INSTREAM WOOD TRANSPORT, AND EFFECTS OF FOREST HARVEST ON GEOMORPHOLOGY AND FISH, IN NORTHERN MINNESOTA STREAMS

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

JACQUES FINLAY AND HEINZ STEFAN, ADVISERS

JUNE 2009

ACKNOWLEDGEMENTS

First and foremost, I thank my family for keeping me both grounded and motivated. I couldn't have asked for better officemates.

Jacques Finlay and Heinz Stefan have been excellent advisers, helping me with the wood project and with all aspects of my PhD. My committee was very involved throughout the process; Lucinda Johnson, Ray Newman, and Bruce Vondracek provided my initial funding and got my projects rolling.

Many other people helped with my projects; they are acknowledged or coauthors in the chapters that follow. I had the opportunity to work with colleagues both new and old during my PhD, and I look forward to ongoing collaboration. Financial support is acknowledged in each chapter; I benefitted from two teaching assistantships as well.

I am grateful to all.

ABSTRACT

Trees provide critical functions to the ecology of streams. Trees affect hydrology, mitigate sediment inputs, and buffer water temperatures by providing shade. Watersheds with a higher proportion of mature forest tend to have less variable hydrographs, and older trees provide larger pieces of wood to streams. Instream wood itself affects nearly every process in stream ecology.

Despite their ecological importance, trees and instream wood have been greatly modified by humans. The studies described in this dissertation advance current knowledge as follows:

We demonstrate that headwater streams in northern forests can require ten years to recover from a large input of fine sediment, depending on the occurrence of stormflows.

Our analyses suggest that, at the basin scale, warmer air temperatures in summer are more important to the abundances of some headwater fish species than instream habitat or spring precipitation. The analyses also lend support to previous findings that riparian forest harvest can cause local stream warming.

Wood transport in streams is a dynamic process. Forty-one percent of over 800 wood pieces were mobilized (at least 10m) during a study period by a single high flow event. Thirty-two percent of the mobilized pieces became entrapped again before leaving their study reach.

Mobilization of wood in streams is a complex function of both mechanical and hydraulic factors. Eleven potential predictor variables were studied, and seven were identified as significant to wood mobilization using multiple logistic regression. The seven predictors were burial, effective depth, length ratio, bracing, rootwad presence, downstream force ratio, and draft ratio.

Entrapment of wood in streams is related primarily to the length ratio and weight of the wood pieces. The mechanisms for entrapment are not always clear; wood pieces may simply be entrapped wherever they are located when high water recedes.

Together, this dissertation suggests that forest harvest should avoid excess sediment inputs (due to persistence) and stream warming (due to effects on fish). It also develops models that can be used for more informed management of instream wood. Stream managers and restorers can apply the results presented to reverse the impacts of historic logging and wood removal on streams.

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OVERVIEW AND SUMMARY OF RESULTS

Streams have been modified worldwide by logging and wood removal. The relationship between trees, dead wood and stream ecology is very strong, and many adverse effects of logging and wood removal have been observed. As described below, this dissertation addresses gaps in the current knowledge of the relationship between trees, wood and streams to further aid in stream protection and restoration.

The first two chapters of this dissertation examine effects of riparian forest harvest on streams in the Pokegama Creek system near Grand Rapids, Minnesota, over an 11-year study period. Previous studies in other watersheds have related forest harvest to increased stream discharge, increased inputs of fine sediment, decreased inputs of leaf litter and wood, community shifts in aquatic biota, and warmer stream temperatures in summer. We examined effects of experimental forest harvest (2 to 11% of the watersheds) using existing data from 1997 (pre-harvest) to 2000 (four years post-harvest) and new data from 2006 and 2007. Most of our analyses were at the basin scale; we pooled data from 33 50-m sample stream reaches for each of the six years studied.

The last two chapters examine natural wood transport in streams along the north shore of Lake Superior in Minnesota using an extensive field dataset collected over a two-year period. Natural pieces of wood provide a variety of ecosystem functions in streams, including high quality habitat, organic matter retention, increased hyporheic exchange flow and transient storage, and enhanced hydraulic and geomorphic heterogeneity. Given the strong role that wood plays in streams, factors that influence wood transport are therefore critical to the understanding of stream ecology. In previous studies of wood transport the scope was typically constrained to a small number of variables, or laboratory flumes were used, and wood was represented by dowels or flumes. We tracked natural wood pieces in nine streams over distances up to 800m with a resolution of 10m. Seven wood piece characteristics were measured and the location of each piece was documented twice, and related to the hydraulic stream characteristics.

In the first chapter of the dissertation I examine the dynamics of fine sediment in the Pokegama Creek system. Fine sediment can enter a stream channel by aeolian deposition, overland flow, bank erosion or even landslides, or by delivery from roads, or the disturbances created by forest harvest equipment. In a previous study a large input of fine sediment to the Pokegama Creek system within the first year after experimental forest harvest had been documented. We sought to extend the previous study using new data (2006 to 2007) and unpublished historic data to examine the dynamics of fine sediment over a longer time frame. Canopy cover, proportion of unstable banks, surficial fine substrates, residual pool depth, and streambed depth of refusal were used as response variables in repeated measured ANOVAs to test for basin-scale year effects. All response variables showed significant basin-scale year effects, indicating differences between years when considering all sites throughout the basin. The proportion of unstable banks increased for several years post-harvest, coinciding with an increase in fine sediment in the streams. An increase in unstable banks may have been caused by forest harvest equipment, increased windthrow and exposure of rootwads, or increased discharge and bank scour. Fine sediment in the channels had not recovered by summer 2007 (ten years post-harvest), even though canopy cover and unstable banks had returned to 1997 levels.

After several storm events in fall 2007, fine sediment was flushed from the channels and remaining sediment deposits returned to 1997 levels. Although our study design did not discern the source of the initial sediment inputs (e.g., forest harvest, road crossings, other natural causes), we could demonstrate that moraine, headwater streams can require high stormflows to recover from large inputs of fine sediment.

In the second chapter of the dissertation I examine changes of the fish community in the Pokegama Creek system. Pooling data from the study area for each year, significant decreases in the index of biotic integrity and the abundance of brook trout and northern redbelly dace over the study period were demonstrated. Abundance of brook sticklebacks also decreased over time while creek chub abundance increased, although neither trend was significant. We next related fish abundances between 1997 and 2007 to instream habitat (fine substrates and large wood) and environmental conditions (summer air temperature and spring precipitation) at the basin scale. It was determined that lower "index of biotic integrity" scores were significantly related to warmer air temperatures, as were lower abundances for brook trout, northern redbelly dace, and brook sticklebacks. Fish variables were not significantly related to fine substrates in the streambed, large wood, or total spring precipitation at the basin scale. Air temperatures increased only ~0.06° C/yr during the study period (consistent with regional estimates of climate change), but water temperatures near harvest plots with thinned riparian tree cover were warmer than those near plots with riparian buffers (based on an ANOVA using stream temperatures measured in 2006 and 2007). We suggest that summer temperatures may influence fish communities more than fine sediment, large wood, or spring precipitation in forested headwater streams based on the basin-scale relationships from this study. The removal of riparian vegetation exacerbates warming of streams by reduced shading.

The third chapter of the dissertation is an examination of mobilization of natural wood pieces. Mobilization was defined as the displacement of a stationary piece of wood by at least 10m. The characteristics and locations of 865 undisturbed wood pieces (usually > 0.1 m in diameter for a portion > 1 m in length) were documented in summer 2007 in nine streams, each with a study reach 250 to 800 m long (4,190 m total). The locations of the pieces were determined again in fall 2007 after an overbank stormflow event. Hydraulic conditions in the streams during the entire study period were determined using calibrated flow simulation (HEC-RAS) models. Eleven potential predictor variables were studied, and seven were identified as significant to wood mobilization using multiple logistic regression. The composition of the final model indicates that wood mobilization under natural conditions is a complex function of both mechanical factors (burial, length ratio, bracing, rootwad presence, draft ratio) and hydraulic factors (effective depth, downstream force ratio). Although the study included only one stormflow event, the nine streams exhibited a wide range of geomorphic and hydraulic conditions. The model should be applicable to at least a similarly wide range of conditions in other watersheds. The mobilization model can provide guidance to stream management and stream restoration. For example, if stable pieces are a goal for stream management then features such as partial burial, low effective depth, high length relative to channel width, bracing against other objects (i.e., stream banks, trees, rocks, or larger wood pieces), and rootwads are desirable.

The fourth chapter of my dissertation was an examination of wood piece entrapment in a stream. Entrapment was defined to occur when a piece of wood comes to rest after being transported at least 10 m. A total of 344 pieces met met the criterion for entrapment, based on changes in locations before and after the fall 2007 overbank stormflow event. The ratio of wood piece length to effective stream width was the most important independent variable for entrapment; longer pieces are more likely to be entrapped. Multiple logistic regression also showed that piece weight was the second-most important variable for entrapment; heavier pieces are more likely entrapped.

The scaled resolution for the wood transport study was similar to that of flume studies, and a wide natural range of wood piece and stream characteristics was examined. The results can provide guidance to stream modifications where wood entrapment is undesirable (e.g., at road crossings or other infrastructure); the effective stream width required to pass particular wood pieces can be determined by the model. Conversely, the results can be used to determine conditions that enhance entrapment where wood pieces are valued for ecological functions. Entrapment remains difficult to predict in natural streams, and often may simply occur wherever wood pieces are located when high water recedes.

Stream managers and restorers can, if they so choose, apply the results from this dissertation toward reversing the impacts of logging and wood removal on streams.

CHAPTER 1: Relationship of sediment dynamics in moraine, headwater streams in northern Minnesota to forest harvest

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[1] The Unit is jointly sponsored by the U. S. Geological Survey, the University of Minnesota, the Minnesota Department of Natural Resources, and the Wildlife Management Institute

SUMMARY

Fine sediment can enter stream channels through a variety of mechanisms, including aeolian processes, landslides, overland flow, bank erosion, delivery from roads, or forest harvest. The persistence of fine sediment in streams, however, is less well known. This study investigated the dynamics of fine sediment in four moraine, headwater streams in north central Minnesota in relation to forest harvest. We examined the dynamics of fine sediment from 1997 (pre-harvest) to 2007 (ten years post-harvest) at study plots with upland clear felling and riparian thinning, using canopy cover, proportion of unstable banks, surficial fine substrates, residual pool depth, and streambed depth of refusal as response variables. Basin-scale year effects were significant ($P < 0.001$) for all response variables when evaluated by repeated measures ANOVAs. Throughout the study area, the proportion of unstable banks increased for several years post-harvest, coinciding with an increase in fine sediment. Increased unstable banks may have been caused by forest harvest equipment, increased windthrow and exposure of rootwads, or increased discharge and bank scour. Fine sediment in the channels did not recover by summer 2007, even though canopy cover and unstable banks had returned to 1997 levels. After several storm events in fall 2007, ten years after the initial sediment input, fine sediment was flushed from the channels and returned to 1997 levels. Although our study design did not discern the source of the initial sediment inputs (e.g., forest harvest, road crossings, other natural causes), we have demonstrated that moraine, headwater streams can require an enabling event (e.g., high stormflows) in order to recover from large inputs of fine sediment.

INTRODUCTION

The effects of fine sediment on stream ecosystems have been well documented, and can include increased turbidity, reduced ability of aquatic organisms to feed, clogged gills of fish and macroinvertebrates, smothered eggs and larvae, and homogenization of habitats (Waters 1995, Sweka and Hartman 2001). Fine sediment can enter streams through a variety of mechanisms, including aeolian processes, landslides, overland flow, bank erosion, or delivery from roads (Chamberlin et al. 1991, Wondzell 2001, Broadmeadow and Nisbet 2004). However, sediment inputs from aeolian processes are minor in temperate forests (Steedman and France 2000), and landslides are uncommon in streams with hillslopes under 35˚ (Johnson et al. 2007).

Forest harvest can also contribute excess sediment to streams; excess sediment can manifest as increases in total suspended sediment (Gomi et al. 2005), streambed aggradation (Keim and Schoenholtz 1999), or the proportion of surficial fine substrates (Davies and Nelson 1994, Thompson et al. 2009). For example, suspended sediment during stormflow events increased significantly in a Fiji catchment after salvage logging and slash burning; much of the sediment was mobilized from new logging roads and landing areas (Waterloo et al. 2007). Similarly, thinning only 11% of the standing timber volume with horse skidding produced a significant increase in suspended sediment to a stream in Turkey (Serengil et al. 2007a). Hydrographs also indicated significantly more stormflow in both study areas (Waterloo et al. 2007, Serengil et al. 2007b).

An altered stream hydrograph can lead to increased bank erosion (Brooks et al. 1997), and may take decades to recover after forest harvest (Moore and Wondzell 2005).

In a forest harvest study in British Colombia, peak snowmelt discharge remained above pre-harvest levels for the five-year duration of the study (Macdonald et al. 2003). Verry (2004) noted that channel-forming flows double or triple after 60% of a catchment is converted from forest to non-forest conditions in the upper Midwest; however, little work has been done on the effect of elevated flows on sediment inputs.

Input processes aside, few studies have examined recovery of streams after large inputs of sediment (Gomi et al. 2005). In one case, the bedload of fine sediment required more than two years to return to natural levels after road-improvement activities (Kreutzweiser and Capell 2001), and in another case sediment eroded from logging roads and skid trails and was stored in stream channels for 3.4 years (Gomi et al. 2006). In a review of available studies, Gomi et al. (2005) noted that sediment yield usually recovers within one to six years post-harvest, barring landslides. Previous research in Minnesota (Merten 1999, Hemstad and Newman 2006, Hemstad et al. 2008) suggests that levels of fine sediment can increase significantly after forest harvest. However, more research is needed to determine how long fine sediment will persist in channels.

Our objective was to evaluate changes in fine sediment in four headwater streams following timber harvesting in riparian areas in the Sugar Hills moraine of north central Minnesota. We predicted that fine sediment loading would increase after forest harvest, but that sediment levels would return to pre-harvest conditions within 10 years. Hemstad et al. (2008) suggested that basin-scale factors were more important than plot-level factors to sediment in our study area. Although our study did not discern between changes due to forest harvest, road crossings, or natural causes, it did evaluate recovery at the basin scale after a large input of fine sediment.

STUDY AREA

Twelve study plots were located in the Pokegama Creek system in north-central Minnesota (47º 8.039´N, 93º 37.405´W); the basin included four small, forested basins with moraine hills rising five to seven meters above the valley floor and hillslopes of 1 to 30% (Fig. 1). One plot was on an intermittent tributary and was omitted from analyses. Soils and parent material in the Sugar Hills moraine were loamy sands with gravel lenses and cobble/boulder inclusions (Nyberg 1987). The upland soils were fertile and well-drained, supporting late successional forests of sugar maple (*Acer saccharum* Marsh) and basswood *(Tilia americana* Linnaeus). Early successional forests following clearcut logging included: paper birch (*Betula papyrifera* Marsh), aspen (*Populus tremuloides* and *P. grandidenta*) and balsam fir (*Abies balsamea* [Linnaeus] Miller). Riparian forests at the floodplain elevation included black ash (*Fraxinus nigra* Marsh), along with sugar maple and basswood and remnant early succession species (about 10% of basal area). Riparian forests in 1997 averaged 30 m^2/ha of basal area (Palik et al. 2003).

The drainage basins of the four study streams varied in size from 129 to 281 ha (Table 1). Harvested study plots accounted for 2 to 11% of their respective basins, whereas open areas or young forest (<16 years) in the catchment accounted for 25 to 49% of their respective basin. The slope, width, and mean depth of the study streams were measured at each plot location and reaches immediately upstream, along with tree basal area in and above the plots (Table 2). Channel gradients were relatively steep (0.7 to 3.5%, one tributary was 7.2%) because they drained glacial moraine hills. Sediment in the streams was predominately fine sand, as evidenced by the diameter of the 50th percentile of all particles (D_{50}). The substrate contained gravel and cobble sizes at the 84th percentile (D_{84}) where channels had a steeper gradient. Cobble and small boulders were concentrated in the glacial drift of Little Pokegama Creek (Table 2). A paved road ran approximately 250 m to the north and parallel to one stream (Pokegama Creek North), and an existing gravel road with culverts crossed two of the streams (Pokegama Creek North and Pokegama Creek South) just upstream from the study plots. Two additional culvert crossings were farther upstream on Pokegama Creek North (Fig. 1). Beaver dams and impoundments were present below the confluence of Pokegama Creek North and Pokegama Creek South, and well upstream of plots 1 and 2 on Jack Irving Creek.

METHODS

Harvested study plots

Harvest treatments were replicated throughout the four basins. Harvest treatments spanned the stream at each plot (4.9 ha, with 2.45 ha on each side of the stream) and included: unharvested controls (N = 2), 30-m unharvested riparian buffer with the upland clearcut (N = 3), or thinned to 12.3 m^2/ha within a 30-m riparian strip with the upland clearcut (N = 6). Trees were harvested in fall 1997 using either a cut-to-length harvester paired with a forwarder or a feller-buncher paired with a grapple skidder (Palik et al. 2003). Pre-harvest data were collected in 1997 and post-harvest data were collected in

1998-2000 and 2006-2007. Each plot included 150 to 200 m of stream length, and plots were ~200 m apart. Three reaches were sampled at each plot: 50 m immediately upstream of the treatment, 50 m immediately downstream of the treatment, and within the downstream 50 m of the plot (Fig. 1). Study plots were established collaboratively (Merten 1999, Fox 2000, Fredrick 2003, Hanowski et al. 2003, Palik et al. 2003, Hanowski et al. 2007, Hemstad et al. 2008).

Examination of year effects at study plots

A variety of data were collected at the study plots for examination of basin-scale year effects (i.e., overall differences between years when considering all sites). Six variables were measured to characterize stream bank and channel conditions: proportion of unstable banks, canopy cover, surficial fine substrates, embeddedness, streambed depth of refusal, and residual pool depth (Lisle 1987). Visual estimates of the proportion of bank area that was unstable (not covered by vegetation, roots, or rocks) were made in the three 50-m reaches at each plot (Merten 1999, Hemstad et al. 2008). The value for each 50-m reach was the mean of three 17-m sections. Canopy cover was also determined at the center of each 17-m section using a spherical concave forest densiometer in all four directions (Lemmon 1957). Unstable banks and canopy cover were assessed in July 1997-2000 and 2006-2007.

Surficial substrates were examined in the three reaches at each of the 11 study plots. Each 50-m reach at each plot was divided into five 10-m subreaches, to avoid sampling substrates exclusively at the upstream or downstream end of a 50-m reach.

Seven circular quadrats (28 cm in diameter) were placed in random locations in each 10-m subreach to visually estimate the percentage of sand, silt, or clay (i.e., fine substrates) on the streambed surface (for a total of 1,155 quadrats per year). Embeddedness was estimated in each quadrat as the degree to which larger substrates were buried in fine substrates (e,g., a quadrat with cobbles half-buried in sand was 50% embedded, whereas a quadrat with only fine substrates visible was 100% embedded). Surficial substrates were examined in July 1997-2000 and 2006-2007.

Sediment storage in the channel was evaluated using depth of refusal and residual pool depth. At each of the 11 study plots, the ten riffles with the largest substrates and the ten deepest pools were sampled. Depth of refusal was determined at each riffle and pool by probing with a rod to determine the thickness of the fine sediment layer (i.e., sand or silt) in the stream channel. A tapered aluminum rod was used to probe the sediment. The depth of refusal for each plot was the mean of the ten riffles and ten pools. Depth of refusal was measured in summer 1997, 1998, 2006, and 2007. Residual pool depth (i.e., pool depths minus riffle depths) was determined for each plot in summer 1997, 2006, and 2007 with a laser level following Lisle (1987).

In fall 2007, rain events that totaled 112 mm above the August/September mean for the study period caused high flows throughout the study area (Minnesota State Climatology Office). Depth of refusal data were collected at all plots in November 2007 to investigate whether sediment had been flushed from the streams by these high flows.

Previous work documented short-term effects of forest harvest on sediment in the Pokegama Creek system, and suggested that basin-scale effects were more important than local-scale effects or harvesting technique (Hemstad et al. 2008). Therefore, year effects were evaluated at all study plots, regardless of harvest treatment, using repeated measures ANOVAs that included our new data from 2006-2007. Two factors were included in each analysis: a factor for year and a blocking factor for the four streams. The blocking factor was necessary to address a lack of independence between sampling units on the same stream. Variables were transformed as needed to reduce heteroscadasticity and improve normality. A repeated measures ANOVA was examined separately for canopy coverage, unstable banks, embeddedness, and surficial fine substrates. In addition, repeated measures ANOVAs were used to evaluate year effects on depth of refusal and residual pool depth, using a year factor but no blocking factor (due to greater separation between sampling units and lower replication). When ANOVAs were significant ($P < 0.05$), Tukey's HSD comparison was used to compare differences in mean values for the response variable between years. The statistical software R was used for all analyses (Ihaka and Gentleman 1996).

Comparisons with Pfankuch Channel Stability Rating

We compared our methods for assessing fine sediment to the Pfankuch Channel Stability Rating (Pfankuch 1975), an established method for assessing geomorphic stability. The rating uses qualitative categories for 15 metrics to describe conditions of stream banks and channels, and sums the values into a score from 38 (the most stable condition) to 152 (the most disturbed condition). In 2007 the Pfankuch Channel Stability Rating was determined at each of the 12 study plots, and was compared with simple regressions against our measures of surficial fine substrates, embeddedness, depth of refusal, and residual pool depth (combining data from all three reaches at each plot).

RESULTS

Year effects at study plots

Canopy cover, unstable banks, embeddedness, and surficial fine substrates were significantly different across years during the study period (Table 3). Although canopy cover was unaffected by harvest itself (i.e., 1997 and 1998 were not significantly different), canopy cover declined as a result of windthrow by 2000 and had recovered to pre-harvest levels by 2006 (Fig. 2A). The proportion of unstable banks increased between 1997 and 2000, but had recovered by 2007 (Fig. 2B). Embeddedness increased from 1997 to 1998 and remained above pre-harvest levels through 2007 (Fig. 2C). Surficial fine substrates also increased from 1997 to 1998, but partially recovered in 1999 after a heavy summer storm (Fig. 2D). The proportion of surficial fine substrates again increased significantly relative to pre-harvest levels in 2000 and 2006, but recovered in 2007.

Sediment storage was also significantly different across years during the study period. Residual pool depths were shallower than pre-harvest conditions in both 2006 and 2007 (Fig. 3A). Depth of refusal was not significantly different between 1997 and 1998 but increased significantly between 1998 and 2006, and remained significantly greater than pre-harvest levels in summer of 2007 (Fig. 3B). However, following heavy rains in fall 2007 large amounts of freshly deposited sand were noted on the floodplains and depth of refusal in November was no longer significantly different from pre-harvest levels (Fig. 3B).

Comparisons with Pfankuch Channel Stability Rating

The Pfankuch Channel Stability Rating was correlated highly and positively with the proportion of surficial fine substrates (R^2 = 0.78, Fig. 4). The correlations with other variables were weaker; the R^2 for embeddedness, residual pool depth, and depth of refusal were 0.4, 0.31, and 0.28.

DISCUSSION

Our study demonstrated that headwater streams in moraine landscapes may require ten years to recover after a large input of fine sediment, depending on the rate of stream bank revegetation and the frequency of large storm events. Our fine sediment variables relate to overall channel stability; the proportion of surficial fine substrates correlated particularly well with the Pfankuch Stream Channel Stability Rating, which includes visual assessments of surficial conditions. Correlations were weaker for embeddedness, depth of refusal, and residual pool depth, all of which assess the thickness of the layer of fine sediment rather than surficial coverage. Embeddedness, depth of refusal, and residual pool depth values remained significantly changed ten years after the input of sediment between 1997 and 1998. The year effects we documented may be related to changes in bank scour, windthrow, storm events, and damage from forest harvest equipment.

Bank scour throughout the study area may have contributed fine sediment through at least 2000, as evidenced by higher proportions of unstable banks. Banks were fully revegetated by 2007, by which time bank scour was presumably reduced. Excess sediment (i.e., embeddedness, depth of refusal, and residual pool depth) remained in the streams through summer 2007. Storm events in fall 2007 led to high streamflows that flushed enough sediment onto the floodplain to return depth of refusal values to 1997 conditions.

Local weather patterns can influence windthrow, sediment storage, and sediment transport (Brooks et al. 1997). Storm events occurred during 1998 and 1999 (Minnesota State Climatology Office), followed by a period through 2001 with no storm events when sediment likely stayed in the channel. Heavy rainfall events occurred again in 2001-2005, many caused by summer storms with high winds that may have caused windthrow and inputs of associated sediment (Grizzel and Wolff 1998). Another period followed from 2006 through mid-2007 when sediment likely remained in the channel, until the storms of fall 2007 led to sediment deposition onto the floodplains. The analysis of decade-long studies should be interpreted in the context of such weather cycles.

Windthrow along the channel banks (Hemstad et al. 2008) may also have led to increases in unstable banks and channel sediment (Grizzel and Wolff 1998). Rootwads exposed by windthrow influenced channel morphology in places by adding associated sediment, partially blocking the channel, and inducing bank cutting around the rootwad. Studies of windthrow in riparian buffers in the upper Midwest are rare (Heinselman 1955, Heinselman 1957, Elling and Verry 1978) but suggest that windthrow rates are greatest near the edge of buffers (*sensu* Martin and Grotefendt [2007]), thus wider buffers protect streamside trees from windthrow.

High discharge may also have contributed to the increases in unstable banks and channel sediment. The streams in the Pokegama Creek system may have experienced increases in bankfull discharge due to increases in water yield from harvested areas (Verry 2004, Brooks et al. 1997, Macdonald et al. 2003, Detenbeck et al. 2005, Moore and Wondzell 2005, Waterloo et al. 2007). Although the harvested percentages of the four basins were only 2 to 11%, Serengil et al. (2007b) found hydrologic effects after 11% of a basin was harvested. Lower thresholds may simply be precluded by the accuracy of hydrologic measurements (Verry 1986). Hemstad et al. (2008) found few plot-level effects of forest harvest in the Pokegama Creek system from 1997-2000, but suggested that basin-scale changes may have masked impacts at the plot level. Hemstad and Newman (2006) also found few plot-level effects in the Knife River basin in northeast Minnesota, but observed basin-scale increases in unstable banks and surficial fine substrates 0-2 years after forest harvest. It is noteworthy that the greatest changes in surficial fine substrates and embeddedness during the study period occurred immediately after forest harvest, indicating a possible response to altered hydrology or soil disturbance from harvesting equipment.

Small tributary channels, if impacted by harvesting equipment, can also contribute to sediment loading in mainstem channels. Study plot 3 contained a small, yet steep (7.2%) intermittent tributary 1.2 m wide and 15 cm deep that was crossed repeatedly with harvesting equipment (*sensu* unrestricted harvest treatment of Keim and Schoenholtz

[1999]). The machine traffic broke down the banks and razed the intermittent channel. In subsequent years the channel was reformed by bankfull discharges, delivering large amounts of fine sand into the mainstem of Pokegama Creek North. The pool in Pokegama Creek North just below the confluence of the tributary was nearly filled with sediment (89% loss of cross sectional area) and mean depth was reduced by 82% (E. Verry, unpubl. data). Use of a temporary bridge at a designated crossing site on the intermittent tributary would likely have preserved channel dimensions and prevented sediment delivery to the mainstem channel. Minnesota's voluntary guidelines for forest harvest now recommend such crossings for intermittent channels as well as perennial channels (MFRC 2005).

CONCLUSION

Previous research has shown that headwater streams can be negatively impacted by fine sediment following riparian logging and concomitant changes in land use in the catchment (Kreutzweiser and Capell 2001, Gomi et al. 2005, Hemstad et al. 2008). Although our study did not discern between changes due to forest harvest, road crossings, or natural causes, we evaluated recovery after a large input of fine sediment. Our study demonstrated that moraine, headwater streams can require an enabling event (e.g., high stormflows) in order to recover from large inputs of fine sediment. Although study plots were relatively small (4.9 ha) and retained some riparian trees, we observed basin-scale year effects for fine sediment in the stream channels that are consistent with forest harvest effects documented elsewhere (Gomi et al. 2005).

Some recommendations may help mitigate loading of fine sediment following forest harvest. First, we concur with others (e.g., Brooks et al. 1997, Verry 2004, Detenbeck et al. 2005) that it is wise to minimize alterations to hydrology and bank scour by reducing the percentage of the basin that is harvested. Second, impacts of roads and crossings should be minimized, such as by preventing machine traffic within a riparian buffer (Keim and Schoenholtz 1999, Lacey 2000). When crossings are necessary, erosion control measures should be taken and bridge spans or culverts should be large enough to accommodate stormflows without causing backwater effects or hydraulic contraction (Johnson 2002). Similarly, harvesting and forwarding around and across intermittent stream channels should use temporary bridges at designated crossing points to protect the stream banks (MFRC 2005). Our third recommendation is to manage riparian areas for sustainable stocks, where the annual growth increment exceeds the losses due to windthrow. Forests, and streams, can provide a variety of products and ecological services (Neuman 2007). Continued research on the linkages between forest harvesting and sedimentation can allow more informed decisions about forest management.

ACKNOWLEDGMENTS

This work was funded by the Minnesota Department of Natural Resources Division of Fisheries, the Minnesota Forest Resources Council, the National Council for Air and Stream Improvement, the U.S. Forest Service, the Minnesota Environment and Natural Resources Trust Fund, and Minnesota Trout Unlimited. Charlie Blinn and Brian Palik selected the study plots and supervised the manipulations. John Hansen and Jim

Marshall of UPM-Kymenne Corporation Blandin provided access to the study plots. Forest harvest was completed by Rieger Logging. We sincerely thank the following for assistance with data collection: Andy Arola, Brenda Asmus, Jason Bronk, Rebecca Bronk, Ryan Carlson, Bill Coates, Jacquelyn Conner, Carrie Dorrance, Art Elling, MaryKay Fox, Jo Fritz, Sarah Harnden, Deacon Kyllander, Marty Melchior, Steffen Merten, Mateya Miltich, Brittany Mitchell, Erik Mundahl, Elliot Nitzkowski, Ian Phelps, Lisa Pugh, Jeff Rice, David Schroeder, Jeremy Steil, Dustin Wilman, and Jason Zwonitzer. The Statistical Consulting Service at the University of Minnesota provided R code for analysis. Comments from Jacques Finlay, Heinz Stefan, and two anonymous reviewers improved the quality of the manuscript.

TABLES AND FIGURES

Table 1

Watershed areas for each study stream, open or young forest area, and the area of harvested plots. Areas are based on 1977 and 2003 air photos with on-site reconnaissance in 1997. Open areas include road rights of way, harvested riparian plots, and other harvest areas with trees less than 16 years old in the watershed.

	(ha) Total	(ha) 1977 open	(ha) 2003 open	(%) 2003 open	Study plots	(ha) Harvest plots	(%) Harvest plots
Jack Irving	281	99.8	138.5	49	1, 2	4.8	2
Pokegama North	168	23.7	42.8	25	3, 4, 5	11.7	7
Pokegama South	135	52.6	62.8	47	6, 7, 8	7.9	6
Little Pokegama	129	14.8	23.8	18	9, 10,11, 12	13.7	11

Table 2

Channel characteristics (slope, width, mean depth), sediment particle sizes, and tree basal area in the riparian management zone one year after forest harvest. Data were collected from riffles to yield the minimum channel cross section needed for bankfull flow.

Plot	Channel			Particle diameter at percentile				Basal
(number)	slope (%)	width (m)	depth (m)	D35 (mm)	D50 (mm)	D84 (mm)	D90 (mm)	area (m^2/ha)
Jack Irving Creek								
Plot 1	2.3	1.8	0.40	0.08	0.09	1	50	18.6
Plot 2	3.0	2.4	0.15	0.08	0.09	1	23	15.4
Pokegama Creek North								
Plot 3	1.4	1.9	0.21	0.09	0.10	65	128	20.4
Tributary to Plot 3	7.2	1.2	0.15	0.08	0.10	5	10	-
Plot 4	1.2	2.1	0.44	0.06	0.07	0.10	0.11	15.7
Plot 5	1.5	2.5	0.27	0.09	0.10	32	45	21.3
Pokegama Creek South								
Plot 6	1.5	1.9	0.31	0.08	0.10	1	8	14.6
Plot 7	1.9	2.1	0.30	0.06	0.06	4	6	30.1
Plot 8	1.4	2.3	0.30	0.06	0.40	55	90	25.9
Little Pokegama Creek								
Plot 10	1.0	2.3	0.37	0.16	0.32	100	120	30.3
Plot 11	2.5	2.9	0.38	0.09	0.60	128	180	14.4
Plot 12	2.3	3.0	0.40	0.09	0.10	128	150	30.4

Table 3

Basin-scale year effects for canopy cover, unstable banks, embeddedness, and surficial fine substrates from 1997 (pre-harvest) to 2007 (ten years post-harvest) using repeated measures ANOVAs. The significance of the year factor is shown for each response; blocking factors are not shown.

	Df	Sum Sq	F value	p
Canopy cover	5	450.98	13.0034	<0.001
Residual error	152	1054.33		
Unstable banks	5	5111.7	14.3824	<0.001
Residual error	152	10804.5		
Embeddedness	5	11958.2	30.8455	<0.001
Residual error	152	11785.5		
Surficial fines	5	5325	13.5825	<0.001
Residual error	152	11919		

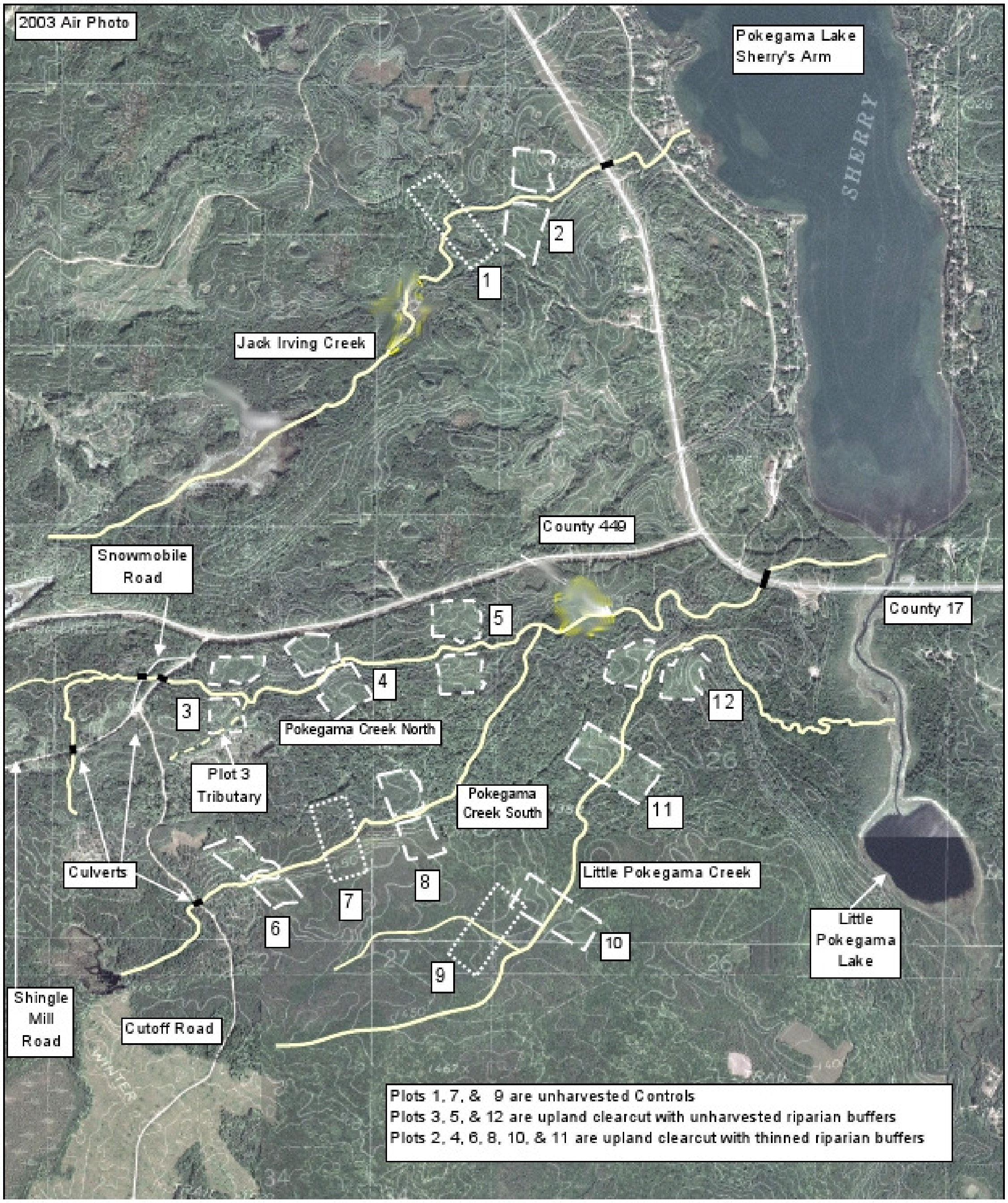


Figure 1. Pokegama Creek system showing riparian plots (numbered), stream channels and tributaries, roads, and beaver impoundments.

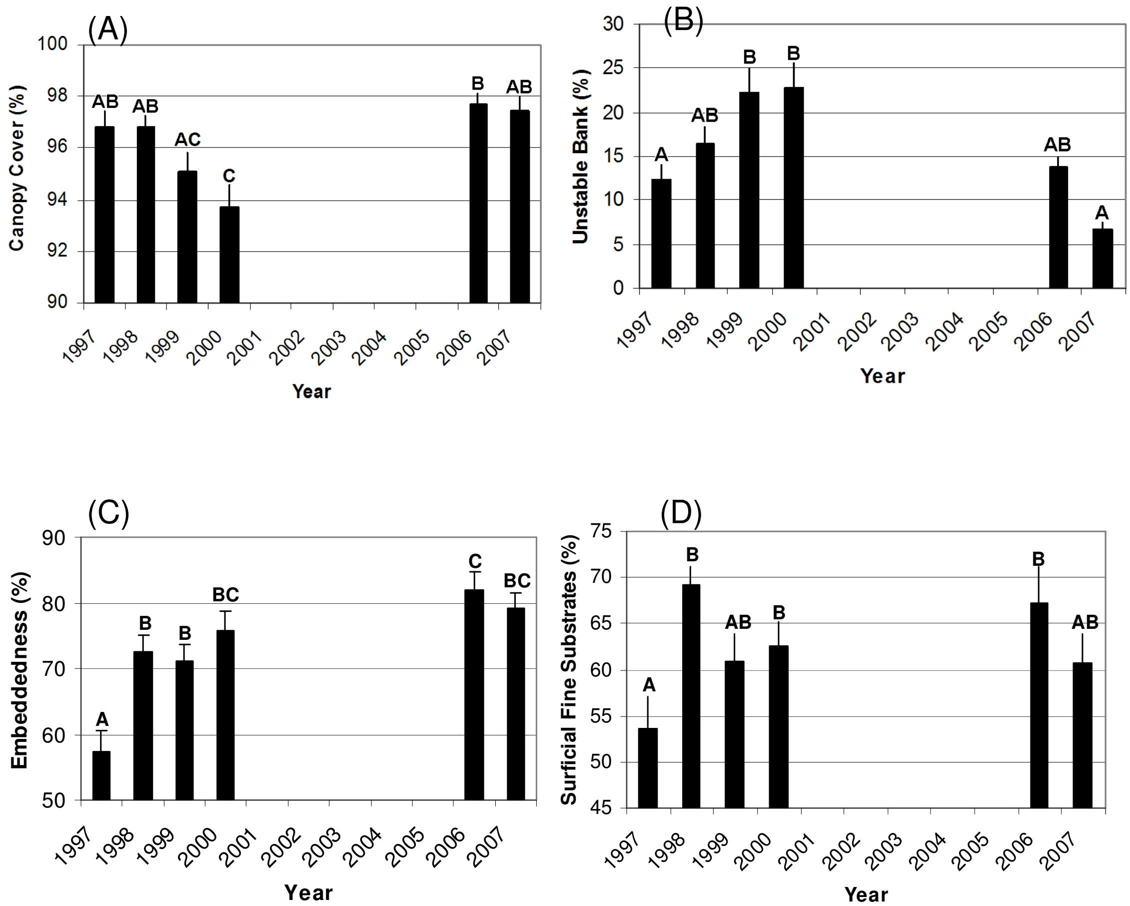
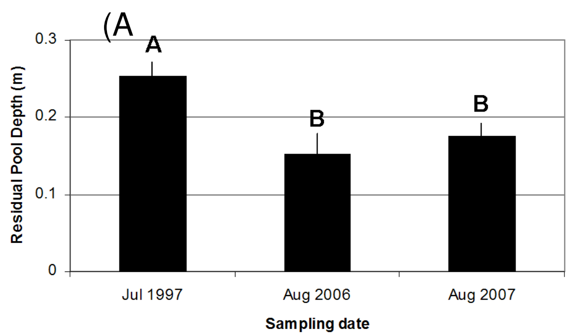


Figure 2. (A) Canopy cover remained high in 1998 the year after harvest, declined in 1999 and 2000 from windthrow, and recovered by 2006. (B) Unstable banks increased in the 3 years after harvest but recovered by 2006. (C) Embeddedness increased after harvest and remained high, (D) as did the proportion of surficial fine substrates. For all graphs, error bars are 1 s.e., columns with a letter in common are not significantly different ($P < 0.05$, Tukey's HSD).



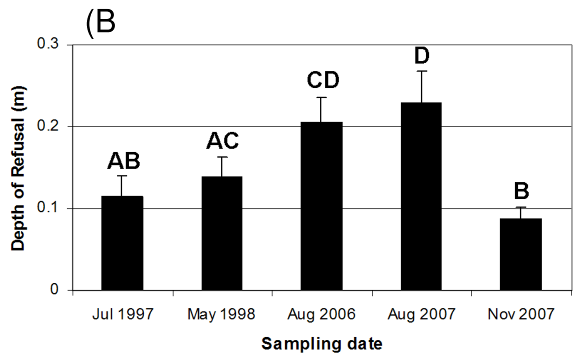


Figure 3. (A) Residual pool depth reflected filling with sand after the pre-harvest 1997 measurement, (B) depth of refusal increased through all sample periods until after a large storm in November 2007. For all graphs, error bars are 1 s.e.; columns with a letter in common are not significantly different ($P > 0.05$, Tukey's HSD).

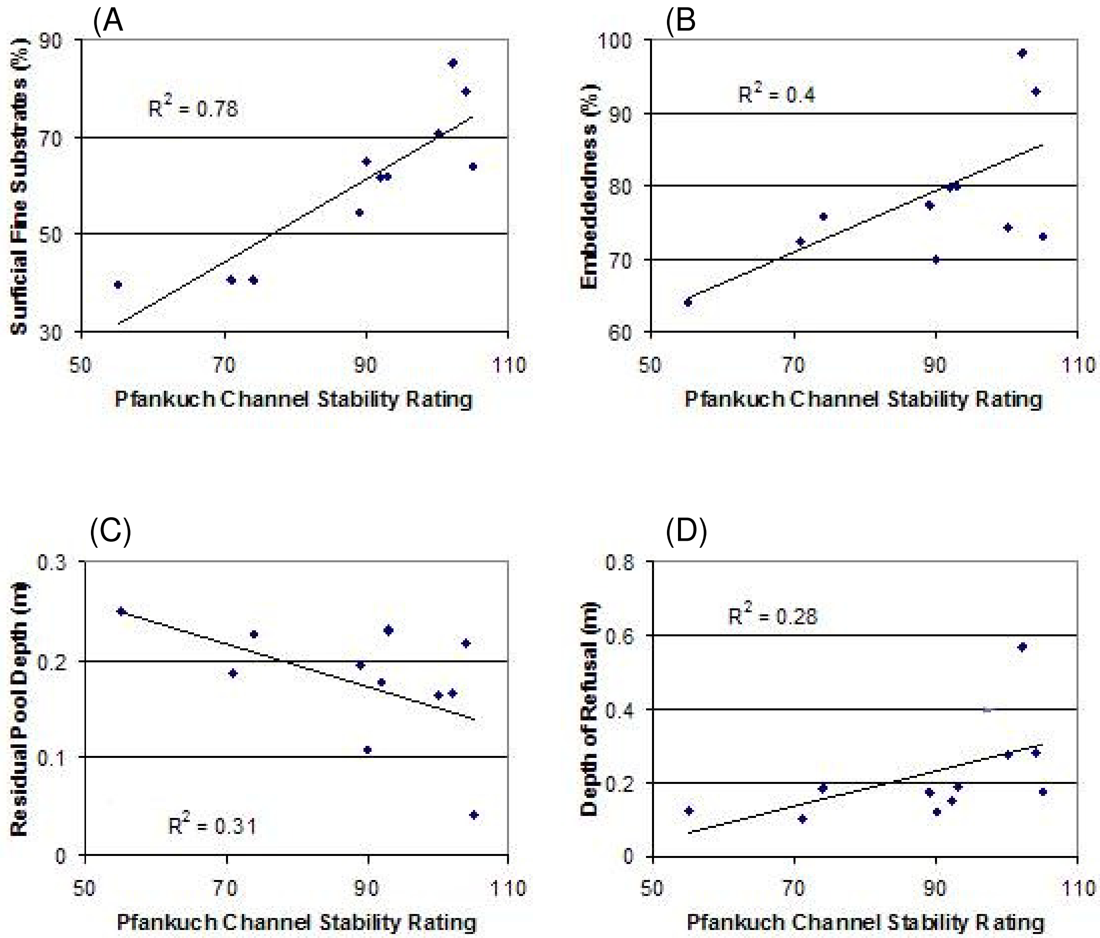


Figure 4. Comparison from 2007 for Pfankuch Channel Stability Ratings against (A) proportion of surficial fine substrates, (B) embeddedness, (C) residual pool depth, and (D) depth of refusal.

CHAPTER 2: Relations between fish abundances, summer temperatures, and forest harvest in a northern Minnesota stream system from 1997 to 2007

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[2] The Unit is jointly sponsored by the U. S. Geological Survey, the University of Minnesota, the Minnesota Department of Natural Resources, the Wildlife Management Institute, and the U.S. Fish and Wildlife Service.

SUMMARY

We examined fish abundances and instream habitat in four headwater streams between 1997 and 2007 in a basin in a northern hardwood forest. The streams were subjected to experimental riparian forest harvest (2-11% of the watersheds) in fall 1997, including upland clearcuts with 30-m unharvested buffers and upland clearcuts with 30-m riparian strips thinned to 12.3 m^2/ha basal area. Unharvested control sites were also sampled in the basin. We related fish abundances between 1997 and 2007 to instream habitat (fine substrates and large wood) and environmental conditions (summer air temperature and spring precipitation) at the basin scale.

Fine sediment increased in the streambed throughout the basin by summer 1998. We also noted a significant decrease for fish index of biotic integrity ($r = -0.91$), and abundance of brook trout ($r = -0.99$) and northern redbelly dace ($r = -0.86$) over the study period. Abundance of brook stickleback also decreased over time ($r = -0.70$) while creek chub abundance increased ($r = 0.79$), although neither trend was significant.

Summer air temperatures increased during the study period. Across the basin, abundances of most species were negatively related to mean summer air temperature. Lower index of biotic integrity scores were significantly related to warmer temperatures ($r^2 = 0.56$), as were lower abundances for brook trout ($r^2 = 0.53$), northern redbelly dace ($r^2 = 0.85$), and brook sticklebacks ($r^2 = 0.62$). Fish variables were not significantly related to fine substrates in the streambed, large wood, or total spring precipitation at the basin scale.

Based on stream temperatures measured at the end of the study period, thinned riparian treatments caused the stream to warm significantly more than riparian buffer treatments. However, stream warming in unharvested control treatments was not significantly different from other treatments (i.e., riparian buffer or thinned riparian).

We suggest that summer air temperatures may influence fish communities more than fine sediment, large wood, or spring precipitation in forested headwater streams based on the basin-scale relationships from this study. Removal of riparian vegetation may exacerbate effects of climate warming by reducing shade.

INTRODUCTION

Forest harvest can affect fish populations in streams through a variety of mechanisms. Forest harvest has been related to increased stream discharge, increased inputs of fine sediment, decreased inputs of leaf litter and wood, and community shifts in invertebrates and other biota (Salo & Cundy 1987, Chamberlin, Harr & Everest 1991, Palik, Zasada & Hedman 2000). Forest harvest can also cause warmer stream temperatures in summer (Brown 1970, Beschta et al. 1987, DeGroot, Hinch & Richardson 2007). Warmer temperatures can lead to changes in growth rates for fish and invertebrates (Weatherley & Ormerod 1990) and alter the competitive balance between species (Baltz, Moyle & Knight 1982, Reeves 1985). Although warming effects from forest harvest may be masked by variability in air temperatures (Eaton & Scheller 1996, Pilgrim, Fang & Stefan 1998), warming from any cause is of obvious importance to aquatic ectotherms, particularly in light of ongoing climate change (Austin & Colman 2008, Rosenzweig et al. 2008).

The effects of forest harvest may be detected most readily at the basin scale (Hemstad & Newman 2006, Martel, Rodriguez & Berube 2007), particularly in basins that correspond to the spatial scale of fish life cycles (Fausch et al. 2002). Although many studies have examined site-level effects of forest harvest (Broadmeadow & Nisbet 2004), few have examined multiple streams across multiple years (DeGroot et al. 2007). Williams et al. (2002) determined in the Ouachita Mountains that instream habitat varied by basin, year, logging treatment, and basin/treatment interaction; macroinvertebrates varied by year and basin, but basin was the only significant factor for fish. By filtering out natural spatial variability, Martel et al. (2007) detected reductions in long-lived, large invertebrates when < 1% of the area of basins were clearcut in Quebec, Canada. However, temporal replication for both studies was limited to two or three years of sampling (Williams et al. 2002, Martel et al. 2007).

When examined at the basin scale, stream hydrology may be strongly affected by forest harvest (Salo & Cundy 1987, Chamberlin et al. 1991). For example, peak snowmelt discharge increased relative to unharvested watersheds for at least five years post-harvest in British Columbia, Canada (Macdonald et al. 2003). Increases in snowmelt discharge may persist for 15 years post-harvest in hardwood forests of the north-central USA (Verry 1986). Moore & Wondzell (2005) provide a review of effects of forest harvest on hydrology, confirming that recovery takes place on a decadal time scale. A more flashy hydrograph following forest harvesting can have direct effects on fish assemblages by favoring some species over others (Poff & Allen 1995), and can also increase turbidity and sediment loading in streams. Serengil et al. (2007a) noted that thinning only 11% of the standing timber volume with horse skidding produced a detectable increase in streamflow during the rainy season in Turkey, as well as a significant increase in suspended sediment (Serengil et al. 2007b). Forested land cover can affect not only turbidity, but also bedload, embeddedness, and channel stability (Sutherland, Meyer & Gardiner 2002).

Sediment in streams can have deleterious effects on stream invertebrates and fish (Waters 1995). Matthaei et al. (2006) added sediment directly to agricultural streams that were degraded from past land use, and found reduced densities for some common macroinvertebrate taxa. Their experimental approach was reminiscent of Alexander & Hansen (1986), who conducted experimental sediment additions and documented lower trout numbers due to reduced egg-to-fingerling survival. Juvenile salmon prefer interstitial spaces that are relatively free of sediment (Finstad et al. 2007).

Forest harvest can also affect supplies of wood and leaf litter to streams. Wood inputs may exhibit a long-term reduction after forest harvest (Murphy & Koski 1989), which may reduce available habitat for macroinvertebrates (Johnson, Breneman & Richards 2003) and fish (Crook & Robertson 1999). Natural levels of large wood have tremendous ecological value as providers of habitat and shapers of geomorphology (Angermeier & Karr 1984, Beechie & Sibley 1997, Quist & Guy 2001, Johnson et al. 2003, Borg, Rutherford & Stewardson 2007). Large wood also increases retention of leaf litter (Ehrman & Lamberti 1992, Larranaga et al. 2003, Quinn, Phillips & Parkyn 2007);

even if large wood is unchanged forest harvest can directly reduce leaf litter inputs (Oelbermann & Gordon 2000, Kreutzweiser, Capell & Good 2004). In the Pokegama Creek system in north-central USA, litter inputs were significantly reduced after riparian harvest, despite a 30-m riparian buffer (Palik et al. 2000). In addition, forest harvest can lead to increases in light levels, periphyton, and macrophytes (Kedzierski & Smock 2001, Kiffney et al. 2003, Davies et al. 2005), and may induce changes in fish communities (Bojsen & Barriga 2002, Nislow & Lowe 2006).

The objective of the current study was to examine changes in fish abundances in the Pokegama Creek system, Minnesota, USA over an 11-year time frame in light of experimental forest harvest, habitat conditions, and variation in local climate. Previous studies in the Pokegama Creek system examined effects for three years post-harvest on fish and habitat (Hemstad, Merten & Newman 2008) and leaf litter inputs (Palik et al. 2000). Although few significant treatment effects were observed at the site level in the first few years after harvest (Hemstad et al. 2008), a longer temporal scale and broader spatial scale may be more appropriate (Fausch et al. 2002). We collected new data nine and ten years post-harvest and used basin-scale analyses to test our prediction that sensitive fish species would decline in abundance after harvest (Salo & Cundy 1987, Chamberlin et al. 1991) but then recover due to canopy closure. We also sought to use local weather data to determine the influence of summer air temperature and amount of spring precipitation on fish abundances.

METHODS

Study area and sites

The study was conducted on four headwater streams in the Pokegama Creek system, south of Grand Rapids in north-central Minnesota (Fig 1). The streams flow into Pokegama Lake. The basin was forested and dominated by northern hardwoods (Palik, Ceases & Egeland 2003). Prior to the study the mean basal area of forest stands was 30 m^2/ha (Palik et al. 2003). Topography included moraine hills rising ~5 m above the valley floor, with hillslopes of 1-30% (E. Verry, unpubl. data). Bankfull widths at the study sites were ~2 m and stream slopes were 0.7 to 3.5%. Soils were generally fertile with well-drained loamy sands (Palik et al. 2003), including occasional gravel lenses and cobble/boulder inclusions.

In 1997, twelve study sites were established along the four headwater streams, although one site on an intermittent tributary was excluded from all following analyses (Fig 1). The eleven remaining sites were each about 4.9 ha, with 2.45 ha on each side of the stream; sites were generally ~200 m apart. Each site included 150-200 m of stream length. Harvest treatments at each site were either unharvested control (N = 2), upland clearcut with 30-m unharvested buffers (riparian buffer, N = 3), or upland clearcut with 30-m riparian strips thinned to 12.3 m^2/ha basal area (thinned riparian, N = 6). All forest harvest was conducted in fall and winter of 1997. The total harvested areas represented 2 to 11% of the four catchments, which is near the lower threshold for harvest effects in prior studies (Martel et al. 2007, Serengil et al. 2007a, Serengil et al. 2007b). As suggested by analyses using data from 1997 to 2000 (Hemstad et al. 2008), the current study investigated changes and relationships at the basin scale. Thus, the following analyses did not differentiate between harvest treatments at the site scale, with the exception of the site-level analysis of stream warming.

Data collection

Fish were sampled during August in 1997 (pre-harvest), 1998-2000, and 2006-2007. Fish were sampled in three 50-m reaches at each site; 50 m immediately upstream of the site, the lowermost 50 m of the site, and 50 m immediately downstream of the site (Fig 1). All sampling was conducted with a Wisconsin AbP-3 backpack electrofisher (Engineering Technical Services, University of Wisconsin, Madison, Wisconsin). A coldwater fish index of biotic integrity (IBI) value was calculated for each 50-m reach (Mundahl & Simon 1999). The IBI increases with the proportion of species that are ranked as intolerant, top carnivores, and coldwater obligates (e.g., brook trout [*Salvelinus fontinalis*]) and decreases with the proportion of tolerant species (e.g., central mudminnow [*Umbra limi*, Kirtland] or creek chub [*Semotilus atromaculatus*, Mitchill]). The southern stream (Fig 1) contained > 99% brook trout, thus brook trout analyses only used data from that stream, analyses for other individual species only used data from the three northern streams, and the IBI analyses used data from all four streams. The nearest coldwater stream outside the study area was 5 km away.

Abundance estimates were calculated for each species in each 50-m reach. During the first pass, fish were electrofished from the 50-m reach, identified to species, and marked with a caudal fin clip. The fish were then redistributed throughout the reach. Approximately an hour after the first pass, a second electrofishing pass was completed through the reach. Fish captured during the second pass were identified to species, and checked for a fin clip. This method allowed calculation of an abundance estimate for each species using both a depletion method and a mark-recapture method (PopPro; Kwak 1992). If catchability (Kwak 1992) for a species was ≥ 0.8, the depletion method was used. If catchability was < 0.8, but the ratio of recaptured fish to total second-pass fish (r/c ratio) was > 0.2, the mark-recapture method was used. If catchability was 0.5-0.8 or the r/c ratio was 0.15-0.2, the method toward the higher end of its range was used. When catchability was < 0.5 and the r/c ratio was < 0.15, the sum of captures for the first and second pass was used; the sum never exceeded ten fish in such cases.

Large wood was assessed in July 1997-2000 and 2006-2007 as an indicator of fish habitat. Large wood was assessed at five evenly-spaced transects in each 50-m reach. The total length was recorded for each piece of large wood that intersected a transect and that met the following criteria: the piece had to include a portion within the bankfull channel that was at least 0.05 m in diameter for at least 1 m of length. Large wood measurements were summarized as total length density (m/m^2), which is the length of pieces per unit area of stream bed (Johnson et al. 2006).

Surficial fine substrates were examined in July 1997-2000 and 2006-2007 as an indicator of habitat quality. Each 50-m reach was divided into five equal subreaches, to avoid sampling exclusively at the upstream or downstream end of a 50-m reach. Seven circular quadrats (28 cm in diameter) were assessed in random locations in each 10-m subreach to visually estimate the areal percentage of the substrate that was sand, silt, or clay (i.e., fine substrates). Thus, we sampled 7 quadrats x 165 subreaches to equal 1,155 quadrats per year.

Basin-scale trends in fish or habitat variables were examined using the mean from all sites in the Pokegama Creek system each year. Univariate regressions were used to investigate temporal trends for the basin means for fish index of biotic integrity and abundances, and to investigate relationships between fish and habitat variables (i.e., large wood and fine substrates) at the basin scale. Univariate regressions were also used to examine the relationships between fish variables and two climate variables. The first climate variable was summer air temperature, using the mean air temperature from June through August of each year at the nearest monitoring station 10 km to the north (Minnesota State Climatology Office). The second climate variable was total spring precipitation, the cumulative precipitation from April 1 through July 12 (prior to field sampling) of each year. The proportion that each fish species contributed to total fish abundance was also examined with a rank abundance curve for each year sampled.

Site-level effects on stream temperature were examined in 2006 and 2007 during August (the warmest month). An Onset® Pro v2 temperature recorder was placed 0-50 m upstream and another was placed 0-50 m downstream of each site. Each recorder was cabled to a brick in the deepest pool available and was set to measure water temperature every 15 minutes. The response variable examined for water temperature was the mean temperature in August for the downstream recorder minus the mean temperature in August for the upstream recorder (i.e., site-level warming). Of the 24 recorders set each year, two became exposed to air due to low water levels, one was buried by bedload, and one was vandalized; the corresponding sites were omitted from the site-level analysis. A two-factor ANOVA was used to evaluate site-level warming, using the software R (Ihaka & Gentleman 1996). The first factor for the ANOVA was year (2006 versus 2007) and the second factor was treatment (unharvested control, riparian buffer, or thinned riparian). No transformations were necessary; Tukey's HSD was used to compare mean values.

Water temperatures for June through August (the summer months preceding fish sampling) were also estimated throughout the study period at each 50-m reach. A univariate regression was used to determine the relationship between mean daily air temperature (Minnesota State Climatology Office) and mean daily water temperature at each temperature recorder for June through August 2007 (Erickson & Stefan 2000). The air-water temperature relationships from 2007 were used along with historical air temperatures to estimate the mean June-August water temperature at each 50-m reach during the study period (using the air-water relationship from the nearest temperature recorder). The estimates of historical water temperatures did not account for changes in canopy cover, and are therefore only an approximation of past thermal conditions.

RESULTS

The IBI scores and fish abundances generally indicated trends over the study period (Table 1). IBI scores decreased significantly over time (Table 1), as did mean abundance for brook trout and northern redbelly dace (*Phoxinus eos*, Cope, Table 1). Mean abundance of brook stickleback (*Culaea inconstans*, Kirtland) also decreased over time while creek chubs increased, although neither trend was significant ($r = -0.70$ and

0.79, P = 0.12 and 0.06). Central mudminnow and finesecale dace (*Phoxinus neogaeus*, Cope) showed no trend. Other species (i.e., emerald shiner [*Notropis atherinoides*, Rafinesque], fathead minnow [*Pimephales promelas*, Rafinesque], Iowa darter [*Etheostoma exile*, Girard], and northern pike [*Esox lucius*, Linnaeus]) were uncommon (Table 1) and were not included in species-level analyses. In terms of relative abundances, brook trout were the most abundant species from 1997 through 1999 but declined to fourth and third most abundant by 2006 and 2007. Central mudminnows were fourth or fifth most abundant from 1997 through 2000 and became the most abundant species in 2006 and 2007 (Fig 2).

Some changes occurred with instream habitat and local weather. Fine substrates increased after 1997, large wood decreased, and total spring precipitation increased through 1999 and subsequently decreased (Table 2). On average, summer air temperatures increased over the study period by 0.062 °C/year at the nearest weather station (Fig 3), which is comparable to the regional trend of 0.06 °C/year (Austin & Colman 2008).

Fish index of biotic integrity and abundances were not significantly related to habitat variables or spring precipitation at the basin scale (Table 3). However, some fish variables were significantly related ($P \leq 0.05$) to estimated summer air temperatures. IBI scores and abundances for brook trout, northern redbelly dace, and brook stickleback (Fig 4) as well as finescale dace ($r^2 = 0.49$, not shown) were negatively related to warmer summer air temperatures. Abundances of creek chub or central mudminnow were not significantly related to any variables. For the relationships between mean daily air temperature and mean daily water temperature at the temperature recorders the coefficient of determination (r^2) ranged from 0.36 to 0.77 (the average r^2 was 0.66).

There were significant site-level treatment effects on stream warming (i.e., downstream-upstream differences in water temperature, Fig 5). The ANOVA for site-level warming showed that the year factor was not significant ($P = 0.65$), but the treatment factor was significant ($P = 0.02$). Tukey's HSD comparison indicated that warming was significantly greater ($P = 0.01$) in thinned riparian sites compared to riparian buffer sites. However, warming at the unharvested control sites was not significantly different from the riparian buffer sites or the thinned riparian sites ($P > 0.17$).

DISCUSSION

We found that IBI scores and the abundances of brook trout, northern redbelly dace, and brook stickleback were significantly related to mean summer air temperatures at the basin scale, but not to fine substrates, large wood, or total spring precipitation. Below we discuss overall changes in the fish community, followed by discussion of changes in abundance for common species.

Although the four headwater streams in this study were all within a single basin, the spatial scale matched well with the life cycles of the fish species (Fausch et al. 2002). Brook trout were apparently isolated in one of the streams, and the other small-bodied species likely spent their entire life cycles within the stream system. IBI scores showed a significant negative trend over the study period, and abundances of more sensitive species (i.e., brook trout, northern redbelly dace [Stasiak 1972], and brook stickleback [Winn 1960]) also appeared to decline. Meanwhile, the abundance of tolerant creek chubs increased.

Overall fish numbers were markedly lower in 2006 and 2007; there are several possible explanations for the decline. First, diminished leaf litter inputs after forest harvest (Palik et al. 2000) may have led to bottom-up trophic effects, as could decreased retention of leaf litter due to less large wood in the channels (Ehrman & Lamberti 1992, Larranaga et al. 2003, Quinn, Phillips & Parkyn 2007) or reduced nutritional quality of leaf litter from increasing CO_2 (Tuchman et al. 2002). Second, another study in the Pokegama Creek basin documented a decrease in macroinvertebrate diversity from 1997 through 2000, driven largely by increasing proportions of Chironomids (Chizinski et al. *In Review*). Chironomids may be less available as prey for the fish species in the Pokegama Creek system, which could potentially lead to increased mortality over time through chronic undernourishment. Third, total spring precipitation in 2006 and 2007 was the lowest of the study period, thus low water levels (Lake 2003) are another possible explanation for reduced fish numbers.

The fish community in the Pokegama Creek system appears to have responded to different environmental conditions over the study period. Prior research in the Pokegama Creek system showed a negative relationship between IBI scores and fine substrates from 1997-2000 (Hemstad et al. 2008). However, our analyses showed no relationship between IBI scores and fine substrates at the basin scale. Our analyses indicate a strong connection between summer air temperatures and the fish community; warmer temperatures may favor some species (e.g., creek chub) at the expense of others (e.g., brook trout).

Brook trout: The abundance of brook trout declined consistently during the study period. Based on previous research with salmonids (Alexander & Hansen 1986, Waters 1995, Finstad et al. 2007) a chronic response to elevated levels of fine sediment was feasible. While low levels of large wood provide little habitat for epidendritic macroinvertebrates (Johnson et al. 2003), we found no relation between brook trout abundance and large wood. Our study design could not rule out bottom-up trophic effects or reduced availability of macroinvertebrate prey as explanations for the chronic reduction in brook trout abundance, although the study basin was free from confounding effects of agriculture (Durance & Ormerod 2009). Overall, the most compelling explanation for the brook trout decline is that warming temperatures over the study period caused mortality (or emigration to the nearest coldwater stream 5 km south). Although the highest seven-day mean water temperatures we observed (17.9° C in 2006 and 17.4° C in 2007) did not reach the critical thermal maximum of 22.3° C for brook trout (Eaton et al. 1995), sublethal thermal effects on fish can be subtle (Boughton et al. 2007). Invertebrate production may have been limited by high levels of fine sediment (Waters 1995, Matthaei et al. 2006) or warming temperatures (Durance & Ormerod 2007), and thus precluded fish from consuming sufficient quantities of invertebrates during warmer temperatures (Ries & Perry 1995).

Northern redbelly dace: Abundance of northern redbelly dace decreased significantly over time. At the basin scale, northern redbelly dace abundance had a negative relation to warmer air temperatures in summer. Stasiak (1972) noted that northern redbelly dace prefer streams with a constant flow of cool groundwater; warmer summer temperatures in our study may have caused direct mortality or emigration.

Brook stickleback: Abundance of brook sticklebacks decreased over time, although not significantly. As for northern redbelly dace, brook stickleback abundance at the basin scale was negatively related to warmer air temperatures in summer. Brook sticklebacks require cool water (Winn 1960), but they are also sensitive to environmental degradation (Lyons 2006). Although increased fine sediment after forest harvest (Hemstad et al. 2008) could have reduced invertebrate prey numbers (Waters 1995, Matthaei et al. 2006), there was no significant relationship between fine substrates and brook stickleback abundance.

Creek chub: The creek chub was the only species that increased significantly over time. Contrary to previous studies, creek chub abundance was not significantly related to large wood (Quist & Guy 2001) or spring precipitation (Franssen et al. 2006) at the basin scale. The increasing temporal trend for creek chubs is not surprising, as previous studies have also documented increases in creek chub numbers after forest harvest (Jones et al. 1999, Sutherland et al. 2002). Creek chub abundance may have increased due to less predation on their eggs and fry from other species (i.e., northern redbelly dace and brook stickleback), or less competition for invertebrate prey. Creek chubs may also have gained a competitive advantage from warmer water temperatures, as has been documented with other pairs of species (Baltz, Moyle & Knight 1982, Reeves 1985). Finally, creek chubs build a clean gravel nest by exporting mouthfuls of sand and importing gravel (Ross

1977), which may have made their reproductive success more resistant to increased levels of fine sediment.

Central mudminnow: The abundance of central mudminnows was fairly stable for the duration of the study, and was not related to temperature or habitat variables at the basin scale. Central mudminnows are eurythermal (Klinger, Magnuson & Gallepp 1982), generalist feeders (Paszkowski 1984) and can use fine sediment as habitat by burrowing into the substrate (Peckham & Dineen 1957). Central mudminnows appear to have become the most abundant species in 2006 and 2007 by default, as most species had declined in abundance and creek chubs, though on the rise, remained relatively uncommon.

Warming due to forest harvest: Stream warming was significantly greater in thinned riparian sites relative to riparian buffer sites, possibly due to patches of open canopy (Hemstad et al. 2008). Although stream warming associated with narrowed buffers has been documented in the past (Beschta et al. 1987), the current study is unusual in that we have documented warming ten years post-harvest. Removal of riparian vegetation may exacerbate the effects of warmer air temperatures by reducing shade. However, the sample size was limited for testing site-scale warming, and it is not clear why warming at unharvested control sites was not significantly different from other treatments.

CONCLUSION

In summary, this study demonstrated relationships between temperature and abundance of sensitive fish species. Ongoing climate change (Rosenzweig et al. 2008) can be more important to fish communities than direct anthropogenic effects (Daufresne & Boet 2007), highlighting a pressing need to protect cool water temperatures (Eaton & Scheller 1996, Pilgrim et al. 1998, Stefan, Fang & Eaton 2001, Chu et al. 2008). The effects of warmer temperatures on fish may be exacerbated in streams where degraded habitat prevents prey production from keeping pace with increased metabolic demands (Ries & Perry 1995). Forest management can preserve cool water temperatures by maintaining or restoring wide forested buffers with sufficient overstory to fully shade the stream (Beschta et al. 1987). Based on previous literature (Salo & Cundy 1987, Chamberlin et al. 1991), a conservative approach would be to maintain pre-harvest levels of leaf litter inputs, hydrologic fluctuations, large wood inputs, and fine sediment loading. In addition, practitioners restoring harvested sites should consider mitigation of warming temperatures (e.g., restoring full shade) along with other ecological processes (Muotka & Syrjanen 2007).

ACKNOWLEDGMENTS

This work was funded by the Minnesota Department of Natural Resources Section of Fisheries, the Minnesota Forest Resources Council, the National Council for Air and Stream Improvement, the U.S. Forest Service, Minnesota Trout Unlimited, and the Minnesota Environment and Natural Resources Trust Fund as recommended by the

Legislative Citizen Commission on Minnesota Resources. Charlie Blinn and Brian Palik selected the study sites and supervised the manipulations. John Hansen and Jim Marshall of UPM-Kymenne Corporation Blandin provided access to the study sites. Forest harvest was completed by Rieger Logging. Field assistance was provided by Andy Arola, Brenda Asmus, Jason Bronk, Rebecca Bronk, Ryan Carlson, Bill Coates, Jacquelyn Conner, MaryKay Fox, Jo Fritz, Sarah Harnden, Marty Melchior, Steffen Merten, Mateya Miltich, Brittany Mitchell, Erik Mundahl, Elliot Nitzkowski, Ian Phelps, Lisa Pugh, Jeff Rice, David Schroeder, Jeremy Steil, Kevin Stroom, Dustin Wilman, and Jason Zwonitzer. The Statistical Consulting Service at the University of Minnesota provided R code for analysis. Comments from Jacques Finlay, Heinz Stefan, and two anonymous reviewers improved the quality of the manuscript.

TABLES AND FIGURES

Table 1. Yearly average IBI score, total fish abundance, and mean number of fish by species per 50-m reach, based on calculated abundance estimates. Standard errors of the mean are in italics. The Pearson correlation coefficient (r) and p-value (p) are for the regression with year. *species was too rare

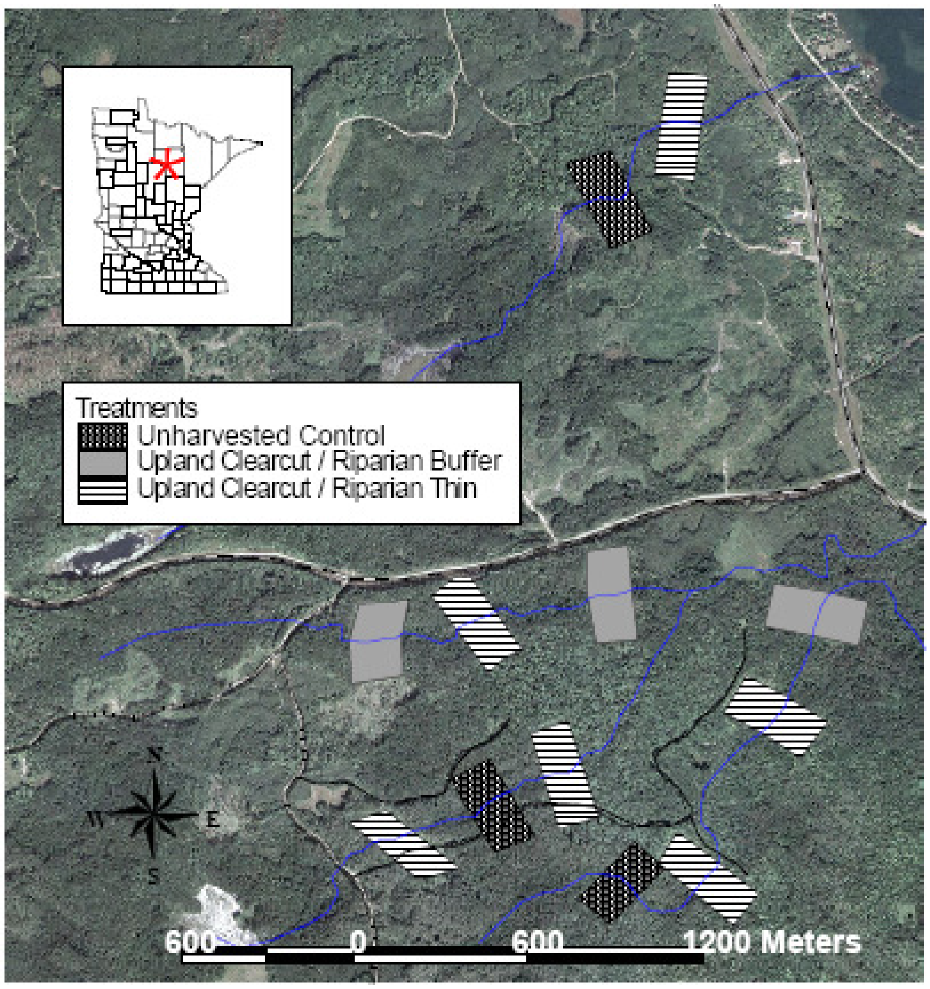
	1997	1998	1999	2000	2006	2007	r	p
IBI score	57.78	55.56	62.92	59.86	39.44	39.31	-0.91	0.01
	5.84	*5.54*	*5.19*	*5.71*	*5.16*	*6.24*		
Brook trout	13.34	12.77	10.16	8.84	1.03	1.83	-0.99	0.00
	5.29	*4.16*	*3.57*	*2.31*	*0.55*	*0.79*		
Northern redbelly dace	4.8	3.85	2.41	5.23	0.89	0.36	-0.86	0.03
	2.15	*2.21*	*0.84*	*2.32*	*0.37*	*0.19*		
Brook stickleback	10.69	11.35	1.92	8.78	2.19	3.19	-0.70	0.12
	4.93	*2.86*	*0.6*	*2.87*	*0.81*	*1.88*		
Creek chub	0.06	0.71	0.14	1.02	0.86	1.83	0.79	0.06
	0.06	*0.33*	*0.09*	*0.39*	*0.29*	*0.94*		
Central mudminnow	4.74	7.57	1.75	3.74	5.39	3.42	-0.14	0.79
	1.26	*1.44*	*0.55*	*0.87*	*1.35*	*1.22*		
Finescale dace	0.16	5.57	2.09	19.11	1.83	1.22	-0.19	0.72
	0.16	*2.01*	*0.79*	*8.38*	*0.78*	*0.44*		
Fathead minnow	0	11.34	1.01	0.53	0	0	*	*
	0	*4.04*	*0.45*	*0.51*	*0*	*0*		
Iowa darter	0	0	0.03	0	0	0	*	*
	0	*0*	*0.03*	*0*	*0*	*0*		
Northern pike	0	0	0	0	0	0.03	*	*
	0	*0*	*0*	*0*	*0*	*0.03*		
Emerald shiner	0	0	0.03	0	0	0	*	*
	0	*0*	*0.03*	*0*	*0*	*0*		

Table 2. Yearly average values for all reaches for the proportion of fine substrates, large wood, estimated summer water temperature, and total spring precipitation. Standard errors are in italics.

	1997	1998	1999	2000	2006	2007
Fine substrates	53.6	69.2	60.9	62.6	67.2	60.8
(%)	*3.4*	*1.9*	*2.9*	*2.6*	*4.1*	*3.1*
Large wood	0.03	0.021	0.016	0.017	0.017	0.015
(m/m^2)	*0.006*	*0.003*	*0.003*	*0.004*	*0.003*	*0.002*
Estimated summer water temperature (°C)	15.31	15.33	15.57	15.03	15.95	15.70
Total spring precipitation (mm)	274	388	404	260	247	231

Table 3. Coefficients of determination (r^2) for IBI scores and fish abundances in relation to the proportion of fine substrates, large wood, summer air temperature, or total spring precipitation at the basin scale. P-values are in italics.

	Fine substrates (%)	Large wood (m/m^2)	Summer air temperature (°C)	Total spring precipitation (mm)
Index of Biotic Integrity	0.08 *0.59*	0.10 *0.54*	0.56 *0.05*	0.41 *0.17*
Brook trout	0.07 *0.61*	0.41 *0.17*	0.53 *0.05*	0.40 *0.18*
Northern redbelly dace	0.07 *0.62*	0.34 *0.23*	0.85 *0.01*	0.05 *0.67*
Brook stickleback	0.01 *0.86*	0.48 *0.13*	0.62 *0.03*	0.02 *0.81*
Creek chub	0.10 *0.55*	0.37 *0.20*	0.05 *0.35*	0.32 *0.23*
Central mudminnow	0.28 *0.28*	0.14 *0.46*	0.01 *0.45*	0.01 *0.92*
Finescale dace	0.05 *0.67*	0.07 *0.61*	0.49 *0.07*	0.01 *0.85*



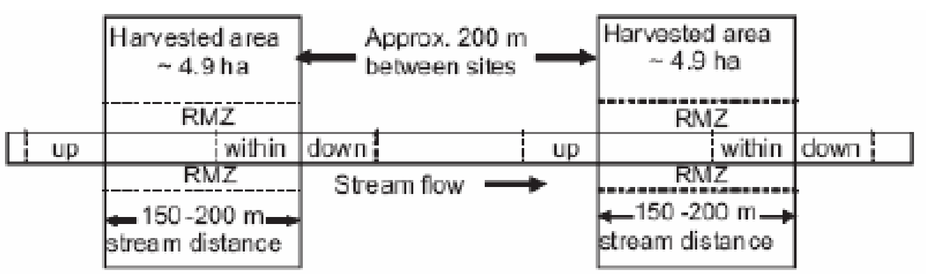


Fig 1. Study sites located near Grand Rapids, Minnesota, USA. Each site is 4.9 ha. Sampling reaches are shown at two hypothetical sites at bottom (not to scale). RMZ = 30m wide riparian management zone.

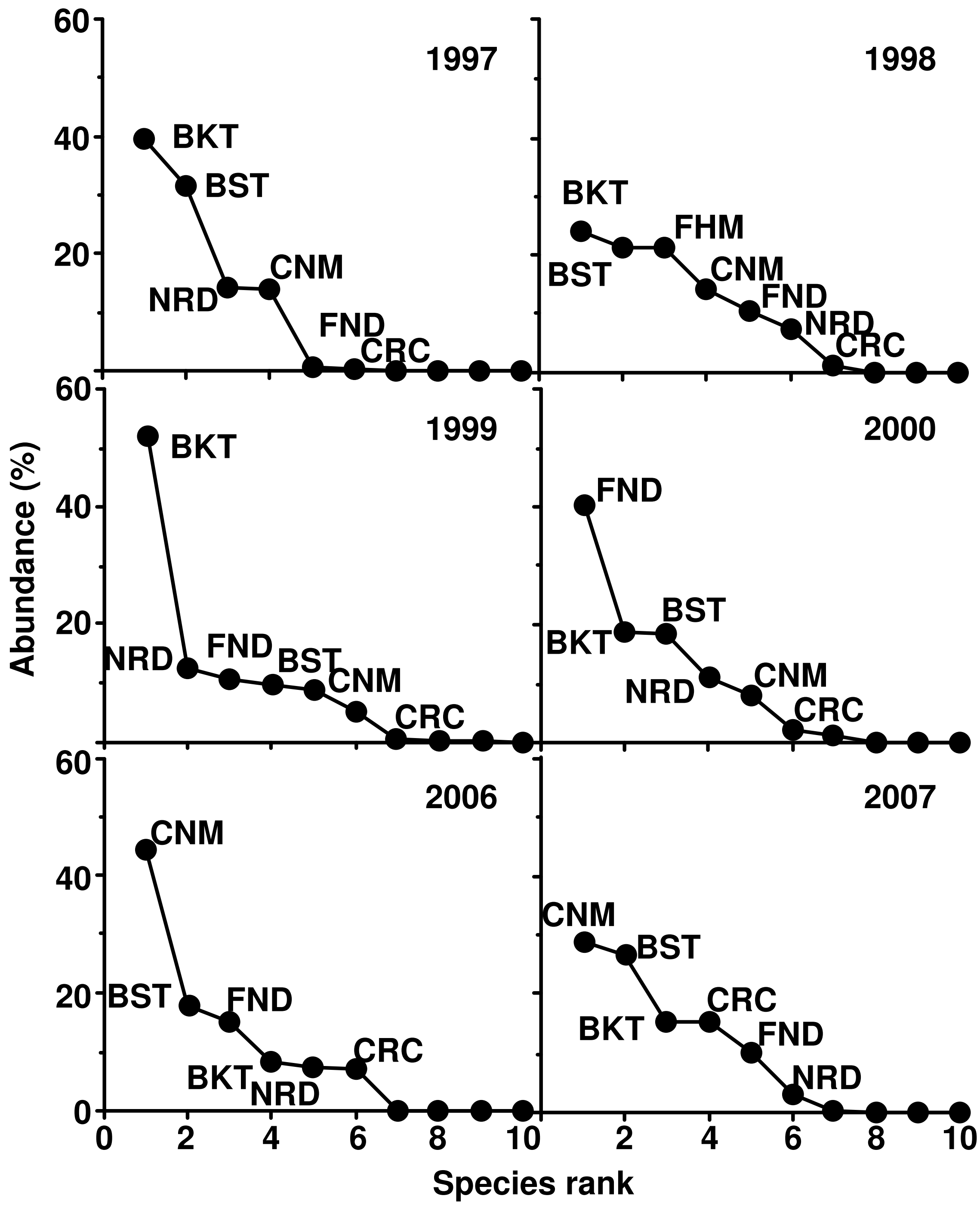


Fig 2. Rank abundance curves for fish species across all sites. BKT = brook trout, BST = brook stickleback, NRD = northern redbelly dace, CNM = central mudminnow, FND = finescale dace, CRC = creek chub, FHM = fathead minnow.

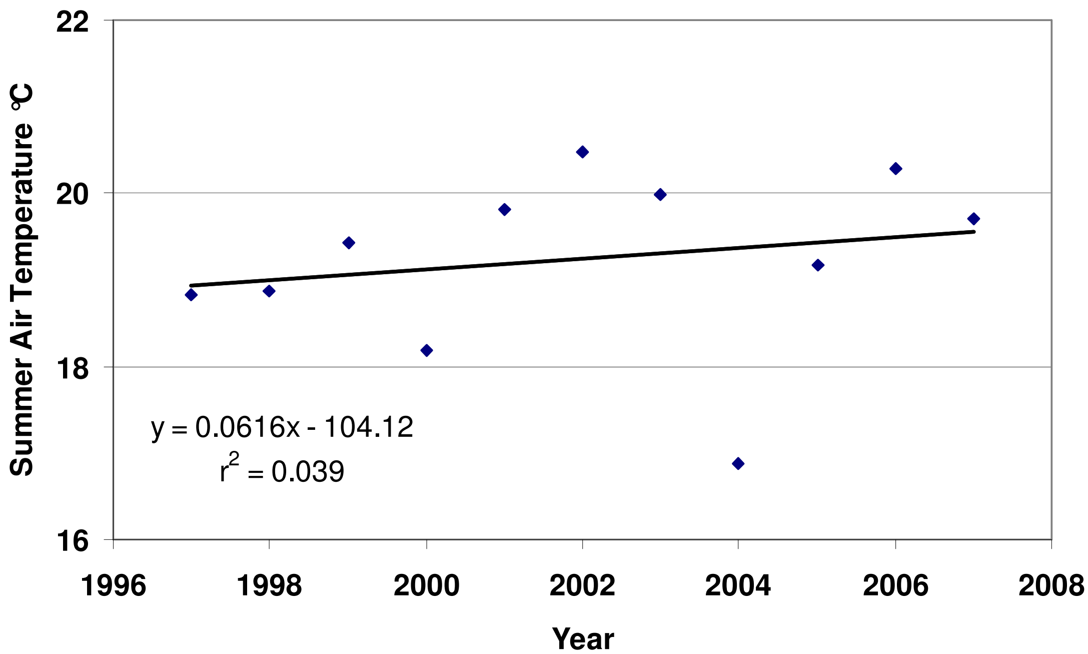


Fig 3. Mean summer air temperatures for June through August 1997 through 2007.

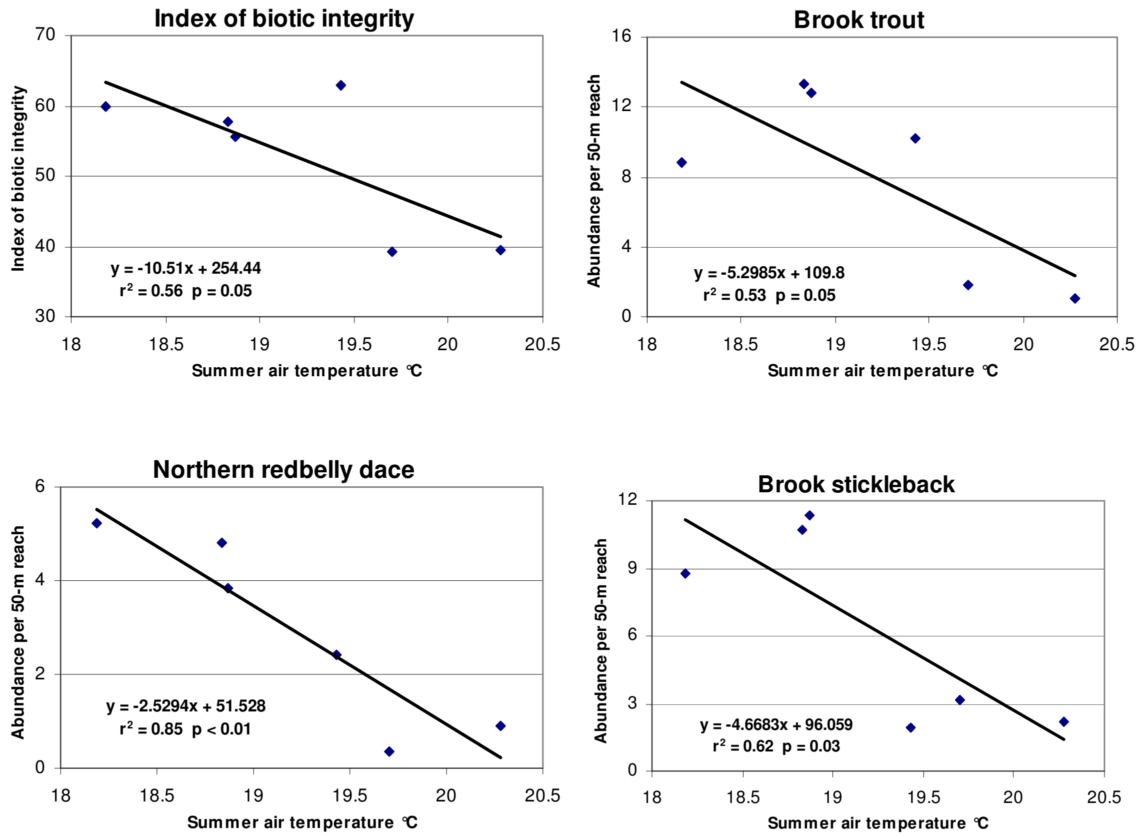


Fig 4. The relationship between mean summer air temperature from June through August and the IBI scores and abundance (annual mean for all 50-m reaches in the basin) of brook trout, northern redbelly dace, and brook stickleback.

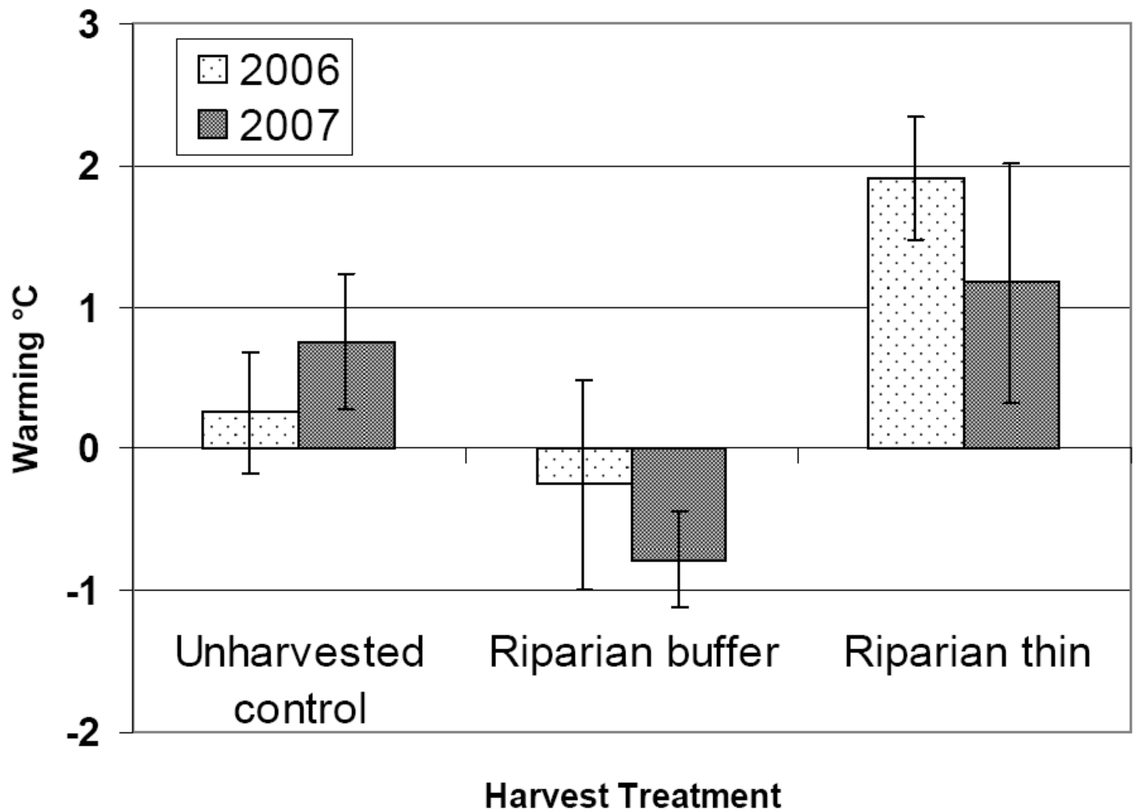


Fig 5. Mean August temperature just downstream of each site minus the mean August temperature just upstream of each site (i.e., stream warming) by harvest treatment and year. Error bars are the standard error of the mean.

CHAPTER 3: Factors influencing wood mobilization in Minnesota streams

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SUMMARY

Natural pieces of wood provide a variety of ecosystem functions in streams, including high quality habitat, organic matter retention, increased hyporheic exchange flow and transient storage, and enhanced hydraulic and geomorphic heterogeneity. The amount and longevity of wood in streams is influenced by a variety of processes, including recruitment, fluvial entrapment, burial, and decay. Wood mobilization (when a stationary piece of wood is displaced by at least 10 m) is also a critical process in determining the residence time of wood in a specific location. The characteristics and locations of 865 undisturbed wood pieces (> 0.05 m in diameter for a portion > 1 m in length) were documented in nine streams along the north shore of Lake Superior in Minnesota in summer 2007. The locations of the pieces were determined again in fall 2007 after an overbank stormflow event to determine the factors that influence mobilization of stationary wood pieces in natural streams. Hydraulic conditions in the streams during the entire study period were determined using calibrated hydraulic simulation models. Seven of 11 potential predictor variables were identified with multiple logistic regression as significant to mobilization: burial, effective depth, ratio of piece length to effective stream width (length ratio), bracing, rootwad presence, downstream force ratio, and draft ratio ($p < 0.001$, $r^2 = 0.39$). Overall, the composition of the final model indicated that wood mobilization under natural conditions is a complex function of both mechanical factors (burial, length ratio, bracing, rootwad presence, draft ratio) and hydraulic factors (effective depth, downstream force ratio). Although our study only

included one stormflow event, the nine streams exhibited a wide range of geomorphic and hydraulic conditions, thus our model should be applicable to at least a similarly wide range of conditions in other watersheds. The model can provide guidance to stream management and restoration. For example, if stable pieces are a goal for stream management then features such as partial burial, low effective depth, high length relative to channel width, bracing against other objects (e.g., stream banks, trees, rocks, or larger wood pieces), and rootwads are desirable. Using the model equation from this study, stewards of natural resources can better manage instream wood for the benefit of stream ecosystems.

INTRODUCTION

Natural pieces of wood enhance habitat conditions and promote key ecosystem functions in streams. Wood pieces provide stable substrate for invertebrates and biofilms, entrap leaves and other organic matter, afford overhead cover for fish, promote hyporheic exchange flow and transient storage, enhance hydraulic heterogeneity, and encourage pool formation and channel meandering (Angermeier and Karr 1984, Beechie and Sibley 1997, Gregory et al. 2003, Johnson et al. 2003, Mutz and Rohde 2003, Eggert and Wallace 2007, Stofleth et al. 2008). The frequency and character of wood inputs varies in space and time (Latterell and Naiman 2007, Golladay et al. 2007), and is strongly affected by riparian management (Flebbe and Dolloff 1995, Kreutzweiser et al. 2005, Czarnomski et al. 2008).

Many mechanisms control the transport of wood in streams. For example, wood may be mobilized and carried downstream by fluvial entrainment, entrapped in narrow or shallow sections of a stream, or ejected onto the floodplain. Wood may also be gradually removed by decay processes, or become buried only to be exposed later by stream meandering (Latterell and Naiman 2007). In this paper we analyze wood mobilization, the process of a stationary piece of wood being set into motion in a stream.

Wood mobilization is important for several reasons. From an ecological perspective, wood mobilization changes local stream functions. Traditionally, wood was considered "debris" and removed from many streams to increase hydraulic conveyance capacity and reduce flooding (Walter and Merritts 2008). From a stream restoration perspective, it is valuable to know whether newly-installed woody habitat will remain in place. Wood mobilization is analogous to incipient motion of sediment particles; both processes are also difficult to predict (Braudrick and Grant 2000).

Wood mobilization has been investigated in a number of field studies (Bilby 1984, Lienkaemper and Swanson 1987, Berg et al. 1998, Jacobsen et al. 1999, Warren and Kraft 2008, Wohl and Goode 2008). The most frequently cited predictor of mobilization that has emerged from these studies is the ratio of the length of a wood piece to the bankfull width of the stream channel (Gurnell et al. 2002, Hassan et al. 2005). This length ratio is related to the probability that the piece of wood becomes braced against stream banks, rocks, or riparian trees before traveling an appreciable distance.

Wood mobilization has also been investigated in laboratory flumes, where experimental conditions can be controlled and standardized. In a pioneering flume study, the most important factors for mobilization were the orientation of the piece of wood relative to flow (from parallel to perpendicular to flow) and the presence of rootwads (Braudrick and Grant 2000). In contrast to field studies, piece length did not influence mobilization (Braudrick and Grant 2000). Two reasons were suggested for the contrast with mobilization observed in natural channels. First, all pieces investigated were shorter than the channel width, making it impossible for a piece to resist mobilization by bracing against both banks. Second, the laboratory channel was of uniform depth and width and void of obstructions. A later flume experiment improved prediction of mobilization by including greater detail on the hydraulic conditions immediately surrounding each wood piece (Bocchiola et al. 2006).

Another study attempted to combine the detailed hydraulic predictions of flume studies with the realism of a field study, and determined that mobilization was influenced by the ratio of piece diameter to water depth (Haga et al. 2002). However, that study had two major limitations. The 63 wood pieces were artificially introduced and were not representative of those found in natural streams; the pieces were cut shorter than the channel width, were similar in size, and had branches removed. Further, the hydraulic data were of low resolution; the 5.5-km study reach was divided into 24 sections and hydraulic conditions were averaged for each section.

In this paper we describe the conduct and results of a study in nine streams to determine the factors most influential on wood mobilization. The diversity of wood piece characteristics representative of natural streams, a variety of geomorphic stream conditions, and a fine resolution of hydraulic information were used in the study. In the analysis, we relate mobilization potential to mechanical factors and forces, which in turn are linked to geometry and density of the wood pieces, their position in the stream, and hydraulic stream parameters such as water velocity, depth and width. We acquired an extensive field dataset on 865 wood pieces and measured stream levels and discharge on a 15-minute time scale. We also simulated water surface profiles and stream depths at cross-sections every 10 m. Actual observations of wood mobilization were statistically tested against predictor variables to develop a predictive model of wood mobilization. We selected initial predictor variables based on a literature review of the forces acting on wood pieces in natural streams.

FORCES ACTING ON WOOD PIECES IN A STREAM AND POTENTIAL MOBILIZATION PREDICTORS

Any object in a stream will be mobilized when the total forces acting on it in the downstream direction exceed those in the upstream direction. The difficulty in predicting mobilization lies in identifying and quantifying all the forces acting on a given piece of wood, particularly in a field setting. Below we describe selected forces acting on single pieces of wood in natural streams.

Floatation

The simplest case of wood mobilization is an individual piece lying on a stream bed and not interacting with other objects (e.g., stream banks, live vegetation, boulders, or other pieces of wood). Such a piece is held in place solely by gravity and friction with the stream bed. In a natural setting where flows are temporally dynamic, one must first determine whether movement is caused by floatation, when friction with the stream bed is eliminated. Floatation occurs when buoyancy (F_B)[5] exceeds the weight (F_W). Buoyancy and weight are expressed by the relationships (1) and (2)

$$F_B = g\,\rho_w\,V_{sub} \qquad (1)$$

and

$$F_W = g\,\rho_{log}\,V_{log} \qquad (2)$$

where g is gravity, ρ_w is the density of water, V_{sub} is the submerged volume of the piece, ρ_{log} is the density of the piece, and V_{log} is the total volume of the piece. Calculating V_{sub} requires information on the size, submerged depth, and spatial position of the piece (Appendix B, Erdmann and Merten *In Review*).

When buoyancy exceeds weight for a piece of wood, the draft (Figure 1) is less than the water depth. The formula to determine the draft (D) of a cylindrical piece with radius (r) can be estimated from Braudrick and Grant (1997) as

$$D = 2r\,(0.05 + 0.9\,(\rho_{log}/\rho_w)) \qquad (3)$$

[5] A list of all variables and symbols used in this study is given in Appendix A.

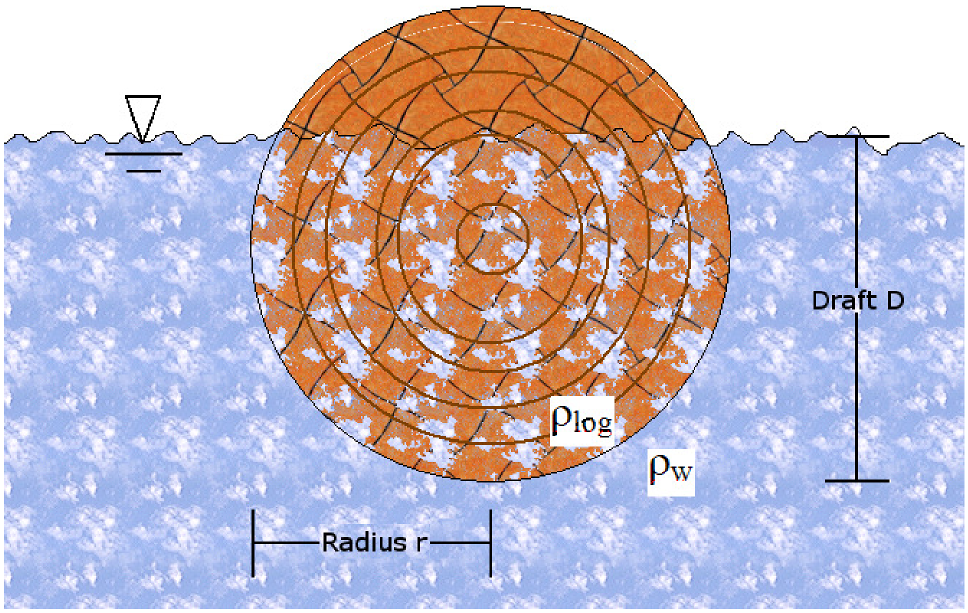

Figure 1. Draft of a floating piece of wood, shown in cross-section. Draft (*D*) is a function of the density of the piece (ρ_{log}) and the water (ρ_w), and the radius of the piece (*r*).

Interactions with the stream bed

If floatation does not occur, a piece may still move by sliding along the stream bed if the force of friction (F_F) is insufficient to hold the piece in place. Friction is

$$F_F = (F_W - F_B)\, f_{bed} \cos \alpha \qquad (4)$$

where f_{bed} is the coefficient of friction on the stream bed and α is the stream slope or gradient. Besides sliding, a piece may also move by rolling, but the moment forces involved are beyond the scope of this study.

Pieces of wood may be partially buried in the stream bed; some studies suggest that burial is the most important determinant of mobilization (Berg et al. 1998, Wohl and Goode 2008). A partially-buried piece requires a greater force to mobilize it compared to an exposed piece (Brooks et al. 2006). The opposite process also occurs in streams; buried pieces may become unburied by stream meandering (Latterell and Naiman 2007) and thus subject to mobilization.

Interactions with the flow

A piece will slide when the hydrodynamic drag (F_D) exerted by the water is sufficient to overcome friction (F_F) with the stream bed. The hydrodynamic drag acting on a piece is approximated as

$$F_D \approx (U^2/2)\, \rho_w\, C_d\, A_N + (U^2/2)\, \rho_w\, C_f\, A_{SA} \cos^3 \theta \qquad (5)$$

where U is the mean water velocity, C_d is the form drag coefficient, A_N is the submerged area normal to flow, C_f is the skin friction drag coefficient, A_{SA} is the submerged surface area of the piece, and θ is the plan-view orientation of the piece relative to the flow (Figure 2). The submerged area normal to flow (A_N) is a complex function of the size, submerged depth, and spatial position of the piece (Appendix B, Erdmann and Merten *In Review*). The total drag is the sum of form drag and skin friction drag (equation 5). The submerged surface area (A_{SA}) of a piece can be approximated as

$$A_{SA} \approx \pi\, L\, d_{sub} \qquad (6)$$

up to the maximum when $d_{sub} = 2r$, where L is the length of the piece and d_{sub} is the submerged depth of the piece.

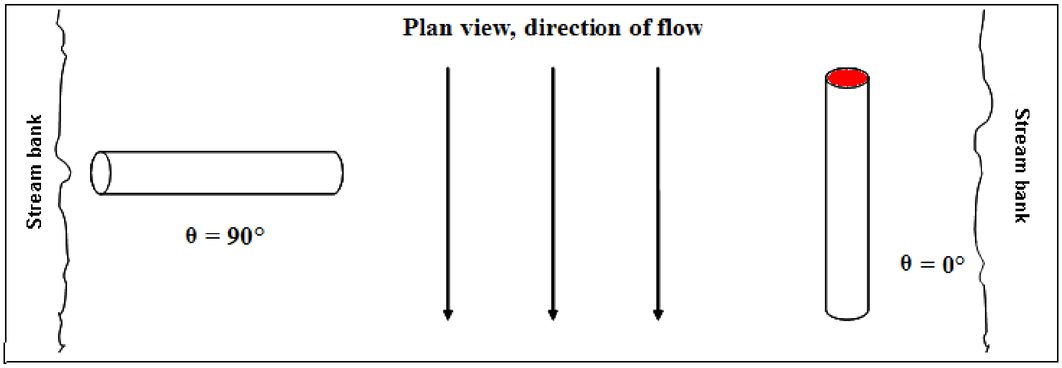

Figure 2. Plan view of channel with pieces of wood oriented perpendicular to the flow ($\theta = \pi/2$ radians) and parallel to the flow ($\theta = 0$ radians).

Form drag coefficients (C_d) are a function of the shape of the object, its position in the stream, and a Reynolds number defined as

$$Re = 2r\,U/\,v \qquad (7)$$

where v is the kinematic viscosity. In a simple case where the stream bed, stream banks, and water surface are far away from the piece, they will have little effect on the drag coefficients. For that case (approximating an infinite fluid), drag coefficients on many different shapes of bodies have been studied extensively, and can be found in the published literature (e.g. Hoerner 1965). Brooks et al. (2006) reviewed the literature and selected a drag coefficient of 1.2 for wood in streams, whereas Bocchiola et al. (2006) used dowels in flumes to obtain a drag coefficient of 1.41. Natural pieces of wood may have greater drag due to skin friction than the smooth dowels used by Bocchiola et al. (2006), thus we have included the skin friction component of equation (5) with a skin friction drag coefficient $C_f = 0.005$ (Olson 1961).

The flow around a piece may also produce differences in pressure that result in a vertical lift force. In an infinite fluid, the lift force (F_L) acting on a piece can be estimated as

$$F_L \approx U^2/2\, C_{lp}\, A_N \cos\theta + U^2/2\, C_{lg}\, A_N \sin\theta \qquad (8)$$

where C_{lp} and C_{lg} are the lift coefficients for pitch and gap lift. Pitch lift can be positive (upwards) or negative (downwards) depending on the pitch of the piece relative to the stream bed (γ, Figure 3); a piece with positive pitch has positive lift and a piece with negative pitch has negative lift. Pitch lift coefficients (C_{lp}) for objects of various shapes are given by Hoerner (1985). The pitch lift coefficient for a cylinder is insensitive to the fineness ratio (i.e., diameter/length, Hoerner 1985), making a javelin a suitable surrogate for a piece of wood in terms of pitch lift. Pitch lift is greatest for pieces oriented parallel to the direction of flow ($\theta = 0$). For a javelin the pitch lift coefficient can be estimated as

$$C_{lp} = sin^2\, \gamma\, cos\, \gamma \qquad (9)$$

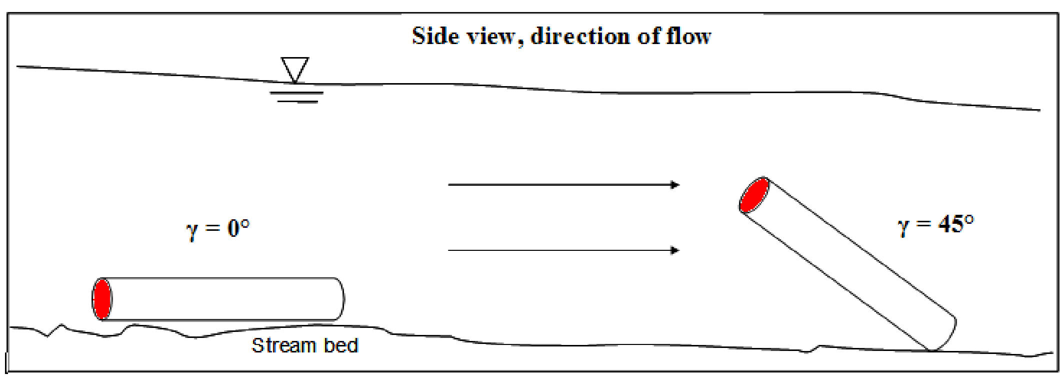

Figure 3. Side view of channel illustrating pieces of wood pitched parallel to the stream bed (γ = 0 radians) and at 45° to the stream bed (γ = π/4 radians).

Unlike pitch lift, gap lift (C_{lg}) is greatest for pieces oriented perpendicular to the flow ($\theta = \pi/2$), and always acts in a downward direction. Gap lift is a function of piece diameter and the gap between the piece and the stream bed, and is caused by the Bernoulli effect (Lei et al. 1999). When water must pass through a constricted opening (the gap) the velocity increases and the pressure decreases; the decreased pressure under the piece causes a downward force. Gap lift coefficients can be estimated from Lei et al. (1999) as

$$C_{lg} \approx 0.0916\ (G/2r)^{-0.5911} \qquad (10)$$

with a maximum value of $C_{lg} = 0.55$.

Role of hydrology

Stream hydrology is a major determinant of wood transport. Any piece of wood will be mobilized at a sufficient discharge, just as the largest boulders are mobilized during extreme floods (Gordon et al. 2004). Discharge depends on hydrologic factors including climate (mainly precipitation) and watershed characteristics such as topography, geology, soils, vegetation, and artificial or natural storage (Gordon et al. 2004). Under uniform flow conditions, the water level and mean velocity at a channel cross-section can be related using Manning's equation (Olson 1961)

$$U = Q/A_{wet} = n^{-1} R^{2/3} \alpha^{1/2} \qquad (11)$$

where U is mean stream velocity, Q is the discharge rate, A_{wet} is the wetted area, n is Manning's roughness coefficient for the channel, and R is the hydraulic radius (approximated by the water depth in a wide channel). Manning's roughness coefficient

(n) is a function of the substrate, shape, and vegetation of a channel (Arcement and Schneider 1989). Channel roughness is also influenced by obstructions, generally rocks and wood, which can have more direct effects on mobilization.

Interactions with obstructions

In natural streams, pieces of wood are often braced against obstructions in the channel. Rocks, islands, or fallen trees can provide support and prevent the mobilization of a wood piece. To become mobilized, a braced piece must rise up and over a bracing object, requiring a net upward force. As with floatation of an unbraced piece, buoyancy plus hydrodynamic lift must be greater than the weight of the piece, but vertical friction (F_V) must also be overcome. Vertical friction acts between a braced piece and the bracing object and is related to the hydrodynamic drag (F_D), where

$$F_V = F_D f_{brace} \cos \psi \qquad (12)$$

and f_{brace} is the coefficient of friction of the bracing object and ψ is the angle of the upstream face of the bracing object.

Wood pieces may also be braced against stream banks and live vegetation. Particularly during overbank flows, a piece may become braced against trees at the edge of the floodplain; a piece braced against trees is unlikely to be lifted over them. A piece may also become wedged between stream banks and require a substantial force to be mobilized. Moment forces may cause a piece to pivot off a bracing obstruction, but this type of motion is beyond the scope of this study.

Theoretical predictors of wood mobilization

Based on the preceding discussion, a number of theoretical variables emerge for predicting wood mobilization. Some relevant forces have been described above, specifically F_B, F_W, F_F, F_D, F_L, and F_V. These forces can be combined into ratios that are most likely to promote or resist mobilization. Examples are a vertical force ratio (R_V, equation 13) and a downstream force ratio (R_D, equation 14)

$$R_V = (F_W + F_V)/(F_B + F_L) \quad (13)$$

$$R_D = F_F/F_D \quad (14)$$

The vertical force ratio (R_V) thus describes the relative force acting in a downward direction, whereas the downstream force ratio (R_D) describes the relative force acting in an upstream direction. If either ratio is < 1 then mobilization is theoretically possible, and ratios closer to zero imply a greater likelihood of mobilization. Thus, we expect that mobilization is most likely for pieces where the buoyancy, lift, and hydrodynamic forces are high and the weight, vertical friction, and horizontal friction forces are low.

Additional forces that can be expected to influence wood mobilization include the resisting force due to burial in the stream bed and the normal force exerted by bracing objects. Neither force could be quantified under our experimental conditions; we thus considered these forces to be either present or absent (i.e., buried/unburied, braced/unbraced).

Aside from forces, the probability of mobilization may also be related to other physical and positional attributes of a wood piece. These attributes make a piece more or less likely to be in contact with the stream bed, banks, or other obstructions. We identified five physical attributes likely to influence mobilization: the length ratio (L^*, ratio of piece length to the effective stream width), draft ratio (D^*, ratio of piece draft to mean depth in the channel), branching complexity, rootwad presence, and blockage (the percentage of the wetted channel cross-sectional area occupied by the piece). We also expected two positional attributes to influence mobilization. The lateral distance of the wood piece from the stream bank is important because pieces in the channel are more likely to be mobilized than those among floodplain trees, and effective depth is important because pieces on the channel bottom are more likely to be mobilized than those suspended above it. We next designed a field study, described below, to test our predictions.

METHODS

Study area and streams

The study area was in forested watersheds along the north shore of Lake Superior in Minnesota. High flows occur in area streams after spring snowmelt, but overbank stormflows are also common in summer or fall. Nine streams with continuous discharge data available (15-minute intervals) were selected for study (Figure 4). The study streams were the Beaver River, French River, Knife River, Little East Knife River, Little West Knife River, Sucker River, Talmadge Creek, Upper Knife River and West Split Rock River. These nine streams represented a wide range of geomorphic conditions; stream beds were dominated by cobble and gravel (Figure 5) and mean bankfull widths ranged from 3.4 to 24.4 m.

A single study reach 250 to 800 m in length was established in each stream, for a total of 4,190 m. Each study reach was divided into 10-m sections marked with wire flags, flagging tape, and GPS. In all instances, the particular 10-m section from which data were collected was noted. Data were collected from June to November 2007. During the peak discharges in October 2007 wetted widths in the nine streams ranged from 3.4 to 90.7 m and mean cross-sectional water depths from 0.3 to 3.1 m.

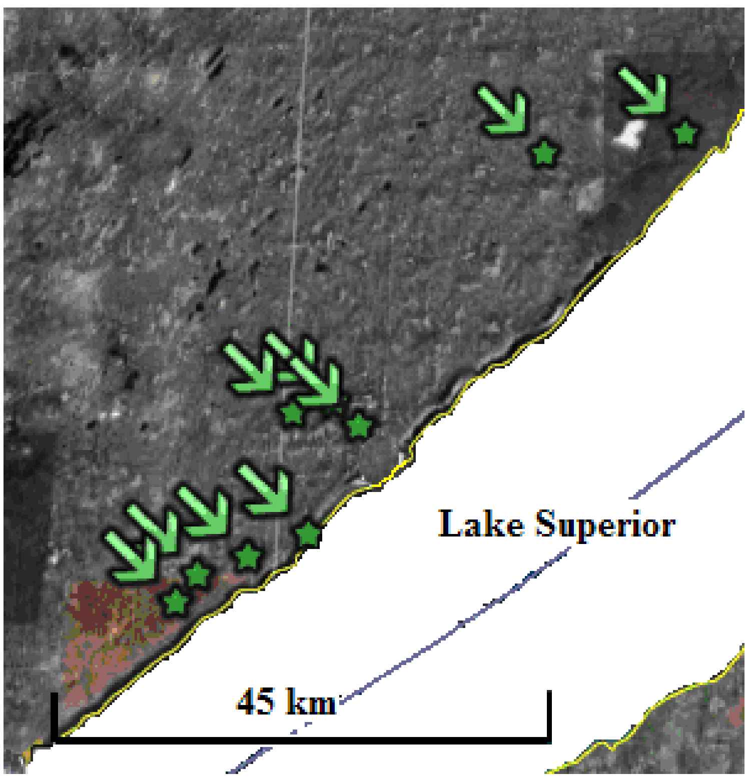

Figure 4. Study sites (stars with arrows) along the north shore of Lake Superior in Minnesota. Duluth, Minnesota is in the southwest corner and Silver Bay, Minnesota is in the northeast corner.

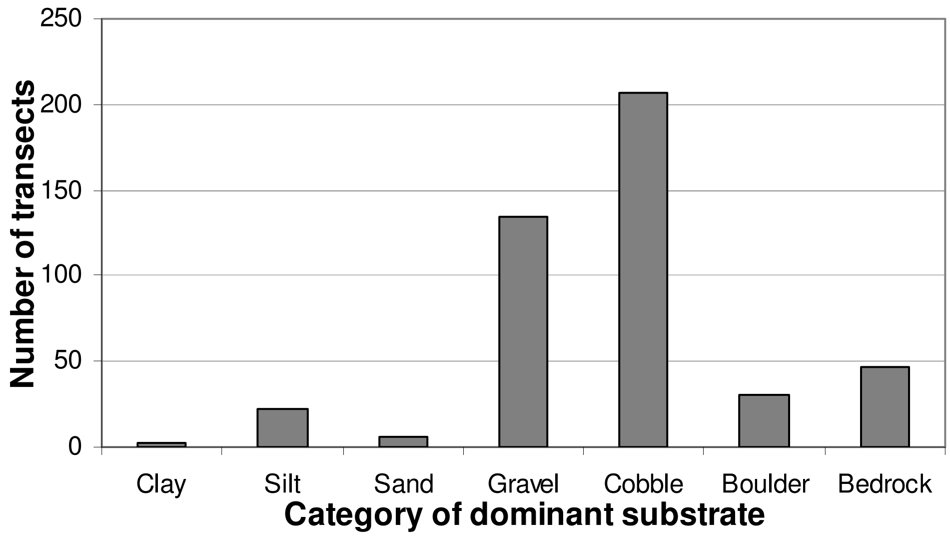

Figure 5. Number of stream bed transects by dominant substrate for the nine streams.

Water levels in summer 2007 were low (Figure 6) due to extreme drought conditions (USDA Drought Monitor, 8/14/07). However, storms from mid-September through mid-October produced heavy rainfall in the study area. Rainfall observers within 10 km of Lake Superior from Duluth to Silver Bay recorded a mean of 25.3 cm of rainfall (s.d. = 2.3) from 9/15/07 to 10/15/07, compared to 19.6 cm for the entire period from 6/15/07 to 9/15/07 (Minnesota State Climatology Office). The rainfall caused a stormflow with a recurrence interval of 1.1 years at the only study stream with a long-term hydrologic record (Knife River, per the St. Louis County Soil and Water Conservation District). Although the hydrologic records were insufficient to estimate the recurrence intervals at other study streams, the relatively uniform rainfall in the study area suggests that the recurrence interval at other study streams was comparable to the Knife River. Overbank flows were observed at all nine study streams during the stormflow event.

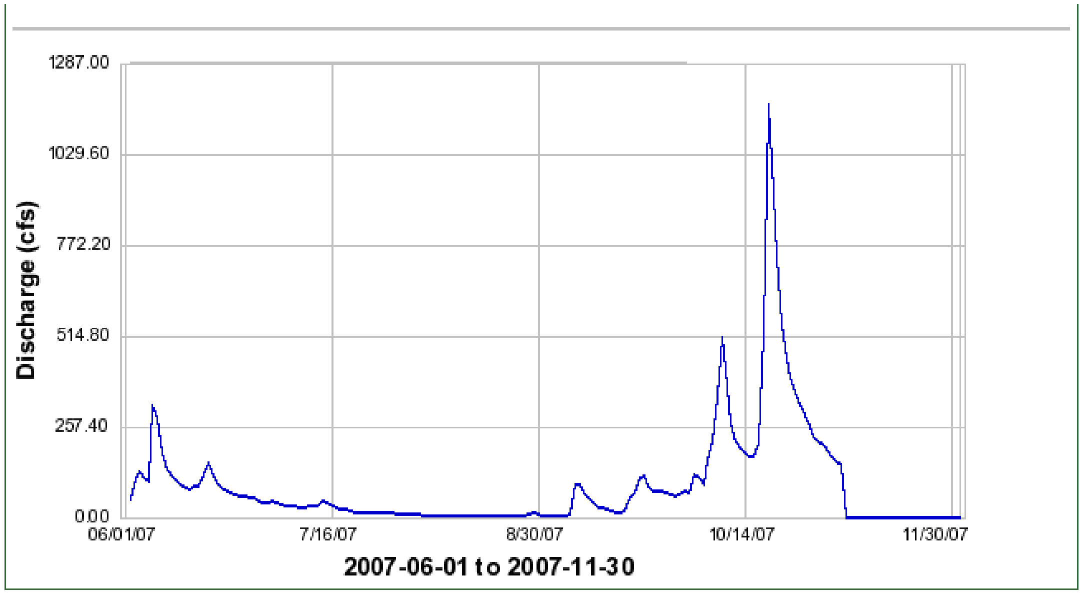

Figure 6. Hydrograph for the Poplar River from June to November 2007. Hydrographs for other study streams were similar. Data from Minnesota Pollution Control Agency.

Wood data collection

In June through August of 2007, all preexisting natural pieces of wood (> 0.1 m in diameter for a portion > 1 m in length) in the study reaches were located and marked. A subset (n ≈ 20) of smaller pieces (> 0.05 m in diameter for a portion > 1 m in length) were also located and marked in each study reach, for a total of 963 pieces. All pieces that lay within the channel or that had a portion over 0.05 m in diameter extending into the bankfull channel were assessed. Pieces were included if they were entirely dead but still rooted, or still alive but entirely uprooted. Each piece was marked with flagging tape and one (n=334) or three (n=629) individually numbered tags. Measurements were taken on each piece as described below to obtain the parameters listed in Table 1. All marked pieces in the study reaches were located again in mid-October through November 2007 after floodwaters from the early October storm had receded.

Total length (for the portion over 0.01 m in diameter) and diameter of each piece were measured using a tree calipers at the ends and middle. Each piece was treated as a cylinder for estimation of total volume, using the total length and mean diameter (i.e., the sum of both end diameters and twice the middle diameter all divided by four). The presence of rootwads was noted. The orientation of each piece was estimated as the horizontal angle relative to the flow (θ, Figure 2) using categories of 0, $\pi/6$, $\pi/3$, and $\pi/2$ radians. The pitch of each piece relative to the stream bed (γ, Figure 3) was visually estimated using categories of 0, $\pi/6$, $\pi/4$, $\pi/3$, and $\pi/2$ radians; pitch was also measured on a subset of pieces ($n = 374$) using a clinometer. Pieces where a clinometer was employed used the clinometer measurement; the remainder of the pieces used a corrected clinometer measurement based on the relationship between visual estimates and clinometer measurements ($r^2 = 0.73$).

The branching complexity was assessed for each piece as described by Newbrey et al. (2005), where higher branching complexity corresponds to a greater number of branches and twigs. The density of each piece was also determined using a sample obtained with an increment borer. It was noted if a piece was braced against other pieces, live trees, rocks, or the stream channel (including pieces that had a portion above the stream bed pinned under other pieces or rocks) or was buried. A piece of wood was considered buried if > 5% of its cross-sectional area was embedded into the substrate or if either end was buried in the substrate (including pieces that were entirely dead but still rooted).

The location of the midpoint of each piece was noted by measuring its longitudinal location within its 10-m section, the elevation relative to the existing water level, and the lateral distance from the nearest bank. The elevation of the midpoint of the piece relative to the existing water level was used in conjunction with continuous discharge data and the hydraulics models described below to determine the absolute elevation of each piece.

Forces acting on each piece were estimated based on characteristics of the piece and local hydraulic conditions. The buoyancy (F_B), weight (F_W), and friction against the stream bed (F_F) were calculated using equations (1), (2), and (4). The hydrodynamic drag (F_D), lift force (F_L), and frictional force against braces (F_V) were calculated using equations (5), (8), and (12). A bed coefficient of friction f_{bed} = 0.2 was used, the mean of values for sliding and rolling on gravel determined by Bocchiola et al. (2006). The vertical coefficient of friction f_{brace} = 0.2 and $\psi = \pi/2$ radians were also used.

Table 1. Variables measured or calculated for each piece of wood.

	Measured variables	
Length > 0.1m in diameter	Branching complexity	Density ρ_{log}
Total length L	Bracing	Orientation to flow θ
Mean diameter $2r$	Lateral distance from bankfull	Pitch from streambed γ
Elevation	Burial	Rootwad presence
	Calculated variables	
Volume V_{log}	Draft D	Effective depth
Weight F_W	Buoyancy F_B	Vertical force ratio R_V
Submerged volume V_{sub}	Hydrodynamic drag F_D	Downstream force ratio R_D
Area normal to flow A_N	Friction force on bed F_F	Length ratio L^*
Surface area A_{SA}	Blockage	Draft ratio D^*

Wood mobilization response data

Changes in the locations of wood pieces were determined in fall 2007; the locations of all tagged pieces that were initially marked in summer 2007 and had remained in each study reach were again determined in October-November. Each piece generated a logistic data point: 0 if the piece remained within 10 m of its original longitudinal position or 1 if it moved downstream at least 10 m. By this definition, the response variable for mobilization addressed at the 10-m scale whether pieces initially at rest remained at rest over the time frame of this study. Although pieces were not remeasured, only nine pieces were known to have broken (based on the position of the tags; the shorter portion of the piece was disregarded).

Geomorphic data

Data on stream geomorphology were collected in all study reaches in summer 2007. A survey laser and measuring tape was used to survey cross-sections every 10 m, except at the two largest streams where 40 of 80 (Beaver River) or 12 of 50 (Knife River) 10-m sections were surveyed. Cross-sections were referenced to one another using frequent turning points (Harrelson et al. 1994). Elevations were recorded near inflection points along the cross-section. The bed slope was calculated for each reach as the slope between the lowermost points at the upstream and downstream ends of the reach. The innermost lateral location of bank vegetation > 0.02 m in stem diameter was noted on both sides of each cross-section and used to estimate the effective stream width (Figure 7) available to transport wood. Estimates of Manning's roughness coefficient were made by the methods of Arcement and Schneider (1989), using separate estimates for the stream channel and floodplain of each study reach.

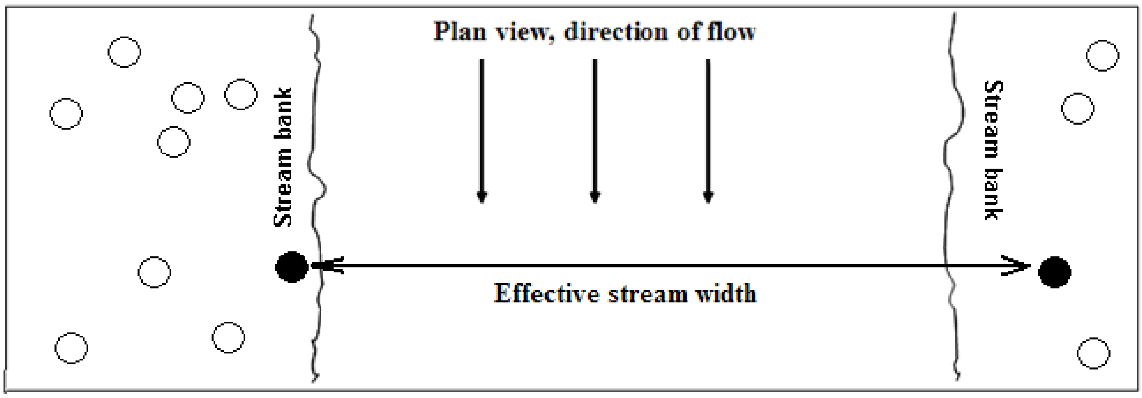

Figure 7. Plan view of stream channel illustrating lateral positions of trees (open circles) large enough to brace a floating piece of wood. Effective stream width was the lateral distance between the innermost trees (closed circles) for each 10-m section of stream or the actual wetted width, whichever was shorter.

Hydraulic analysis

The computer simulation model HEC-RAS 4.0 (available online)[6] was used to calculate hydraulic characteristics at each 10-m section during overbank stormflows in fall 2007; HEC-RAS is appropriate for studying stream characteristics at a 10-m resolution (Brooks et al. 2006). Based on the geomorphic survey data, HEC-RAS was used to estimate unit stream power, stage, mean water velocity, and energy grade slope (Gordon et al. 2004) at each 10-m section at the peak discharge in fall 2007. The velocity estimates from the HEC-RAS models represent a cross-sectional average.

[6] (http://www.hec.usace.army.mil/software/hec-ras/)

To calibrate the hydraulic model for each study reach, the initial value for channel roughness was varied (between 0.02 and 0.07) to obtain the best fit between predicted water stages and observed stages during summer 2007. The r^2 values between predicted and observed water stages for the summer 2007 discharges ranged from 0.77 to 1.00, indicating good prediction of hydraulic characteristics.

Calculation of wood piece variables using hydraulic variables

The peak discharge during overbank flows in fall 2007 was used to determine the hydraulic variables in Table 1. The effective channel width was defined as the wetted width that was available to transport wood, taken as either the lateral distance between the innermost trees (Figure 7) or the modeled wetted width, whichever was less. The length ratio (L^*) was calculated for each piece as the piece length divided by the effective channel width in the initial 10-m section where the piece was located. The absolute elevation of each piece was determined by applying the measured difference between the piece elevation and the existing water level to the modeled stage (Figure 8). Using the absolute elevation for each piece, the distance between the lowermost point on each piece and the water surface (i.e., the effective depth) was determined for the fall overbank flows. The draft ratio (D^*) for each piece was calculated as the draft divided by the mean depth in the channel in the initial 10-m section. Blockage by each piece was estimated as A_N/A_{wet} using the original orientation and pitch of the piece. The hydrodynamic drag acting upon each piece was calculated using equation (5). The form drag coefficient C_d used was 1.41 (Bocchiola et al. 2006) and the skin friction drag coefficient C_f used was

0.005 (Olson 1961). The vertical force ratio (R_V) and downstream force ratio (R_D) were calculated for each piece using equations (13) and (14). Based on the observed distributions of R_V and R_D, the maximum value for R_V was set to 100 and the maximum R_D was set to 10, including cases where the denominator was zero (i.e., the piece was above the water level, Figure 8). The predictor variables did not account for flexing or breakage of pieces, mobilization by jarring contact from other pieces or sediment in transit, flexing or movement of bracing obstructions themselves, mobilization via rolling or pivoting (as opposed to floatation or sliding), or human intervention.

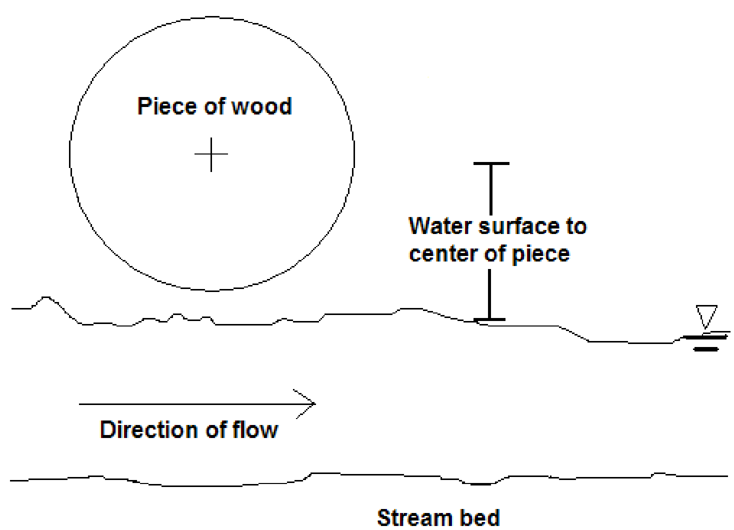

Figure 8. Side view of stream channel illustrating a piece of wood suspended above the water surface. The measured difference between the water surface and the center of the piece was applied to the modeled stage to estimate the absolute elevation of the piece.

Data analysis

Multiple logistic regression (Weisberg 1985) was used to model the mobilization response. Unlike multiple linear regression or discriminant function analysis, logistic regression analysis does not require normally distributed response variables, nor does it assume homogeneous variances for the response variable (Weisberg 1985). The binomial response variable for this study (mobilization) is well-suited for logistic regression but not for multiple linear regression. In addition, the sample size of 963 pieces provided a suitable representation of possible cases. A multiple logistic regression model was developed using the logistic mobilization data as the response variable. Each tagged piece represented one data point. The predictor variables for the full model were selected to account for known mechanisms of wood transport: vertical force ratio (R_V), downstream force ratio (R_D), burial, bracing, ratio of piece length to effective channel width (length ratio, L^*), ratio of piece draft to mean depth in the channel (the draft ratio, D^*), branching complexity, rootwad presence, blockage, lateral distance from bankfull, and effective depth of the piece. The final model was chosen using the stepAIC function of the statistical software R (available online)[7] to determine the model with the fewest predictors that would each make a significant improvement to the AIC (Weisberg 1985). The Variance Inflation Factor (VIF) was examined for all predictor variables in the final model to evaluate collinearity; predictors with VIF > 2 were culled. The final model produced a probability of mobilization for pieces under specific conditions; the goodness of fit was evaluated using Nagelkerke's r^2 (Nagelkerke 1991) and variables were ranked by importance according to the absolute value of their Wald Z Score.

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[7] (http://www.r-project.org/)

RESULTS

Range of variables

A total of 963 pieces of wood were tagged and measured, but some were excluded from analyses. Two spanning logjams were present at the study reaches; wood pieces that were in either logjam (n = 98) were omitted from analyses. Pieces in a logjam move via congested flow (Braudrick et al. 1997), whereas this study focused on uncongested flow where mobilization of a piece is independent of other pieces.

Wood pieces that were not in logjams (n = 865) exhibited a range of characteristics (Table 2). For example, the mean piece length was 3.8 m with a standard deviation (*s.d.*) of 3.0 m, mean diameter was 0.18 m (*0.13 m*), and mean wood density was 0.75 g/cm^3 (*0.31* g/cm^3). Many characteristics appeared to follow a chi-square distribution (Appendix C), which is acceptable because multiple logistic regression makes no assumptions about the distributions of predictor variables (Weisberg 1985).

Table 2. Mean *and standard deviation* for wood piece characteristics in summer 2007, and geomorphic and hydraulic stream characteristics during peak discharges in fall 2007.

	Units	Mean	
Buoyancy (F_B)	N	12	*30*
Weight (F_W)	N	13	*30*
Wood density (ρ_{log})	g/cm^3	0.75	*0.31*
Piece length (L)	m	3.8	*3.0*
Diameter ($2r$)	m	0.18	*0.13*
Volume (V_{log})	m^3	0.18	*0.49*
Pitch from stream bed (γ)	rad	0.18	*0.17*
Effective depth	m	1.06	*0.76*
Submerged volume (V_{sub})	m^3	0.12	*0.30*
Draft (D)	m	0.12	*0.10*
Friction on stream bed (F_F)	N	0.7	*2.8*
Piece surface area (A_{SA})	m^2	2.2	*3.0*
Hydrodynamic drag (F_D)	N	573	*963*
Orientation to flow direction (θ)	rad	0.73	*0.49*
Area normal to flow (A_N)	m^2	0.34	*0.47*
Lift (F_L)	N	0.003	*0.025*
Water velocity (U)	m/s	1.5	*0.5*
Vertical force ratio (R_V)	-	17	*49*
Downstream force ratio (R_D)	-	1.1	*3.2*
Length ratio ($L*$)	-	0.47	*0.50*
Draft ratio ($D*$)	-	0.14	*0.16*
Branching complexity	-	12	*39*
Blockage	-	0.06	*0.12*
Lateral distance from bankfull	m	6.7	*15.6*
Wetted width	m	23	*17*
Effective stream width	m	12.2	*8.0*
Energy grade slope	m/m	0.011	*0.011*
Unit stream power	N/m s	138	*137*
Mean depth in channel	m	1.13	*0.59*

Geomorphic and hydraulic conditions also covered a wide range during peak flows in fall 2007, whether all data were combined (Table 2) or examined by stream (Table 3). The mean wetted width was 23 m (*17 m*), and the mean water depth in the channels was 1.13 m (*0.59 m*). The mean water velocity in the channels was 1.5 m/s (*0.5 m/s*), and unit stream power in the channels had a mean of 138 N/m s (*137 N/m s*).

Table 3. Mean *and standard deviation* for geomorphic and hydraulic stream characteristics for each study site during peak discharges in fall 2007. Depth, velocity, and power values do not include water in the floodplain.

Stream	Mean depth (m)		Water velocity (m/s)		Power (N/m s)		Bed slope (m/m)	Bankfull width (m)		Peak flow (m^3/s)
Beaver River	1.66	*0.30*	0.86	*0.32*	15	*35*	0.001	16.0	*3.0*	21.7
French River	0.74	*0.17*	1.53	*0.34*	119	*84*	0.020	11.3	*2.5*	12.0
Knife River	1.51	*0.29*	1.44	*0.22*	137	*57*	0.006	24.4	*5.3*	54.7
Lt. East Knife	1.48	*0.22*	1.17	*0.42*	78	*135*	0.004	3.4	*0.9*	7
Lt. West Knife	0.53	*0.15*	1.15	*0.33*	40	*36*	0.012	3.7	*0.8*	2.1
Sucker River	0.98	*0.13*	1.84	*0.33*	252	*169*	0.016	9.9	*2.2*	17.5
Talmadge Cr.	0.78	*0.14*	1.62	*0.25*	247	*135*	0.025	5.3	*1.6*	7.0
Upper Knife	0.84	*0.08*	1.48	*0.25*	93	*46*	0.009	6.6	*1.1*	8.3
W Split Rock	2.48	*0.28*	1.92	*0.45*	153	*108*	0.007	6.9	*0.9*	54.4

Of the 865 wood pieces used in this study, 356 (41%) were mobilized during the study period. The mean length and diameter for mobilized pieces was 2.84 and 0.15 m whereas the mean length and diameter for stable pieces was 4.53 and 0.19 m. Mean wood density was 0.75 and 0.76 g/cm^3 for mobilized and stable pieces.

Mobilization model

The final model for mobilization was highly significant ($p < 0.001$) and had seven predictor variables (Table 4). An additional variable (blockage) was present in the final model but was culled due to a high VIF (2.656). The seven remaining predictor variables were burial, effective depth, length ratio (L*), bracing, rootwad presence, downstream force ratio (R_D), and draft ratio (D*). Each predictor had a p-value < 0.05 and a VIF < 2, indicating that the variables were not collinear. Nagelkerke's r^2 for the final model was 0.39, corresponding to a Goodman-Kruskal gamma of 0.67 and Kendall's tau-a of 0.32.

Table 4. Variables retained in the final model for mobilization; n = 865 pieces of wood. Overall model $p < 0.001$ and Nagelkerke's $r^2 = 0.39$.

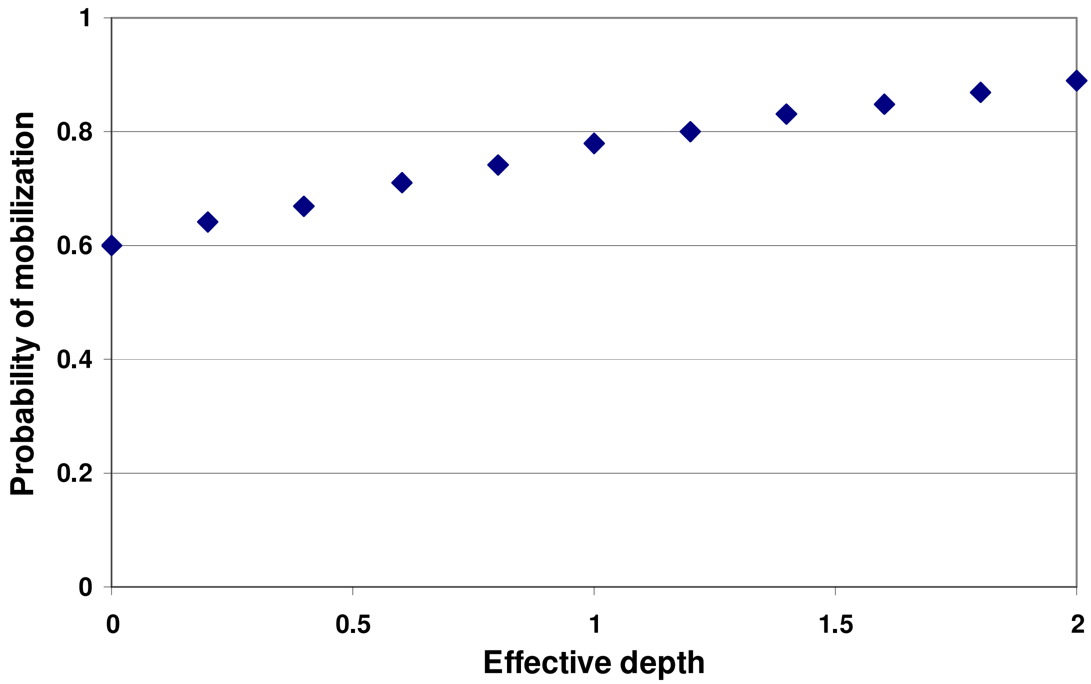
	Coefficient	S.E.	Wald Z	p-value	VIF
Intercept	0.385	0.233	1.65	0.098	
Burial	-2.643	0.345	-7.67	<0.001	1.088
Effective depth	0.858	0.137	6.27	<0.001	1.266
Length ratio	-1.517	0.261	-5.80	<0.001	1.178
Bracing	-0.774	0.171	-4.54	<0.001	1.055
Rootwad presence	-0.799	0.261	-3.06	0.002	1.021
Downstream force ratio	-0.091	0.035	-2.59	0.010	1.115
Draft ratio	-1.592	0.741	-2.15	0.032	1.183

Model sensitivity to changes in individual predictors

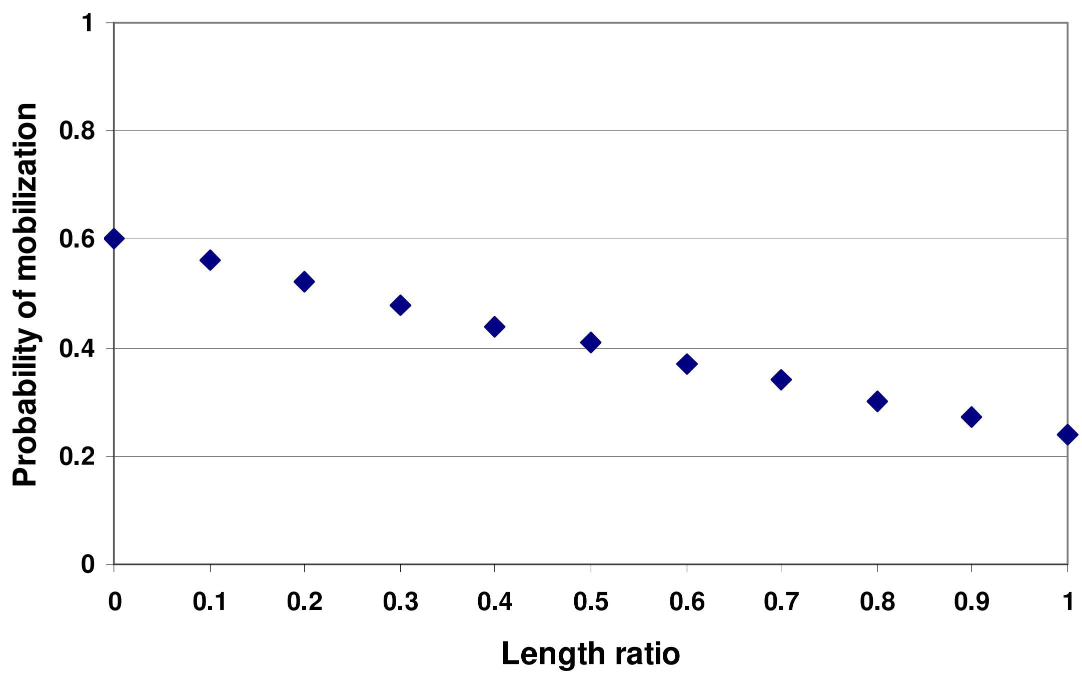
The probability of a positive response (i.e., mobilization) can be expressed for individual predictors using a logistic equation as

$$P = \exp(\beta_0 + \beta_1 x_1)/(1 + \exp(\beta_0 + \beta_1 x_1)) \qquad (15)$$

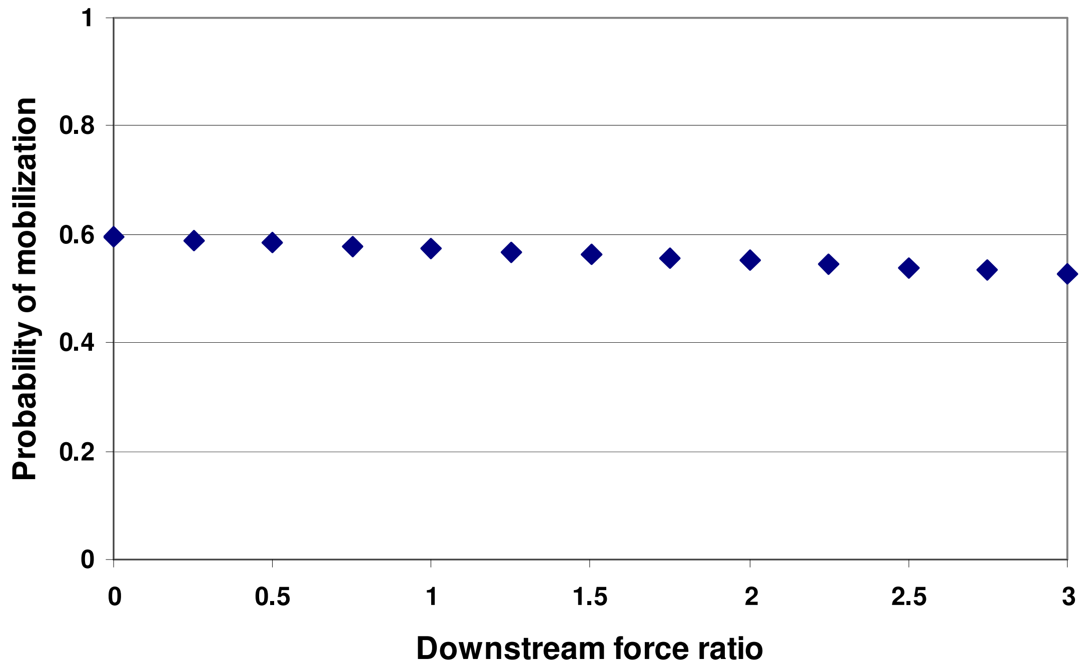
where β_0 was the intercept (e.g., 0.385 in Table 4), β_1 was the model coefficient for the variable of interest, x_1 was the value for the variable of interest, and all other variables were held constant. Using the model coefficient for burial (-2.643 in Table 4) equation (15) indicated that a piece which was not buried ($x_1 = 0$) had a 0.60 probability of being mobilized, whereas a piece that was buried ($x_1 = 1$) had a 0.09 probability of being mobilized. Taking the difference (0.09 – 0.60 = -0.51) showed that a piece that was buried was 51% less likely to be mobilized, assuming all other variables were held constant. Similarly, a piece that was braced was 19% less likely to be mobilized than an unbraced piece, and a piece with a rootwad was 20% less likely to be mobilized than one without. Increasing the effective depth of a piece by one standard deviation from 1.06 m (the mean value) to 1.82 m was associated with a 9% increase in the probability of mobilization (Figure 9). Increasing the length ratio (*L**) by one standard deviation from 0.47 (the mean value) to 0.97 was associated with a 17% decrease in mobilization. Likewise, increasing the downstream force ratio or draft ratio by one standard deviation was associated with reductions of 7% or 6%.



Probability of mobilization
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
Effective depth



Probability of mobilization
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Length ratio



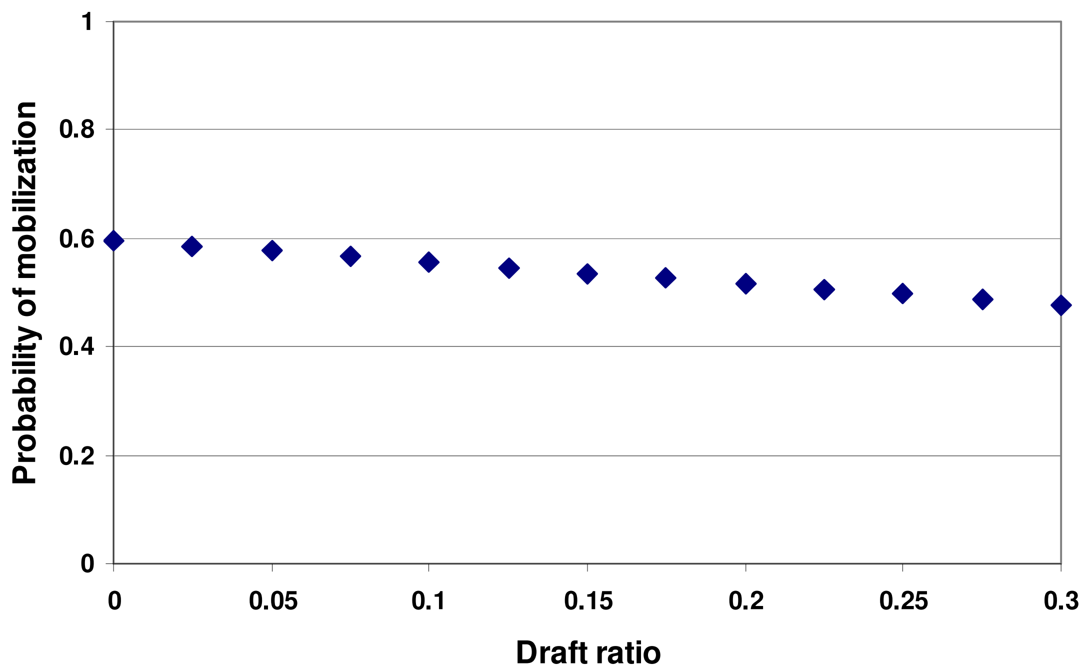


Figure 9. Expected probability of mobilization as a function of the effective depth, length ratio (L^*), downstream force ratio (R_D), or draft ratio (D^*).

Predicting mobilization with the full model

Expanding equation (15) to consider the sensitivity of model projections the full set of predictor variables yields

$$P = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_6 x_6 + \beta_7 x_7) / (1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_6 x_6 + \beta_7 x_7)) \quad (16)$$

where $\beta_1 x_1 \ldots \beta_7 x_7$ correspond to coefficients and values for the seven predictor variables. Combining the prior examples, a piece of wood that was unburied, unbraced, and had no rootwad, effective depth of 1.82, length ratio of 0.47, downstream force ratio of 1.1, and draft ratio of 0.14 had $P = 0.71$. Conversely, a piece that was buried, braced, and had a rootwad, effective depth of 1.06, length ratio of 0.97, downstream force ratio of 4.3, and draft ratio of 0.30 had $P = 0.01$.

Categories for bracing

At the time of tagging in summer 2007, most pieces were not braced (n = 581, Figure 10). Of the 284 pieces that were braced, 104 were braced by other pieces of wood, 79 were braced by live trees, 73 were braced by rocks in the channel, and 28 were braced by the stream banks or channel itself.

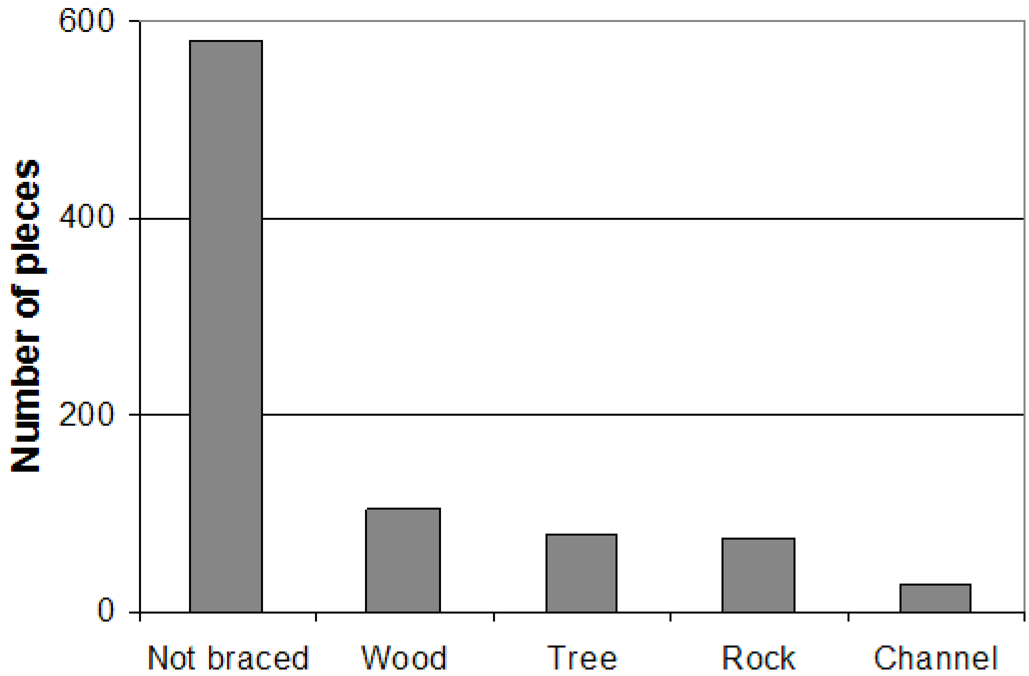


Figure 10. Frequency of bracing of wood pieces in relation to the object on which the piece was braced in summer 2007.

DISCUSSION

Eleven variables were identified through literature review and assessed for their potential influence on mobilization of natural pieces of wood in streams. No known study has examined wood mobilization with such a comprehensive set of potential predictors. Seven of the variables contributed significantly to the prediction of mobilization, as ranked by the absolute value of their Wald Z Score: burial, effective depth, length ratio (L^*), bracing, rootwad presence, downstream force ratio (R_D), and draft ratio (D^*). The overall model had a p-value < 0.001 and $r^2 = 0.39$ (Nagelkerke 1991).

Our study agrees with the statement that predicting wood transport is much more complex than sediment transport (Braudrick and Grant 2000), even with a large field dataset and seven significant predictors. Below we discuss each of the significant predictor variables, describe the characteristics of stable pieces, and make suggestions for future research.

Controls of mobilization

Burial was easily most important variable in the final model for mobilization, based on the Wald Z Score. Pieces that were partially buried were less likely to be mobilized. Burial and unburial can remove or return a substantial amount of wood to streams (Latterell and Naiman 2007). Although few studies have considered the effects of burial on mobilization, when burial is included in analyses it is of primary importance (Berg et al. 1998, Wohl and Goode 2008). Our study demonstrated the importance of burial to mobilization using a quantitative analysis and a large number (865) of wood pieces.

The effective depth of the wood piece was the second most important variable in the final model for mobilization, with more-submerged pieces more likely to be mobilized. Effective depth may function as a composite descriptor of the various mobilizing forces acting on a piece (e.g., buoyancy, hydrodynamic drag and lift). Effective depth also affects the likelihood that a piece will contact the stream bed before escaping a 10-m section. In a turbulent stream, a piece floating in deep water is less likely to contact the stream bed than the same piece floating in shallow water. Effective depth is affected by stream discharge, the importance of which was recognized in the pioneering work by Bilby (1984).

The next important variable in the final model for mobilization was the length ratio (L*). Pieces that were long relative to the effective channel width were less likely to be mobilized. At the 10-m scale, the length ratio may relate to the probability that a piece becomes braced before it can escape the 10-m section. While most previous studies have likewise found a negative relationship between length ratios and mobilization (Bilby 1984, Lienkaemper and Swanson 1987, Berg et al. 1998, Jacobsen et al. 1999, Gurnell et al. 2002, Hassan et al. 2005, Warren and Kraft 2008), one recent study found a positive relationship (Wohl and Goode 2008). Although the contrasting study spanned 11 years, their definition of mobilization included breakage. It is possible that relatively longer pieces are more prone to breakage, which could explain the discrepancy between Wohl and Goode (2008) and other studies. Finally, we used the effective channel width to determine our length ratio (rather than bankfull width or wetted width) to represent the actual width available to transport wood.

Bracing was also a significant predictor of mobilization; a piece that was braced was less likely to be mobilized. Thus, three of the variables predicting mobilization (burial, length ratio, and bracing) are in agreement with the qualitative results of the extensive field study by Berg et al. (1998), which did not assess the remainder of our variables. It bears noting that, of the pieces that were braced in summer 2007, the largest number was held by other pieces of wood, even after pieces in spanning logjams were culled from the dataset. The frequency of wood pieces in a stream may provide a positive feedback by reducing mobilization of other pieces.

Rootwad presence was associated with a lower probability of mobilization. A rootwad presents additional surface area that may become entangled with rocks, vegetation, or other pieces to prevent a piece from being mobilized. Rootwads tend to be sturdy; for example if a rootwad becomes wedged between rocks it may hold the entire piece against substantial hydrodynamic drag. Rootwads also elevate a piece, potentially reducing the submerged volume and thus the buoyancy and hydrodynamic drag (Braudrick and Grant 2000).

Pieces with higher downstream force ratio (R_D) were less likely to be mobilized, meaning pieces with more friction on the stream bed relative to hydrodynamic drag. The downstream force ratio integrates the effects of piece density, volume, and submerged volume into friction and the effects of water velocity and submerged piece area into hydrodynamic drag. The downstream force ratio is lowest when buoyancy is greater than weight (meaning the piece floats and has no friction with the stream bed) and the water velocity is zero (meaning the piece is in slackwater or is above the water level). The influence of downstream force ratio on mobilization was relatively minor after accounting for the five preceding variables.

Draft ratio (D^*) was the least important predictor variable, although the Wald Z Score was still significant ($p = 0.032$). Pieces with higher draft relative to the water depth were less likely to be mobilized. As for the length ratio, the draft ratio may affect the probability that a piece is halted (by friction with the stream bed in this case) before it can escape a 10-m section. Although prior research (Braudrick and Grant 2001, Haga et al. 2002) suggests that draft ratio may be important to entrapment, our analysis found that draft ratio plays a relatively minor role in mobilization.

Four predictor variables were not included in the final model for mobilization: the vertical force ratio (R_V), blockage, branching complexity, and lateral distance from bankfull. The vertical force ratio may overlap with bracing; the vertical friction for pieces that were braced constituted 80% of total vertical forces (i.e., the sum of F_B, F_W, F_L, and F_V) on average. The unimportance of branching complexity supports the assertion that branches do not measurably increase the hydrodynamic drag acting on a piece (Hygelund and Manga 2002). The value for branching complexity is also highly influenced by the presence of small twigs (Newbrey et al. 2005), which break off easily under duress. It bears noting, however, that the definition of mobilization used for this study (i.e., moved at least 10 m) is conservative. Finer-scale definitions of mobilization that include any measurable motion (Bocchiola et al. 2006) may be more sensitive but less ecologically meaningful.

Overall, the composition of the final model indicated that mobilization under natural conditions is a complex function of both mechanical factors (burial, length ratio, bracing, rootwad presence, draft ratio) and hydraulic factors (effective depth, downstream force ratio). Although our study included only a single year, the nine streams exhibited a wide range of geomorphic and hydraulic conditions. Thus, the results from this study are applicable to at least a similar range of conditions in other streams. Four of the final seven predictor variables take discharge into account (i.e., effective depth, length ratio, downstream force ratio, draft ratio) and the remainder have been identified as important in other settings (Berg et al. 1998, Braudrick and Grant 2000, Wohl and Goode 2008).

Applications to stream management

The model equation (16) can be used for management of wood in streams. If a management goal is to have stable wood, pieces can be partially buried, long relative to the channel width, braced against other objects (e.g., stream banks, standing trees, rocks, or larger pieces), have rootwads, and have high draft relative to the water depth. Pieces can also have higher downstream force ratios by having higher density (increasing weight, decreasing buoyancy, and thereby increasing friction with the stream bed) and by being located in slow-moving water or above the waterline (thus minimizing the effective depth).

Although pieces located above the waterline are less likely to be mobilized, they also provide fewer ecological functions to a stream. In particular, pieces that are not submerged do not provide stable substrate or biofilm for aquatic invertebrates, enhance hydraulic heterogeneity, promote hyporheic recharge or transient storage, encourage pool formation and channel meandering, or entrap leaves and other organic matter. However, wood that is within stream channels but above the waterline can still provide overhead cover for fish and is valuable for riparian species such as frogs, turtles, snakes, and waterfowl.

We suggest several possibilities for improving the statistical strength of the mobilization model. First, the resolution of hydraulic information could be increased, with velocity and water level measured in the area immediately around each piece (Bocchiola et al. 2006). Detailed hydraulic data are difficult to obtain in a field setting, however, and the effort must be weighed against other considerations such as investigating a broad range of conditions. Second, the amount of sturdy branches on each piece could be measured in some other way. For example, a branching ratio could be determined for each piece as the combined length of large branches (> 0.05 m in diameter, excluding the main bole of the piece) divided by the length of the main bole. Third, data could be collected to estimate the forces acting on a partially-buried piece, using methods described by Brooks et al. (2006).

Further research is needed to better understand the processes that remove wood from streams. For example, the process of instream decay is known to depend on the tree species (Diez et al 2002) and water chemistry (Gulis et al. 2004) but has received relatively little study (Hassan et al. 2005). Similarly, the processes by which wood becomes buried and unburied in streams merit further study (Hassan et al. 2005, Latterell and Naiman 2007). Perhaps the most important are the sociological reasons for intentional wood removal by humans (Gregory and Davis 1993, Piegay et al. 2005, Wyzga et al. 2009).

CONCLUSION

In this study we have collected an extensive dataset (over 800 wood pieces) to study wood mobilization in streams. This study serves as a template for research on wood mobilization that uses a wide range of piece characteristics and geomorphic stream conditions representative of natural conditions, and uses an appropriate resolution for hydraulic information. We have identified seven factors out of 11 tested that influence wood mobilization in streams, and developed a model that includes all the significant predictors. Using the relationships developed in this study, stewards of natural resources can better manage instream wood for the benefit of stream ecosystems.

ACKNOWLEDGEMENTS

Wood and survey data were collected by Jo Fritz, Ryan Carlson, Dustin Wilman, Nicole Rath, Levi Drevlow, Ryan Johnsen, and April Bebault. Rachael Stanze and Nathan Schroeder collected continuous discharge data from six streams. Logistical support was provided by Tracy Close of Minnesota Department of Natural Resources, Marty Rye of USDA Forest Service, the Minnesota Cooperative Fish and Wildlife Research Unit, and the Natural Resources Research Institute. Mathematical formulas in Appendix B were derived and generously provided by Melissa Erdmann. Funding was provided by the Minnesota Department of Natural Resources and Minnesota Sea Grant.

CHAPTER 4: Entrapment of wood in Minnesota streams determined by a length ratio and weight

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SUMMARY

Wood deposited in streams provides a wide variety of ecosystem functions, including enhancing habitat for key species in stream food webs, increasing geomorphic and hydraulic heterogeneity, and retaining organic matter. Given the strong role that wood plays in streams, factors that influence wood inputs, retention, and transport are critical to stream ecology. Wood entrapment, the process of wood coming to rest after being swept downstream at least 10 m, is poorly understood yet important for predicting stream function and success of restoration efforts. Data on entrapment were collected for a wide range of natural wood pieces (n = 344), stream geomorphology, and hydraulic conditions in nine streams along the north shore of Lake Superior in Minnesota. Locations of pieces were determined in summer 2007 and again following an overbank stormflow event in fall 2007. The ratio of piece length to effective stream width (length ratio) and the weight of the piece were determined to be of primary importance to wood entrapment using multiple logistic regression. There are likely two reasons that both factors were important. First, multiple measurements were made on each piece and in 419 10-m sections of stream, with a scaled resolution similar to that of flume studies. Second, a wide natural range of piece and stream characteristics were examined. This study can inform stream modifications to discourage entrapment at road crossings or other infrastructure by determining the effective stream width required to pass particular wood pieces. Conversely, these results could also be used to determine conditions that encourage entrapment where wood is valued for ecological functions. Although the

regression model was highly significant, it explained only 25% of the variability in entrapment. Entrapment remains difficult to predict in natural streams, and often may simply occur wherever wood pieces are located when high water recedes. The process of wood entrapment in streams merits further study, particularly under natural conditions and by detailed methods such as used here.

INTRODUCTION AND BACKGROUND

Wood pieces deposited in streams provide a wide variety of ecosystem functions. Foremost, wood enhances habitat conditions for key species in stream food webs, including invertebrates and fish (Angermeier and Karr 1984, Berg et al. 1998, Johnson et al. 2003, Eggert and Wallace 2007). Wood also increases hydraulic heterogeneity and transient storage, promotes hyporheic recharge, encourages pool formation and channel meandering, and retains leaves and other organic matter (Beechie and Sibley 1997, Mutz and Rohde 2003, Mao et al. 2008, Stofleth et al. 2008). The frequency and size of wood inputs vary in space and time (Latterell and Naiman 2007, Golladay et al. 2007) and are strongly affected by riparian management (Flebbe and Dolloff 1995, Kreutzweiser et al. 2005, Czarnomski et al. 2008). The importance of wood for stream function is increasingly recognized (Gregory et al. 2003), particularly as the adverse effects of historic “woody debris” removal become more evident (Walter and Merritts 2008).

Given the strong role that wood plays in stream ecosystems, understanding the factors that influence wood inputs and transport is critical to stream ecology and restoration. One aspect of wood transport that is poorly understood is wood entrapment, the process by which moving wood pieces in a stream come to rest after traveling downstream for some distance. Wood entrapment is important for predicting stream functions and success of restoration efforts; wood that is entrapped in a stream reach enhances many local ecological functions. Thus, predicting the dynamics of wood entrapment can be valuable for maintaining or changing the ecological function of natural streams, and for restoring systems that have been degraded due to channel simplification, erosion, and other human-driven changes.

Direct observation of individual pieces of wood is the optimal method for studying wood entrapment. Other field methods rely on the examination of wood standing stocks and assume that wood recruitment is spatially homogeneous, which is unlikely to be true (Latterell and Naiman 2007). Studies assessing movement of individual pieces of wood date to at least Bilby (1984), who concluded that piece length was the primary factor in determining distance traveled before entrapment. Subsequent field studies identified length ratios (i.e., the ratio of piece length to stream width) as important in determining wood entrapment over a range of conditions, as reviewed by Gurnell et al. (2002) and Hassan et al. (2005). For example, Lienkaemper and Swanson (1987) determined that the primary factor for entrapment was the ratio of the piece length to the channel width. Although the largest empirical study to date (n = 2,105 pieces) found little correlation between piece length and distance traveled ($r^2 = 0.11$, Jacobsen et al. 1999), the lack of correlation was likely due to the use of pieces much shorter than the width of the large river studied (Gurnell et al. 2002, Hassan et al. 2005).

Although field studies of entrapment characterize pieces of wood in terms of mean length and mean diameter, there are other attributes which may be important but were not considered in previous models. For example, wood pieces with more branches and twigs have greater branching complexity (Newbrey et al. 2005) which may increase entrapment rates due to entanglement of branches in rocks or bank vegetation. Momentum and draft (Figure 1) of a piece may also influence whether it can overcome resistance from the stream bed or obstructions.

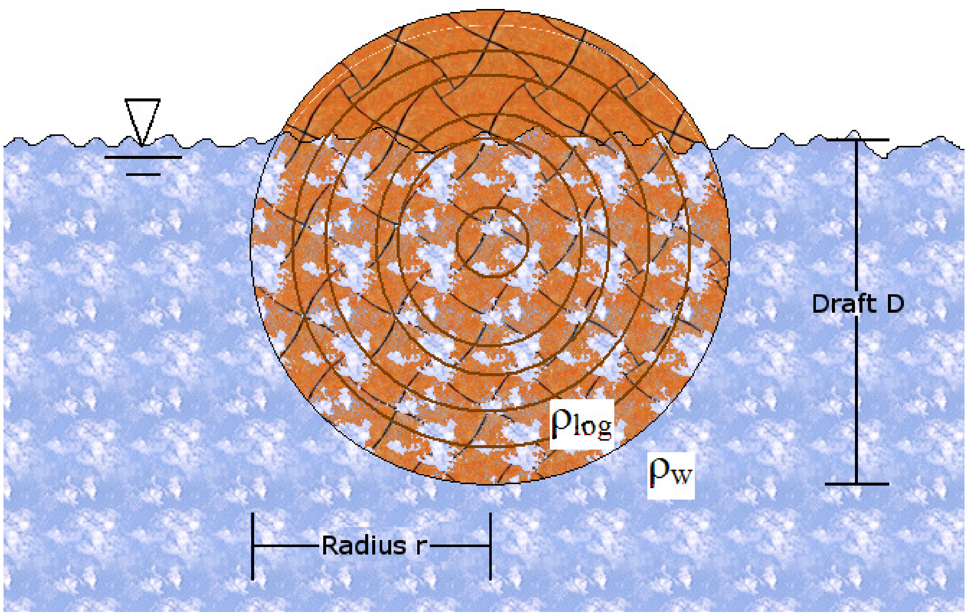


Figure 1. Draft for a floating piece of wood in a stream cross-section. Draft is a function of the density of the piece and the water, and the radius of the piece.

Two laboratory studies used dowels in flumes to examine wood entrapment in greater detail under simplified conditions. Braudrick and Grant (2001) used a flume to examine the influence of piece length and diameter relative to channel width, depth, and sinuosity. Although little correlation was found with dowel entrapment, the detailed measurements set a new standard for examinations of entrapment. Using a similar approach with dowels in a flume, Bocchiola et al. (2006) developed robust predictions of entrapment by floating dowels through a gauntlet of obstructions. However, it remains unclear how well the results from flume studies can predict entrapment under the heterogeneous conditions found in natural streams.

Studies by Haga et al. (2002) provided a starting point for integrating the detailed mechanistic approach of flume studies with the realism of a field study. A 5.5-km reach was divided into 24 segments, and mean water depth during peak discharges was estimated for each segment. A total of 63 tagged pieces were placed in the stream channel and tracked over a 13-month period; entrapment generally followed hydraulic predictions related to the ratio of piece diameter to water depth (Haga et al. 2002). However, it is unclear whether their results are representative of natural conditions, as all pieces studied were cut to similar length, were shorter than the bankfull width, had branches removed, and were similar in density.

Overall, studies of wood entrapment to date leave a number of questions unanswered. Can the probability of entrapment be predicted for a given ratio of piece length to channel width? Does the ratio of piece diameter to water depth proposed by Haga et al. (2002) predict entrapment over a natural range of wood piece characteristics? Does branching complexity or rootwad presence play a role in entrapment? The resolution of previous field measurements may have overlooked important mechanisms, whereas results from studies with dowels or flumes may not apply to natural wood in natural streams.

Our objective in this paper is to predict and test the mechanisms controlling wood entrapment, using a natural range of characteristics for wood pieces, stream geomorphology, and hydraulic conditions. We integrate extensive and detailed measurements, usually made only in flume studies, with field measurements in nine streams. We analyze the hydraulic conditions encountered by the wood pieces in 10-m sections by numerical modeling, and analyze the data using mechanistic approaches as well as empirical models. We first outline the mechanisms involved with wood entrapment to develop a theoretical basis for entrapment in streams.

MECHANISMS FOR ENTRAPMENT

A piece of wood traveling downstream may be entrapped in a variety of ways. For example, the piece may come into contact with the stream bed and be stopped by friction, or become lodged against an obstruction such as a boulder. Factors that can cause wood to be entrapped in streams are described below.

Role of hydrology and hydraulics

Pieces of wood are often mobilized and entrained during peak discharge (Bilby 1984, Wohl and Goode 2008), when unit stream power, water levels, and velocities in the channel are highest. Powerful streams have greater potential to transport wood, with unit stream power (ω) defined as

$$\omega = \rho_w gRU\alpha \quad (1)$$

where ρ_w is the density of water, g is gravity, R is the hydraulic radius for the channel (approximated by the water depth in a wide stream), U is the stream velocity, and α is the stream slope (Gordon et al. 2004). Under uniform flow conditions the water level and mean velocity for a channel cross-section can be related by Manning's equation

$$U = n^{-1} R^{2/3} \alpha^{1/2} = Q/A_{wet} \tag{2}$$

where n is Manning's channel roughness coefficient, Q is the discharge rate, and A_{wet} is the wetted cross-sectional area (Gordon et al. 2004). Channel roughness is a function of the channel's shape, substrate, and vegetation (Arcement and Schneider 1989). Channel roughness is also influenced by obstructions, such as rocks, boulders, and stationary wood pieces, which can have more direct effects on entrapment.

Interactions with the stream bed

In the simplest case, we consider an individual piece of wood traveling down a wide stream, under conditions where interaction with the stream bed is the only mechanism for entrapment. If no obstructions (e.g., large boulders, islands, fallen trees) are present, the piece may stop when it encounters a shallow stream reach and contacts the stream bed. If the shallow area is extensive, it may exert sufficient friction to reduce or stop the piece's forward momentum and cause the wood to be entrapped. The momentum (M) of a wood piece is defined as

$$M = m\, U \tag{3}$$

where *m* is the mass of the piece (i.e., density multiplied by volume). Piece velocity (*U*) is approximately equal to water velocity for a floating piece that is not in contact with the stream channel (Braudrick and Grant 2001).

The draft (*D*, Figure 1) is the primary variable that controls whether a wood piece will contact the stream bed. Draft refers to the submerged depth of a floating piece, and can be estimated from Braudrick and Grant (1997) from piece radius and density as

$$D = 2r\,(0.05 + 0.9\,(\rho_{log}/\rho_w)) \quad (4)$$

where *r* is the radius of the piece and ρ_{log} is the density of the piece. A piece contacts the stream bed when the draft exceeds the water depth; the ratio of piece draft to the water depth (draft ratio) is therefore an indicator of entrapment potential. Water depth can be quite variable in natural streams (Gordon et al. 2004) even when obstructions are not present; overall conditions can be summarized using the mean depth in the channel.

The blockage may also affect the probability that a wood piece will make contact with the stream bed or banks. Blockage is the proportion of the wetted area occupied by the piece. Blockage is heavily influenced by the orientation of the piece; blockage is least for pieces oriented parallel to the direction of flow and greatest for those oriented perpendicular to the flow. Pieces tend to orient themselves parallel to flow once mobilized (Braudrick and Grant 2001). The orientation of a piece also affects the probability that it will encounter shallow areas; a piece oriented perpendicular to the direction of flow is more likely to encounter shallow areas than a piece oriented parallel to the flow.

Interactions with obstructions in the stream channel

In natural streams, stationary obstructions are often present, such as large boulders, islands, and other pieces of wood. The process of entrapment by obstructions is determined by several contingencies. First, a piece must encounter an obstruction. The probability of encounter is a function of the density of obstructions present (Bocchiola et al. 2006), the draft of the piece relative to the elevation of the obstruction, and the orientation of the piece (with pieces oriented parallel to the flow least likely to encounter obstructions). Second, the obstruction must be sufficiently anchored to resist the forces exerted by the impact of a moving wood piece. If the obstruction is a smaller piece of wood, for example, it may become dislodged and the original piece may escape entrapment. Third, the piece must not pivot off the obstruction. The moment forces that determine whether a piece will pivot are a function of the location along the piece that encounters the obstruction; pieces that contact an obstruction at their midsection are less likely to pivot than pieces that encounter an obstruction near either end.

A wood piece may also encounter a group of obstructions. If a piece becomes at once braced against multiple obstructions, the chance of dislodging the obstructions is diminished. For example, the aggregate resisting force exerted by several small rocks may be sufficient to entrap a large floating piece, even if the piece would have dislodged any one of the rocks in isolation. A group of obstructions may also reduce the probability that a piece will pivot and continue downstream; a piece that bridges multiple obstructions affords less hydraulic leverage.

Interactions with stream banks and vegetation

Stream banks can entrap pieces of wood via two mechanisms. First, long pieces may become wedged across the stream channel. The primary factor in determining the distance a piece travels (which depends on the probability of entrapment) is the ratio of the piece length to the bankfull channel width (Lienkaemper and Swanson 1987, Gurnell et al. 2002, Hassan et al. 2005). We define a ratio of piece length to stream width as a length ratio. Second, a wood piece may become entrapped against the stream banks in sinuous streams. Braudrick and Grant (2001) predicted that pieces would become entrapped on the outside of meander bends, as measured by the radius of curvature for the stream. The forward momentum of a piece may carry it against the outside bank when the meander bend has a small radius of curvature, providing an opportunity for the piece to be entrapped by the bank.

Bank vegetation can also be important to entrapment (Jacobsen et al. 1999, Millington and Sear 2007, Opperman and Merenlender 2007). During high discharge, pieces may become entangled in live vegetation and held fast if the vegetation has sufficient structural strength. Riparian vegetation can thus reduce the wetted stream width that is effectively available to transport wood.

Predictors for wood entrapment

Based on the preceding discussion, we assembled seven variables as potential predictors for entrapment of wood pieces in natural streams. We considered six variables as likely to affect the probability that a piece would contact the stream bed, banks, or other obstructions: piece weight, draft ratio, length ratio, branching complexity, rootwad presence, and blockage. We considered an additional variable (momentum) as likely to affect the probability that a piece is pushed past an obstruction after an encounter. Previous studies have shown length ratio or draft ratio as important and have either not detected or not examined a contribution from weight, branching complexity, rootwad presence, blockage, and momentum. To test the relation of our seven variables to entrapment, we designed a field study in northern Minnesota that encompassed a wide range of conditions found in temperate forested streams.

FIELD DATA COLLECTION

Study design

We examined the mechanisms of wood entrapment in nine streams of forested watersheds along the north shore of Lake Superior in Minnesota (Figure 2). The streams had continuous discharge data available; a study reach was established in each stream near the discharge gage. The study reach at each stream was 250 to 800 m in length (4,190 m total) and was divided into 10-m sections (marked with wire flags, flagging tape, and GPS) as the basis for piece locations and geomorphic conditions. Stream beds were dominated by cobble and gravel (Figure 3), and mean bankfull widths of the nine study reaches ranged from 3.4 to 24.4 m.

Water levels in summer 2007 were low (Figure 4) due to extreme drought conditions (USDA Drought Monitor, 8/14/07). However, storms from mid-September through mid-October produced heavy rainfall in the study area; rainfall observers within

10 km of Lake Superior from Duluth to Silver Bay recorded an average of 25.3 cm of rainfall (s.d. = 2.3) from 9/15/07 to 10/15/07, compared to 19.6 cm for the entire period from 6/15/07 to 9/15/07 (Minnesota State Climatology Office). The rainfall caused a stormflow with a recurrence interval of 1.1 years at the only study stream with a long-term hydrologic record (Knife River, per the St. Louis County Soil and Water Conservation District). Although the hydrologic records were insufficient to estimate the recurrence intervals at other study streams, the relatively even rainfall throughout the study area (i.e., 25.3 cm with s.d. of 2.3) suggests that the recurrence interval at other study streams was comparable to the Knife River. Overbank discharges were observed at all nine study streams during the stormflow event.

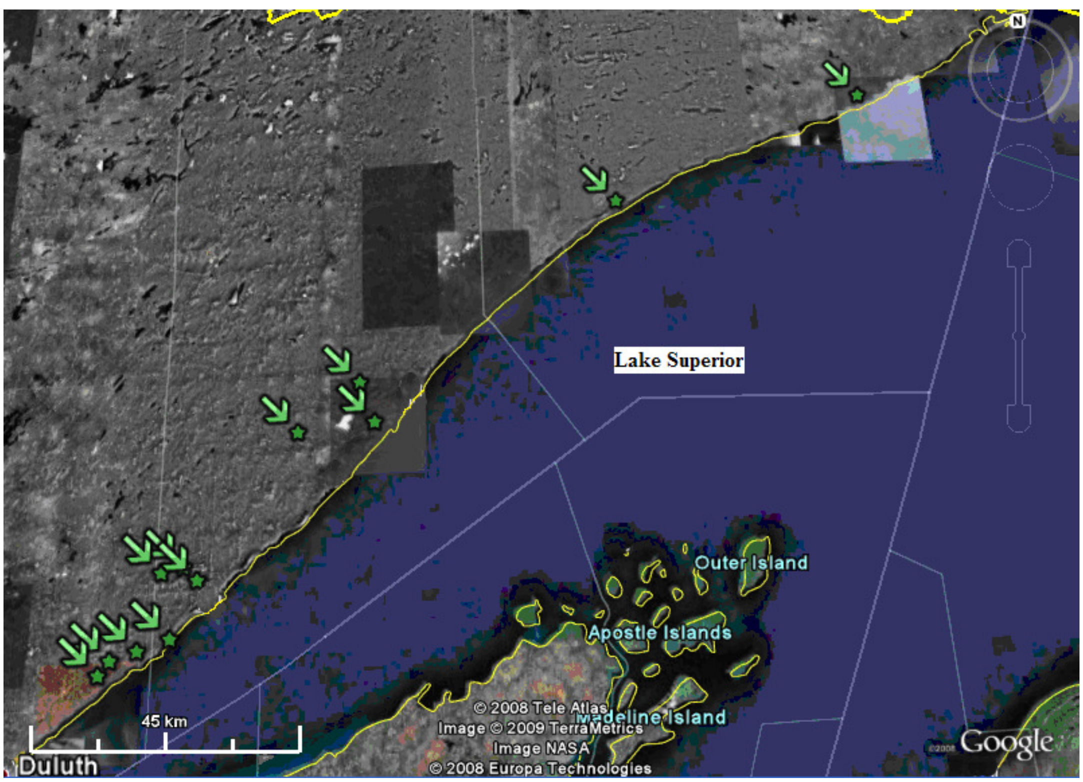


Figure 2. Study sites (stars with arrows) along the north shore of Lake Superior in Minnesota. The three northernmost sites were not sampled in fall 2007. Duluth, Minnesota is in the southwest corner and the Canadian border is in the northeast corner.

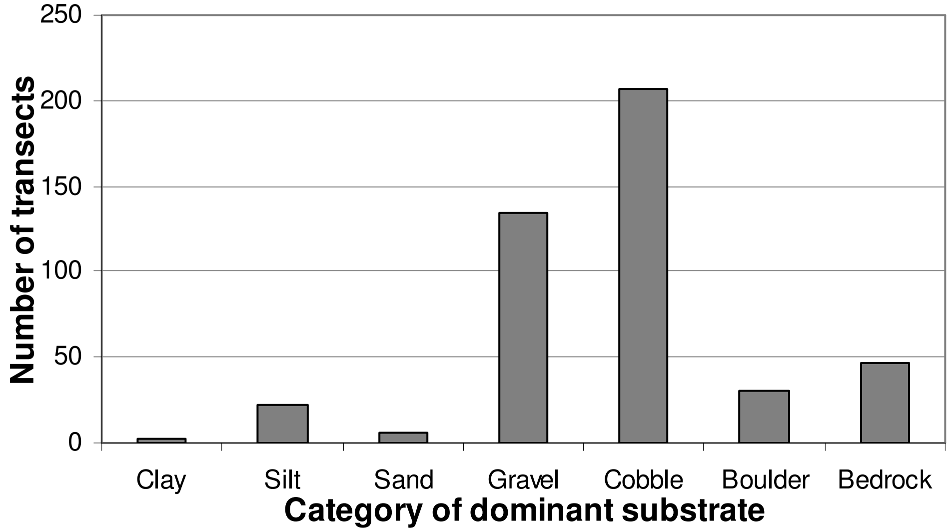


Figure 3. Number of stream bed transects by dominant substrate, for the nine streams combined.

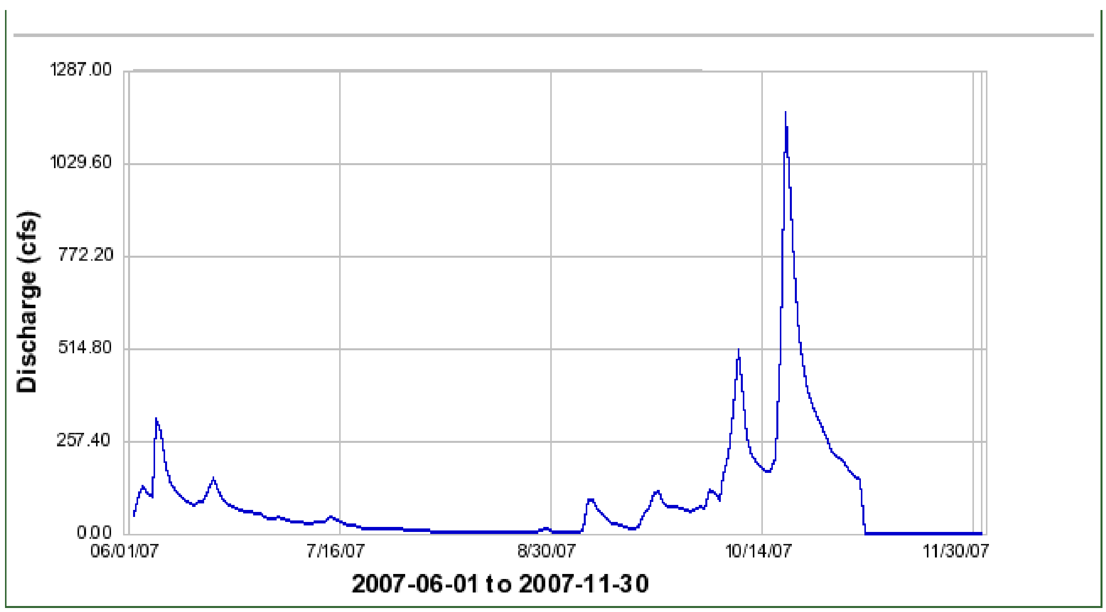


Figure 4. Hydrograph for the Poplar River during the study period from June to November 2007. Hydrographs at other study streams were similar. Data from Minnesota Pollution Control Agency.

Wood data

In June through August of 2007, all preexisting wood pieces (> 0.1 m in diameter for a portion > 1 m in length) in the study reaches were located and marked. A subset ($n \approx 20$) of smaller pieces (> 0.05 m in diameter for a portion > 1m in length) were also located and marked in each study reach, for a total of 956 pieces. Pieces were included if they were entirely dead but still rooted, or still alive but entirely uprooted. Measurements were taken on each piece as described below to obtain the parameters listed in Table 1. All pieces that lay within the channel or that had a portion > 0.05 m in diameter extending into the bankfull channel were included. Each piece was marked twice with flagging tape and one (n=334) or three (n=629) individually numbered tags. Total length (for the portion > 0.01 m in diameter) and mean diameter were measured using a tree calipers at both ends and the middle of each piece. Rootwads were noted if present. All marked pieces in the study areas were located again in mid-October through November 2007 (after floodwaters had receded), including pieces that had been ejected onto the floodplain. Branching complexity was assessed for each piece following Newbrey et al. (2005), and density was determined using a sample obtained with an increment borer. Weight of each piece was estimated as the product of volume and density, and draft of each piece was estimated using the density and mean radius per equation (4).

Table 1. Variables measured or calculated, see text for details.

Measured by piece	**Measured by 10-m section**
Total length	Cross-sectional elevations
Diameter (*2r*)	Stream gradient (slope)
Wood density (ρ_{log})	Effective stream width
Branching complexity	
Rootwad presence	
Calculated by piece	**Calculated by 10-m section**
Volume (V_{log})	Mean velocity in channel (*U*)
Weight	Mean channel depth
Draft (*D*)	Unit stream power in channel (ω)
Length ratio (L^*)	Wetted area in channel
Draft ratio (D^*)	
Momentum (*M*)	
Blockage	

Entrapment was examined further with a new cohort of pieces in 2008. All new (i.e., unmarked) pieces that were > 0.1 m in diameter for a portion > 1 m in length were located in June through August 2008 in each study reach. Three additional study reaches were sampled where all pieces had been marked in summer 2007 but not revisited in fall 2007, while one reach sampled in fall 2007 was not revisited in summer 2008. Pieces that were clearly recruited locally from riparian trees within the study reach (n = 22 freshly fallen trees) were excluded in 2008; all other new pieces (n = 178) were assumed to have moved from upstream of the reach. The method of entrapment was noted for each new piece using the following categories: lying loose in the channel, braced by rocks, braced by other pieces of wood, braced by the stream banks or bed, braced by live trees but with the center of the piece remaining within 1 m of the bankfull channel, or ejected onto the floodplain with the center > 1 m outside the bankfull channel.

Stream geomorphic data

Data on stream geomorphology were collected for all study reaches in summer 2007. Cross-sections were surveyed every 10 m in each study reach using a measuring tape and a laser level on a tripod (Harrelson et al. 1994), except at the two largest streams where 40 of 80 (Beaver River) or 12 of 50 (Knife River) 10-m sections were surveyed. The bed slope was calculated for each reach using the difference in elevation between the lowermost points at the upstream and downstream ends of the reach. The effective stream width was estimated for each 10-m section as the shortest unobstructed width for flows 0.5 m above bankfull (Figure 5). Vegetation was considered to be obstructive if it was at least 0.02 m in stem diameter. Initial estimates of Manning's roughness coefficient for the channel and the floodplain were made using the methods of Arcement and Schneider (1989).

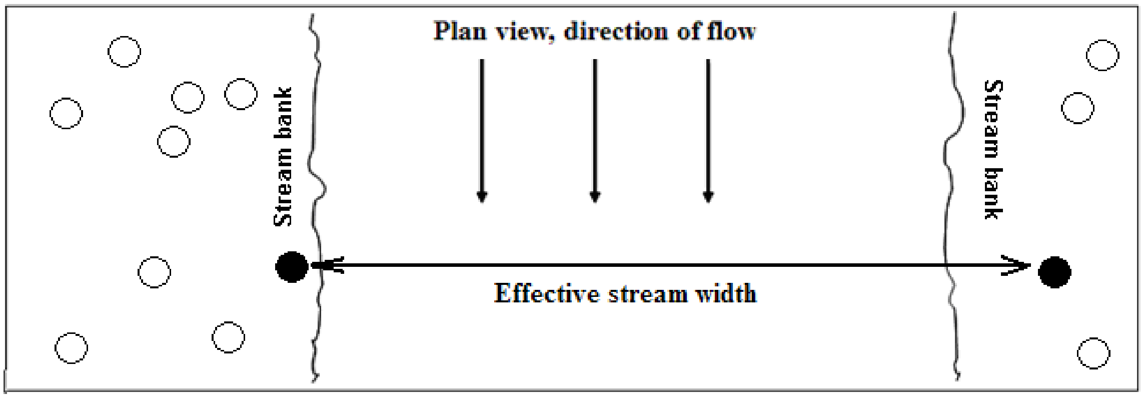


Figure 5. Plan view of channel illustrating lateral positions of trees (open circles) large enough to brace a floating piece of wood. Effective stream width was defined as the lateral distance between the innermost trees (closed circles) for each 10-m section of stream or the actual wetted width, whichever was shorter.

Hydraulic data

The computer simulation model HEC-RAS 4.0 (available online)[10] was used to calculate hydraulic parameters for each 10-m section; HEC-RAS is appropriate for studying stream characteristics at the 10-m resolution (Brooks et al. 2006). Based on geomorphic survey data, HEC-RAS was used to estimate unit stream power, stage, velocity, and energy grade slope (Gordon et al. 2004) at each 10-m section for discharges corresponding to the peak flow during overbank conditions in fall 2007. Although overbank flows were included in the models and used for wetted width, only the portion of the discharge that was in the bankfull channel was considered when calculating mean velocity, depth, unit stream power, and wetted area (Table 1).

To calibrate the hydraulic model for each study reach, the initial estimate for Manning's channel roughness coefficient was varied (between 0.02 and 0.07) to obtain the best fit between the predicted and observed stream stage as measured at each cross-

[10] (http://www.hec.usace.army.mil/software/hec-ras/)

section during summer 2007. The final r^2 values between the predicted and observed stream stages ranged from 0.77 to 1.00.

Wood entrapment

In fall 2007, after floodwaters had receded, we located tagged wood pieces in each study reach. Pieces that traveled downstream at least 10 m were used; pieces that did not move or that moved less than 10 m were not classified as mobilized and were thus culled from the dataset. The dataset of pieces that moved at least 10 m was split into two groups: those that left the study reach and were not found and those that traveled downstream but were entrapped before leaving the study reach. We used a logistic response for subsequent analyses of entrapment; pieces in the former group were assigned a 0 and pieces in the latter group were assigned a 1. Although pieces were not remeasured, only seven mobilized pieces were known to have broken (based on the position of the tags; the shorter portion of the piece was disregarded). For each piece that left the study reach, we recorded the specific 10-m sections the piece passed through, and associated the mean geomorphic and hydraulic data of those sections with that piece. For each piece that moved but was entrapped within the study reach we used the geomorphic and hydraulic data of the section in which the piece was entrapped.

DATA ANALYSIS METHODS

Data from wood pieces, stream geomorphology, and hydraulic simulations were used to quantify predictor variables considered likely to influence wood entrapment. The length ratio was piece length divided by effective stream width, and the draft ratio was piece draft divided by mean depth in the channel. Blockage was calculated as the submerged area (assuming the piece was oriented parallel to flow as suggested by Braudrick and Grant 2001) divided by the wetted channel area. Weight of each piece was its volume multiplied by density, and momentum of each piece was calculated using equation (3) assuming the piece traveled at the same velocity as the flow (Braudrick and Grant 2001).

A multiple logistic regression model was developed to determine the factors most important to wood entrapment, using the logistic entrapment data as the response variable. The predictor variables for the initial model were length ratio, weight, draft ratio, branching complexity, rootwad presence, blockage, and momentum. The final model was chosen using the statistical software R (available online)[11] to examine the best fit between possible combinations of predictor variables and the logistic response variable. The final model had the lowest AIC among all models with Variance Inflation Factor < 2 for all predictor variables (to avoid collinearity). The regression equation for the final model produced a probability of entrapment for a given piece passing through a given 10-m section.

RESULTS

A total of 956 pieces of wood were tagged and measured, but most were excluded from analyses for several reasons. First, pieces (n=98) were excluded if they were

[11] (http://www.r-project.org/)

initially part of a spanning logjam. These pieces would be expected to exhibit congested flow, where all pieces in the logjam would travel downstream en masse rather than independently from one another (Braudrick et al. 1997). Two spanning logjams were initially present; both were completely mobilized by the high discharge in fall 2007 and likely did not influence entrapment of other pieces. Second, an additional 12 pieces were excluded because they became entrapped by a culvert at the downstream end of a study reach. Entrapment by culverts was only observed at one of the study reaches, where two 6-m culverts had been placed side by side for a road crossing. Third, pieces (n = 502) were excluded if they traveled less than 10 m between summer and late fall 2007, thus there were a total of 344 wood pieces for analysis of entrapment.

Wood pieces and streams covered a range of characteristics (Table 2). For example, the mean piece length was 2.8 m with a standard deviation (*s.d.*) of 2.1 m, mean diameter was 0.15 m (*0.13 m*), and mean wood density was 0.74 g/cm^3 (*0.33 g/cm^3*). The mean wetted width of the streams was 24 m (*15 m*), and mean water depth in the channels was 1.3 m (*0.6 m*). The mean water velocity in the channels was 1.4 m/s (*0.6 m/s*), and unit stream power in the channels had a mean of 125 N/m s (*113 N/m s*). Many characteristics appeared to follow a chi-square distribution (Appendix D), which is acceptable because multiple logistic regression is not constrained by the distributions of predictor variables (Weisberg 1985). The study streams varied within and among themselves in geomorphic and hydraulic characteristics (Table 3).

Table 2. Mean and *standard deviation* for characteristics of wood pieces and 10-m stream sections at the nine study reaches.

	Units	Mean	
Piece length	m	2.8	*2.1*
Length ratio	-	0.31	*0.36*
Diameter (*2r*)	m	0.15	*0.13*
Wood density (ρ_{log})	g/cm^3	0.74	*0.33*
Draft (*D*)	m	0.1	*0.09*
Draft ratio	-	0.09	*0.11*
Branching complexity	-	6	*22*
Volume (V_{log})	m^3	0.11	*0.5*
Blockage	-	0.01	*0.02*
Weight	N	8	*27*
Vertical force ratio	-	1.1	*0.2*
Momentum	kg m/s	10	*29*
Wetted width	m	24	*15*
Mean depth in channel	m	1.3	*0.6*
Water velocity (*U*)	m/s	1.4	*0.4*
Unit stream power (ω)	N/m s	125	*113*
Energy grade slope	m/m	0.008	*0.009*
Effective stream width	m	13.4	*7.6*

Table 3. Mean and *standard deviation* for hydraulic and geomorphic characteristics for each study site during peak discharges in fall 2007. Depth, velocity, and power values do not include water in the floodplain.

	Mean wetted depth (m)		Water velocity (m/s)		Power (N/m s)		Bed slope (m/m)	Bankfull width (m)		Peak discharge (m^3/s)
Beaver River	1.66	*0.30*	0.86	*0.32*	15	*35*	0.001	16.0	*3.0*	21.7
French River	0.74	*0.17*	1.53	*0.34*	119	*84*	0.020	11.3	*2.5*	12.0
Knife River	1.51	*0.29*	1.44	*0.22*	137	*57*	0.006	24.4	*5.3*	54.7
Lt. East Knife	1.48	*0.22*	1.17	*0.42*	78	*135*	0.004	3.4	*0.9*	7
Lt. West Knife	0.53	*0.15*	1.15	*0.33*	40	*36*	0.012	3.7	*0.8*	2.1
Sucker River	0.98	*0.13*	1.84	*0.33*	252	*169*	0.016	9.9	*2.2*	17.5
Talmadge Cr.	0.78	*0.14*	1.62	*0.25*	247	*135*	0.025	5.3	*1.6*	7.0
Upper Knife	0.84	*0.08*	1.48	*0.25*	93	*46*	0.009	6.6	*1.1*	8.3
W Split Rock	2.48	*0.28*	1.92	*0.45*	153	*108*	0.007	6.9	*0.9*	54.4
*Brule River	2.27	*0.61*	2.20	*0.61*	515	*439*	0.012	22.2	*3.3*	104.0
*East Beaver	1.20	*0.26*	1.14	*0.35*	91	*76*	0.008	11.7	*3.2*	16.3
*Poplar River	1.82	*0.33*	3.07	*0.55*	1111	*432*	0.034	10.9	*2.4*	62.3

*2008 bracing study only

Of the 344 wood pieces that met the criteria for this study, 110 (32%) were entrapped before leaving the study reach; the mean length and diameter for entrapped pieces was 3.42 and 0.19 m whereas the mean length and diameter for non-entrapped pieces was 2.51 and 0.13 m. Mean wood density was 0.81 and 0.71 g/cm^3 for entrapped and non-entrapped pieces.

The final model for entrapment was highly significant ($p < 0.001$) and included four predictor variables (Table 4). Nagelkerke's r^2 for the final model was 0.25, corresponding to a Goodman-Kruskal gamma of 0.50 and Kendall's tau-a of 0.22. The four predictor variables were the length ratio, weight, branching complexity, and rootwad presence. However, branching complexity and rootwad presence contributed little to the model. The individual p-values for branching complexity and rootwad presence were > 0.05, and rootwad presence would have been excluded from the final model if the AIC penalty were increased from 2 to 3.

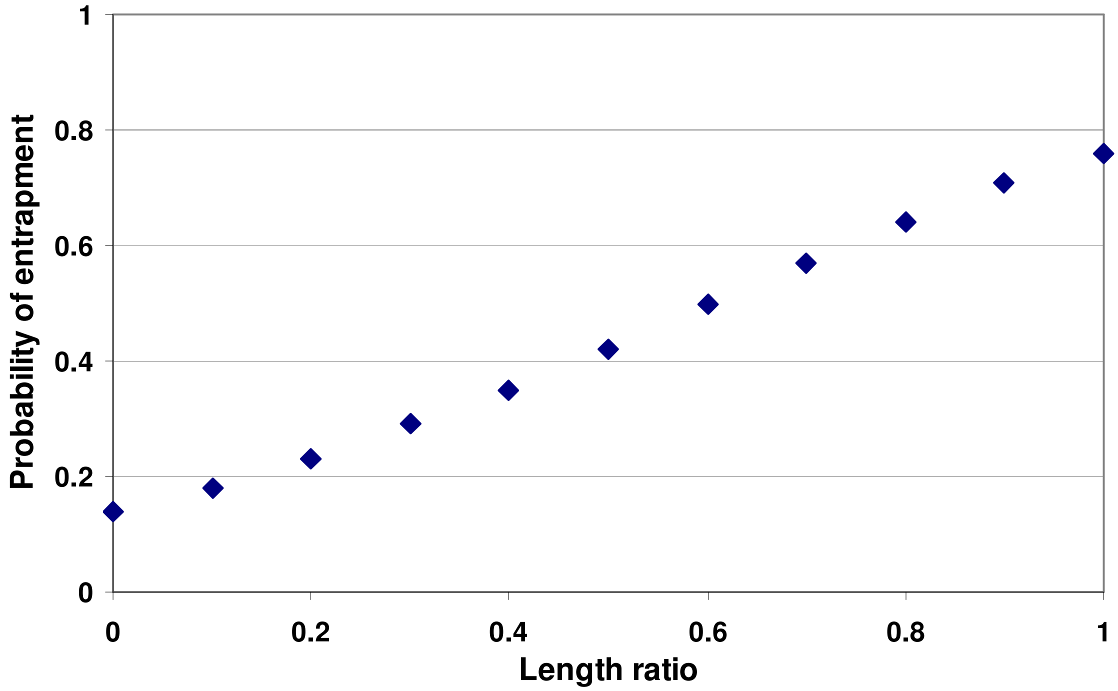
Table 4. Variables retained in the final model for entrapment; n = 344 pieces of wood. Overall model $p < 0.001$ and Nagelkerke's $r^2 = 0.25$.

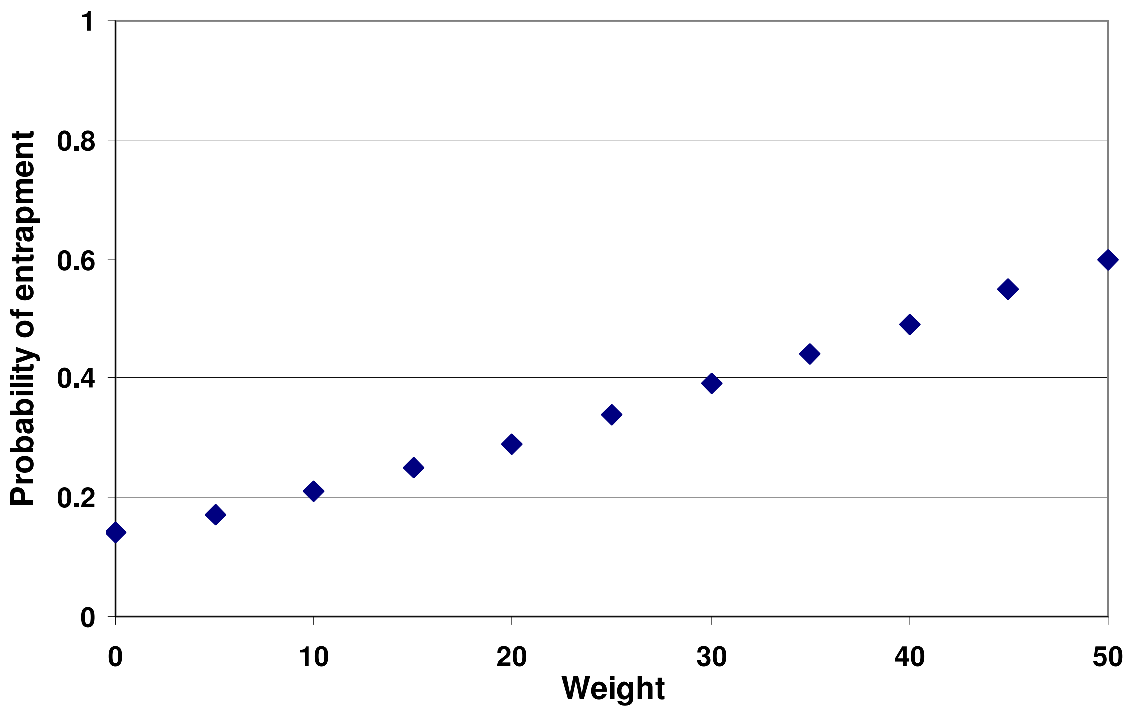
	Coefficient	S.E.	Wald Z	p-value	VIF
Intercept	-1.783	0.214	-8.34	<0.001	
Length ratio	2.959	0.618	4.79	<0.001	1.205
Weight	0.044	0.018	2.41	0.0158	1.169
Br Complexity	-0.011	0.007	-1.72	0.0846	1.230
Rootwad	-0.805	0.573	-1.41	0.1599	1.034

Using the multiple logistic regression results, the probability (*P*) of entrapment was calculated for each predictor as

$$P = \exp(\beta_0 + \beta_1 x_1)/(1 + \exp(\beta_0 + \beta_1 x_1)) \quad (5)$$

where β_0 was the intercept (e.g., -1.783 in Table 4), β_1 was the model coefficient for the variable of interest, and x_1 was the value for the variable of interest, with all other variables held constant. Using the model coefficient for the length ratio (2.959 in Table 5), equation (5) indicated that a piece with the mean length ratio ($x_1 = 0.31$) had a 0.30 probability of being entrapped, whereas an increase to one standard deviation above the mean (($x_1 = 0.67$) was associated with a 0.55 probability of entrapment. Taking the difference (0.55 – 0.30 = 0.25) indicated that a piece with the higher length ratio was 25% more likely to be entrapped, assuming all other variables were held constant. Similarly, increasing the weight of a piece from the mean value (8) to one standard deviation above the mean (35) was associated with a 15% increase in the probability of entrapment (Figure 6). Branching complexity and rootwad presence had weaker effects on entrapment. Decreasing the branching complexity from 6 (the mean value) to 1 (no branches, the least value) was associated with a 1% increase in the probability of entrapment, and the probability of entrapment was 7% lower if a rootwad was present.


Probability of entrapment
Length ratio
0
0.2
0.4
0.6
0.8
1


Probability of entrapment
Weight
0
10
20
30
40
50

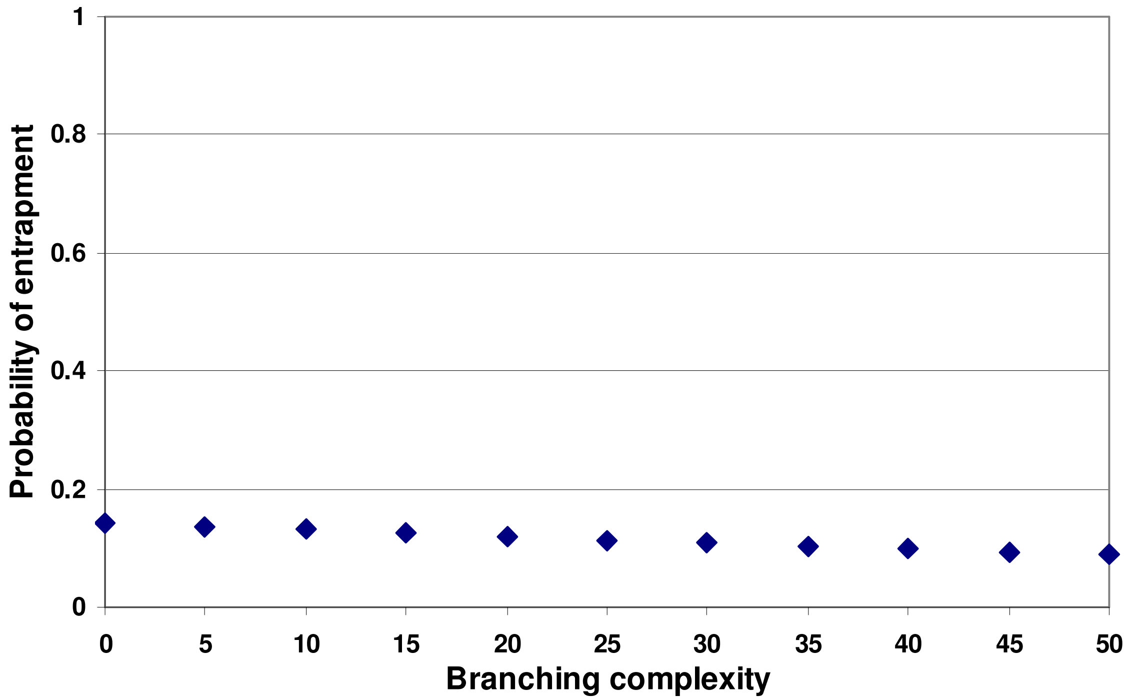


Figure 6. Expected probability of entrapment as a function of the length ratio, weight, or branching complexity.

Expanding equation (5) to consider changes in the full set of predictor variables yields

$$P = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4) / (1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4)) \quad (6)$$

where $\beta_1 x_1 \ldots \beta_4 x_4$ correspond to coefficients and values for the four predictor variables. Combining the prior examples, a piece of wood with length ratio of 0.31, weight of 8, branching complexity of 6, and a rootwad had a probability of entrapment $P = 0.20$. Conversely, a piece with length ratio of 0.67, weight of 35, branching complexity of 1, and no rootwad had $P = 0.85$.

A total of 166 new pieces were entrapped in 2008 (Figure 7). The most common method of entrapment was pieces that were lying loose in the channel (n = 72), followed by pieces that were braced by other pieces of wood in the channel (n = 48), ejected onto the floodplain (n = 18), braced by rocks in the channel (n = 14), braced by the stream banks or bed (n = 9), and braced by live vegetation in the channel (n = 5, mainly trees).

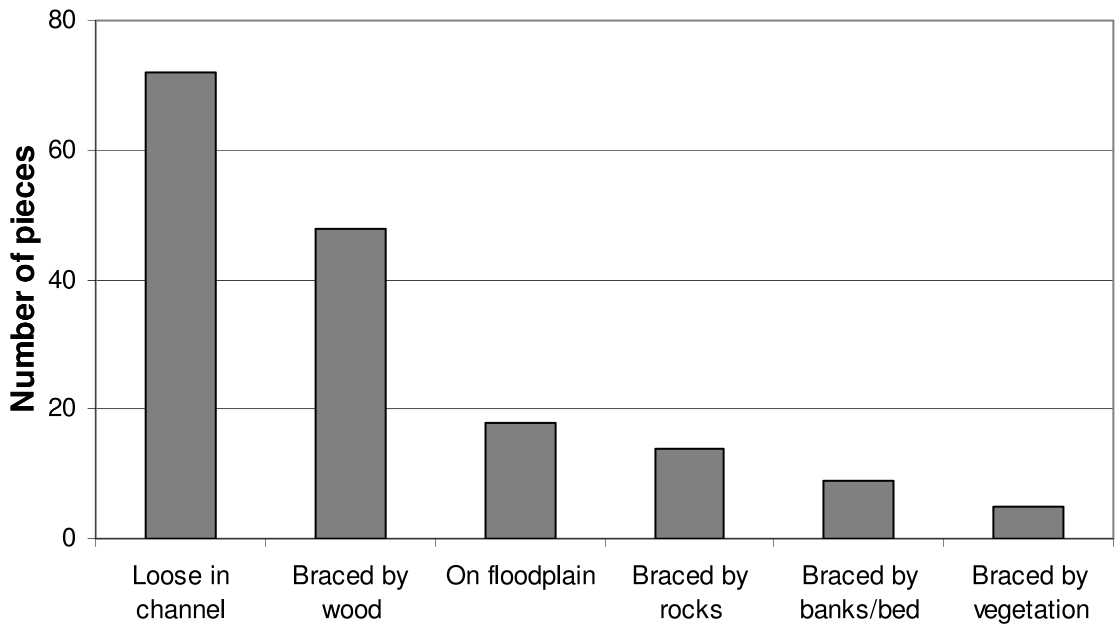


Figure 7. Numbers of new pieces found in 2008 in three stream reaches, according to location or manner in which pieces were braced.

DISCUSSION

We found two factors to be of primary importance for wood entrapment in natural streams: the ratio of piece length to effective stream width (length ratio) and piece weight. The coefficient of determination for the entrapment model, while not high (i.e., 0.25), was substantially stronger than obtained in some studies (e.g., 0.01 by Jacobsen et al. 1999 and 0.06 by Braudrick and Grant 2001). The reason may be that we evaluated a diverse set of conditions. Our study included a natural range of wood pieces, geomorphology, and hydraulics from nine streams, providing the entrapment model with much variability to explain. Although a higher coefficient of determination was obtained using a dense network of obstructions in a flume (Bocchiola et al. 2006), the applicability of those results to natural conditions is unclear.

Pieces with higher length ratios were more likely to be entrapped, according to our multiple logistic regression model. Previous studies have also determined that the ratio of piece length to stream width was of primary importance for entrapment (Lienkaemper and Swanson 1987, Gurnell et al. 2002, Hassan et al. 2005, Wyzga and Zawiejska 2005). However, those studies used bankfull channel width as the measure of stream width rather than effective stream width, which takes into account both the actual wetted width and the infringement of woody vegetation.

Weight was also important in the final model for entrapment; heavier pieces were more likely to be entrapped. Piece weight is the product of volume and density, which both suggest possible explanations for the positive association of weight with entrapment. Greater volume may increase the probability that a piece will contact obstructions, including submerged obstructions as discussed previously (e.g., large boulders, islands, or other pieces of wood) or above-water obstructions such as tree roots and low-hanging branches. Higher piece density increases draft, and thus the likelihood that the piece will contact the stream bed. Weight may therefore relate to the same mechanisms as draft ratio and blockage (i.e., entrapment from contact with obstructions or the stream bed) and is itself a component of momentum.

Branching complexity and rootwad presence were also included in the final model for entrapment. Contrary to our predictions, pieces with higher branching complexity and rootwads were less likely to be entrapped. An unknown mechanism may be at work with branching complexity and rootwad presence, or the variables may be correlated with some unmeasured parameter that decreased the likelihood of entrapment. However, the statistical significance of both variables was weak (the individual p-values for both variables were > 0.05) and the predictors may not be meaningful. Branching complexity is influenced by the number of small twigs (Newbrey et al. 2005), which are unlikely to play a role in entrapment. A small twig could break off if, for example, it became caught between rocks but was unable to resist the hydrodynamic drag acting on the full piece. Future studies might instead consider a branching ratio, such as the combined length of large branches (> 0.05 m in diameter, excluding the main bole of the piece) divided by the length of the main bole.

The final model did not include draft ratio, momentum, or blockage; those variables had no significant influence on entrapment after accounting for length ratio, weight, branching complexity, and rootwad presence. Although previous studies have suggested that draft ratio influences entrapment (Braudrick and Grant 2001, Haga et al. 2002), those studies minimized the influence of the length ratio by using pieces that were shorter than the channel width. Our dataset was much more diverse in terms of length ratio, piece weight, branching complexity, and rootwad presence (Braudrick and Grant 2001, Haga et al. 2002) and covered a natural range of conditions.

The final model equation (6) can be applied to a range of conditions, as outlined in Table 3. Although the current study included only a single year, the study streams exhibited a range of geomorphic and hydraulic conditions, thus the final model is likely applicable to at least a similar range of conditions in other streams. The peak discharges for the study period varied from 2.1 to 54.7 m^3/s at the nine study streams, corresponding to a range of mean wetted widths from 3.8 to 71.2 m. Lengths of pieces were from 1.0 to 15.3 m with estimated weights from 0.08 to 327 N. Our analyses are thus applicable to natural pieces and streams that are of interest to stream managers.

Our study can enhance management of wood in streams. For example, the model equation (6) could be used to determine the effective stream width required to reduce wood entrapment around road crossings or other infrastructure, provided that data were collected on wood characteristics. The requisite stream width, in particular, could be used to design bridge spans or culvert diameters. It bears noting that the pair of culverts in one study reach entrapped a disproportionate number of pieces, including 42 marked pieces (that were excluded from analyses). Using a mean piece length of 2.8 m, our model equation associates a 33% reduction in entrapment with replacing a 3-m culvert with a 6-m span bridge.

Alternatively, our study may also be applied to promote wood entrapment in managed or restored streams where wood is valued for its ecological functions. The model equation (6) can be used to determine the effective stream width required to entrap pieces of a given length. Alternatively, the model can be used for a given stream width to determine the length of pieces required to become entrapped. If natural wood pieces of the required size are not available, short-term wood additions and long-term riparian management may be used to increase present and future standing stocks of instream wood (Murphy and Koski 1989, Czarnomski et al. 2008).

Regardless of input levels, entrapment of wood in streams begets more wood in streams (Abbe and Montgomery 2003, Bocchiola et al. 2008, Warren and Kraft 2008). Of the new pieces of wood that were entrapped in 2008, more pieces were entrapped by other pieces of wood than were ejected onto the floodplain or entrapped by rocks, stream banks, or vegetation. No spanning logjams were present in 2008; scattered pieces of wood provide valuable ecological functions and a positive feedback toward further wood accumulation even without the influence of spanning logjams.

CONCLUSION

Entrapment remains difficult to predict in natural streams. Although the model derived in this study explained more variability in entrapment than previous field studies, the coefficient of determination was only 0.25. Of the new pieces entrapped in 2008, a full 43% were lying loose in the channel and not entrapped by any obvious mechanism. In some cases, entrapment may simply occur wherever the piece is located when high water recedes (Jacobsen et al. 1999), and be unrelated to characteristics of the piece or the stream channel. The process of wood entrapment in streams merits further study for predicting wood's ecological functions and the success of restoration efforts.

ACKNOWLEDGEMENTS

Wood and survey data were collected by Jo Fritz, Ryan Carlson, Dustin Wilman, Nicole Rath, Levi Drevlow, Ryan Johnsen, and April Bebault. Rachael Stanze and Nathan Schroeder collected continuous discharge data from six streams. Logistical support was provided by Tracy Close of Minnesota Department of Natural Resources, Marty Rye of USDA Forest Service, the Minnesota Cooperative Fish and Wildlife Research Unit, and the Natural Resources Research Institute. Funding was provided by the Minnesota Department of Natural Resources and Minnesota Sea Grant.

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APPENDIX A. List of symbols

Symbol	Definition
F_B	Buoyancy force
g	Gravity
ρ_w	Density of water
V_{sub}	Submerged volume of piece
F_W	Weight
ρ_{log}	Density of piece
V_{log}	Total volume of piece
D	Draft of piece
2r	Radius of piece
F_F	Friction on stream bed
f_{bed}	Stream bed friction coefficient
α	Stream bed gradient (slope)
F_D	Hydrodynamic drag
U	Stream velocity
C_d	Form drag coefficient
A_N	Submerged area normal to flow
C_f	Skin friction drag coefficient
A_{SA}	Submerged surface area of piece
θ	Orientation relative to flow
L	Length of piece
d_{sub}	Submerged depth of piece
ν	Kinematic viscosity
γ	Pitch from stream bed
F_L	Lift force
C_l	Lift coefficient
Q	Discharge
A_{wet}	Wetted area of stream
n	Manning's roughness coefficient
R	Hydraulic radius
F_V	Vertical friction
f_{brace}	Coefficient of friction on brace
ψ	Vertical angle of brace
R_V	Vertical force ratio
R_D	Downstream force ratio
L*	Length ratio
D*	Draft ratio
P	Probability of mobilization
β_0	Intercept coefficient
β_n	Coeffieient for n^{th} variable

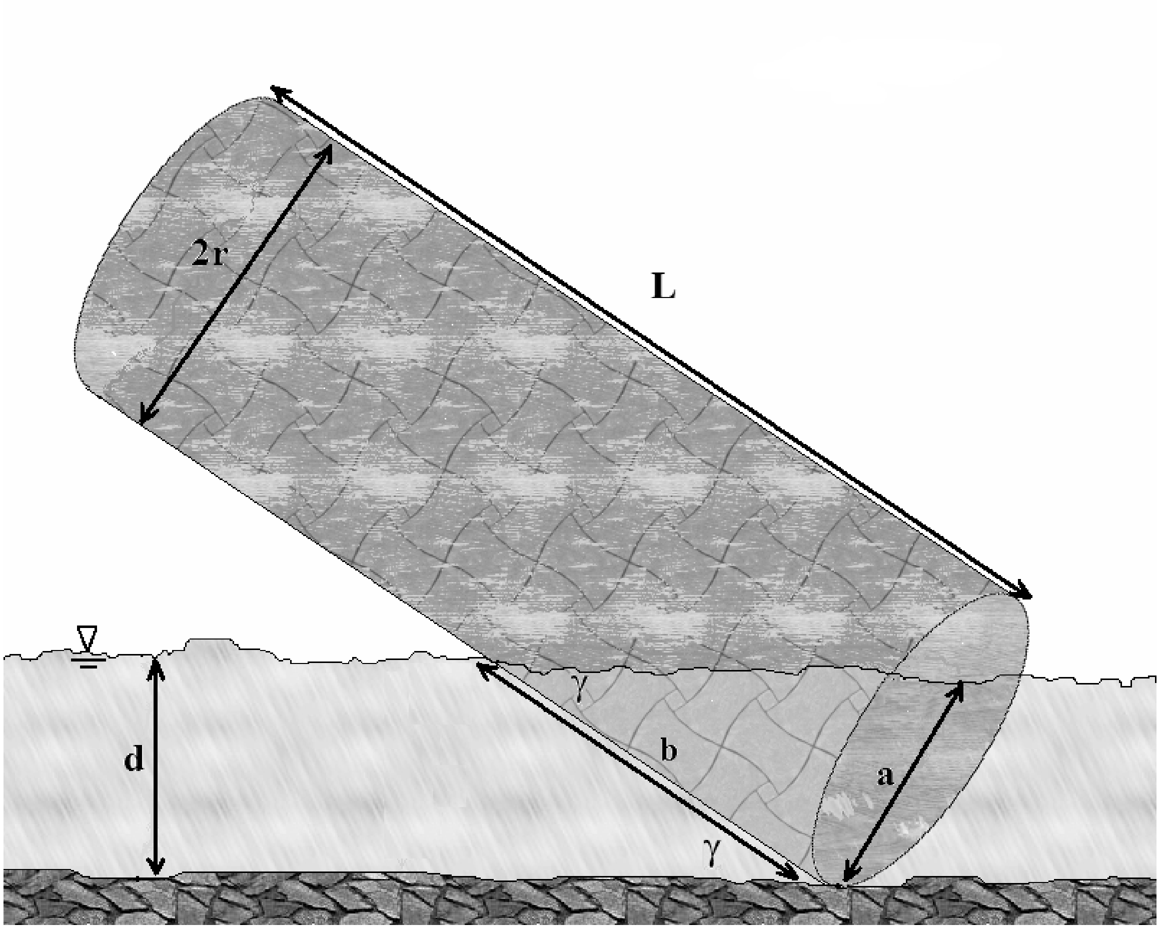
APPENDIX B. Calculating Submerged Volume and Area Normal to Flow

Submerged Volume

Case 1. Piece is horizontal. For a cylindrical piece resting flat on the stream bed the submerged volume is a function of water depth, where

$$V_{sub} = L\left[r^2 \sin^{-1}\left(\frac{-r+d}{r}\right) + (-r+d)\sqrt{2dr - d^2} + \frac{\pi}{2}r^2\right]$$

where L is the length of the piece, r is the radius of the piece, and d is the effective depth (Figure 1). In this case, and all cases below, the maximum value is the volume of the entire cylinder if it is completely submerged.



Appendix Figure 1. Mathematical values are illustrated for a piece of wood in a stream.

Case 2. If the piece is raised at a pitch γ (radians) relative to the stream bed (perhaps by a branch or rootwad, Figure 1) the submerged volume becomes a function of a and b, where a = d/cos(γ) and b = d/sin(γ) and 0 radians < γ ≤ π/2 radians. The first case is where a < 2r and b < L where

$$V_{sub} = \frac{2}{3\tan(\gamma)}(2ar - a^2)^{3/2} + \frac{(a-r)}{\tan(\gamma)}\left[r^2 \sin^{-1}\left(\frac{-r+a}{r}\right) + (-r+a)\sqrt{2ar-a^2} + \frac{\pi}{2}r^2\right]$$

Case 3. When a < 2r and b > L the formula includes m, where m = tan(γ) (d/sin(γ) – L)

$$V_{sub} = \frac{2}{3\tan(\gamma)}(2ar-a^2)^{3/2} + \frac{(a-r)}{\tan(\gamma)}\left[r^2\sin^{-1}\left(\frac{-r+a}{r}\right) + (-r+a)\sqrt{2ar-a^2} + \frac{\pi}{2}r^2\right]$$

$$-\left(\frac{2}{3\tan(\gamma)}(2mr-m^2)^{3/2} + \frac{(m-r)}{\tan(\gamma)}\left[r^2\sin^{-1}\left(\frac{-r+m}{r}\right) + (-r+m)\sqrt{2mr-m^2} + \frac{\pi}{2}r^2\right]\right)$$

Case 4. When a > 2r and b < L the formula includes l, where l = d/sin(γ) – 2r/tan(γ)

$$V_{sub} = \pi r^2 l + \frac{\pi r^3}{\tan(\gamma)}$$

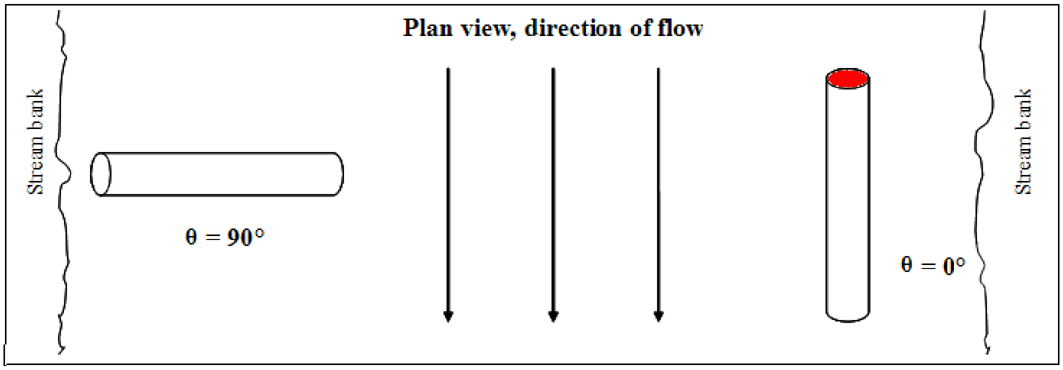
Case 5. When a > 2r and b > L the formula is

$$V_{sub} = \pi r^2 l + \frac{\pi r^3}{\tan(\gamma)}$$

$$-\left(\frac{2}{3\tan(\gamma)}(2mr-m^2)^{3/2} + \frac{(m-r)}{\tan(\gamma)}\left[r^2\sin^{-1}\left(\frac{-r+m}{r}\right) + (-r+m)\sqrt{2mr-m^2} + \frac{\pi}{2}r^2\right]\right)$$

Submerged Area Normal to Flow

The submerged area normal to the flow can be estimated by adding the area normal to the flow for the upstream face of the piece (a circle, with maximum value of πr^2, Figure 2) to the area normal to the flow for the remainder of the piece (a rectangle, with maximum value of 2rL). The equations used depend upon both γ (the pitch relative to the stream bed, in radians) and θ (the orientation relative to the flow, in radians, Figure 2).



Appendix Figure 2. Plan view of channel illustrating example pieces of wood oriented perpendicular to the flow ($\theta = \pi/2$ radians) and parallel to the flow ($\theta = 0$ radians). The upstream face of each piece is shaded.

Case 1. Piece is horizontal and parallel to the flow. In this case the area normal to the flow is comprised entirely of the submerged area of the upstream face, where

$$A_{sub} = \left[r^2 \sin^{-1}\left(\frac{-r+d}{r}\right) + (-r+d)\sqrt{2dr-d^2} + \frac{\pi}{2}r^2\right]$$

Case 2. Piece is vertical ($\gamma = \pi/2$ radians). In this case the area normal to the flow is

$$A_{sub} = 2rh$$

which is a rectangle, where h is the lesser of d or L.

Case 3. Piece perpendicular to the flow, a < 2r, and b < L. The upstream face of the piece has no area normal to the flow, and the area for the remainder of the piece is

$$A_{sub} = \frac{d^2}{2\sin(\gamma)\cos(\gamma)}$$

Case 4. Piece perpendicular to the flow, a < 2r, and b > L. The upstream face of the piece has no area normal to the flow, and the area for the remainder of the piece is

$$A_{sub} = \frac{L}{\cos(\gamma)}\left(d - \frac{L\sin(\gamma)}{2}\right)$$

Case 5. Piece perpendicular to the flow, a > 2r, b < L. The upstream face of the piece has no area normal to the flow, and the area for the remainder of the piece is

$$A_{sub} = 2r\left(\frac{d}{\sin(\gamma)} - \frac{r}{\tan(\gamma)}\right)$$

Case 6. Piece perpendicular to the flow, a > 2r, b > L. The upstream face of the piece has no area normal to the flow, and the area for the remainder of the piece is

$$A_{sub} = 2r\left(\frac{d}{\sin(\gamma)} - \frac{r}{\tan(\gamma)}\right) - \frac{\tan(\gamma)}{2}\left(\frac{d}{\sin(\gamma)} - L\right)^2$$

Case 7. Piece is parallel to the flow, is neither horizontal nor vertical, and d < 2r. In this case the area normal to the flow includes area from both the upstream face of the piece and the remainder of the piece. The area from the upstream face of the piece is

$$A_{sub} = \cos(\gamma)\left[r^2\sin^{-1}\left(\frac{-r+d}{r}\right) + (-r+d)\sqrt{2dr-d^2} + \frac{\pi}{2}r^2\right]$$

and the area for the remainder of the piece is

$$A_{sub} = 1/(2\tan(\gamma))\ ((d-r)^2-r^2) + (d-r)/\tan(\gamma)\ (d-2r)$$

Case 8. Piece is parallel to the flow, is neither horizontal nor vertical, d > 2r, and d > L sin(θ). In this case the area normal to the flow includes area from both the upstream face of the piece and the remainder of the piece. The area from the upstream face of the piece is

$$A_{sub} = \cos(\gamma)\left[r^2 \sin^{-1}\left(\frac{-r+d}{r}\right) + (-r+d)\sqrt{2dr-d^2} + \frac{\pi}{2}r^2\right]$$

and the area for the remainder of the piece is

$$A_{sub} = r\ (d\text{-}r)/\tan(\gamma)$$

Case 9. Piece is parallel to the flow, is neither horizontal nor vertical, d > 2r, and d > L sin(θ). In this case the area normal to the flow includes area from both the upstream face of the piece and the remainder of the piece. The area from the upstream face of the piece is

$$A_{sub} = \cos(\gamma)\left[r^2 \sin^{-1}\left(\frac{-r+d}{r}\right) + (-r+d)\sqrt{2dr-d^2} + \frac{\pi}{2}r^2\right]$$

and the area for the remainder of the piece is

$$A_{sub} = r\ (L\ \sin(\gamma)\text{-}r)/\tan(\gamma)$$

Case 10. Piece is not vertical and is neither parallel nor perpendicular to the flow. In this case the area normal to the flow includes area from both the upstream face of the piece and the remainder of the piece. The area from the upstream face of the piece is

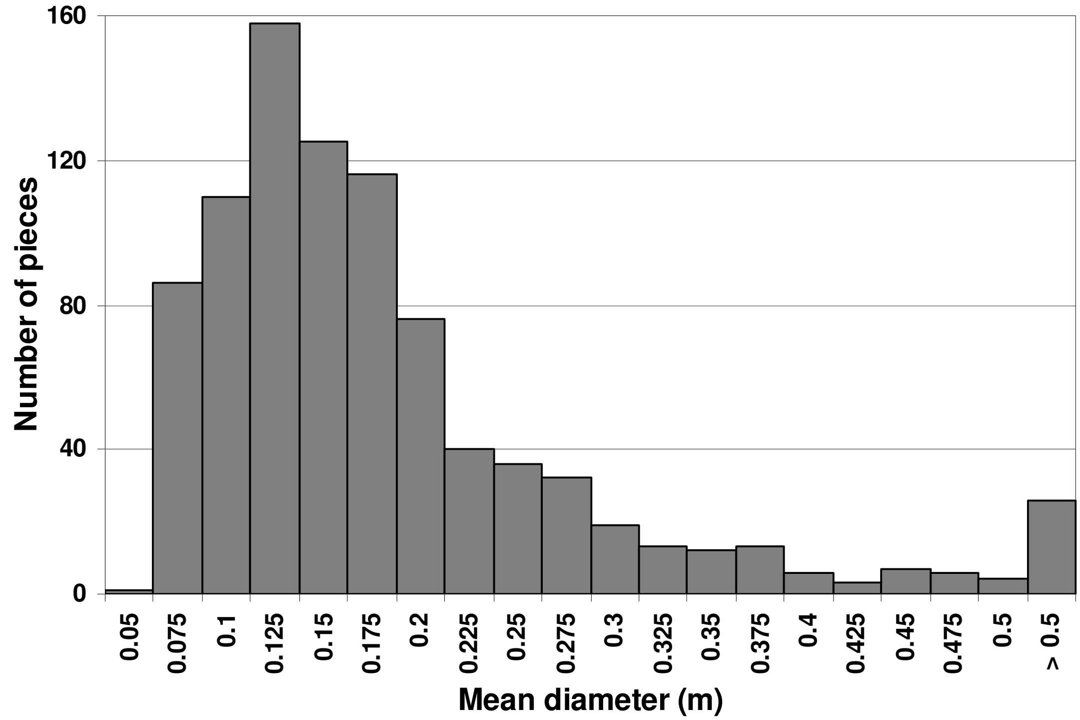
$$A_{sub} = \cos(\gamma)\ \cos(\gamma)\left[r^2 \sin^{-1}\left(\frac{-r+d}{r}\right) + (-r+d)\sqrt{2dr-d^2} + \frac{\pi}{2}r^2\right]$$

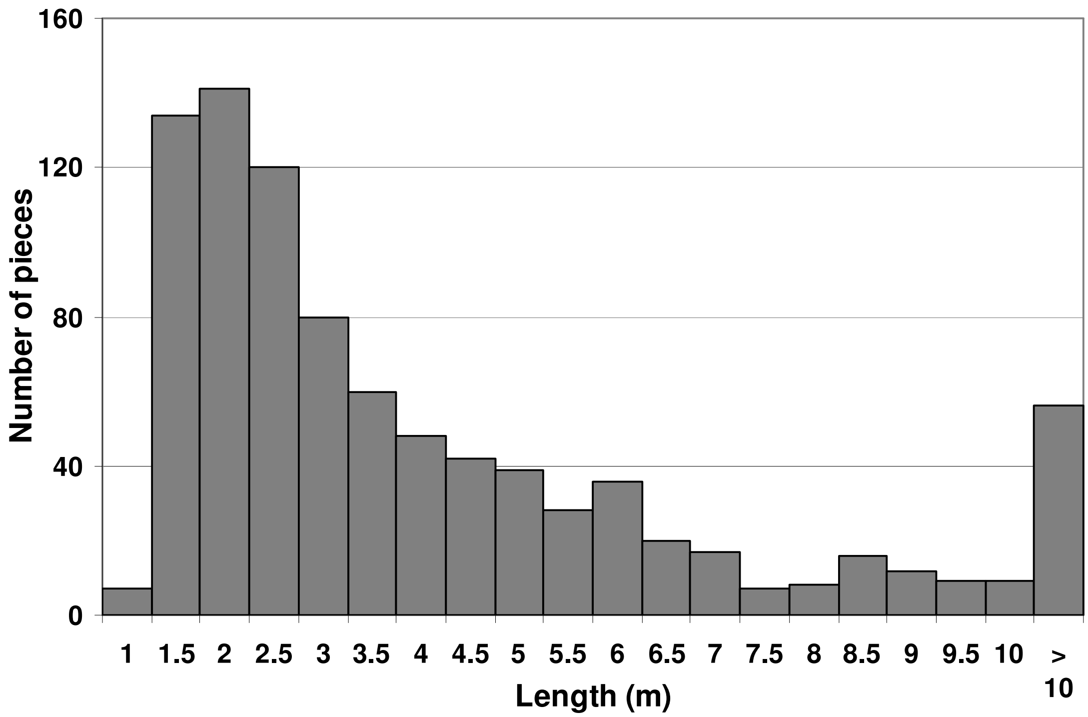
and the area for the remainder of the piece can be approximated by

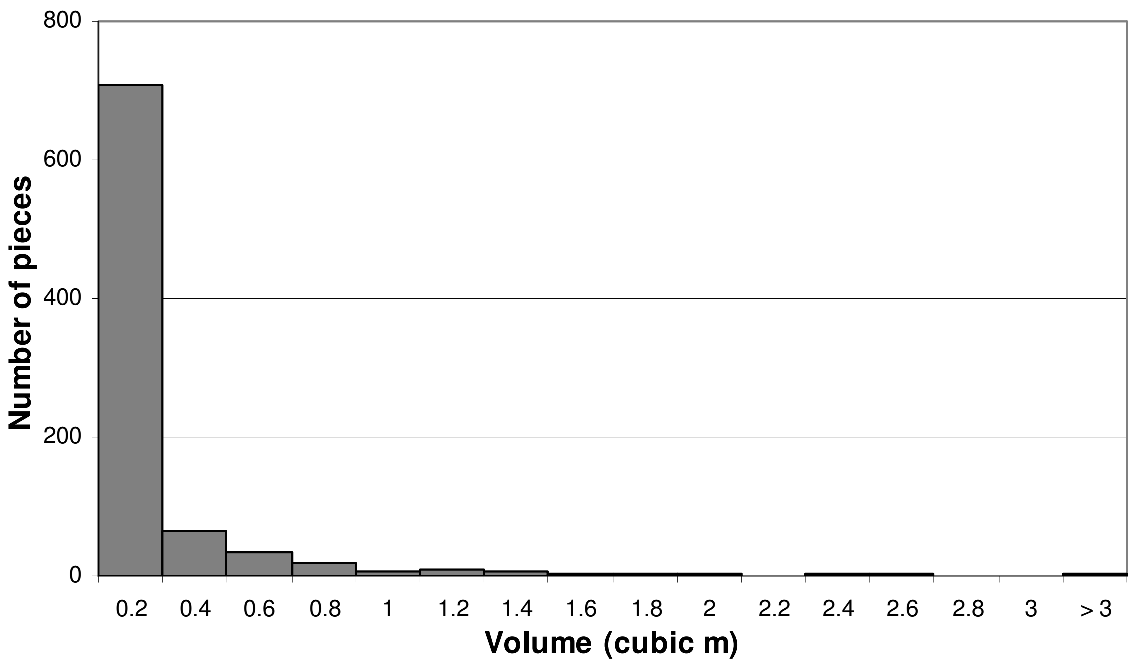
$$A_{sub} = \cos^2(\theta)\ X + \sin^2(\gamma)\ Y$$

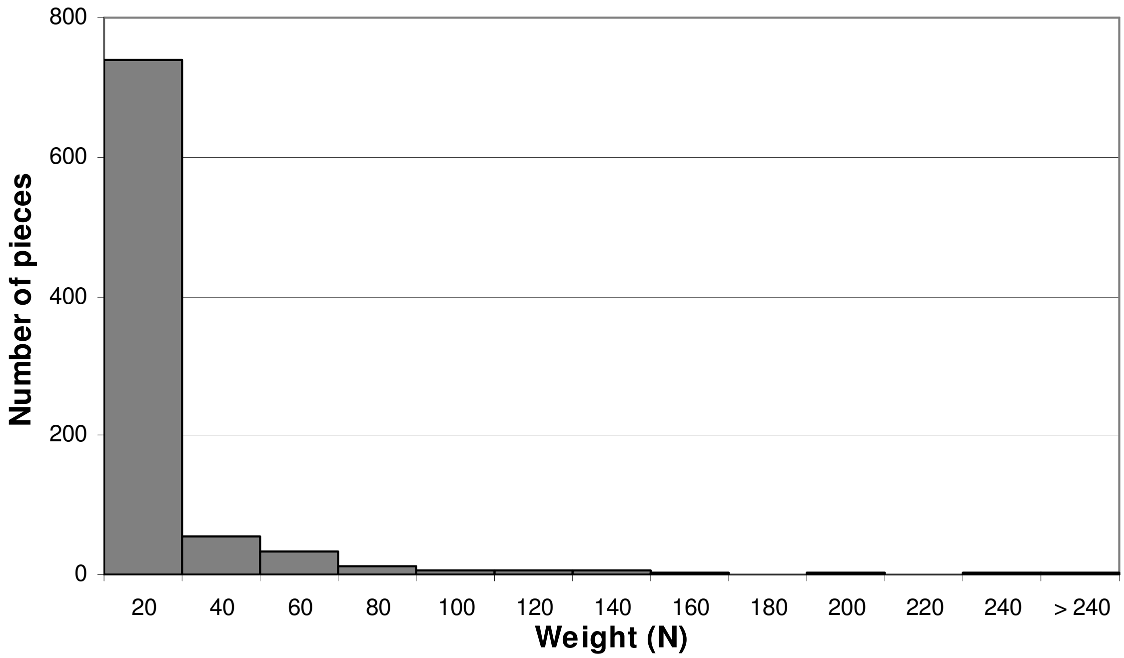
where X is the value for the remainder of the piece according to the appropriate Case 7-9 (depending on the values of a and b), Y is the value according to the appropriate Case 3-6, and θ is the orientation of the piece relative to the flow (in radians, Figure 2).

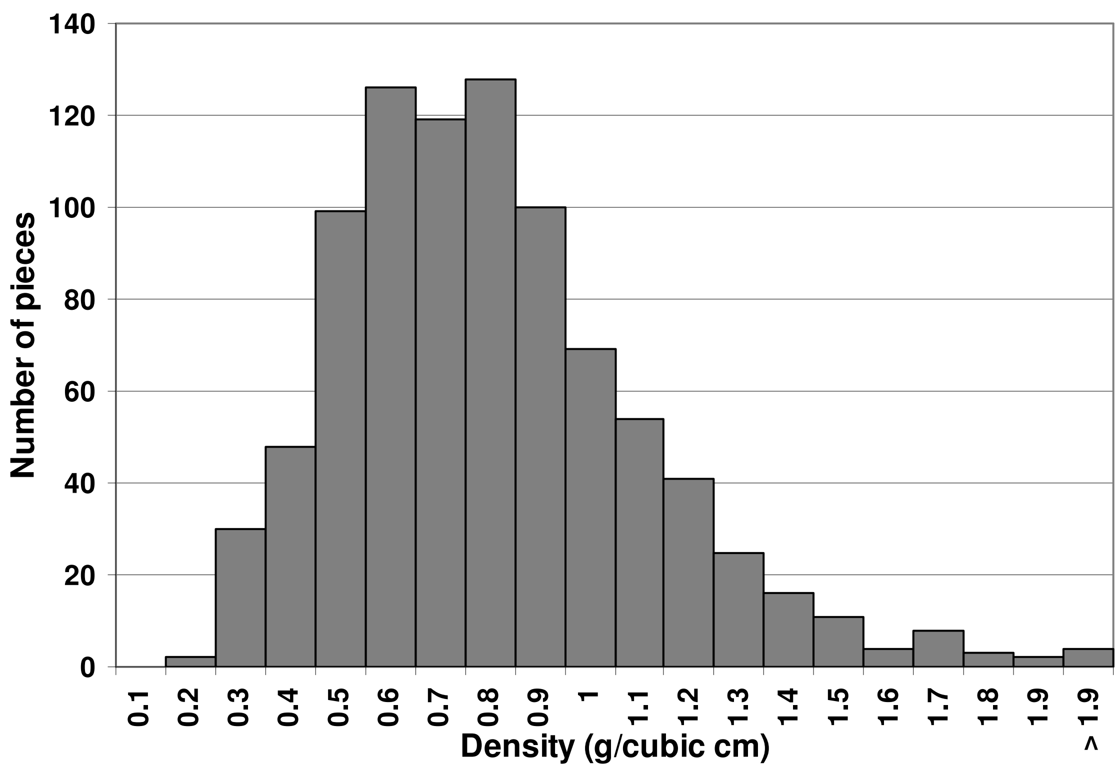
APPENDIX C. Histograms of data from 858 pieces of wood evaluated in this study.

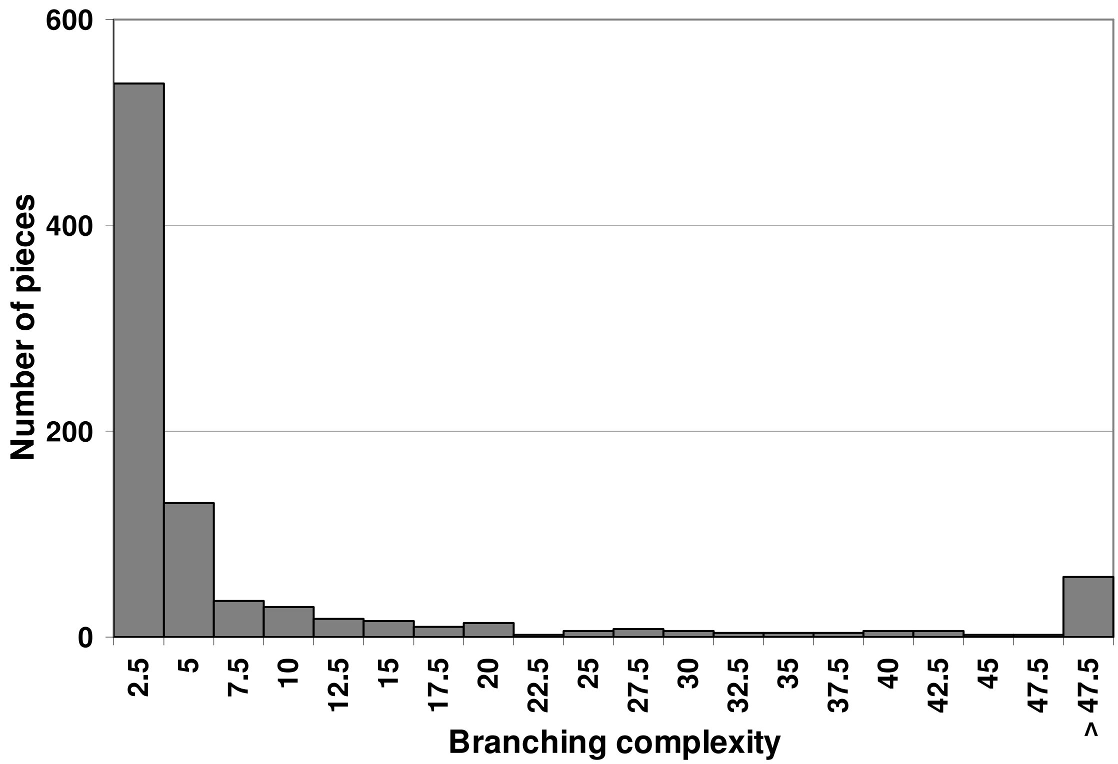


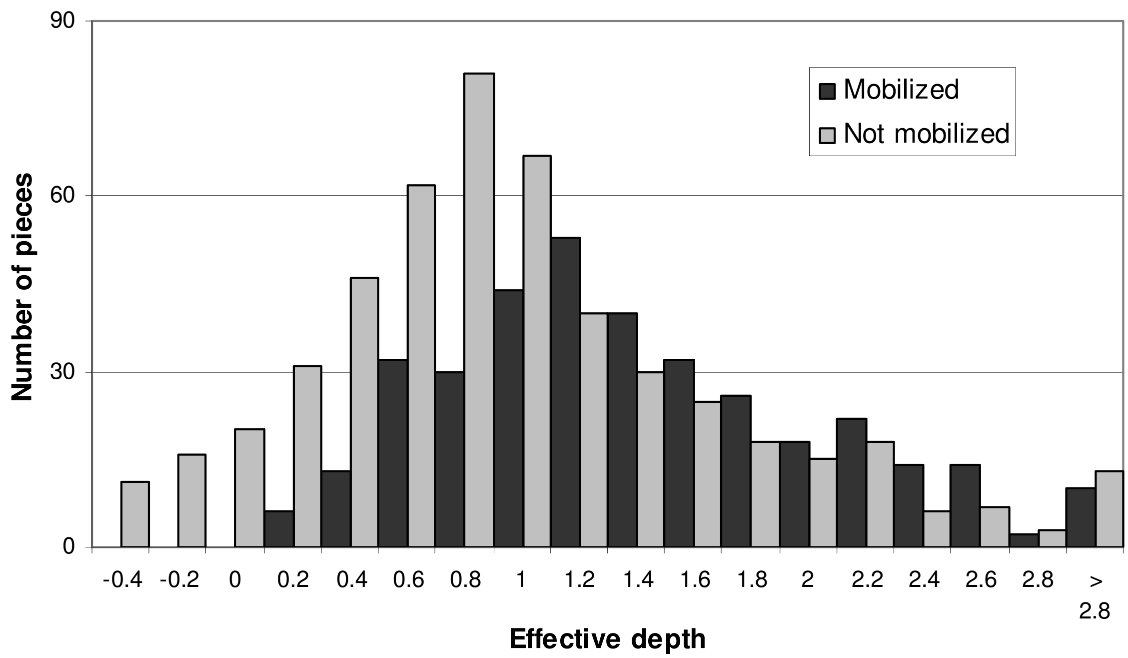

160
120
80
40
0
Number of pieces
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
> 10
Length (m)

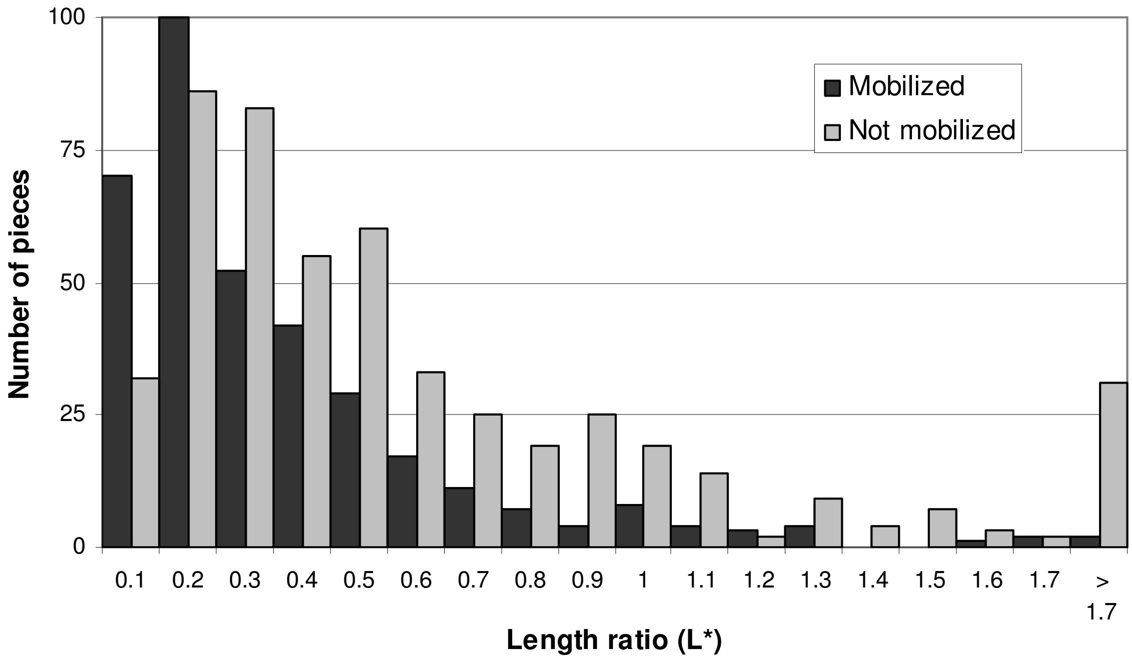

800
600
400
200
0
Number of pieces
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
> 3
Volume (cubic m)


800
600
400
200
0
Number of pieces
20
40
60
80
100
120
140
160
180
200
220
240
> 240
Weight (N)

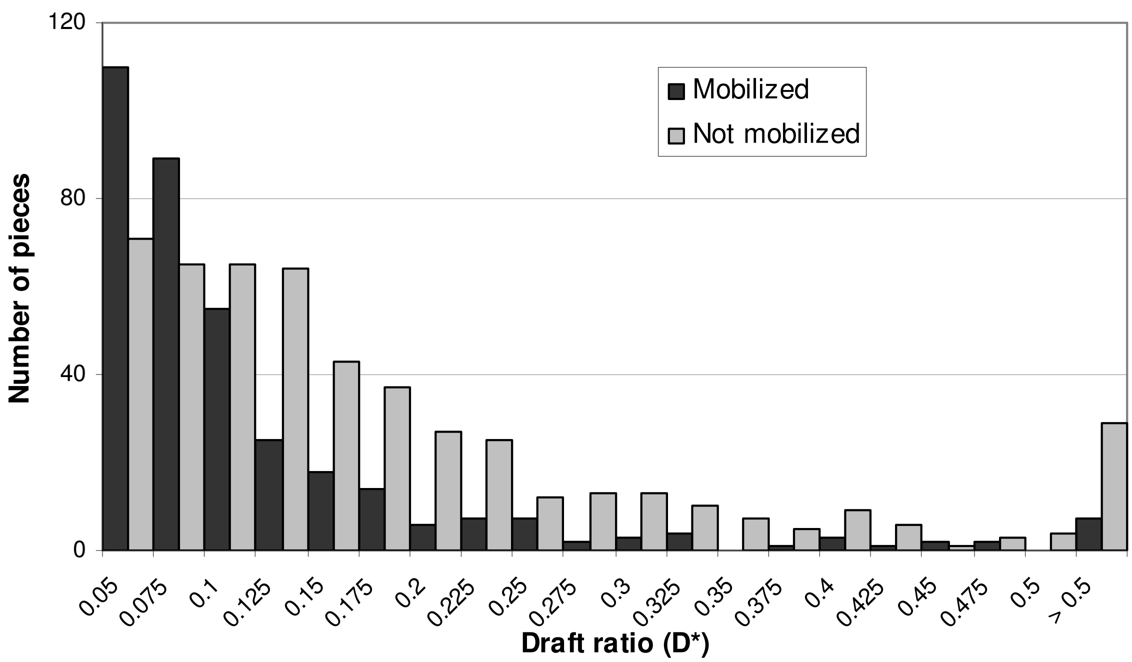

140
120
100
80
60
40
20
0
Number of pieces
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
> 1.9
Density (g/cubic cm)


600
400
200
0
Number of pieces
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
37.5
40
42.5
45
47.5
> 47.5
Branching complexity


90
60
30
0
Number of pieces
Mobilized
Not mobilized
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
> 2.8
Effective depth

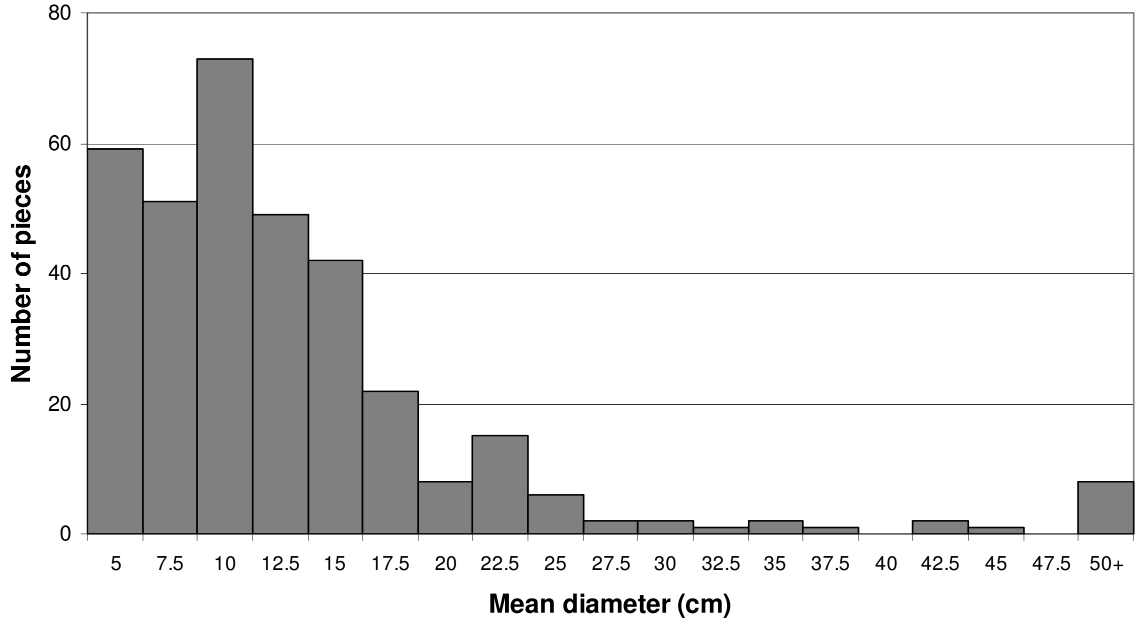


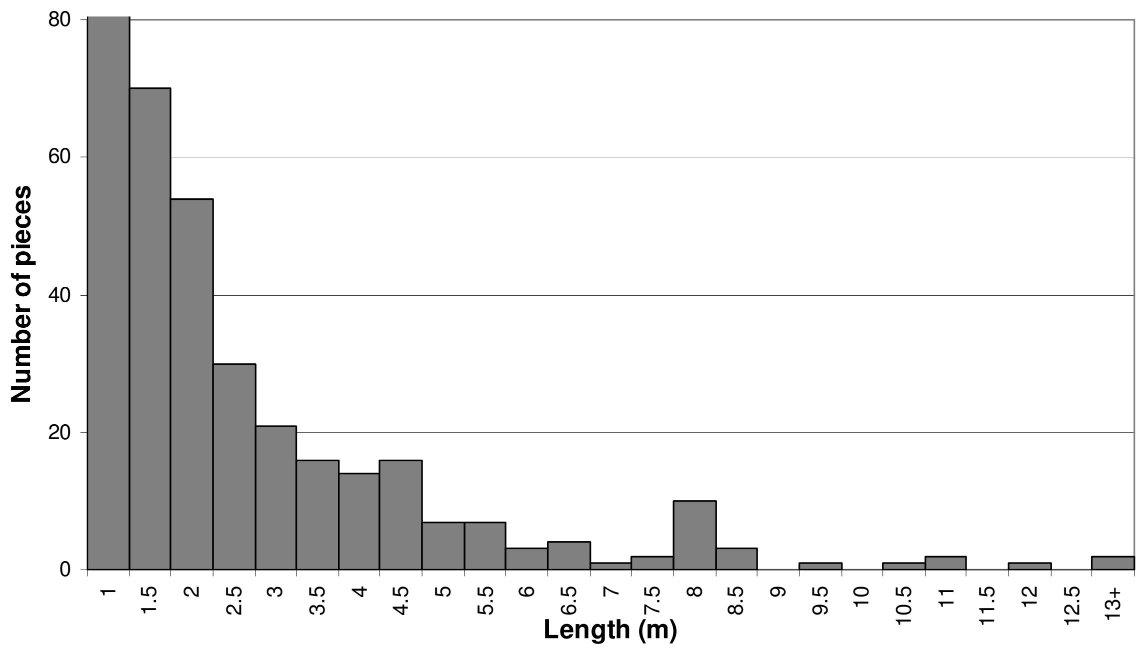
Mobilized
Not mobilized
Number of pieces
Length ratio (L*)
100
75
50
25
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
> 1.7

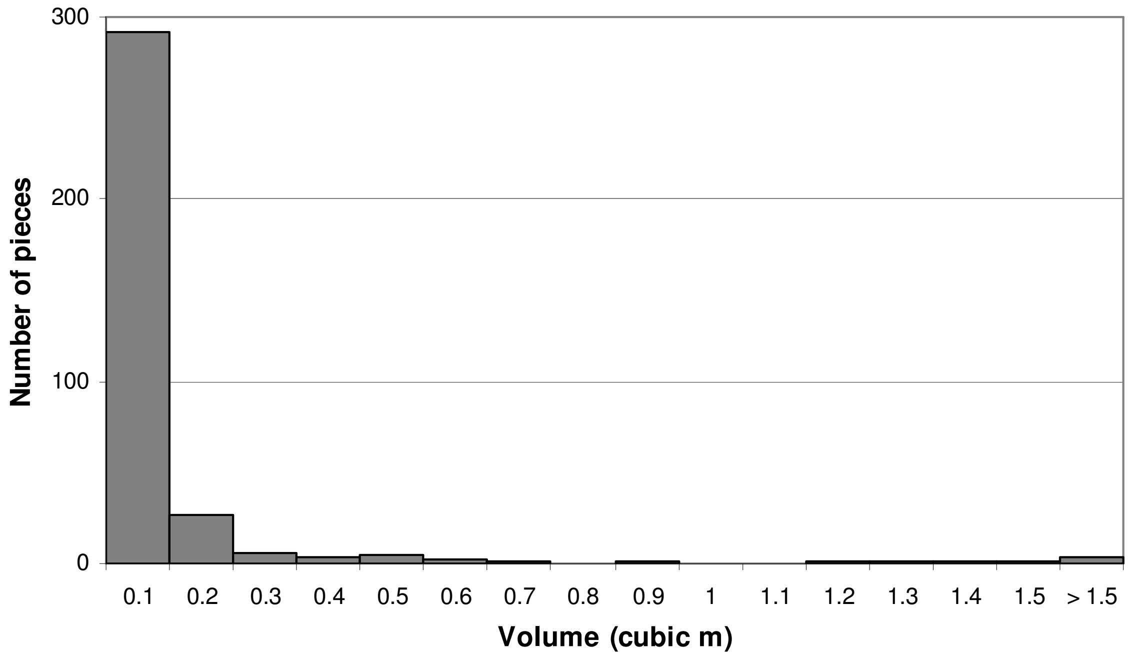


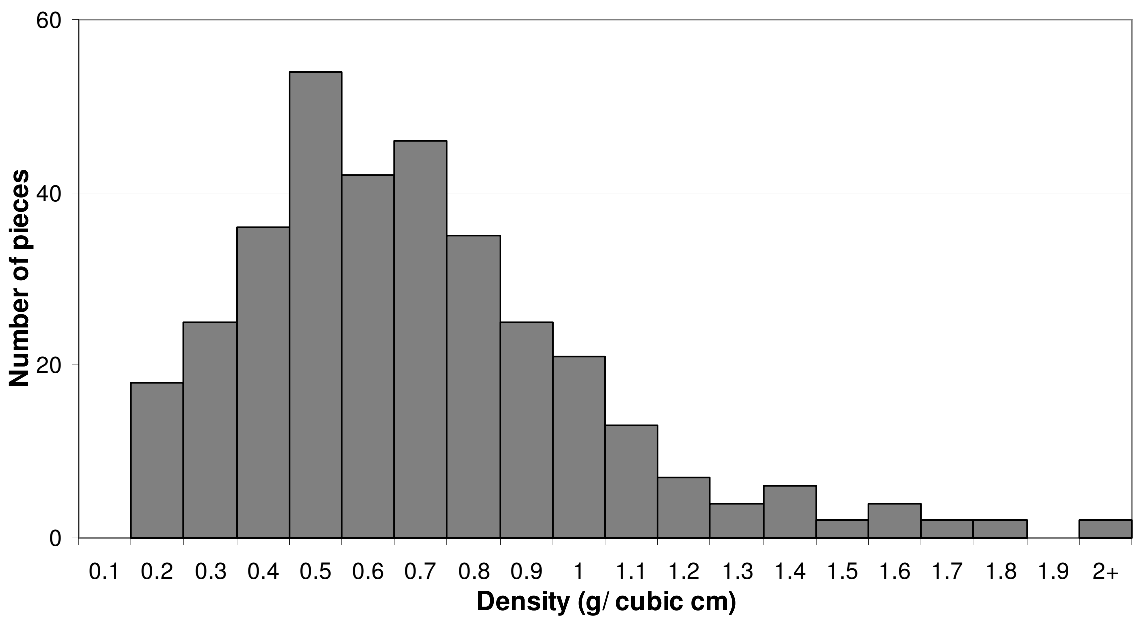
Mobilized
Not mobilized
Number of pieces
Draft ratio (D*)
120
80
40
0
0.05
0.075
0.1
0.125
0.15
0.175
0.2
0.225
0.25
0.275
0.3
0.325
0.35
0.375
0.4
0.425
0.45
0.475
0.5
> 0.5

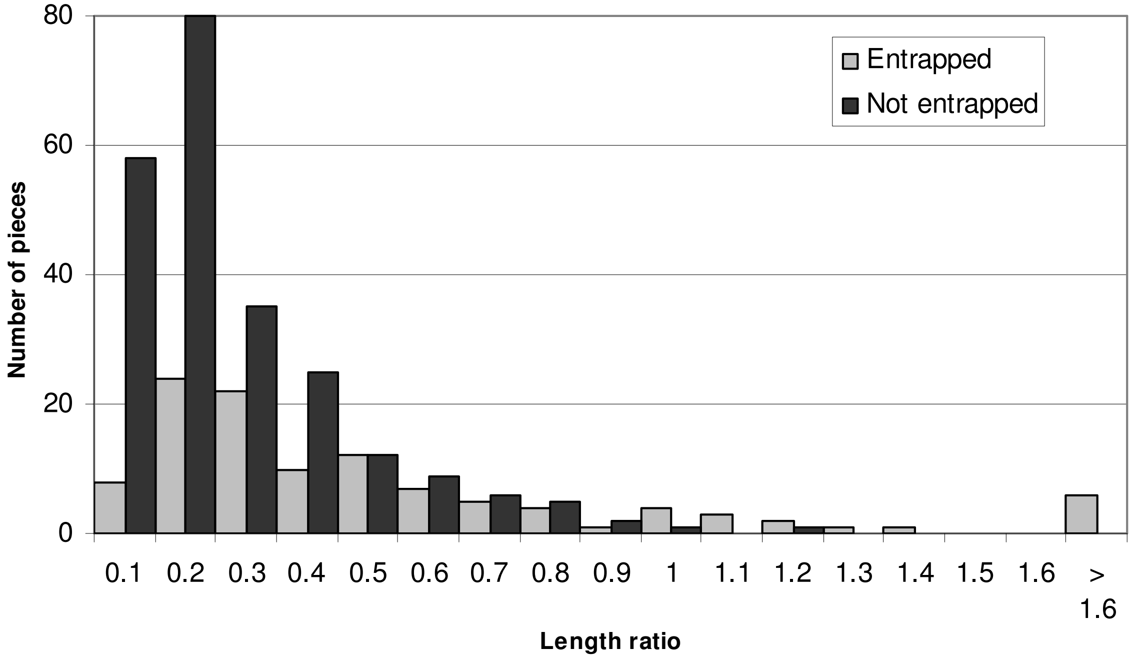
APPENDIX D. Histograms of data from 344 pieces of wood evaluated in this study.

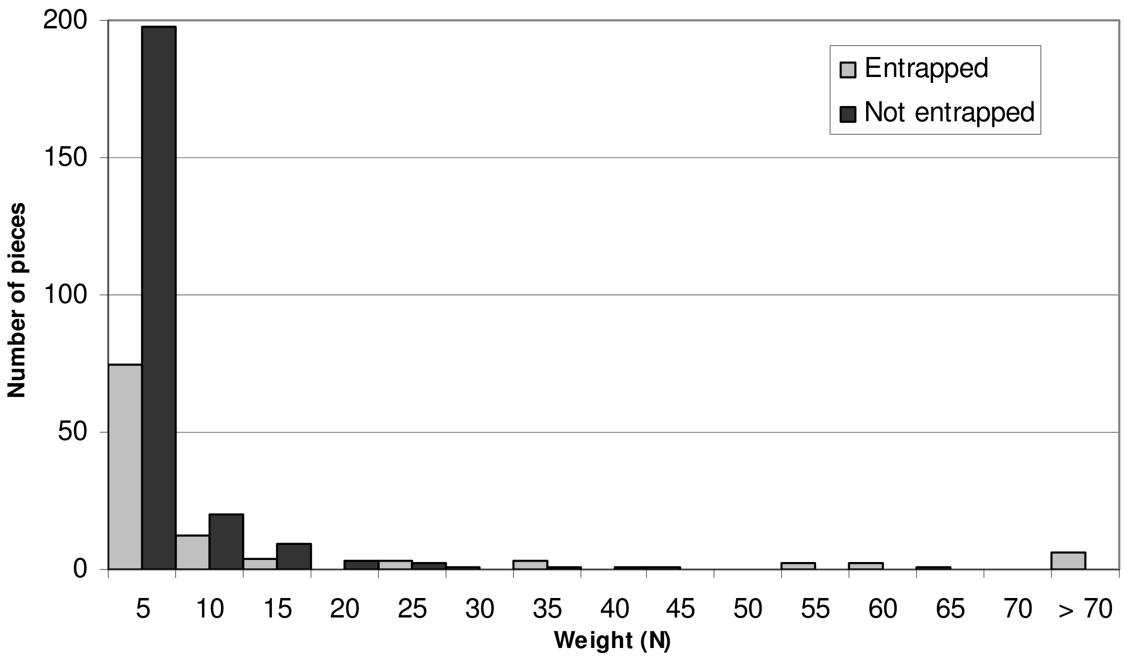


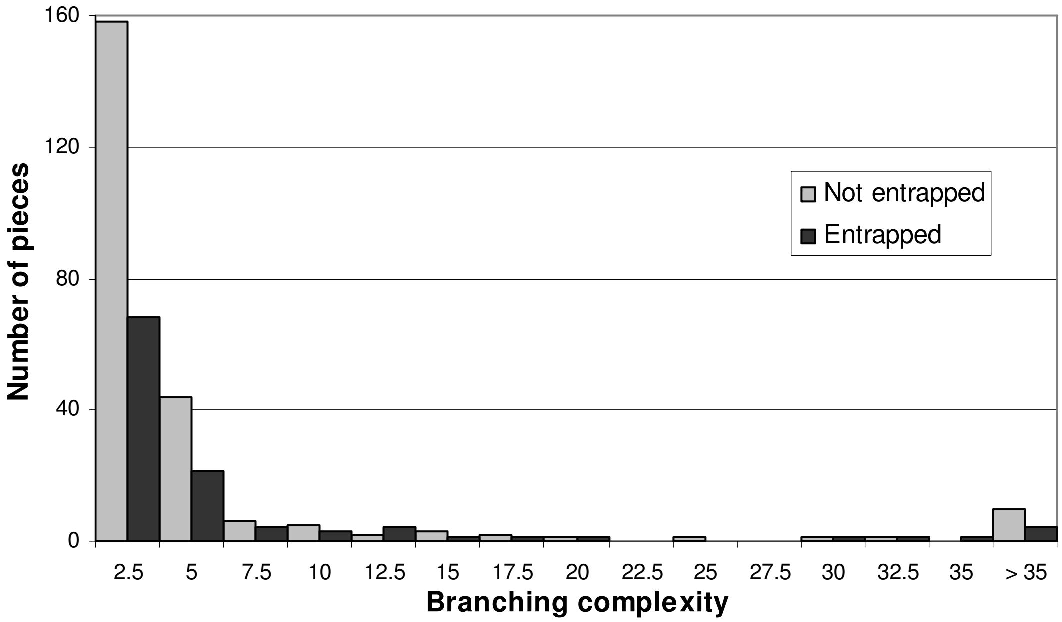



300
200
100
0
Number of pieces
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
> 1.5
Volume (cubic m)


60
40
20
0
Number of pieces
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2+
Density (g/ cubic cm)


Entrapped
Not entrapped
Number of pieces
0
20
40
60
80
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 > 1.6
Length ratio


Entrapped
Not entrapped
Number of pieces
0
50
100
150
200
5 10 15 20 25 30 35 40 45 50 55 60 65 70 > 70
Weight (N)


160
120
80
40
0
Number of pieces
Not entrapped
Entrapped
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
> 35
Branching complexity