DOI: 10.1007/s00267-003-3042-2

Influence of Woody Debris on Channel Structure in Old Growth and Managed Forest Streams in Central Sweden

NIKLAS DAHLSTRÖM*
CHRISTER NILSSON
Department of Natural and Environmental Sciences
Mid Sweden University
SE-851 70 Sundsvall, Sweden

ABSTRACT / Anecdotal information suggests that woody debris have had an important channel-forming role in Swedish streams and rivers, but there are few data to support this view. We identified 10 streams within near-natural and 10 streams within managed forest landscapes in central Sweden, and quantified their channel characteristics and content of woody debris. All pieces of woody debris greater than 0.5 m in length and greater than 0.05 m in base diameter were included. The near-natural forests were situated in reserves protected from forest cutting, whereas the managed forests had previously faced intensive logging in the area adjacent to the stream. The two sets of streams did not differ in general abiotic characteristics such as width, slope, or boulder cover, but the number of wood pieces was twice as high and the wood volume almost four times as high in the near-natural streams. This difference resulted in a higher frequency of debris dams in the near-natural streams. Although the total pool area did not differ between the two sets of streams, the wood-formed pools were larger and deeper, and potentially ecologically more important than other pools. In contrast to what has been believed so far, woody debris can be a channel-forming agent also in steeper streams with boulder beds. In a stepwise multiple regression analysis, pool area was positively and most strongly related to the quantity of woody debris, whereas channel gradient and wood volume were negatively related. The frequency of debris dams increased with the number of pieces of woody debris, but was not affected by other variables. The management implications of this study are that the wood quantity in streams in managed forests would need to be increased if management of streams will target more pristine conditions.

Woody debris is an important component in rivers and streams in forested landscapes, where it alters the fluvial environment in many different ways and at several spatial scales (Harmon and others 1986, Bisson and others 1987, Bilby and Ward 1989). Woody debris modifies channel form predominantly by forming steps and pools along the channel (Robison and Beschta 1990a, Ralph and others 1994, Richmond and Fausch 1995). It reduces current velocity and increases retention and storage capacity of water, sediment, organic matter, and organisms (Anderson and Sedell 1979, Bilby and Likens 1980, Bilby 1981). It also increases habitat complexity and creates critical habitats for aquatic species (Swanson and others 1976, Keller and Swanson 1979, Bisson and others 1982). Woody debris also increases overbank flows (Jeffries and others 2003), and the development of sand and gravel bars that provide sites for colonization of riparian vegetation (Fetherston and others 1995, Abbe and Montgomery 1996). Woody debris in streams typically accumulates and forms debris dams that can be associated with several stream channel elements, such as waterfalls, dammed pools, and plunge pools (Heede 1972, Gurnell and Sweet 1998). Sedimentation and retention of particulate organic matter are generally enhanced in debris dams relative to other channel structures because the material is trapped when filtered through the network of roots, twigs, and branches in the dam (Ehrman and Lamberti 1992). The geomorphic effect of wood in streams depends on the form and size of the pieces, their species origin, and the stream size and channel slope (Harmon and others 1986, Bilby and Ward 1989, Robinson and Beschta 1990b, Nakamura and Swanson 1993, Beechie and Sibley 1997).

Forestry and associated wood removal in riparian areas have reduced the quantity of wood pieces in streams, and thus reduced the heterogeneity of channel morphology (Bilby and Ward 1991, Ralph and others 1994, Montgomery and Piegay 2003). In most Swedish streams, this reduction is caused by timber harvesting in riparian zones, which reduced the debris source, and clearings prior to log driving. During the

KEY WORDS: Debris dams; Streams; Logging; Sweden; Woody debris

Published online March 23, 2004.

*Author to whom correspondence should be addressed; *email:* niklas.dahlstrom@mh.se

log driving era between the mid 1800s and late 1900s, large woody debris and rocks were removed from streams, and channels were straightened. In addition, dead standing conifers were removed from the riparian zone and used to build frames for stone-filled deflectors and small dams for water storage. In the boreal Swedish forest as a whole, commercial forestry practices have reduced the amount of large woody debris on land by approximately one order of magnitude (Linder and Östlund 1998, Fridman and Walheim 2000). In some cases, timber harvests have also added woody debris to streams, especially twigs and branches from cut trees. These inputs may have important morphological effects on small streams, but the finer woody debris decays faster and is more easily transported downstream than larger pieces (Bilby and Bisson 1998). The few Swedish streams that have escaped completely from logging and log driving are located mainly in national parks and forest reserves, but these areas cover less than 5% of the Swedish nonmountainous, boreal forest region (Esseen and others 1997). These near-natural streams provide opportunities for assessing the amounts and importance of wood under more pristine conditions, and for comparing the loads and effects of woody debris in streams between old growth and managed forests.

Evaluations of the effects of commercial forestry in Sweden have brought attention to the low amounts of woody debris in forested ecosystems (Samuelsson and others 1994), largely because many wood-inhabiting terrestrial organisms suffer from lack of habitat. However, the degree to which this reduction has also affected streams has not been evaluated. Large areas of the boreal forest landscape of Sweden are covered by coarse glacial till and as a result, channel roughness in streams is relatively high, even without wood. The presence of multiple channel obstructions with an armor layer of boulders suggests that boulders may control channel morphology in small streams, and that woody debris may have minor effects on channel morphology. However, a recent study by Faustini and Jones (2003) suggests that wood also can influence steep and boulder-rich streams. We therefore chose to take a closer look at the conditions of such small forested streams in Sweden and to do that in areas with different histories of forestry. The objectives of the study were twofold: (1) to explore whether woody debris has any significant geomorphic function in small Swedish boreal forest streams despite steep slopes and a high proportion of coarse bed material, and (2) To compare the amounts and characteristics of woody debris and channel morphology of such streams between old growth and managed forest landscapes.

Methods

Selection of Study Sites

The study area was located in the middle and northern boreal zone (Ahti and others 1968) of central Sweden (Figure 1). The mean annual temperature in this area is approximately 2°C and 30–40% of the annual precipitation (600–800 mm) falls as snow during the winter. Base flow conditions usually occur during late winter and late summer. The streams in the area have their annual peak flow in spring as a result of snowmelt, but may also flood as a result of heavy rains in summer and autumn (Raab and Vedin 1995). The bedrock consists of Precambrian granites and gneisses and is covered by Quaternary deposits, mainly of coarse till and peat (Lundqvist 1987).

To quantify the differences in amounts of woody debris and channel form between old-growth forests and commercially cut forests, we studied 20 stream reaches, selected to be representative of small streams in Swedish boreal forests. Streams influenced by log driving, channel clearings, or other human activities except forestry were avoided. Study sections were selected to be homogeneous with regard to channel gradient, valley profile, soil, and forest type. Every chosen reach was single-channeled and bordered by mature forest stands with a closed canopy layer developed on podsolized glacial till, dominated by *Picea abies* with an understory of *Vaccinium myrtillus.* In total, 1716 m of stream length were surveyed. Reach lengths varied between 32 and 189 m, with a mean of 86 m, with generally longer reaches in wider streams. Half (10) of the stream reaches were situated in managed forests that previously had been clear-cut or had experienced intensive selective cuttings approximately 50 to 100 years ago. Cut stumps of different species, ages, and sizes were frequent in the managed forests. The other half (10) of the reaches were situated in old-growth forest reserves. A few old, cut stumps of mostly large Scots pine trees (*Pinus sylvestris*), cut approximately 80–120 years ago, were found along some of the old-growth forest streams. According to the limited number of visible traces of human activities, the old-growth forest could be termed near natural and used for quantifying human impacts on the quality and quantity of woody debris in the managed forest streams. The stream reaches ranged between 250 and 510 m above sealevel. in elevation, that is, they were all above the highest postglacial coastline. Predominant tree species were Norway spruce (*P. abies*), birch (*Betula pubescens* and *B. pendula*), and Scots pine that reached approximately 25 to 30 m in height and 0.5 m in bole diameter.

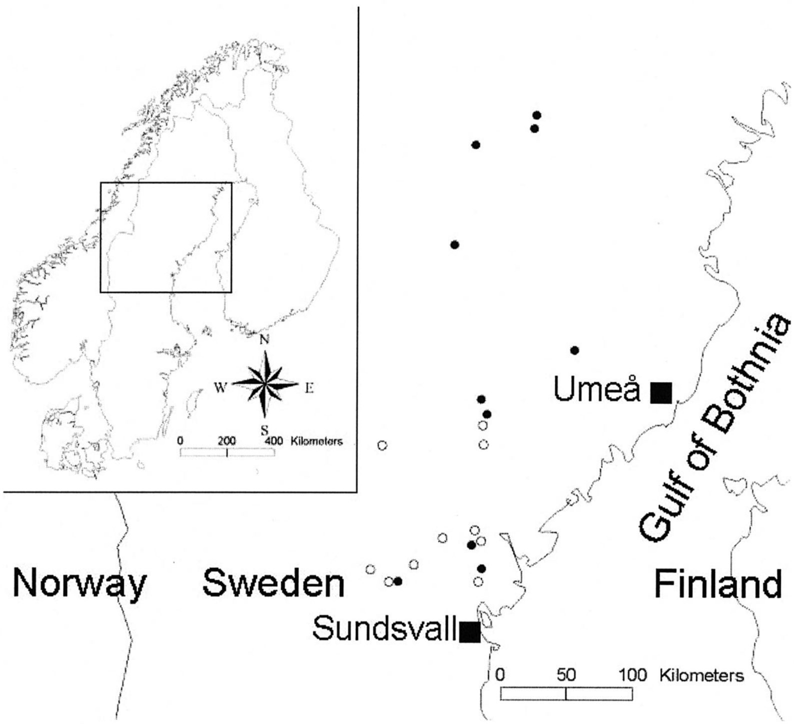

Figure 1. The study sites in northern central Sweden. (●) Stream reaches in old growth forests. (○) Managed forests.

Quantification of Channel Variables

Fieldwork was conducted during base flow conditions in the late summers of 1999 to 2001. Reach sinuosity was determined by dividing the thalweg length (i.e., the length of the deepest section of the channel) by the straight downstream length. Channel gradient was measured with a level and rod. Channel units were mainly steps (waterfalls), riffles, and pools. Steps were defined as any vertical drop spanning at least two thirds of the wetted channel width. The proportion of vertical drop in elevation was calculated in each of the surveyed stream reaches as the drop in elevation accounted for by the summed height of waterfalls divided by the total drop in channel elevation. Pools were classified as dammed pools (including backwater pools), scour pools, and plunge pools following Bisson and others (1982). The bankfull channel width was measured at 2- to 3-m intervals; the mean length and mean wetted width of all channel units were also quantified. Measurements of pools also included maximum depth and the depth of the downstream hydraulic control, defined as the shallowest part of the thalweg at the downstream end of the pool. Residual depth was calculated as the difference in elevation between maximum pool depth and the depth of the downstream hydraulic control (Lisle 1987). The pool-forming material was divided into wooden and nonwooden. Debris dams were defined as accumulations of organic matter spanning at least two thirds of the width of the wetted channel. The proportion of boulders (i.e., stones >256 mm in diameter) covering the bottoms was visually estimated in each reach.

The number and volume of all pieces of woody debris greater than 0.5 m in length, and greater than 0.05 m in maximum diameter at base were quantified based on our field observations that small wood pieces affect channel morphology in our study sites. An extrapolation of the observation by Beechie and Sibley (1997) that the size of pool-forming pieces decreases with decreasing stream size suggests that pieces smaller than 0.1 m in diameter may have important channel-forming effects in streams with bankfull widths less than 5 m. All pieces of woody debris fulfilling the minimum criteria were included if any part of them was situated within, or was hanging above the bankfull stream channel, but separate measurements were made on the wood parts located outside the channel. The volume of woody debris was estimated assuming shapes of truncated cones. All pieces of woody debris were classified according to their orientation as 0°, 45°, and 90° based on the angle of their main stem relative to the direction of the stream channel. The influence of individual

Table 1. Comparison of streams in old growth (n = 10) and managed (n = 10) forests in central Sweden

Abiotic characteristics	Old growth forest Mean ± SD (range)	Managed forest Mean ± SD (range)	F	*p*
Stream				
Bankfull channel width (m)	2.0 ± 0.4 (1.4–2.6)	1.9 ± 0.8 (0.7–3.1)	0.24	0.63
Channel gradient (%)	5.4 ± 2.9 (2.6–11)	5.9 ± 3.3 (2.6–13.5)	0.13	0.72
Sinuosity (m/m)	1.2 ± 0.1 (1.1–1.3)	1.2 ± 0.1 (1.1–1.3)	0.14	0.71
Boulder cover (%)	39.0 ± 12.4 (25–60)	47.5 ± 15.0 (25–65)	2.94	0.11
Woody debris				
Frequency (no/100 m)	66 ± 21 (35–98)	36 ± 21 (6–73)	9.94	0.01
Loading (no/ha)	3591 ± 1758 (1654–6586)	2290 ± 1549 (449–4525)	6.31	0.02
Volume (m^3/ha)	93.7 ± 46.1 (37.7–154.4)	24.8 ± 15.7 (5.5–46.9)	18.96	<0.001
Channel morphology				
Pool area (%)	49 ± 6 (40–60)	47 ± 11 (29–64)	0.58	0.48
Proportion of wood-formed pools (%)	39 ± 11 (20–56)	16 ± 13 (0–38)	18.73	<0.001
Pool spacing (channel width/pool)	3.2 ± 1.0 (1.7–5.2)	2.8 ± 1.0 (1.4–4.9)	1.05	0.32
Vertical drop (%)	47 ± 17 (19–72)	37 ± 12 (13–54)	2.42	0.14
Frequency of debris dams (no/100 m)	7.6 ± 3.1 (3.1–13.9)	4.2 ± 4.0 (0–12.5)	6.37	0.02
CV for bankfull channel width (%)	26 ± 9.5 (16–44)	23 ± 6.26 (17–38)	1.41	0.25
Woody pieces				
Length (m)	2.9 ± 3.5	2.3 ± 2.5	8.13	0.004
Diameter (m)	0.11 ± 0.063	0.092 ± 0.047	30.10	<0.001
Volume (m^3)	0.066 ± 0.17	0.030 ± 0.08	28.55	<0.001

wood pieces on stream flow was divided into two classes: (1) some or no effect on stream flow (e.g., pieces in fast water directing parts of the water flow, pieces hanging above the wetted channel, or situated in slow-flowing parts); and (2) major impact on stream flow (e.g., key pieces forming debris dams, pools, or waterfalls).

Data Analysis

Differences in channel characteristics and wood quantities between old growth and managed forests were calculated by comparing channel morphology and amounts and characteristics of woody debris, using analysis of covariance with bankfull channel width as a covariate. Observed pool dimensions and diameters and lengths of pieces of woody debris were not normally distributed, so data were $\log_{10}$-transformed prior to analysis. Categorical comparisons were made with chi-square tests. Relationships between woody debris and channel morphology were examined using stepwise regression analysis with forward selection and $p = 0.1$ to enter or remove variables. Dependent variables were total pool area, proportion of pools formed by wood, pool spacing, frequency of debris dams, proportion of vertical drop in elevation, and coefficient of variation for bankfull channel width. Independent variables used were bankfull channel width, channel gradient, sinuosity, boulder cover, frequency of woody debris, loading of woody debris, and volume of woody debris.

Results

Comparisons Between Old Growth and Managed Forest Streams

The 20 study reaches were all small headwater streams with moderate to high channel gradients (>2.6%), low sinuosity (<1.3), and a high proportion (25–65%) of boulder-sized bed material. They all had poorly incised valleys and lacked floodplains. Deposits of sand and fine organic material occurred sparsely on the bottom of the largest pools. The stream reaches in the old growth and managed forests were similar in terms of bankfull width, channel gradient, sinuosity, and boulder coverage, but streams in old-growth forests had more wood, more debris dams, and wood-formed pools. Piece sizes differed slightly, with coarser (a volume of 0.066 vs. 0.030 m^3) and longer pieces (2.9 vs. 2.3 m) in the old growth compared to the managed forest streams (Table 1). The residual depth and surface area of pools did not differ significantly between the old growth and managed forest streams ($p > 0.05$).

Characteristics of Woody Debris

The loadings of woody debris, expressed as the number of pieces per hectare bankfull surface area, decreased with increasing channel width (old-growth forest streams: $r = -0.80$, $p = 0.005$; managed forest streams: $r = -0.57$, $p = 0.09$). The frequency of woody debris (i.e., number of pieces per 100 m stream

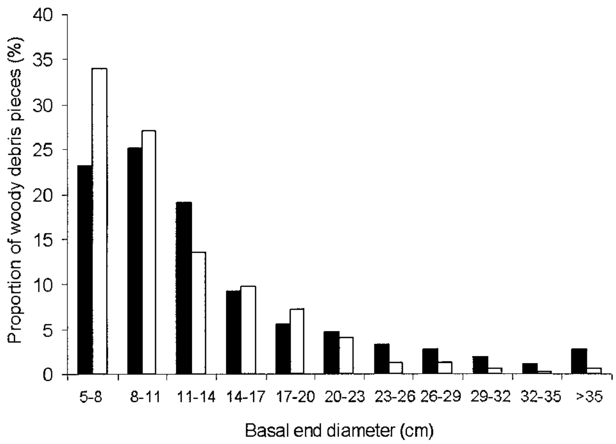

Figure 2. Distribution of basal end diameter of pieces of woody debris in 3-cm intervals. (■) Old growth forest streams, (□) Managed forest streams.

length), and the bankfull volume of woody debris showed no correlation with bankfull width ($p > 0.05$). The diameter and length of wood pieces showed a skewed distribution, with most pieces belonging to the smallest size classes (Figure 2). Of 846 measured pieces, only 5% were more than 10 m long. Forty-eight percent of the wood pieces were classified as large woody debris (LWD; diameter >0.1 m and length >1 m), but LWD represented 94.3% of the total volume. The length, diameter, and volume of single wood pieces were related to bankfull width ($r = 0.28–0.35$, $p < 0.001$ for $\log_{10}$-transformed data).

Geomorphic Effects of Woody Debris

On average, 31% of the wood pieces in the streams belonged to a debris dam, ranging from 0 to 59% in the individual stream reaches. This proportion did not correlate with bankfull width or channel gradient alone but showed a significant correlation with an index of stream power (expressed as bankfull channel width × gradient; $r = 0.56$, $p = 0.01$). Members of debris dams were overrepresented in the orientation class perpendicular to the stream channel, compared to all other pieces ($p < 0.001$, chi-square test). However, there was no difference in piece size between members and nonmembers of debris dams ($p > 0.05$, two-way analysis of variance [ANOVA]). On average, 15% of the wood pieces, ranging from 0 to 32% in the individual stream reaches, were classified as having a major impact on stream flow. Those key pieces represented a wide range of size classes, and had a significantly larger diameter and volume than other pieces ($p < 0.001$, two-way ANOVA. Pieces classified as having a major impact on stream flow were overrepresented in debris dams ($p < 0.001$, chi-square test) and among pieces in the class with a perpendicular orientation to the stream channel compared to all other pieces ($p = 0.031$, chi-square test).

Pool Formation

Thirty-four percent of pools were formed by woody debris, the majority (83%) of which were dammed pools, mainly located upstream of debris dams. The remaining wood-formed pools were plunge pools (15%) and scour-pools (2%). On average, 39% of the pools in the old-growth forest streams were formed by woody debris, and these contributed to 51% of the total pool area. Corresponding figures for the managed forest streams were 16 and 25%. Wood-formed pools had larger surface area and residual depth than all other pools ($p < 0.002$, two-way ANOVA) on $\log_{10}$-transformed data).

Relationships Between Woody Debris and Stream Channel Morphology

Stepwise multiple regression models were produced to determine which of the variables describing channel characteristics and woody debris best explained the variation in channel morphology (Table 2). Wood variables were important predictors of pool area, proportion of pools formed by wood, frequency of debris dams, and variation of bankfull channel width. Pool area was inversely related to channel slope. The proportion of pools formed by woody debris was inversely related to the percentage cover of boulders. The relationship between loading of woody debris and frequency of debris dams was slightly improved by a logarithmic equation (Table 2 and Figure 3).

Discussion and Conclusions

The streams of this study differ from most other streams studied for woody debris in that they were small-sized with high channel gradients and substantial boulder cover. The sizes and loads of wood pieces were small compared to values reported in other studies. Although the size classifications for woody debris differ between studies, the values observed in this study of the streams in old-growth forest are generally lower than in low-order streams of old-growth forest in North America (Harmon and others 1986), but correspond to values in somewhat larger streams in the Rocky Mountains (Richmond and Fausch 1995), and in older native-forest streams in New Zealand (Evans and others 1993). Data on wood amounts in old-growth forest streams in Europe are rare (Montgomery and Piegay 2003), but a set of central European streams bordered with decidu-

Table 2. Variables describing channel characteristics and woody debris included in stepwise regression models describing channel geomorphology

Dependent variable	Regression equation	R^2	p
Total pool area (%)	48.92 + 0.0057 No. of pieces/ha −2.21 Gradient −0.082 Volume of woody debris	68.7	<0.001
Proportion of pools formed by wood (%)	27.68 + 0.70 No. of pieces/100 m − 0.59 Boulder cover	53.9	<0.001
Pool spacing (channel widths/pool)			NS
Number of debris dams/100 m	−27.8 + 10.00 ($\log_{10}$ No. of pieces/ha)	65.0	<0.001
Vertical drop (%)			NS
CV for bankfull channel width (%)	17.42 + 0.0024 No. of pieces/ha	29.9	0.013

CV = coefficient of variation.

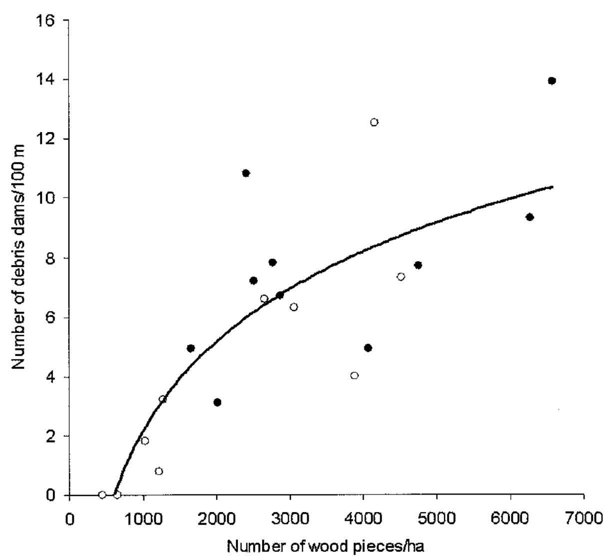

Figure 3. Relationship between the frequency of debris dams and the loading of woody debris. (●) Old-growth forest streams. (○) Managed forest streams. Number of debris dams/100 m = −27.80 + 10.00 ($\log_{10}$ number of pieces/ha); $R^2 = 0.65$, $p < 0.001$.

ous forests in "potentially natural conditions" (Hering and others 2000) contained similar amounts of woody debris compared to the old-growth forests in our study. The relatively small riparian trees and the coarse bed material that result in limited input by bank cutting in our study sites probably explain the observed patterns. For example, Bilby and Wasserman (1989) and Murphy and Koski (1989) found lower input rates in streams with coarse than with fine sediment. Despite the relatively low amounts and limited sizes, woody debris had important geomorphic functions in the studied streams. The proportion of pieces that had a major impact on stream flow at low-flow conditions (mean = 15%) is in the same range as in other studies. Montgomery and others (1995) found that 0 to 40% of LWD pieces contributed to pool formation, and Richmond and Fausch (1995) found that approximately 10% contributed to pool formation.

The observed frequencies of debris dams (Table 1) correspond to values reported from seminatural streams in Great Britain, where frequencies range between 0 to 14 dams/100 m in streams with average bankfull channel widths of approximately the same sizes as the streams in our study (Gurnell and Sweet 1998). The loading of woody debris may be used to predict the frequency of debris dams (Figure 3), but the cause-and-effect relationship remains unclear. Debris dams may accumulate woody debris in the particular stream reach from upstream areas at high flows and thus increase the loading of woody debris. However, the absence of a correlation between the frequency of debris dams and the proportion of wooden pieces included in debris dams suggest that the frequency of debris dams is in fact an effect of the loading of woody debris.

Our study shows that wood contributes to pool formation and that pool area is inversely related to slope. Beechie and Sibley (1997) found similar results in moderate- to low-gradient streams. These findings suggest that if the results can be generally applied, pools and debris dams can potentially be recreated in a predictable way by addition of wood, especially large pieces. Furthermore, our data suggest that the formation of debris dams is a function of the loading of woody debris, and that pieces of woody debris are locally aggregated in debris dams in stream reaches with high abilities to move pieces (i.e., larger streams with steeper slopes). Debris dams in those reaches contain larger numbers of pieces and are probably more compact than debris dams found in smaller stream channels with more gentle gradients.

The proportion of pools formed by woody debris was lower in managed forest streams compared to old-growth streams. However, the acquired figure that only 39% of pools in old-growth forest streams were formed by woody debris is low compared to old-growth forest streams in North America. For example, Richmond and Fausch (1995) found that 76% of the pools in streams in northern Colorado were formed by woody debris. Similar figures are 61% for southeast Alaska (Robison and Beschta 1990b), 70% for Wyoming (Young 1994), and 73% for southeast Alaska and Washington (Montgomery and others 1995). Pools formed by woody debris in the stream reaches in this study, however, generally had a larger surface area and residual depth than the average pools formed by other agents. Several studies of pool formation have reported scouring as the dominant pool-forming process (Myers and Swanson 1997), often acting around piles of woody debris (Bilby and Ward 1991, Montgomery and others 1995). In this study, a high proportion of coarse bed material and small stream sizes inhibit scouring. Several authors claim that dammed pools are ecologically more beneficial than scoured pools (Hawkins and others 1993), because they tend to retain more sediment and organic material (Ehrman and Lamberti 1992).

The largest pieces of woody debris are more likely to form dams and pools in larger streams (Beechie and Sibley 1997). In smaller streams, larger pieces often span the bankfull channel or hang above the active channel and do not contribute to channel formation at base flow conditions (Nakamura and Swanson 1993). Wood pieces that formed pools or created vertical drops in this study differed from other pieces in that they were more typically oriented perpendicularly to the stream channel and had larger diameters. These findings are supported by the stepwise multiple regression analyses, which showed that the number of pieces is a more important variable than volume for the effect of woody debris on channel morphology. Other studies in moderate- and high-gradient forest streams (e.g., Chin 1989, Montgomery and others 1995) report pool spacing in the same range as in the present study. Contrary to other studies (Chin 1999, Beechie and Sibley 1997, Montgomery and others 1995), neither stream reach characteristics nor wood amounts were related to pool spacing in this study. However, the influences of the loading of woody debris on pool spacing in steeper stream reaches are not obvious (Montgomery and others 1995).

Our study shows that, despite the high channel gradients, high proportion of coarse bed material, and limited tree sizes, woody debris can be an important channel-forming agent in small forest streams. Forestry in riparian areas has reduced the amounts of woody debris in streams, the average size of wood pieces and, as a consequence, the proportion of pools formed by woody debris, and the frequency of debris dams. The situation for most other streams in the boreal forest landscape is probably worse than the ones described in this study because of the extensive clearing operations that have taken place during the last 100–200 years. Currently, most of the clearing of watercourses has ended, but tree harvesting in riparian areas limits the future recruitment of woody debris to the streams. Therefore, the streams will not recover unless management policies change. If stream channels are not excavated, channelized, or otherwise modified to such extents that additional restoration measures would be required, restoration operations that combine preservation of riparian forests and wood addition could be practical tools for recreating lost stream channel structures. Interestingly, in many small streams, beaver, which are expanding their distribution in Sweden, have speeded up wood addition to streams. However, beaver will still require riparian woods to operate and cannot be the only restorer.

Acknowledgments

We thank Karin Jönsson and Daniel Holmqvist for help with the field work, and James Helfield and Bengt-Gunnar Jonsson for valuable comments on an earlier draft of this manuscript. We also thank Tim Beechie and Fred Swanson as journal reviewers and an anonymous journal reviewer for their helpful comments. The study was supported by the Ebba and Sven Schwartz' Foundation and the Gunnar and Birgitta Nordin's Fund of the Royal Swedish Academy of Sciences (to N.D.), and the Kempe Foundations and EU Objective 1 (to C.N.).

Literature Cited

Abbe, T. B., and D. R. Montgomery. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research and Management* 12:201–221.

Ahti, T., L. Hämet-Ahti, and J. Jalas. 1968. Vegetation zones and their sections in northwestern Europe. *Annales Botanici Fennici* 5:169–211.

Anderson, N. H., and J. R. Sedell. 1979. Detritus processing by macroinvertebrates in stream ecosystems. *Annual Reviews of Entomology* 24:351–377.

Beechie, T. J., and T. H. Sibley. 1997. Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. *Transactions of the American Fisheries Society* 126:217–229.

Bilby, R. E. 1981. Role of organic debris dams in regulating the export of dissolved organic and particulate matter from a forested watershed. *Ecology* 62:1234–1243.

Bilby, R. E., and P. A. Bisson. 1998. Function and distribution of large woody debris. Pages 324–346 *in* R Naiman, and R.E. Bilby. eds, River ecology and management. Springer-Verlag, New York, New York.

Bilby, R. E., and G. E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology* 61:1107–1113.

Bilby, R. E., and J. V. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* 118:368–378.

Bilby, R. E., and J. V. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and 2nd-growth forests in southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 42:2499–2508.

Bilby, R. E., and L. J. Wasserman. 1989. Forest practices and riparian management in Washington State: data based regulation development. Pages 87–94 *in* R. E. Gresswell, B. A. Barton, and J. L. Kershner. eds, Practical approaches to riparian management. U.S. Department of the Interior, Bureau of Land Management, Billings, Montana.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dollof, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. . Pages 143–190 *in* E. O. Salo, and T. W. Cundy. eds, Streamside management: forestry and fishery interactions. University of Washington, Seattle, Washington.

Bisson, P. A., J. L. Nielson, R. A. Palmason, and L. E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. Pages 62–73 *in* N. B. Armantrout ed, Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Bethesda, Maryland.

Chin, A. 1989. Step-pools in stream channels. *Progress in Physical Geography* 13:391–408.

Chin, A. 1999. The morphologic structure of step-pools in mountain streams. *Geomorphology* 27:191–204.

Ehrman, T. P., and G. A. Lamberti. 1992. Hydraulic and particulate matter retention in a 3rd-order Indiana stream. *Journal of the North American Benthological Society* 11:341–349.

Esseen, P.-A., B. Ehnström, L. Ericson, and K. Sjöberg. 1997. Boreal forest. *Ecological Bulletins* 46:16–47.

Evans, B. F., C. R. Townsend, and T. A. Crowl. 1993. Distribution and abundance of coarse woody debris in some southern New Zealand streams from contrasting forest catchments. *New Zealand Journal of Marine and Freshwater Research* 27:227–239.

Faustini, J. M., and J. A. Jones. 2003. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology* 51:187–205.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology* 13:133–144.

Fridman, J., and M. Walheim. 2000. Amount, structure, and dynamics of dead wood on managed forestland in Sweden. *Forest Ecology and Management* 131:23–36.

Gurnell, A. M., and R. Sweet. 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms* 23:1101–1121.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkamper, J. R. K. Cromack, and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* 15:133–302.

Hawkins, C. P., J. L. Kershner, P. A. Bisson, M. D. Bryant, L. M. Decker, S. V. Gregory, D. A. McCullough, C. K. Overton, G. H. Reeves, R. J. Steedman, and M. K. Young. 1993. A hierarchical approach to classifying stream habitat features. *Fisheries* 18:3–12.

Heede, B. H. 1972. Flow and channel characteristics of two high mountain streams. U.S. Department of Agriculture, Forest Service, Research Paper RM-96.

Hering, D., J. Kail, S. Eckert, M. Gerhard, E. I. Meyer, M. Mutz, and I. Weiss. 2000. Coarse woody debris quantity and distribution in Central European streams. *International Review of Hydrobiology* 85:5–23.

Jeffries, R., S. E. Darby, and D. A. Sear. 2003. The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England. *Geomorphology* 51:61–80.

Keller, E. A., and F. J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* 4:361–380.

Linder, P., and L. Östlund. 1998. Structural changes in three mid-boreal Swedish forest landscapes, 1885–1996. *Biological Conservation* 85:9–19.

Lisle, T. E. 1987. Using "Residual Depths" to monitor pool depths independently of discharge. USDA Pacific Southwest Forest and Range Experiment Station Research Note PSW-394, Berkley, California, 4 p.

Lundqvist, J. 1987. Quaternary deposits of Västernorrland county. Sveriges Geologiska Undersökningar, Uppsala, Sweden.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. *Water Resources Research* 31:1097–1105.

Montgomery, D. R., and H. Piegay. 2003. Wood in rivers: interactions with channel morphology and processes. *Geomorphology* 51:1–5.

Murphy, M. L., and K. V. Koski. 1989. Input and depletion of large woody debris in Alaska streams and implications for streamside management. *North American Journal of Fisheries Management* 9:427–436.

Myers, T., and S. Swanson. 1997. Variability of pool characteristics with pool type and formative feature on small Great Basin rangeland streams. *Journal of Hydrology* 201:62–81.

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. *Earth Surface Processes and Landforms* 18:43–61.

Raab, B., and H. Vedin. 1995. Climate, lakes and rivers. National Atlas of Sweden. Almqvist and Wiksell, Stockholm, Sweden.

Ralph, S. C., G. C. Poole, L. L. Conquest, and R. J. Naiman. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 51:37–51.

Richmond, A. D., and K. D. Fausch. 1995. Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1789–1802.

Robison, E. G., and R. L. Beschta. 1990a. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 47:1684–1693.

Robison, E. G., and R. L. Beschta. 1990b. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA. *Earth Surface Processes and Landforms* 15:149–156.

Samuelsson, J., L. Gustafsson, and T. Ingelög. 1994. Dying and dead trees: a review of their importance for biodiversity. Threatened Species Unit, Swedish Agricultural University, Uppsala, Sweden.

Swanson, F. J., G. W. Lienkaemper, and J. R. Sedell. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. U.S. Department of Agriculture, Forest Service, General Technical Report PNW-56.

Young, M. K. 1994. Movement and characteristics of stream-borne coarse woody debris in adjacent burned and undisturbed watersheds in Wyoming. *Canadian Journal of Forest Research* 24:1933–1938.