New Zealand Journal of Marine and Freshwater Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tnzm20

Measuring woody debris in the small streams of New Zealand's pine plantations

Brenda R. Baillie[a], Tina L. Cummins[b] & Mark O. Kimberley[c]
[a] Liro, Private Bag 3020, Rotorua, New Zealand E-mail:
[b] Liro, Private Bag 3020, Rotorua, New Zealand
[c] New Zealand Forest Research Limited, Private Bag 3020, Rotorua, New Zealand

To cite this article: Brenda R. Baillie, Tina L. Cummins & Mark O. Kimberley (1999): Measuring woody debris in the small streams of New Zealand's pine plantations, New Zealand Journal of Marine and Freshwater Research, 33:1, 87-97

To link to this article: http://dx.doi.org/10.1080/00288330.1999.9516859

New Zealand Journal of Marine and Freshwater Research, 1999, Vol. 33: 87–97
0028–8330/99/3301–0087 $7.00 © The Royal Society of New Zealand 1999

Measuring woody debris in the small streams of New Zealand's pine plantations

BRENDA R. BAILLIE
TINA L. CUMMINS
Liro
Private Bag 3020
Rotorua, New Zealand
email: brenda.baillie@fri.cri.nz

MARK O. KIMBERLEY
New Zealand Forest Research Limited
Private Bag 3020
Rotorua, New Zealand

Abstract To assess the impact of harvesting on woody debris volumes in streams, a method was required with sufficient precision to provide meaningful evaluation and comparison of pre- and post-harvest levels of woody debris. Before harvest, woody debris volumes were measured in 24 first- to third-order stream sites in New Zealand's mature pine plantations (22–34 years of age). An adaptation of the Van Wagner line intersect method was used to measure the small woody debris 1–9 cm in diameter (SWD). All large woody debris ≥10 cm in diameter (LWD) was measured for diameter and length. Woody debris volumes in the stream channel ranged from 2 to 345 $m^3 ha^{-1}$, averaging 112 $m^3 ha^{-1}$ (±34, 95% confidence interval (CI)). Woody debris surface areas averaged 2883 $m^2 ha^{-1}$ (±688), range 220–6769 $m^2 ha^{-1}$. Most of the woody debris volume (87%) was composed of LWD. Sixty-seven percent of the woody debris volume was located above the stream, the remainder was lying in-stream or on the floodplain. Woody debris volumes in streams of mature pine plantations in New Zealand were similar to woody debris volumes in streams of temperate native forests in New Zealand and North America. These sites will be remeasured after harvest to identify any changes in woody debris characteristics.

M98014
Received 16 April 1988; accepted 18 September 1998

Keywords woody debris; large woody debris; New Zealand; pine plantation; stream

INTRODUCTION

Woody debris is an important component in the functioning of forested stream ecosystems (Harmon et al. 1986). Its effect on stream characteristics is both dynamic and complex, and is affected by a wide range of factors including the size, stability, amount, orientation, degree of burial, and position of woody debris in the stream channel. As a result, the presence of woody debris can have a strong influence on channel morphology, reducing and deflecting stream flow, forming pools and backwaters. This increases the hydraulic complexity and diversity of habitats in the stream ecosystem (Swanson et al. 1976; Sedell et al. 1988; Abbe & Montgomery 1996).

The majority of wood enters forested streams from windthrow, bank under-cutting or earthflows (Swanson et al. 1976). Its spatial distribution will depend on a range of factors including stream size, channel slope, geology, climate, forest type and age. Once in the channel, its movement is affected by flooding, although most woody debris is gradually broken down by decomposition processes and invertebrates (Swanson et al. 1976; Sedell et al. 1988). The resistance of woody debris to flooding was emphasised by Evans et al. (1993a) who observed that a small, medium gradient New Zealand stream, effectively retained most of its wood during a 1 in 30-year flood.

In forested streams, woody debris provides a physical retention mechanism, controlling and reducing the extent of downstream movement of organic and inorganic material (Keller & Swanson 1979; Mosley 1981; Bilby & Ward 1989). Woody debris dams are important storage sites of organic material in the stream, increasing the time available for biological processing before the organic material is transported further down stream (Bilby & Likens 1980; Cummins et al. 1995). These sites also provide habitat and food sources for aquatic invertebrates and fish (Harmon et al. 1986; Bisson et al. 1987) and can provide an alternate stable substrate for aquatic fauna in streams with mobile sandy/gravel streambeds (Collier et al. 1997).

In New Zealand, pine plantations cover 1.5 million ha, 6% of the total area of New Zealand. The dominant species is *Pinus radiata* which makes up 91% of the total planted area (NZFOA 1997). Little data is available on the amount and distribution of woody debris in pine plantation streams, particularly in the small first- to third-order streams, where woody debris has the most influence on stream dynamics (Harmon et al. 1986; Sedell et al. 1988; Bilby & Ward 1989). Woody debris characteristics have been measured by: Evans et al. (1993b) in two streams in 10-year-old pine plantations; Quinn et al. (1997), in three streams of 15-year-old pine plantations; and Collier et al. (1998) in three streams in mature and recently harvested pine plantations in New Zealand.

The introduction of the Resource Management Act 1991 (RMA) in New Zealand, has focused attention on harvesting operations along stream edges, the effect on the amount of woody debris in the stream channel, and whether this has adverse impacts on stream ecosystems. A wide variety of harvesting systems and practices are used in New Zealand to harvest along stream edges, and as a result, the amount of woody debris that ends up in the stream is highly variable. Where possible, forest companies are minimising woody debris input in streams.

This paper explains the methodology that was developed to measure woody debris characteristics in small streams in a pre- and post-harvest study. It describes the woody debris characteristics in mature pine plantation streams, before harvesting, and compares these characteristics to those of the temperate (native) forests of New Zealand and North America. The information from this study will be used as a benchmark in future studies to analyse changes in woody debris characteristics after harvesting.

METHOD

Study sites

Woody debris was measured at 24 stream sites in five regions of New Zealand, covering a range of geological and soil types (Table 1). All stream sites were located in *Pinus radiata* plantations ranging in age from 22 to 34 years, apart from one stand of *Pinus nigra*, aged 68 years. The streams were first- to third-order streams (Strahler 1957) with catchment areas varying from 16.4 to 2200 ha. Mean stream channel width varied from 0.5 to 5.5 m (Table 1).

Development of a methodology

Direct weighing of all woody debris, or making measurements along a transect line, are two methods commonly used to measure woody debris (Warren & Olsen 1964; Van Wagner 1968; Brown 1974; Bélanger et al. 1984). Direct weighing was not considered a practical option in this study. Van Wagner (1968) developed a method for estimating wood volume on the ground, based on the line intersect technique of Warren & Olsen (1964). This eliminated the requirement to measure piece length. A line is laid across the area to be measured and the diameter is recorded of every piece of wood which intersects the line. This method applies to randomly orientated cylinders lying on a horizontal surface.

Brown (1974) introduced a corrective factor to Van Wagner's line intersect method to account for ground slope and the non-horizontal angle of the smaller piece sizes (<7.62 cm in diameter), where the tilt was >25°. Brown's (1974) ground slope corrective factor applies to slopes of 20° or more. The ground slope corrective factor was not required in this study, as stream channel slopes in all sites were <20°. Van Wagner (1968) showed that when the non-horizontal angle of the smaller pieces reached 25°, the error was <10%. As the proportion of pieces of wood that fell into this category was small, the non-horizontal corrective factor was not used. Woody debris below the 1 cm diameter class was not recorded as this material contributes to a small portion of the total wood volume. Bélanger et al. (1984) found the piece sizes in the 0–0.63 cm diameter range accounted for 56% of the pieces counted, but only 1–2% of the total volume, in the residual forest biomass of *Picea glauca* and *Pinus contorta* stands in Canada.

Although Van Wagner's method has been used predominantly in post-harvest wood waste assessments, it has also been used to measure woody debris in streams (Wallace & Benke 1984; O'Connor 1992). Wallace & Benke used the line intersect method to estimate volume, mass, surface area, and spatial distribution of woody debris in fourth- and sixth-order streams in south-eastern United States. O'Connor used the line intersect method at 10 sites in an Australian lowland stream system. In both studies, 20 transects were sufficient to achieved 95%

confidence intervals that were generally <50% of the mean.

The Van Wagner line intersect method was trialled in two streams using 21 transects along a 100 m section of stream. The statistical error was high in both streams—210 $m^3 ha^{-1}$ ± 141 $m^3 ha^{-1}$ (95% confidence interval (CI)) for Stream 1; and 37 $m^3 ha^{-1}$ ± 28 $m^3 ha^{-1}$ for Stream 2. This was because of the short transect lengths in the small streams and the high variability of woody debris volumes per transect in the stream channel (Stream 1: 0.1–252 $m^3 ha^{-1}$, Stream 2: 0–241 $m^3 ha^{-1}$). Forty-one

Table 1 Description of study sites.

Region and geology*	Soils†	Catchment area (ha)	Av. stream width (m)	Av. stream depth (mm)	Stream order
Auckland/Coromandel					
Sandstone/mudstone	Ultic	16.4	1.4	68	1
Andesite	Brown (brown granular clays)	65.0	3.6	155	1
Andesite	Brown (brown granular clays)	68.5	3.2	36	1
Andesite	Brown (brown granular clays	20.0	1.7	107	1
Rhyolite	Brown	26.3	1.5	49	2
Central North Island					
Greywacke	Pumice	1150	5.1	316	3
Ignimbrite	Pumice	297	2.5	159	2
Ignimbrite	Pumice	268.5	2.5	171	3
Rhyolite/pumiceous alluvium	Pumice	2200	5.5	351	3
Ignimbrite	Pumice	865	1.4	479	2
Ignimbrite	Podzol	560	2.2	281	2
Rhyolite	Pumice	28.3	1.1	44	1
Hawke's Bay					
Sandstone/siltstone	Pumice	185	2.8	166	3
Alluvial sediment/ greywacke/conglomerate & sandstone	Oxidic (sandy silts developed in pumice)	280	2.4	190	2
Nelson					
Greywacke/schist	Brown (yellow brown earths)	33.5	1.7	48	1
Greywacke/ schist	Brown (yellow brown earths)	63.5	2.6	61	1
Limestone/sandstone/ siltstone	Orthic brown soils	24.6	0.8	118	1
Gravels/conglomerates	Brown (orthic brown soils)	16.7	2.6	6	1
Granite	Brown	26.5	3.0	45	1
Granite	Brown	9.3	2.6	46	1
Southland					
Sandstone/siltstone/ mudstone	Brown (yellow-brown earth/silt loam)	84.0	2.2	75	2
Schist	Pallic	458.0	2.3	109	3
Sandstone/siltstone	Brown	188.5	1.7	61	2
Siltstone/sandstone	brown (sandy/silty loams)	18.5	0.5	15	1

*Department of Scientific and Industrial Research (1972a,b).
†Hewitt (1995); Rijkse & Hewitt (1995).

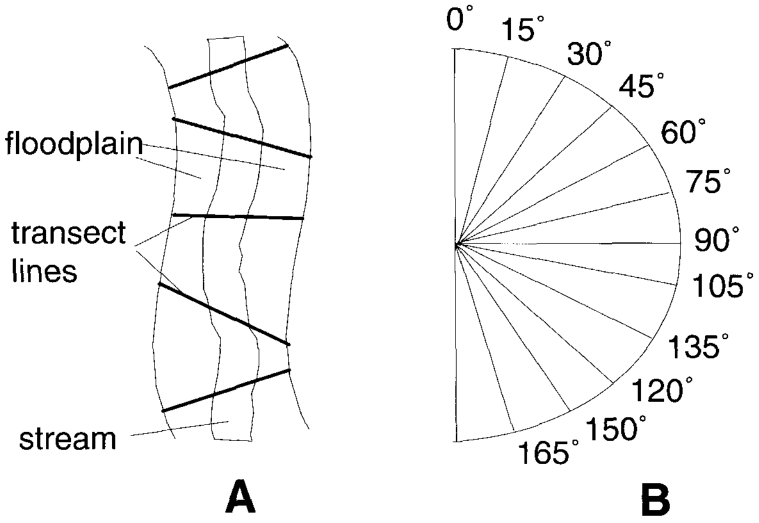


Fig. 1 **A**, Random orientation of transects along the stream channel. **B**, Degrees used to randomly orient transects lines.

transects and 65 transects respectively would have been required to achieve a 95% confidence interval which was <40% of the mean (calculated on ±2 SE). This level of precision would allow comparative analysis of woody debris measurements between sites and in future pre- and post-harvest woody debris analysis. However, this number of transects was impractical for this study, so the woody debris measurements were stratified. Small woody debris in the 1–9 cm diameter classes (SWD) was measured using transects. All large woody debris pieces ≥10 cm in diameter (LWD) in the 100 m section of stream, were measured for diameter and length. In the two trial streams this reduced the 95% CI in transect measurements to 44 and 39% of the mean. The CI refers to the accuracy of the wood volume only over the 100 m length of stream studied. As LWD was completely sampled over this length, only SWD contributed to the calculations of CI.

Measurement

At each site, the stream was visually assessed to select a representative 100 m section of stream channel for the woody debris measurements. Twenty-one transects were randomly orientated 5 m apart along the 100 m section (Fig. 1A), to measure the SWD.

Wood in smaller sized streams is predominantly orientated perpendicular to stream flow (Robison & Beschta 1990). To reduce the error from orientation bias of the wood, transect angles were randomly selected in 15° steps from 0 to 165° (Fig. 1B) (Bell et al. 1996). There was a tendency for transect lines on the 0, 15, and 165° bearings to extend for long distances up the stream channel, particularly if the stream was relatively straight. To limit transect length, the distance was measured across the stream channel at an angle of 45° and this length was laid along the original bearing.

The SWD pieces were tallied in 1 cm diameter classes and classified as in-stream, above stream, or on the floodplain (Fig. 2). Tallying rules followed those outlined in Van Wagner (1968). All LWD within the 100 m section of stream channel was measured for large end diameter (LED), small end diameter (SED), and length and also classified as in-stream, above stream, and on the floodplain.

All dead woody material was measured except for very rotten material which could be easily kicked apart. Woody debris that extended into the substrate was measured up to the point where it was buried.

Measurements were taken of the ground slope, channel bank height and slope, floodplain width, streambank height, and stream width and depth (mean of three depth measurements) (Fig. 2). These measurements were taken at the beginning of the 100 m section of stream reach and repeated where any significant channel morphology changes occurred. The stream and floodplain widths along the 100 m section of stream were used to calculate the area of stream channel in which the woody debris was being measured.

Analysis

SWD volumes for the transects were calculated using the Van Wagner (1968) equation:

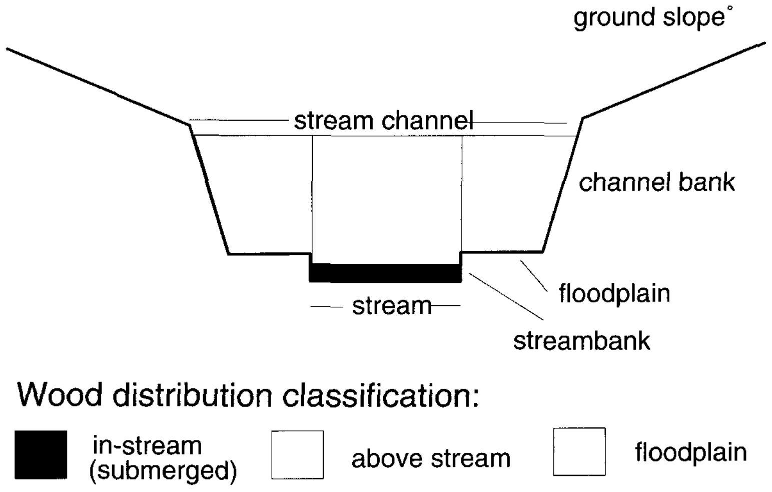


Fig. 2 Channel morphology measurements of the stream channel and classification of wood distribution in the stream channel.

$$V = \Pi^2 \Sigma d^2 / 8L$$

where: V = Volume of wood ($m^3 ha^{-1}$); d = piece diameter (cm); and L = length of transect line (m).

The volume of each piece of LWD was calculated using the 3-dimensional formula of Ellis (1982):

$$V_{piece} = \exp [1.944157 \ln l + 0.029931 (d) + 0.884711 \ln (D - d)/l - 0.038675] + 0.078540 (d^2 l)$$

where: V_{piece} = volume of piece (m^3); D = large end diameter (cm); d = small end diameter (cm); l = length of piece (m); exp = antilog; and ln = natural log.

The volumes of the individual LWD pieces were totalled to give the LWD (m^3) for the 100 m of stream reach. This was converted to $m^3 ha^{-1}$, using the area calculated from the channel morphology measurements. The SWD and LWD volumes were added together to give the total woody debris volume for the site.

A modification of the Van Wagner equation was used to calculate surface area for the SWD (Wallace & Benke 1984):

$$SA = (\Pi^2/2L)\Sigma d$$

where: SA = surface area ($m^2 ha^{-1}$); L = length of transect line (m); and d = piece diameter (m).

LWD surface area was calculated using the formula for the surface area of a cylinder:

$$SA_{piece} = \Pi \times d \times l$$

where: SA_{piece} = surface area (m^2); l = length of piece (m); and d = diameter (m).

LWD surface area ($m^2 ha^{-1}$) was calculated using the same procedure as for LWD volume.

A two-way ANOVA, followed by a least significant difference test was used to determine any significant differences in the distribution of woody debris volumes and surface areas in the stream channel. A one-way ANOVA was used to test for differences in woody debris volumes between stream orders and for any regional variances in woody debris volumes.

Conventional correlation methods and multiple regression analysis were used to test for any relationships between woody debris volumes in the stream channel and *Pinus* stand characteristics of age (years), piece size (m^3), stocking (stems ha^{-1}), volume of wood ($m^3 ha^{-1}$), catchment area (ha), and ground slope (°). Log transformations were used where data was skewed. Conventional correlation methods were also used to compare stream width with mean diameter, mean length, and mean piece volume of the LWD pieces.

RESULTS

Woody debris volume

Woody debris volumes across the 24 stream sites were highly variable, ranging from 2 to 345 $m^3 ha^{-1}$, with a mean volume of 112 $m^3 ha^{-1}$ (Table 2).

Most of the woody debris in the stream channel was composed of LWD (Table 2). LWD volumes averaged 97 $m^3 ha^{-1}$, SWD volumes averaged 15 $m^3 ha^{-1}$. Woody debris volumes were normally distributed across the diameter classes (Fig. 3). Fifty percent of the wood volume was in the 20–24 to 35–39 cm diameter classes.

Although the 95% CI of the SWD volumes at the two initial trial sites were close to 40% of the mean (14 $m^3 ha^{-1}$ ± 6 and 15 $m^3 ha^{-1}$ ± 6 respectively), many sites had confidence intervals greater than this (Table 2). As stated earlier in the methods section, the absolute measurements of the LWD helped to reduce the margin of error for total woody debris volumes.

Figure 4 shows the distribution of the mean woody debris volumes in the stream channel. Ten percent of the total woody debris volume was in-stream, 67% was positioned above the stream, and 23% lay on the floodplain. The volume of woody debris above the stream was significantly higher than the volumes in-stream and on the floodplain ($P < 0.01$).

The mean volumes of woody debris in the first-, second-, and third-order streams were: 112 ± 63, 83 ± 46, and 143 ± 134 $m^3 ha^{-1}$ respectively. No significant differences in wood volumes were found between the stream orders ($P > 0.05$), nor was regional variance a factor in influencing woody debris volumes. No relationships were found when comparing stream width with LWD diameter, length, and piece size.

The age, piece size, stocking, wood volume, catchment area, and ground slope of the *Pinus* stands

Table 2 Woody debris volumes for small woody debris (SWD) (± 95% CI), large woody debris (LWD) and total woody debris for each stream site and mean woody debris volume and surface area for SWD and LWD and total woody debris (± 95% CI). Because of rounding conventions, the addition of the SWD and LWD volumes for each stream site does not necessarily equal the total volume.

Stream site	SWD ($m^3 ha^{-1}$)	95% CI as a % of mean	LWD ($m^3 ha^{-1}$)	Total vol. ($m^3 ha^{-1}$)
1	27 (± 15)	56	118	145
2	2 (± 2)	83	0	2
3	10 (± 15)	147	44	54
4	17 (± 8)	47	36	53
5	14 (± 12)	89	14	28
6	6 (± 5)	82	62	68
7	24 (± 16)	66	121	145
8	14 (± 6)	44	131	144
9	9 (± 4)	44	88	97
10	9 (± 7)	81	99	108
11	3 (± 2)	57	7	10
12	17 (± 9)	52	327	345
13	12 (± 7)	60	171	182
14	14 (± 8)	59	26	40
15	10 (± 6)	63	65	75
16	23 (± 13)	58	130	152
17	17 (± 5)	29	123	140
18	8 (± 4)	53	18	26
19	21 (± 9)	43	99	120
20	20 (± 9)	44	197	217
21	29 (± 13)	45	191	220
22	15 (± 6)	39	58	74
23	31 (± 10)	32	155	187
24	6 (± 11)	170	53	59
Av. volume ($m^3 ha^{-1}$)	15 (±3)		97 (± 32)	112 (± 34)
%	14		86	
Av. surface area ($m^2 ha^{-1}$)	1495 (± 322)		1388 (± 456)	2883 (± 689)
%	52		48	

Fig. 3 Distribution of wood volume by diameter class. All diameter classes are in 5 cm class intervals except for the lowest and highest diameter class. (SWD = small woody debris 1–9 cm in diameter; LWD = large woody debris ≥10 cm in diameter.)

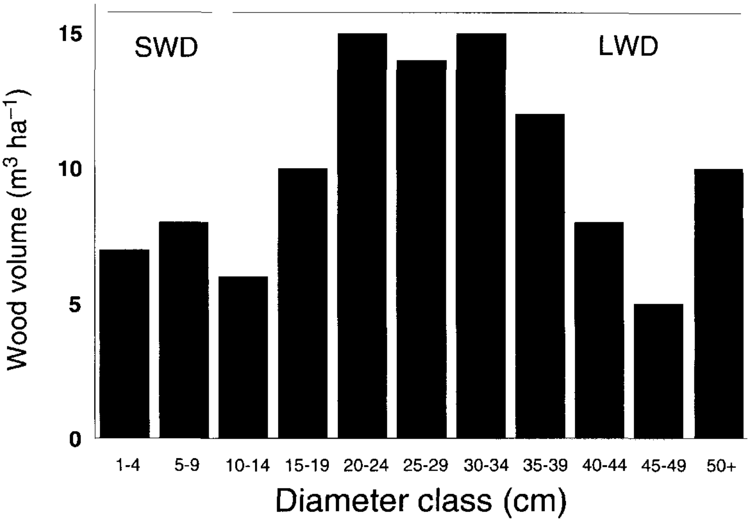
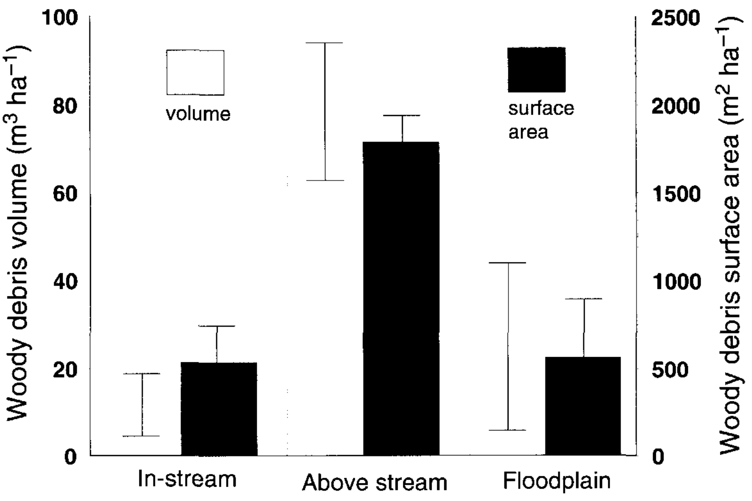


Fig. 4 Mean distribution of woody debris volume and surface area in the stream channel ($n = 24$). Above stream volumes and surface areas differ significantly from in-stream and floodplain volumes and surface area ($P < 0.05$). There was no significant difference between the in-stream and floodplain volumes and surface areas ($P > 0.05$).



showed no significant correlations with woody debris volumes in the stream. Attempts to include more than one variable to predict woody debris volumes in the stream, using multiple regression, failed to find any significant relationships.

Woody debris surface area

Woody debris surface areas averaged 2883 m^2 ha^{-1} (Table 2) ranging from 220 to 6769 m^2 ha^{-1}. Large woody debris surface areas averaged 1388 m^2 ha^{-1}, 48% of the total surface area. The SWD surface areas averaged 1495 m^2 ha^{-1}, 52% of the total surface area (Table 2).

Distribution of woody debris surface area in the stream channel, was similar to the woody debris volumes (Fig. 4). The surface area of the woody debris above the stream was significantly different from the in-stream and floodplain surface areas (two-way ANOVA, $P < 0.05$).

DISCUSSION

Performance of the measurement method

The high statistical errors (Table 2) when using the Van Wagner line intersect method to measure SWD in streams were mainly because of the variability of wood distribution along the stream channel, and the short transect lengths in small streams. Extending the 100 m length to add in extra transects may not reduce the error significantly, especially if the stream character (i.e., channel morphology) changes. The pilot study showed that stratifying the woody debris measurements, so that transects measured the SWD and absolute measurements were taken of the LWD, was a more effective way of reducing the sampling error. It took on average, 4 h (excluding travel time) for two operators to complete the woody debris and channel morphology measurements at each site, using this method.

Both Wallace & Benke (1984) and O'Connor (1992) were able to achieve similar precision (95% confidence intervals) to this study using transects only. Wallace & Benke (1984) were sampling in larger streams than those sampled in this study, which would have increased the length of their transects. Stream widths were not stated in the O'Connor paper, but were likely to be larger than the streams in this study as they were lowland streams.

Maintaining accurate measurements along transect lines can be difficult in areas of concentrated volumes of wood. If the depth of the wood in the stream channel is greater than the arm reach of the operator, and it is unacceptable to disturb the wood, woody debris measurements will be underestimated. Transects would be unsuitable when measuring large accumulations of woody debris such as debris dams.

Randomly-oriented transects were used successfully in small streams to overcome the orientation bias of the wood. However, in wider streams, these transects can potentially extend for long distances along the stream channel, and in some instances, particularly at stream bends, the transects can overlap.

Woody debris characteristics

Woody debris volumes and surface areas in the pine plantation streams of New Zealand have been compared with streams of similar size and order in the temperate native forests of New Zealand (Evans et al. 1993b; Quinn et al. 1997; Collier et al. 1998) and the temperate forests of North America (Harmon et al. 1986; Carlson et al. 1990; Robison & Beschta 1990). Woody debris volumes and surface areas include all material ≥1 cm in diameter, LWD volumes, and surface areas include all material ≥10 cm. Where other studies have used different parameters to these, they have been noted in the text.

Table 3 compares mean woody debris volumes and surface areas from this study with those from other New Zealand studies of woody debris in native forests and pine plantations. Woody debris volumes in this study were similar to those found in streams of mature and 15-year-old pine plantations and older native forests (Evans et al. 1993b; Quinn et al. 1997; Collier et al. 1998) (NB. Evans measured all woody debris >2.5 cm). The young (10-year-old) native and pine plantation streams had mean woody debris volumes which were much lower than the volumes in this study (Evans et al. 1993b).

Windthrow from surrounding stands, and in Southland, remnant native hardwoods, were the main

Table 3 Mean (±95% CI) woody debris volumes, surface areas, and % submerged wood in this and other New Zealand studies, in native forest and pine plantation streams. (NB. Other studies expressed errors as ± 1 SE. These have been doubled to give an approximation to the 95% CI.) (ND = no data.)

	Mean volume (m^3 ha^{-1})	Mean surface area (m^2 ha^{-1})	% submerged wood
Mature pine plantations (n = 24)*	112 ± 34	2883 ± 689	10
Mature pine plantation (n = 3)†	245 ± 98	ND	17
Pine plantation, 15 years old (n = 3)‡	200 ± 100	4500 ± 600	25
Pine plantation, 10 years old (n = 2)§	2.4 ± 2.6	62 ± 46	15
Ancient native forest (n = 2)§	101 ± 22	1971 ± 244	18
Native forest, 120 years old, previously burned (n = 3)§	71 ± 72	2852 ± 3684	6
Native forest podocarp/hardwood (n = 3)‡	50 ± 50	1200 ± 600	25
Regenerating native forest, 10 years old (n = 3)§	2.7 ± 1.6	75 ± 50	13

* This study.
† Collier et. al. (1997).
‡ Quinn et al. (1997).
§ Evans et al. (1993b).

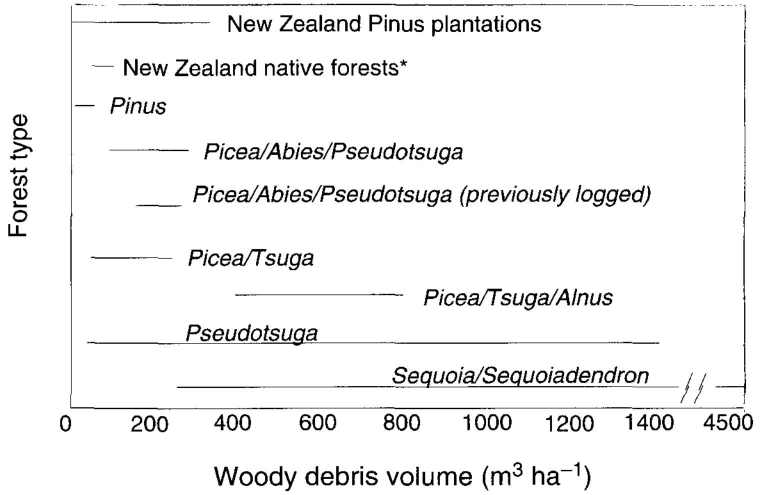


Fig. 5 Range of large woody debris volumes in the pine plantation streams of New Zealand and the temperate forests of North America. (*Total woody debris volume for New Zealand native forests. Note the change in scale along the *x* axis.)

contributors to high LWD volumes in the pine plantation streams (Fig. 3). LWD also accounted for most of the woody debris in the pine plantation and native streams of Quinn et al. (1997). Evans et al. (1993b) found that LWD contributed to c. 50% of wood surface areas in the ancient native forests. However, SWD contributed to most of the woody debris in the 120-year-old forest. Evans et al. (1993b) attributes this to the influence of the amount of SWD in several debris dams to the overall results. The low amounts of LWD in the regenerating native and young pine plantation forests (Evans et al. 1993b) were part of the overall low woody debris volumes in these streams, a factor of their young age and previous land-use history.

Mean woody debris surface areas in this study were similar to those in the older native forests of Evans et al. (1993b), but were higher than surface areas in the young pine plantation and regenerating native forest streams. Surface areas were higher than in the native streams and lower than in the 15-year-old pine plantation streams measured by Quinn et al. (1997).

The submerged wood in the stream channel is immediately available to in-stream biological processing. Wood on the floodplain and above the waterline provides additional sources of wood to the stream channel over time during high water or flooding events or from gradual decay. The percentage of wood that was submerged (in-stream) varied from 6 to 25% across all the stream sites in Table 3. The mean of 10% submerged wood in this study is toward the lower end of the range. As the amount of wood submerged will depend on the state of flow at the time of measurement, the percentage of submerged wood will vary. Flow rates weren't measured in this study, but measurements were made at low flow, to ensure operator safety and clear visibility when locating and measuring woody debris in the water.

Figure 5 compares the range of LWD volumes in the mature pine plantation streams of this study, to those found in the streams of the temperate forests of North America. LWD volumes are similar to those in North American *Picea* forests and unlogged and previously logged forests of *Picea/Abies/Pseudotsuga*, but are at the lower end of the range when compared to streams in *Sequoia/Sequoiadendron* and *Pseudotsuga* forests. LWD volumes were also low compared to streams in the *Picea/Tsuga/Alnus* forests of Southeast Alaska. (Robison & Beschta 1990) (NB. Robison & Beschta defined LWD, as all material ≥20 cm). However, the streams in the *Pinus radiata* stands of this study, have much higher LWD volumes in comparison to North American *Pinus* stands. Although only total woody debris volumes were available for the New Zealand native forest streams, Fig. 5 shows these volumes to be low in comparison to the New Zealand pine plantation streams and the streams of North America.

Although this study found no relationships between stream size and LWD characteristics, this is contrary to the findings of Bilby & Ward (1989) and Robison & Beschta (1990). Bilby & Ward (1989) found that mean diameter, length, and volume of pieces of wood increased as channel width increased, but the frequency of occurrence decreased. Robison & Betscha (1990) found that coarse woody debris volumes per 100 m of stream length increased with stream size whereas total coarse woody debris per unit bankfull area decreased. Similar relationships may exist in the streams of mature pine plantations but the narrow range of stream widths studied (0.5–5.5 m) and the high variability of site characteristics (Table 1) could have obscured any trends.

Although windthrow, and to some degree remnant native hardwoods, account for most of the woody debris in streams before harvesting, harvesting operations can potentially provide the largest source of woody debris in the stream channel (Collier et al. 1998). Post-harvest measurements of woody debris in the streams of this study will identify any changes in the volume and distribution of woody debris resulting from harvesting practices.

ACKNOWLEDGMENTS

We thank the following forestry companies: Carter Holt Harvey Limited, Fletcher Challenge Forests Limited, Ernslaw One Limited, Rayonier NZ Limited, Weyerhaeuser NZ Ltd, PF Olsen and Co Ltd, Hawkes Bay Forests Ltd, and Juken Nissho Ltd for providing the sites for this project and assisting with the field measurements. We also appreciate the constructive comments from Shane McMahon, Pieter Fransen, Kevin Collier, and Rob Davies-Colley on the draft manuscript. This project was funded by the New Zealand Foundation for Research, Science and Technology.

REFERENCES

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

Bélanger, J.; Dumont, J.; Bélanger, G. 1984: Inventory of forest biomass left after logging in western Canada. Special report no. SR-17. Forest Engineering Research Institute of Canada. 41 p.

Bell, G.; Kerr, A.; McNickle, D.; Woollons, R. 1996: Accuracy of the line intersect method of post-logging sampling under orientation bias. *Forest Ecology and Management 84*: 23–28.

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

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

Bisson, P. A.; Bilby, R. E.; Bryant, M. D.; Dolloff, C. A.; Grette, G. B.; House, R. A.; Murphy, M. L.; Koshi, K. V.; Sedell, J. R. 1987: Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Contribution no. 57 *in*: Salo, E. O.; Cundy, T. W. *ed.* Streamside management: forestry and fishery interactions. Seattle, Washington, Institute of Forest Resources, University of Washington. Pp. 143–190.

Brown, J. K. 1974: Handbook for inventorying downed woody material. USDA Forest Service, General technical report INT-16. 24 p.

Carlson, J. Y.; Andrus, C. W.; Froechlich, H. A. 1990: Woody debris, channel features and macroinvertebrates in streams with logged and undisturbed riparian timber in northeastern Oregon, U.S.A. *Canadian Journal of Fisheries and Aquatic Sciences 47*: 1103–1111.

Collier, K.; Baillie B.; Bowman, E.; Halliday, J.; Quinn, J.; Smith, B. 1997: Is wood in streams a damned nuisance? *Water & Atmosphere 5(3)*: 17–21.

Collier, K. J.; Bowman, E. J.; Halliday, J. M. 1997: Short-term changes in water quality and benthic invertebrate faunas following post-harvest manipulations of woody debris in some Whirinaki streams. *NIWA Science and Technology Series no. 44.* 22 p.

Collier, K. J.; Bowman, E. J.; Halliday, J. N. 1998: Changes in water quality and benthic invertebrate faunas following post-harvest manipulation of woody debris in some Whirinaki streams. NIWA Client Report: FOR60203.

Cummins, K. W.; Cushing, C. E. ; Minshall, G. W. 1995: Introduction: an overview of stream ecosystems. *In*: Cushing, C. E.; Cummins, K. W.; Minshall, G. W. *ed.* Ecosystems of the world. 22. River and stream ecosystems. Amsterdam, Elsevier. 9 p.

Department of Scientific and Industrial Research 1972a: New Zealand Geological Survey, North Island (1st ed.). Geological Map of New Zealand 1:1,000,000. Wellington, New Zealand, Department of Scientific and Industrial Research.

Department of Scientific and Industrial Research 1972b: New Zealand Geological Survey, South Island (1st ed.). Geological Map of New Zealand 1:1,000,000. Wellington, New Zealand, Department of Scientific and Industrial Research.

Ellis, J. C. 1982: A three-dimensional formula for coniferous log volumes in New Zealand. *FRI Bulletin no. 20*: 1–12.

Evans, B. F.; Townsend, C. R.; Crowl, T. A. 1993a: The retention of woody debris structures in a small stream following a large flood. *New Zealand Natural Sciences 20*: 35–39.

Evans, B. F.; Townsend, C. R.; Crowl, T. A. 1993b: Distribution and abundance of course woody debris in some southern New Zealand streams from contrasting forest catchments. *New Zealand Journal of Marine and Freshwater Research 27(2)*: 227–239.

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

Hewitt, A. E. 1995: Soil map of the South Island, New Zealand. Soil Classification 1:1000000 scale. Lincoln, New Zealand, Manaaki Whenua, Landcare Research.

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

Mosley, P. M. 1981: The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream. *Earth Surface Processes and Landforms 6*: 571–579.

New Zealand Forest Owners Association Inc 1997: NZ forestry facts and figures '97. 22 p.

O'Connor, N. A. 1992: Quantification of submerged wood in a lowland Australian stream system. *Freshwater Biology 27*: 387–395.

Quinn, J. M.; Cooper, B.A.; Davies-Colley, R. J.; Rutherford, J. C.; Williamson, R. B. 1997: Land use effects on habitat, water quality, periphyton and benthic invertebrates in Waikato hill-country streams. *New Zealand Journal of Marine and Freshwater Research 31(5)*: 579–597.

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

Rijkse, W. C. ; Hewitt, A. E. 1995: Soil map of the North Island, New Zealand. Soil Classification 1:1000000 scale. Lincoln, New Zealand. Manaaki Whenua, Landcare Research.

Sedell, J. R.; Bisson, P. A.; Swanson, F. J.; Gregory, S.V. 1988: What we know about large trees that fall into streams and rivers. *In*: Maser, C.; Tarrant, R. F.; Trappe, J. M.; Franklin, J. F. *ed.* From the forest to the sea: a story of fallen trees. Portland, Oregon. U. S. Department of Agriculture, Forest Service. Pp. 47–81.

Strahler, A. N. 1957: Quantitative analysis of watershed geomorphology. *Transactions of the American Geophysical Union 38*: 913–920.

Swanson, F. J.; Lienkaemper, G. W.; Sedell, J. R. 1976: History, physical effects and management implications of large organic debris in western Oregon streams. USDA Forest Service General Technical Report (PNW-56). 15 p.

Van Wagner, C. E. 1968: The line intersect method in forest fuel sampling. *Forest Science 14*: 20–26.

Wallace, B. J.; Benke, A. C. 1984: Quantification of wood habitat in subtropical coastal plain streams. *Journal of Fish and Aquatic Science 41*: 1643–1652.

Warren, W. G.; Olsen, P. F. 1964: A line intersect technique for assessing logging waste. *Forest Science 10*: 267–276.