence or absence of a debris dam as categorical predictors accounted for a significant proportion of variation in the proportion of fines within the streambed ($N = 84$, $R^2 = 0.96$, $p < 0.01$). Using this model and accounting for site-specific effects, the presence of a debris dam increased 20–25% the proportion of fines within the streambed at a given transect location. Similar linear models showed a decrease in the proportion of gravel and pebble substrates at debris dam locations, but these decreases were not significant ($p = 0.28$ and $p = 0.32$, respectively). A linear model including site location and the presence or absence of a debris dam as categorical predictors also accounted for a significant proportion of variation in stream bankfull width ($N = 84$, $R^2 = 0.97$, $p < 0.01$).

Using 1999 data, no significant relationship was found between ice storm tree canopy damage and mean pool depth, or the number of pools in streams (for both first- and third-order streams). However, gradient was a significant predictor for the number of pools per metre.

Based on 2000 field data, a significant proportion of the variation in the number of debris dams per kilometre was accounted for by the proportion of riparian trees with ice storm damage (Fig. 4; $N = 8$, $R^2 = 0.61$, $p < 0.02$). A significant proportion of the variation in total debris dam volume within a stream reach was also accounted for by the proportion of

Table 1. Characteristics of stream study reaches from 1999 surveys.

Watershed	Stream order	No. of transects with intersected CWD	Proportion damaged trees	Mean bankfull width (m)	Gradient (%)	No. of pools	No. of debris dams	Summed debris dam volume (m^3)
Beede Brook	1	11	0.08	3.4	18.8	5	8	9.5
	1	11	0.04	6.5	NA	6	3	3.0
	3	21	0.03	13.2	4.4	16	10	6.8
	1	7	0.04	4.8	9.0	6	4	6.8
Rocky Branch	1	12	0.44	2.9	7.1	6	9	11.5
	1	12	0.20	4.8	8.5	7	6	8.3
	3	23	0.16	9.3	4.8	16	11	11.3
	1	12	0.29	5.4	8.3	7	11	13.0
Spruce Mill	1	7	0.05	4.9	7.8	7	1	0.5
	1	7	0.09	3.4	7.2	6	1	1.0
	1	6	0.09	8.4	5.9	3	2	0.5
	3	23	0.13	9.6	0.8	4	6	5.5
Cold Brook	1	9	0.05	6.0	2.9	2	2	0.5
	1	9	0.03	5.5	4.7	4	3	1.5
	1	8	0.02	3.5	2.3	2	1	0.3
	3	26	0.03	7.4	0.1	7	7	7.8
Nichols Brook	1	9	0.27	7.5	2.4	5	4	7.5
	1	11	0.33	3.5	9.0	5	5	4.0
	3	22	0.26	13.6	4.7	19	11	25.5
	1	11	0.15	6.9	1.7	5	4	4.0
Styles Brook	1	12	0.27	4.4	5.2	5	7	5.0
	3	25	0.21	11.6	3.1	14	9	6.5
	1	11	0.15	4.4	7.5	6	5	5.5
	1	9	0.13	4.6	5.8	3	3	3.3
Salmon River	1	8	0.26	4.4	7.3	2	1	0.5
	3	26	0.25	11.5	1.5	7	14	50.5
	1	6	0.49	5.8	2.2	4	2	3.0
Johns Brook	1	8	0.06	6.5	22.4	6	1	0.3
	1	12	0.32	6.3	14.2	7	10	13.8
	1	9	0.26	4.7	14.8	9	0	0.0
	3	22	0.10	20.0	6.2	16	4	2.5
Alder Brook	1	12	0.19	3.8	1.0	3	3	1.3
	3	26	0.26	11.7	1.5	2	11	20.5
	1	11	0.28	4.3	2.7	5	4	2.3
	1	10	0.30	1.3	1.1	6	0	0.0
The Branch	1	11	0.12	7.0	1.6	5	3	3.5
	1	6	0.18	3.9	6.0	9	2	0.5
	1	5	0.09	6.4	6.7	8	2	0.5
	3	23	0.05	12.3	3.2	18	4	3.3
Little Ausable	1	7	0.27	1.8	1.7	2	2	0.5
	1	11	0.27	3.2	4.5	4	1	0.5
	1	12	0.08	2.9	2.1	NA	8	8.0
	3	24	0.20	8.2	0.5	4	13	12.5

Note: CWD, coarse woody debris; NA, not available.

riparian trees with canopy damage (Fig. 5; $N = 8$, $R^2 = 0.69$, $p < 0.02$). When bankfull width was included in the linear model as an additional independent variable, the proportion of variation in number and volume of debris dams accounted for by the model increased slightly ($R^2 = 0.83$ and 0.74, respectively), but bankfull width was not a significant predictor ($p = 0.05$ and $p = 0.35$, respectively).

Discussion

The most consistent and widespread impact of the 1998 ice storm on first-, second-, and third-order streams of the eastern Adirondacks was increased number and volume of debris dams. Our 1999 data suggested that tree canopy damage was a significant factor in predicting volume of debris dams in first- and third-order streams and number of debris dams in third-order streams. In 2000, we conducted follow-up surveys in which we counted and estimated the volume of all debris dams within 1-km study reaches; these surveys were specifically designed to examine the impact of ice storm related tree canopy damage on stream debris dams. These longer stream reaches were evaluated to encompass the physical scale at which debris dams form in small streams, which could have been obscured by the limited scale of the 1999 first-order study reaches (60 m). Transects perpendicular to the channel, used in 1999, are also an inefficient

Table 2. Characteristics of stream study reaches from surveys taken in 2000.

Stream	Stream order	Proportion damaged trees	Mean bankfull width (m)	Gradient (%)	Number of dams	Summed debris dam volume (m^3)	Reach length (m)
Black Brook	3	0.31	13.4	4.4	9	25	850
McNalley Brook	2	0.53	6.1	6.1	46	186	900
Rocky Branch	2	0.51	8	6.6	30	123	700
Derby Brook	2	0.16	7.2	6.5	13	21	900
Spruce Mill Brook	1	0.34	9	6	29	70	1000
Phelps Brook	2	0.42	5.4	4.7	22	41	900
Slide Brook	2	0.27	8.8	6	26	72	1000
Nichols Brook	2	0.61	10	5.5	34	115	1000

Fig. 1. Number of debris dams intersected by transects in (*a*) first- and (*b*) third-order streams shown as a function of the proportion of streamside trees with canopy damage (1999 surveys). Broken line shows fit of significant linear model for third-order streams ($N = 11$, $R^2 = 0.45$, $p < 0.03$); linear model for first-order streams was not significant ($N = 30$, $R^2 = 0.07$, $p > 0.13$).

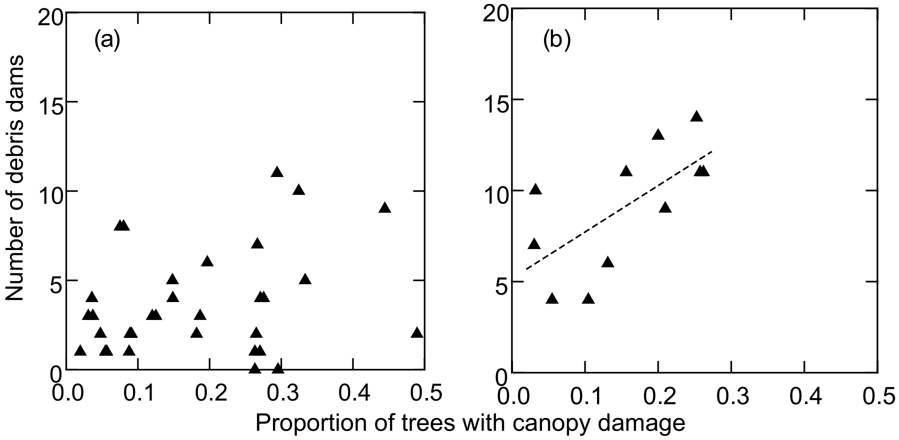
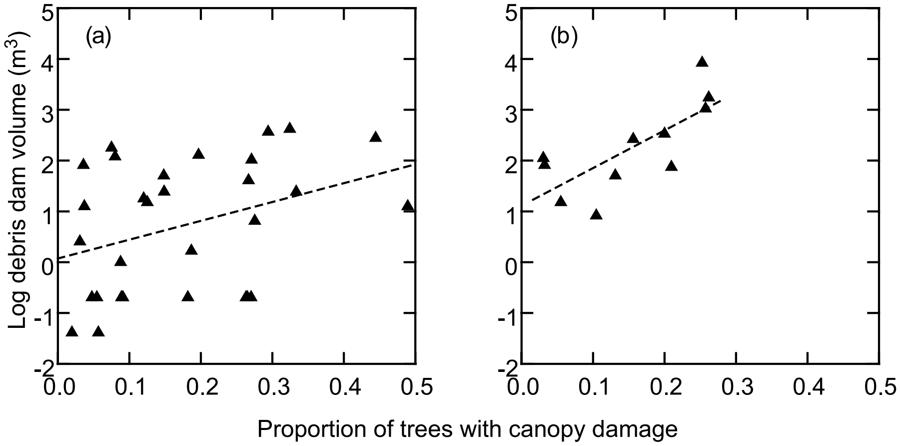


Fig. 2. Log summed volume of debris dams intersected by transects in (*a*) first- and (*b*) third-order streams shown as a function of the proportion of streamside trees with canopy damage (1999 surveys). Broken line shows fit of significant linear model for first- ($N = 30$, $R^2 = 0.13$, $p < 0.05$) and third-order streams ($N = 11$, $R^2 = 0.55$, $p < 0.01$).



method for evaluating debris characteristics. Results from the 2000 surveys showed less variability than the 1999 surveys in the relationship between tree canopy damage and both debris dam number and volume.

We also evaluated the function of debris dams produced by the 1998 ice storm, 1 year after their formation. At transect locations where debris dams were located, streambed substrates consisted of more fines and showed a slightly smaller proportion of gravel and pebbles. This is consistent with the observation that smaller silt particles often settle behind debris dams that obstruct stream flow (Megahan 1982). In contrast with some studies in the western U.S. (Keller and Swanson 1979; Richmond and Fausch 1995; Montgomery et al. 1996), woody debris resulting from the 1998 ice storm was not extensively associated with pool formation. We attribute this to the geomorphology of our study area in which boulders and rocky substrate were the dominant pool-forming elements. Our results support observations by Berg

Fig. 3. Box plots of the ratio of coarse woody debris (CWD) length to bankfull width for woody debris intersected by transects in first- ($N = 300$) and third-order streams ($N = 255$) during 1999 surveys. Values that fall beyond the whiskers but within three interquartile ranges are denoted by asterisks. Values beyond three interquartile ranges are denoted by solid circles.

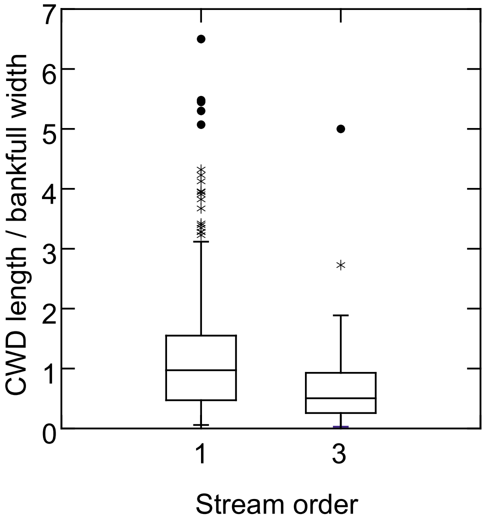
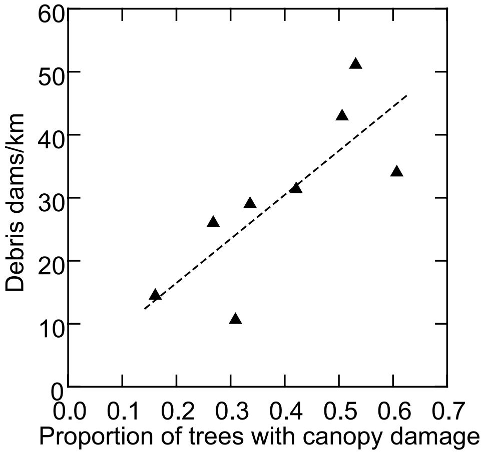


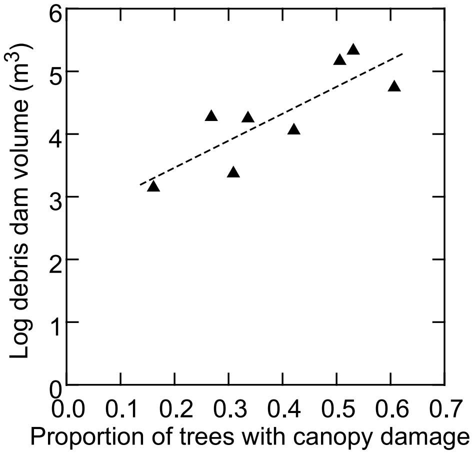
Fig. 4. Number of debris dams per kilometre in second-order streams shown as a function of the proportion of streamside trees with canopy damage (2000 surveys). All debris dams along stream reaches 700–1000 m long were included in this survey. Broken line shows fit of significant linear model ($N = 8$, $R^2 = 0.61$, $p < 0.02$).



et al. (1998) and Faustini and Jones (2002) that channel structure in steep mountain streams is controlled by nonfluvial processes, such as large boulders deposited by historic glacial or mass movement processes.

CWD in first- and third-order streams likely experienced different transport processes. Greater channel width generally corresponds to greater stream energy, which in turn is responsible for transporting large pieces of wood (Lienkaemper and Swanson 1987). In the Pacific Northwest, Nakamura and Swanson (1994) found that all transported pieces of CWD were shorter than mean bankfull width. CWD was generally shorter than bankfull width in our third-order streams but usually exceeded bankfull width in our first-order streams. We found stronger relationships between stream woody debris and tree canopy damage in third-order streams compared with first-order streams, in which transport of CWD would have been restricted. We also found that CWD length in first-order streams was significantly shorter than in third-order streams, which is consistent with observations that CWD piece length and diameter were significantly shorter in first- versus third-order streams within Pacific Northwest forests (McDade et al. 1990).

Fig. 5. Log total volume of debris dams per kilometre in second-order streams shown as a function of the proportion of streamside trees with canopy damage (2000 surveys). All debris dams along stream reaches 700–1000 m long were included in this survey. Broken line shows fit of significant linear model ($N = 8$, $R^2 = 0.69$, $p < 0.02$).



Debris dams in our study area generally consisted of large accumulations of small organic material, including wood, aggregated around a debris dam forming element (i.e., boulders or fallen trees or branches). In third-order streams, we found a significant relationship between streamside tree diameter and diameter of the largest piece of woody debris within debris dams. This result suggests that for third-order streams dam-forming elements consisted of large logs originating from trees in the adjacent streamside. The lack of this relationship for first-order streams may reflect the fact that large fallen trees in first-order streams tend to span the stream above the water surface rather than create debris dams, though branches from these trees can provide structural dam-forming elements.

Although we anticipated that individual pieces of CWD would be more frequent in ice storm impacted sites within our 1999 surveys, tree canopy damage was not generally related to the number of transects at which CWD was intersected within either first- or third-order streams. Smaller pieces of wood might have aggregated into debris dams during high flows after the ice storm, obscuring any relationship between canopy damage and individual pieces of CWD. However, in third-order streams, we found that tree canopy damage was related to an increase in individual pieces of CWD >10 cm diameter and “new” pieces of CWD (all diameters) showing no decay. It is possible that less large woody debris was transported into first-order streams than into third-order streams from adjacent streamside forests. It is also likely that more wood was deposited directly into third-order streams because of wider canopy openings and the tendency of trees to grow (and tilt) towards such openings (Lienkaemper and Swanson 1987). In support of this, Seischab et al. (1993) found greater ice storm related canopy damage among trees with asymmetric crown growth that were growing along forest and field edges.

Bankfull width was greater at debris dam locations, but we cannot distinguish if debris dams caused or were caused by greater bankfull width. CWD may increase bank erosion where fallen trees and debris dams can sufficiently redirect stream flow to undercut the structural support of stream banks (Keller and Swanson 1979; Harmon et al. 1986; Trimble 1997). Alternatively, bank erosion is often a primary mechanism by which woody debris enters forested streams (Keller and Swanson 1979); therefore, trees may have fallen into our study streams where bank erosion had already occurred, enhancing the possibility of subsequent debris dam formation. Debris dams in the study area also frequently formed in association with large boulders, and water flowing around such boulders might have widened the stream channel before the debris dam formation.

Our results support the observation that disturbances such as the 1998 ice storm are responsible for dominant inputs of woody debris, usually exceeding background levels of wood input (Benda et al. 1998; Bragg 2000). In New Hampshire forests, woody debris inputs increased immediately after logging, then decreased as a result of dominance by young trees, and then subsequently increased with forest age (Hedin et al. 1988). CWD loading in southern Appalachian streams increased over a 300-year period, though “carry-over” debris obscured much of this relationship because of large wood inputs in mid-successional forest stages (Hedman et al. 1996). By increasing the number and volume of debris dams in CWD-poor streams, the 1998 ice storm accelerated the process of wood accumulation in streams associated with second-growth forests (Hedin et al. 1988). Ice storms may increase both short-term and long-term CWD recruitment in these systems in that dead standing trees and downed wood from an ice storm may increase CWD inputs to streams for many years.

Ice storms have been recognized for (*i*) influencing forest communities and terrestrial habitats (Bruederle and Stearns 1985; Seischab et al. 1993; Mou and Warrillow 2000), (*ii*) depositing extensive woody debris on the forest floor (Hooper et al. 2001), and (*iii*) producing greater tree canopy damage near streams (Rhoads et al. 2002). Our results expand these observations by demonstrating that ice storms can influence stream ecosystems at a broad spatial scale by providing major sources of stream woody debris, thereby mediating forest–stream interactions. Although weather records are inadequate to fully characterize the frequency and geographic extent of ice storm related wood deposition events, available data suggest that these disturbances could regularly influence forest–stream interactions. Ice-forming conditions during the 1998 ice storm were comparable to the conditions in at least three storms that have affected New York and New England since 1948 (DeGaetano 2000). Although most ice storms are small-scale in spatial extent, a 1936 ice storm affected 2.4 million ha in southern New York and northern Pennsylvania (Downs 1938; Seischab et al. 1993), and the 1998 ice storm impacted an estimated 35 million ha in New York, New England, and Quebec. Because debris dams are important components of stream ecosystems and ice storms are regular disturbances occurring throughout eastern North America, ice storms should be recognized as events with potentially widespread impacts upon stream ecosystem structure and function.

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