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Spatial distribution and influence of large woody debris in an old-growth forest river system, New Zealand

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Abstract

A field survey was undertaken to determine the quantity, spatial distribution and influence of large woody debris (LWD) in a fifth-order river system in old-growth forest in New Zealand. LWD attributes were assessed at 25 sites distributed in the headwaters and along the main stem of the Whirinaki River system (73 km^2). LWD volume, number of pieces, piece length and piece size, were positively correlated with bankfull width, whereas the number of pieces/unit area, LWD/unit area, number of pieces suspended across the channel and LWD influence on channel morphology, were negatively correlated. Pieces influencing channel morphology were larger, longer and more stable than average. We identified four key zones in the river system based on LWD spatial distribution patterns and influence on habitat complexity. Zonal boundaries occurred where there were changes in the transport capacity, fluvial processes, channel width and geomorphic structure of the channel. The results of this study highlight the need to understand the characteristics, spatial distribution patterns and influence of LWD at the catchment level when undertaking protective, management or rehabilitation programmes in forested river ecosystems.

Keywords: Large woody debris; Channel unit; Catchment; Spatial distribution; Pool; Indigenous forest; Gradient

1. Introduction

Large woody debris (LWD) is an important component of forested stream ecosystems, influencing stream hydraulics, channel morphology, sediment and organic matter routing and storage, habitat complexity and biological communities (Keller and Swanson, 1979; Harmon et al., 1986; Bilby and Ward, 1989; Bilby and Bisson, 1998; Benke and Wallace, 2003; Dolloff and Warren, 2003; Swanson, 2003). LWD enters stream systems via a range of chronic and episodic processes (Keller and Swanson, 1979; Bilby and Bisson, 1998; Reeves et al., 2003). The source area and amount of contributing LWD to stream systems varies according to the species, composition and age of riparian forests, local topography, channel characteristics and disturbance history.

The relative importance of geomorphic and hydrologic processes that control input, loadings, redistribution and morphological influence of LWD vary with position in the stream network (Keller and Swanson, 1979; Bilby and Bisson, 1998; Gurnell, 2003; Swanson, 2003; Chen et al., 2006). In steep forested headwaters, input processes such as avalanches, landslides, and debris torrents can deliver large quantities of debris to the stream system, often from distances well beyond the immediate stream channel (Keller and Swanson, 1979; Bilby and Bisson, 1998; Reeves et al., 2003). Where there is insufficient discharge and stream power in these small streams, LWD pieces remain relatively immobile (Bilby and Ward, 1989; Robison and Beschta, 1990; Gurnell, 2003; Swanson, 2003). In medium-sized streams, there is an increase in LWD recruitment from tree mortality and bank undercutting (Keller and Swanson, 1979; Robison and Beschta, 1990; Martin and Benda, 2001). Hydraulic processes dominate, as stream size and depth increases; LWD pieces are less likely to span the channel, and are more likely to mobilise with increasing discharges. The number of LWD pieces tends to decrease down the stream system with a corresponding increase in piece diameter, length, and volume (Bilby and Ward, 1989; Robison and Beschta, 1990; Richmond and Fausch, 1995; Gurnell, 2003; Chen et al., 2006). Dam frequency and channel-spanning

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dams also decrease as dam size and inter-spacing increases down the stream channel (Keller and Swanson, 1979; Martin and Benda, 2001; Abbe and Montgomery, 2003). In-channel inputs of LWD operate throughout the river system, and are mainly derived from downstream movement of LWD. In wider channels of larger rivers where LWD no longer spans the channel and discharge regime can move most pieces in high flows, flotation is a significant process and the rivers geomorphic structure is an important control on LWD retention and debris dam structure (Keller and Swanson, 1979; Harmon et al., 1986; Abbe and Montgomery, 2003; Gurnell, 2003).

Morphological function of LWD also exhibits trends within a catchment. LWD is often a primary agent in step and pool formation and controls routing of sediment, particulate organic matter and nutrients through channel networks (Mosley, 1981; Harmon et al., 1986; Bilby and Ward, 1989; Richmond and Fausch, 1995; Bilby and Bisson, 1998; Rosenfeld and Huato, 2003). Its influence on all these factors tends to decline along the stream system as LWD loadings decrease and channels widen. Key factors influencing the stability and retention of LWD pieces throughout a river network include the ratio of piece length and diameter to bankfull width and depth, wood density, and degree of anchoring, with rootwads greatly increasing piece stability (Martin and Benda, 2001; Abbe and Montgomery, 2003; Gurnell, 2003).

Our knowledge and understanding of LWD dynamics within a river network has been derived by integrating information from a large number of studies, over a wide range of stream types and sizes, in varying forest types, using a range of sampling methods. Few studies have examined spatial distribution of LWD over a range of stream sizes within a large catchment using consistent sampling methods (Swanson, 2003). Martin and Benda (2001) and Reeves et al. (2003) are two examples, although neither study sampled the steeper headwater streams.

In New Zealand, reach-scale studies to date have examined LWD loadings and influence on stream channel morphology in a number of stream systems, focusing on smaller sized streams in both indigenous and exotic pine plantation forests (Mosley, 1981; Evans et al., 1993; Baillie et al., 1999; Baillie and Davies, 2002; Meleason et al., 2005), but distribution patterns of LWD and morphological influence have not been studied at the catchment level. The objectives of this study were to (a) describe and quantify the amount and spatial distribution of LWD in a large catchment of old-growth forest and (b) determine the influence of LWD on channel morphology and habitat complexity.

2. Study area

The Whirinaki River is located in the Whirinaki Forest Park in the central North Island of New Zealand (Fig. 1). This catchment was chosen for the study as it provided a large fifth-order river system in old-growth forest, representative of the dominant indigenous forest type in New Zealand. The catchment area is 73 km^2 and altitude ranges from 580 to 1180 m.a.s.l. Hillslopes are steep, >35° in the headwaters, and

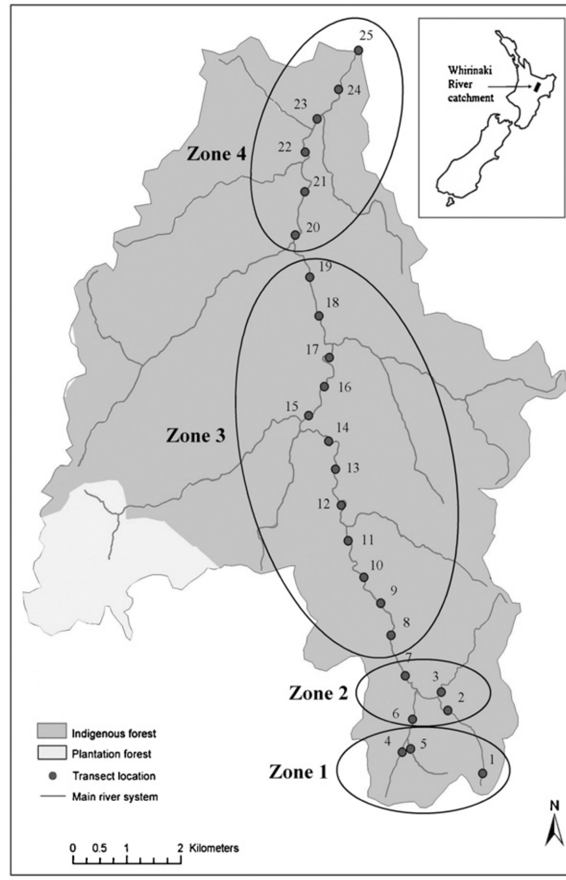

Fig. 1. Forest type, transect location and zones in the Whirinaki catchment.

26–35° throughout most of the catchment, except for a plateau area in the south-western corner (slope 0–3°) (Ministry of Works and Development, 1979). Geology is predominantly graywacke in the southern section of the study area with overlying Podzolised Orthic Pumice Soil, and predominantly ignimbrite in the remaining northern and eastern areas with associated Humose Orthic Podzol Soil (Grindley, 1960; Ministry of Works and Development, 1979; Hewitt, 1998). Mean annual rainfall in the area is 1523 mm (New Zealand Meteorological Service).

The indigenous forest (Fig. 1) is primarily beech (*Nothofagus* sp.) or beech-rimu (*Dacrydium cupressinum*) forest (Nicholls, 1974), which developed following the Taupo eruption 1850 BP (Wilmhurst and McGlone, 1996). Beech or mixed beech forests comprise approximately 68% of New Zealand's indigenous forests (Wardle, 1984). Silver and red beech (*Nothofagus menziesii*, *Nothofagus fusca*) were the dominant riparian tree species throughout the river system, additional species included tawari (*Ixerba brexiodes*), kamahi (*Weinmannia racemosa*) and tree ferns (mainly *Cyathea smithii*). The plateau area in *Pinus radiata* plantation forest (Fig. 1) was outside the main study area.

Catchment areas upstream from transects ranged from 0.2 km^2 in the headwaters to 73 km^2 at the downstream end of the study area. Bankfull width ranged from 1.5 m in the headwaters to 18.0 m in the lower part of the river system.

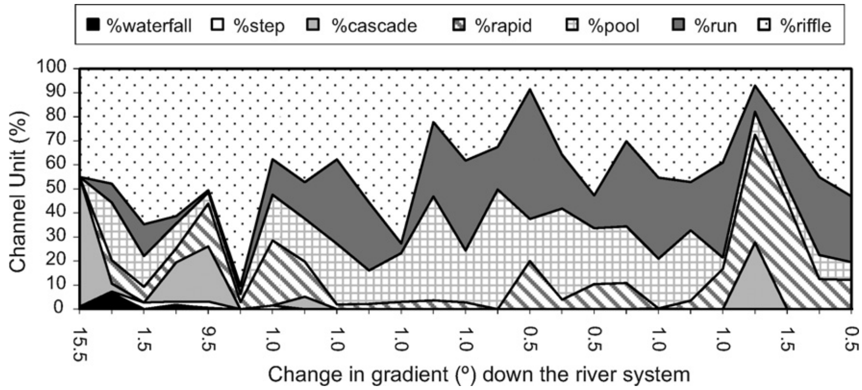

Fig. 2. Channel unit composition in the Whirinaki River system.

Channel gradients ranged from 1.5° to 15.5° in the headwaters and were ≤2° along the remainder of the channel system. Riffles were the dominant channel unit in the Whirinaki River system, followed by runs, pools and rapids (Fig. 2). Waterfalls, cascades and steps were confined to the steeper headwater sites or where mean gradient was ≥2° (Fig. 2).

3. Methods

Twenty-five transects, 200 m in length, and orientated parallel to the stream channel were spaced at approximately 1-km intervals in the headwaters and along the main stem of the channel of the Whirinaki River (Fig. 1). Several transects were relocated from their original position because of access and safety issues. Bankfull width was measured to the nearest 0.1 m at 10-m intervals along each transect and averaged. Channel gradient was measured to the nearest 0.5° using a clinometer. Gradients less than 0.5° were recorded as 0.1 for calculation purposes. Several gradient readings were taken to capture as much of the transect length as possible and an average gradient weighted by distance was calculated for each site. Channel units (i.e. pool, riffle, and run) were defined using the hierarchical classification system of Hawkins et al. (1993) and the length of each unit along the 200 m transect was measured to the nearest 0.1 m. Pool type (Hawkins et al., 1993) and pool-forming factors were recorded for each pool. For each transect, we measured the length of transect where only one channel unit spanned the channel width (simple habitat) and the length where two or more units spanned the channel width (complex habitat). The factors creating the complex habitat were recorded for each section of complex habitat, i.e. LWD, gravel bar, etc.

All LWD ≥ 10 cm in diameter and 1 m length, within the bankfull channel was measured for small-end diameter, mid-stem diameter and large-end diameter. The three diameters were averaged to calculate mean diameter for each piece. The length submerged or above the water column was recorded. The volume of each piece was calculated using Newton's formula (Harmon and Sexton, 1996):

$$V_{\text{piece}} = \frac{L(A_b + 4A_m + A_t)/6}{10,000} \quad (1)$$

where V_{piece} = volume of piece (m^3); L = length of piece (m); A_b = area at the base of the piece (cm^2); A_m = area at the mid-point of the piece (cm^2); and A_t = area at the top of the piece (cm^2). The width, height, and depth of rootwads were summed to give an approximate volume and were excluded from LWD diameter and length statistical analysis. LWD volumes in each transect were expressed as $m^3\ ha^{-1}$ using bankfull width and transect length to calculate streambed area.

Each piece was classified according to orientation ((1) parallel to stream flow; (2) 90° to stream flow; (3) 45/225° to stream flow; (4) 135/315° to stream flow) and position in the channel (suspended across channel; partly suspended across channel; on the channel floor; along bank edge; in a debris dam). Each piece was assessed as stable if it had one or more of the following characteristics: a rootwad, length extended outside the channel, or the piece was partially buried. Where possible, the source of each piece was recorded. LWD influence on channel morphology was described as follows: no influence, sediment storage, step formation, flow deflection, bank armouring, wood storage, organic matter (twigs, leaves, fine organic matter) storage and pool formation. Key riparian species most likely to supply LWD to the stream system were recorded at each site (see Section 2), along with descriptive notes on LWD and debris dam distribution patterns in the stream channel.

4. Analysis

Correlation analysis was used to examine the relationships between bankfull width, gradient and catchment area. Descriptive statistics were used to analyse channel unit composition and LWD characteristics. Linear regression was used to examine relationships between bankfull width and a range of LWD characteristics.

Paired *t*-tests were used to determine whether LWD orientation and position in the channel differed from a random distribution pattern and linear regression was used to examine longitudinal distribution patterns using bankfull width as the dependant variable. *t*-Tests using SAS statistical software (Version 9) were performed on log-transformed (geometric) mean diameter and (geometric) mean length to test for significant differences in the dimension of LWD pieces influencing versus those LWD pieces not influencing channel morphology. Paired *t*-tests were used to compare LWD piece stability and piece length to bankfull width ratios, between pieces influencing versus those not influencing channel morphology. Based on these results and field notes, we identified four zones of LWD distribution and influence. One-way ANOVA was used to test for significant differences in key LWD and pool attributes between zones. Log-transformations were used where appropriate. Angular transformation was used for all percentage variables. Results were considered significant if $P \leq 0.05$.

5. Results

The three catchment variables of catchment area, bankfull width and gradient were highly correlated ($r = 0.82$–0.98). Initial analysis of a range of LWD-dependent variables with the three catchment variables showed that in most instances, strongest correlations were with bankfull width, followed by catchment area and gradient. Therefore results are presented for bankfull width only, with reference to the other catchment variables where appropriate.

5.1. LWD characteristics

A total of 2799 pieces of LWD were measured in the 25 transects. Details of LWD characteristics are in Table 1. The majority of pieces were ≤10 m in length and the majority of piece diameters were ≤40 cm. There was a significant increase in the number of pieces and a significant decrease in pieces/unit area with increasing bankfull width (Fig. 3a). Geometric mean piece length increased significantly down the river system (Fig. 3b). However, LWD geometric diameters showed a weak and slightly negative downstream trend. As a result, mean piece size (m^3) showed a weakly positive, but insignificant relationship, with bankfull width. LWD volume/unit length (m^3/200 m) showed a significant increase in a downstream direction, whereas LWD volume/unit area showed a significant negative trend (Fig. 3c). Most of the LWD volume was above the water column, averaging 80% (range 57–97%), with 20% on average (range 3–43%) submerged in the water.

The percentage of pieces orientated parallel or perpendicular to stream flow (classes 1 and 2) were significantly higher than

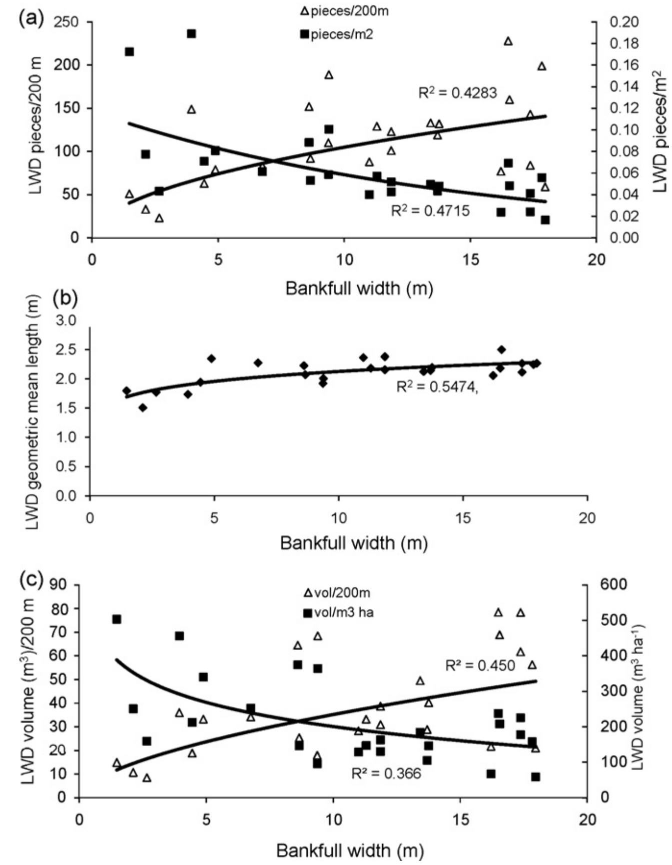

Fig. 3. Relationships between bankfull width and (a) LWD piece frequency and LWD piece density; (b) LWD piece length; (c) LWD volume/unit length and LWD volume/unit area. $P \leq 0.01$ for all trendlines.

if the pieces had been randomly orientated whereas the percentage of pieces in orientation classes 3 and 4 were lower (Table 2). Downstream trends in the four orientation classes were in most cases either weak or absent. The percentage of pieces in position 1 and position 4 (Table 2) were significantly lower and higher, respectively, than if the pieces had been randomly positioned. Sixty percent of pieces suspended across the stream channel were located in the six headwater sites and decreased significantly down the river system with increasing bankfull width ($R^2 = 0.80$; $P < 0.01$). The percentage of pieces in position 2 showed a weaker but significant decrease down the

Table 1
LWD characteristics in the Whirinaki River

	Transect mean	Range of transect means	R^2 values bankfull width
Abundance (pieces/200 m)	112	23–228	0.43**
Density (pieces/unit area (m^2))	0.06	0.02–0.19	0.47**
Diameter (cm)[a]	22.5	18.5–28.9	0.18*
Length (m)[a]	2.1	1.5–2.5	0.55**
Mean piece size (m^3)	0.35	0.16–0.93	0.07
Vol (m^3/200 m)	39	9–78	0.45*
Vol/unit area ($m^3 ha^{-1}$)	212	59–503	0.37*
Piece length (m) to bankfull width (m) ratio	0.29	0.12–1.21	0.98**

*$P \leq 0.05$; **$P \leq 0.01$; $n = 25$.
[a] Geometric mean.

Table 2
LWD source and location

Orientation	1	2	3	4	
%	33	29	19	18	
Position	1	2	3	4	5
%	5	21	19	32	23
Source[a]	Bank undercutting	Upslope windthrow	Bank edge windthrow	Landslide/slip	Unknown
%	41	25	17	2	15

[a] *in situ* pieces only, $n = 247$. Orientation—(1) parallel to stream flow; (2) 90° to stream flow; (3) 45/225° to stream flow; (4) 135/315° to stream flow. Position in the channel—(1) suspended across channel; (2) partly suspended across channel; (3) on the channel floor; (4) along bank edge; (5) in a debris dam.

river system ($R^2 = 0.24$; $P < 0.01$ for bankfull width) whereas the percentage of pieces in position 5 increased ($R^2 = 0.55$; $P < 0.01$ for bankfull width).

Forty percent of the pieces were classified as stable. The main stability factor was partial burial in the bank or substrate (65%), followed by the piece length extending outside the channel (16%) or possessing a rootwad (13%). Five percent of pieces had a combination of stability factors. We identified 9% of LWD pieces as *in situ*, and the majority were sourced from bank undercutting (Table 2). There were no identifiable downstream trends in *in situ* LWD sources.

5.2. LWD influence on channel morphology and habitat diversity

Of the 2799 LWD pieces measured, 1351 pieces (48%) were influencing channel morphology, and 468 (35%) of those pieces were influencing more than one aspect of channel morphology. Wood storage, bank armouring and sediment storage were key morphological functions of LWD in the Whirinaki river system (Fig. 4). The proportion of pieces influencing wood storage was positively correlated with bankfull width ($R^2 = 0.42$; $P < 0.01$); bank armouring was negatively correlated with bankfull width ($R^2 = 0.32$; $P < 0.01$), whereas sediment storage showed no trends at all. LWD influenced pool formation in 43% of all pools ($n = 219$) and the density of pools influenced by LWD was positively correlated with LWD volume ($R^2 = 0.35$; $P < 0.01$). LWD influence was highest for debris pools, backwater pools and plunge pools (93, 76 and 45% of all pools, respectively).

The pieces influencing channel morphology had significantly larger diameters and lengths, higher piece length to bankfull width ratios, and a higher proportion of stable pieces than pieces with no influence. There were 83 key LWD pieces forming debris dams and they were longer (mean length 4.5 m), larger (mean diameter 36 cm) and more stable (75% of key pieces) than average. Sixty-two percent of the key pieces were orientated across the stream channel.

Habitat complexity was 0% in the three smallest headwater sites and low in the three remaining headwater sites (3–8% of channel length). Habitat complexity varied along the remainder of the river channel (Fig. 5) but showed a significant increase with increasing bankfull width ($R^2 = 0.47$; $P < 0.01$). LWD, gravel bars and variations in substrate influenced habitat complexity in the upper to middle sections of the river system (Fig. 5). In the lower section, mid-channel islands were the key contributors to habitat complexity, with an exception in a steeper section of rapids and cascades (transect 22) where the influence of LWD dominated. The unit length of complex habitat averaged 6.7 m and was significantly shorter than the average length of simple habitat at 9.7 m (paired *t*-test, $P = 0.01$, $n = 22$).

5.3. Zonal patterns of LWD distribution and influence

We identified four main zones of LWD distribution patterns in the Whirinaki River system (Table 3). In Zone 1, the three small headwater sites (Fig. 1), wood loadings were lower than the three remaining zones (Table 3). The majority of pieces were *in situ*, and high proportions were suspended across the channel. Debris dams were absent and influence of LWD on channel morphology and habitat complexity was low (Table 3). The majority of plunge pools were located in the headwater sites (Zones 1 and 2) and pools were absent at one site.

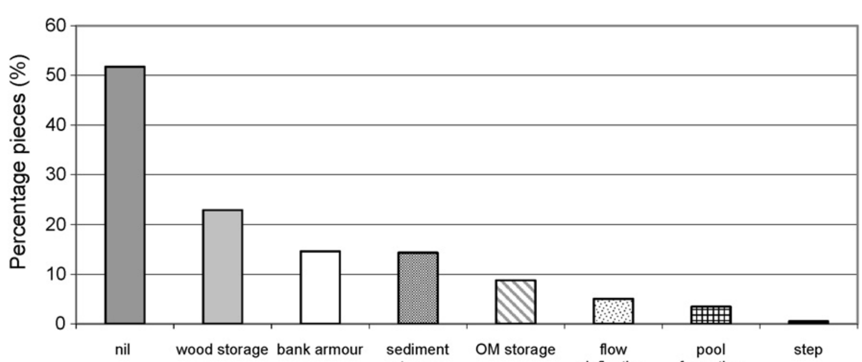

Fig. 4. Morphological function of LWD in the Whirinaki river system. *Note*: total > 100% as some pieces provided multiple functions.

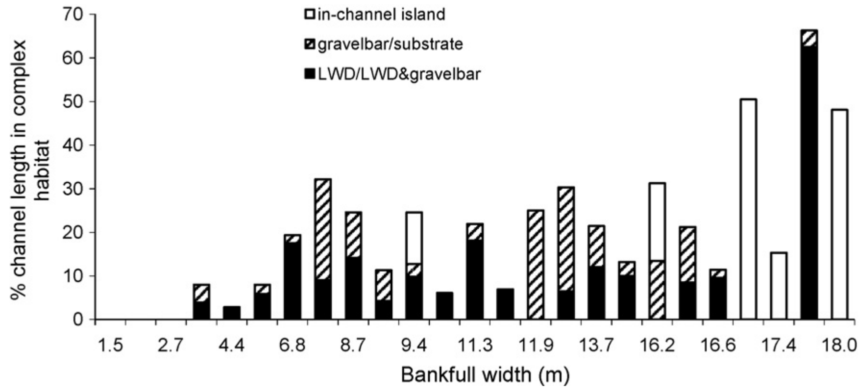

Fig. 5. The influence of LWD and other factors on channel unit complexity.

Table 3
Zonal characteristics of LWD in the Whirinaki River system

	Zone 1	Zone 2	Zone 3	Zone 4
No. of transects	3	4	12	6
Bankfull width (m)	1.5–2.7	3.9–8.6	9–18	16–18
Mean LWD vol ($m^3\ ha^{-1}$)	11 b	38 ab	40 a	50 a
Mean no. of pieces	36 b	111 a	133 a	109 a
Mean % suspended pieces	27 a	9 b	1 c	0.2 c
Mean % pieces in debris dam	0 c	16 b	26 ab	31 a
Piece influence on habitat complexity (mean %)	0 b	6 ab	15 a	3 b
Piece influence on channel morphology (mean %)	34 a	44 a	37 a	42 a
Piece influence on pool formation (mean %)	4 b	51 a	47 a	36 ab
Mean no. of pools	8 ab	13 a	10 a	4 b

*Figures with the same letters are not significantly different ($P \geq 0.05$).

In Zone 2 (Fig. 1), wood loadings increased along with influence on channel morphology and habitat complexity. The proportion of pieces spanning the channel width was significantly lower than Zone 1 but higher than the two downstream zones (Table 3). Debris dams spanned the channel and there was an increase in the proportion of pieces stored in debris dams. The average number of pools and influence of LWD on pool formation was highest in this zone. Lateral pools increased significantly in this and the remaining two downstream zones and were rarely found where mean gradient was $\geq 3^\circ$.

Zone 3 (Fig. 1) was characterised by a pool/riffle/run morphology (Fig. 2). Wood loadings, and influence on channel morphology and pool formation were similar to Zones 2 and 4 but LWD influence on habitat complexity was highest in this zone (Table 3). As bankfull width increased beyond 9 m, there were fewer channel-spanning LWD pieces. There was a significant increase in the proportion of pieces in debris dams (Table 3), wood storage sites were predominantly along the outer bends or at the head of gravel bars and debris dam interspacing increased.

While wood loadings in Zone 4 were similar to Zones 2 and 3, LWD influence on habitat complexity was lower (Table 3). Instead in-channel islands were the main contributor to habitat complexity for Zone 4 (Fig. 5) and provided additional storage sites for wood. Channel-spanning pieces were rare and pools were scarce in Zone 4.

6. Discussion

There were distinct catchment-scale distribution patterns of channel units and LWD in the Whirinaki River system. Longitudinal trends in LWD frequency, volume, length, piece size and position were obvious along the river system and most strongly related with bankfull width. The influence of LWD on channel morphology decreased along the river system as LWD loadings declined. Most of these trends are similar to other catchment studies (Bilby and Ward, 1989; Robison and Beschta, 1990; Abbe and Montgomery, 2003; Chen et al., 2006), in spite of the smaller piece dimensions compared to the Pacific Northwest. As stream size and power increases, piece retention and stability decreases and only the larger more stable pieces which are more resistant to movement downstream are likely to remain in place, and influence channel morphology. However, we did not find an increase in piece diameter down the river system. This is in contrast to some other studies (Bilby and Ward, 1989; Robison and Beschta, 1990; Chen et al., 2006) but similar to Beechie and Sibley (1997) who also found no correlation between LWD diameter and channel width. The non-random orientation of pieces in the channel indicated that angle of tree entry and fluvial processes were influencing piece orientation. LWD was a key pool-forming factor in the Whirinaki River system, influencing pool formation in 43% of the pools. This figure is similar to Beechie and Sibley (1997) and Baillie and Davies (2002); but lower than Richmond and Fausch (1995).

There were no obvious longitudinal trends in sources of LWD to the stream channel. Bank undercutting and wind throw were the principle wood delivery processes to the channel along the Whirinaki River system, similar to some other studies (Keller and Swanson, 1979; Bilby and Bisson, 1998; Martin and Benda, 2001). Only a quarter of *in situ* pieces were from upslope sources. The low contribution of upslope sources of LWD to the headwater streams of the Whirinaki River, even in the steeper headwater streams, may indicate relatively stable hill slopes, or timing of sampling during a relatively stable period in the disturbance regime of the catchment. In steep headwater sites, upslope processes such as landslides and avalanches can deliver large amounts of LWD to streams (Keller and Swanson, 1979; Lienkaemper and Swanson, 1987). However, in Reeves et al. (2003) upslope sourcing of LWD was highest in middle stream reaches and in the U-shaped valleys of Martin and Benda's (2001) study, landslides were a minor source of LWD for streams. This shows that the contribution of upslope sources to in-stream LWD does vary between sites depending on factors such as topographical features, hill slope stability and vegetation composition.

Piece length, diameter, stability and geometric mean length to bankfull width ratios were important factors in determining which pieces were likely to influence channel morphology and debris dam formation in the Whirinaki. These features were consistently higher in influential pieces throughout the river system. Rootwads, degree of burial, piece length and diameter and associated ratios with bankfull width and depth, are critical factors in determining piece stability and influence on channel morphology and debris dam formation in river systems, as previously reported by other studies (Martin and Benda, 2001; Abbe and Montgomery, 2003; Gurnell, 2003; Rosenfeld and Huato, 2003).

Changes in transport capacity, fluvial processes and geomorphic characteristics in the Whirinaki River system, defined the transitional boundaries between zones of LWD distribution patterns. When tested in a single large river system with consistent methodology, we found similar zonal patterns of LWD distribution and influence to those in Gurnell's (2003) review paper, which were derived from a variety of studies. In Zone 1 (Fig. 1), there was insufficient stream power to move LWD pieces and in one site, pools were absent, indicating insufficient stream power during high flows to initiate scouring processes. Small colluvial reaches such as these have a limited transport capacity (Montgomery and Buffington, 1997) and are unlikely to provide a source of LWD and sediment to the lower river system, except in extreme hydrological events or debris flows.

In Zone 2, the increase in channel width and stream power increased the capacity of fluvial processes to shift wood down the river system, redistributing pieces into distinct accumulations. However, channel width constrained movement of larger pieces and a high proportion of individual pieces and debris dams still spanned the channel width, typical of streams this size (Keller and Swanson, 1979; Robison and Beschta, 1990; Bilby and Bisson, 1998; Chen et al., 2006).

In, Zone 3 where bankfull widths increased beyond 9 m, the influence of channel width on piece retention diminished and there was a shift to fluvial processes and the geomorphic structure of the river system dominating wood distribution. Fluvial processes redistributed LWD pieces into debris dams predominantly located along the outside of meander bends although in-channel obstructions to wood movement such as heads of gravel bars also provided wood storage sites. Presence of sediment deposits such as gravel bars indicated that in this section of the river system, sediment supply exceeded the transport capacity of the river system.

Similar processes operated in Zone 4, with in-channel islands providing additional wood storage sites and a major contribution to habitat complexity. The exception was a transect in a higher gradient bedrock controlled section of river. In spite of the high transport capacity usually associated with this type of morphology (Montgomery and Buffington, 1997), LWD levels were comparable with adjacent transects and LWD was the key influence on habitat complexity.

7. Conclusion

This study demonstrates the importance of sampling both the headwaters and the main stem of a river system to capture catchment-wide LWD distribution patterns. Distribution patterns can change rapidly in headwater sites where there are considerable changes in bankfull width, gradient and stream power over comparatively short distances. While most LWD studies have focused solely on the role of LWD in providing habitat diversity we have been able to quantify the impact of LWD on habitat diversity in relation to other contributing factors in the wider river network.

The characteristics and location of pieces likely to be retained in a river system and their contribution to habitat diversity varies throughout the river network. This information can provide guidance to managers when manipulating, enhancing or protecting LWD sources in large river systems. For example the retention of appropriate pieces following harvest can assist in minimising harvest impacts on aquatic ecosystems and accelerating post-harvest recovery. Judicial use of LWD can also enhance habitat for a variety of in-stream and riparian species and provides a management tool in the conservation of endangered species (Benke and Wallace, 2003; Dolloff and Warren, 2003; Steel et al., 2003; Baillie and Glaser, 2005; Nicol et al., 2007).

This study, contributes to our global understanding of the role of LWD in old-growth forested stream ecosystems and shows similar results to other large catchment scale studies in the northern hemisphere forests, primarily in the Pacific North-West region of the United States of America (Bilby and Ward, 1989; Martin and Benda, 2001; Abbe and Montgomery, 2003; Chen et al., 2006). However, this study has focused on a single catchment and requires replication in other forest types (natural and man-made), with differing levels of natural and human disturbance. These results highlight the need to understand river systems and associated LWD patterns at the catchment level when undertaking protective, management or rehabilitation programmes in forested river ecosystems.

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