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Effects of land use on the channel morphology of streams in the Moutere Gravels, Nelson, New Zealand

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Abstract

Land use can affect channel morphology, especially in small catchments (up to 5–8 km^2). Previous studies have suggested that stream channels in pasture catchments are usually narrower than those in forested catchments due to the erosional resistance of grass, and its ability to trap and retain sediment. In the Hakarimata Ranges, Waikato, New Zealand, where the bedrock is predominantly sandstone, siltstone and mudstone, streams in small catchments converted from pasture to pine plantations are in the process of widening back to a forest channel morphology, releasing the sediment retained in the banks by the grass sod. As the majority of new pine plantations are on pastureland or reverting pastureland, the possibility of increased sedimentation in streams during this conversion process may be a problem in some areas.

The Moutere Gravels in Nelson provide an area of contrasting geology, hydrology and climate to the Hakarimata Ranges for assessing the influence of land use on channel morphology. This study compared channel morphology characteristics in 15 streams in small-sized catchments, with 5 stream catchments each in pasture, pine plantation and native forest.

There were no significant differences in bankfull width, channel width, channel depth and cross-sectional area of streams in catchments with the three types of land use in the Moutere Gravels. However, width-to-depth ratios were significantly higher in the pasture streams than in the forest streams, median particle size was significantly lower in the pasture and pine plantation sites than in the native forest sites and there were more pools in the forest streams, in part attributable to the presence of woody debris.

It is suggested that low sediment yields, infrequent floods of sufficient magnitude to influence channel morphology, and the cohesive channel bank material in the Moutere Gravels may explain the lack of effects of land use on channel morphology in these small catchments.

The results from the Moutere Gravels suggest that factors other than land use can sometimes exert a stronger influence on channel morphology in small catchments.

Keywords

channel morphology, land-use, Moutere Gravels, streams, Nelson, pine plantation, pasture, native forest, large woody debris, pools

Introduction

Channel morphology is dynamic, changing in response to factors such as discharge, sediment delivery, and stream bed and bank roughness (Beschta and Platts, 1986; Montgomery and Buffington, 1998). The channel can adjust to these factors in a number of ways, including changes in width and depth, cross-section shape, gradient, bed material composition, channel sinuosity, and bedform (Figure 1). Channel morphology reflects the processes that formed the channel. The morphology of a stream channel, along with its hydrological characteristics, will in turn influence the stream's biological communities (Vannote *et al.*, 1980).

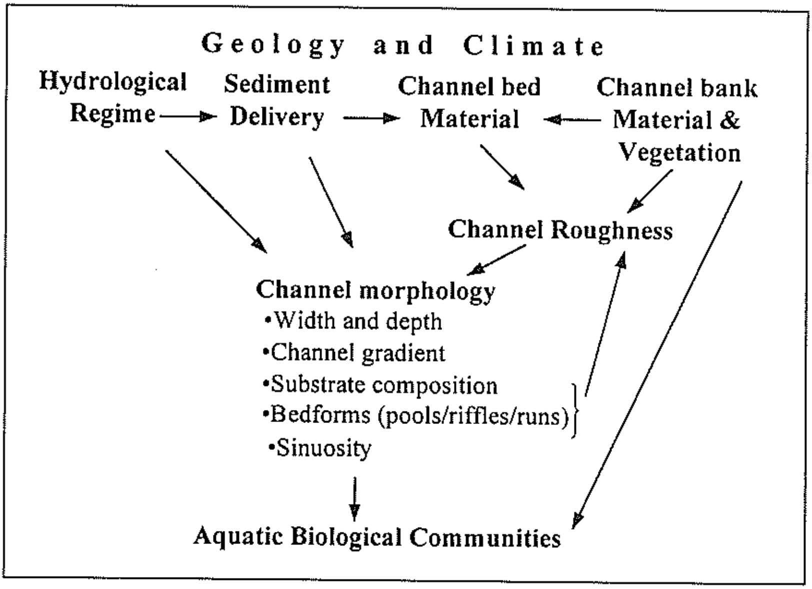

Figure 1 – Factors affecting channel morphology (adapted from Montgomery and Buffington, 1998)

Riparian vegetation can influence channel morphology by contributing to bank stability, by changing shear strength through root reinforcement of bank materials, by increasing channel roughness, and by providing large woody debris to the stream channel (Keller and Swanson, 1979; Gray *et al.*, 1989; Montgomery and Buffington, 1998; Abernethy and Rutherford, 1999). Large woody debris in the stream channel can increase channel bed roughness, dissipate flow energy, and provide sediment storage sites, and it can have a strong influence on pool formation (Keller and Swanson, 1979; Mosley, 1981; Smith, 1992b; Montgomery *et al.*, 1995; Montgomery and Buffington, 1998), especially in smaller-sized, low-gradient streams (Bisson *et al.*, 1987; Bilby and Ward, 1989; Bilby and Bisson, 1998). Any change in land use that significantly alters the riparian vegetation and delivery of large woody debris to the stream channel can potentially affect channel morphology.

Comparative land-use studies both in New Zealand and overseas have found differences in channel morphology between streams flowing through pasture and forested areas. The effect, in most cases, was most obvious in small catchments with areas of up to 5–8 km^2, and less obvious in larger catchments with areas greater than 10 km^2 (Zimmerman *et al.*, 1967; Murgatroyd and Ternan, 1983; Clifton, 1989; Sweeney, 1993; Quinn *et al.*, 1997; Trimble, 1997; Davies-Colley, 1997). Quinn *et al.* (1997) compared stream channels in forested and pasture catchments, while the remaining studies compared stream channels in catchments with sections of forest and pasture. In all these studies, stream channels in forested sites were significantly wider than channels in pasture sites. In most cases, stream widths tended to be more variable in the forest streams, cross-sectional area was usually larger, and channel banks were less stable compared to those of pasture streams. These studies showed that the influence of riparian vegetation could override the effects of other factors, such as hydrology, geology, and sediment regime, in influencing channel morphology in streams.

The differences in channel morphology between forest and pasture streams have been attributed to several mechanisms (Zimmerman *et al.*, 1967; Murgatroyd and Ternan, 1983; Quinn *et al.*, 1997; Davies-Colley, 1997). The narrower widths of pasture streams were attributed to the ability of grass sods to trap and retain sediment and to stabilise channel banks, increasing their resistance to fluvial scour. The wider channels of the forest streams were attributed to the lesser ability of tree roots to hold and retain sediment, resulting in more active bank erosion, and to localised channel widening caused by large woody debris obstructing the stream channel.

In the Hakarimata Ranges, New Zealand, streams flowing through an area converted from pasture and now covered by a first rotation crop of 15-year-old pines were intermediate in width between the narrower pasture and wider native forest streams. Just under half the bank length in these streams was unstable, with either bare soil or actively eroding or slumping banks (Quinn *et al.*, 1997). Davies-Colley (1997) hypothesized that the clearance of native forests and subsequent establishment of land in pasture has led to a period of channel narrowing as grasses have trapped and stored sediment over time, building up the channel banks. The active bank erosion in the pine plantation streams in Quinn *et al.*'s (1997) study indicates that these streams are in the process of widening back to a morphology typical of forest streams. These changes are thought to be a response to increasing shade as the pine plantations mature, causing pasture grasses to die off and leaving the channel banks more vulnerable to lateral stream erosion.

Pine plantations cover an estimated 1.731 million hectares, 6% of New Zealand's land area (NZFOA, 2000); the principle species is *Pinus radiata*. Most of the new afforestation in New Zealand, estimated at 65,000 ha/yr, is occurring on pasture or reverting pastureland (Maclaren, 1996; Glass, 1997; MAF, 2000). There is the potential for this change in land use to cause a period of stream bank erosion, and high turbidity and sediment yield during the channel adjustment phase as the stream channel widens (Quinn *et al.*, 1997; Davies-Colley, 2000). Increased sedimentation could adversely affect both the on-site and downstream environment, including aquatic invertebrates and fish, and estuaries and harbours. The duration of this adjustment phase, and whether it is likely to occur in regions of New Zealand with differing geology, hydrology and climatic conditions, are presently unknown.

This paper assesses the influence of land use on channel morphology in the Moutere Gravels of Nelson, a contrasting region to the Hakarimata Ranges, and the implications for conversion of pastureland to pine plantations.

Study area

Geology, geomorphology and soils

The Moutere Gravels, a thick late Pliocene-early Pleistocene deposit, lie in the Moutere Depression, which formed in the Pliocene-Pleistocene during the uplift of the Tasman Mountains to the west and the Nelson Ranges to the east (Rattenbury *et al.*, 1998). The Moutere Gravels cover approximately 134,000 ha (Figure 2) and consist of uniform yellow-brown, silty, clay-bound gravel with deeply weathered subrounded to well-rounded clasts mainly composed of sandstone and semi-schist (Rattenbury *et al.*, 1998). Linear valleys and ridges, oriented predominantly E–W and SE–NW, with regular spaced tributaries, are a typical geomorphic expression of the Moutere Gravels. The hillslopes show distinct asymmetry, with steep southern sides and more gently sloping northern sides. The soils in these gravels are predominantly Hill soils transitional between yellow-grey (Pallic Soils) and yellow-brown earths (Brown Soils) at the seaward end of the Moutere Gravel formation, with yellow-brown earths (Brown Soils) covering the remainder of the area (Chittenden *et al.*, 1966). Soils at all the sites in this study are classed as yellow-brown earths (Rosedale silt loam, Rosedale hill, Stanley hill, Spooner hill, Korere hill and Hope hill series). These soils are shallow, acidic, low in fertility and lacking in phosphorus, calcium and potassium.

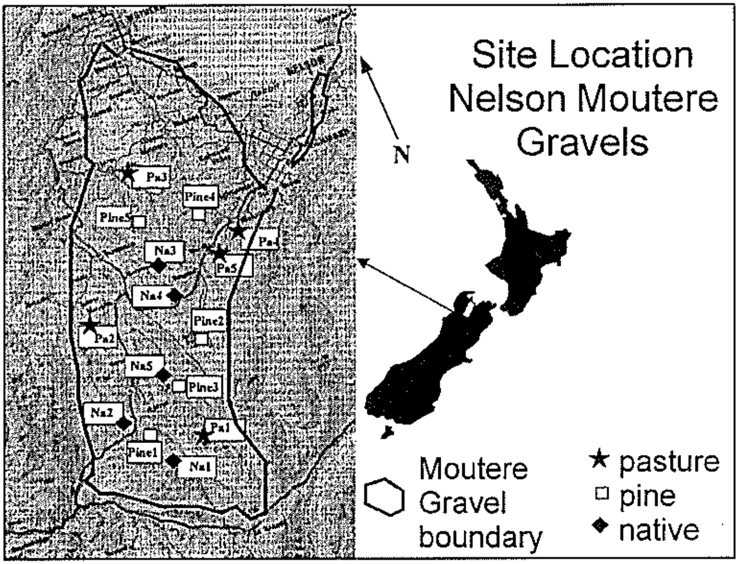

Figure 2 – Location of the pasture, pine plantation and native forest sites in the Nelson Moutere Gravels

Climate

The Nelson district is one of the sunniest places in New Zealand, averaging around 2,400 hours of sunshine a year, with a mean temperature of 12°C (53–54°F) (Beatson, 1985; de Lisle and Kerr, 1965). Although rainfall tends to be evenly distributed throughout the year, Nelson experiences dry periods in the summer and land underlain by the Moutere Gravels is particularly susceptible to drought during these periods (Shirley *et al.*, 1979; de Lisle and Kerr, 1965). In areas on the Moutere Gravels, annual rainfall ranges from 950–1000 mm at the seaward end of the formation, increasing to 1500–1600 mm at the southern end (Tasman District Council, date unknown).

Vegetation

Extensive beech forests covered most of the Moutere Gravels prior to 1840 (Wall, 1985; Ward and Cooper, 1997). Over the next 100 years European settlers and their descendants replaced most of the original land cover with pasture, pine plantations and cultivated crops. About 80% of the original native forest cover on the Moutere Gravels has been lost since European settlement (Wall, 1985). Most of the Moutere Gravels is now covered in native forest or pine plantations, or pasture grazed by sheep and cattle (Wall, 1985). Much smaller flat areas, mainly towards the coast, are used for the production of various crops.

Hydrology

The Moutere Gravels have a limited capacity to store water. Water is stored close to the surface and streams tend to dry up in summer (Shirley *et al.*, 1979; Johnston, 1979; Duncan, 1995). Base flow discharges in the Moutere Gravels are very low. For example, for February 1979 (a period with a 12-year drought frequency) specific discharges (*l*/sec/km^2) for the Moutere Gravels were 0.22, for the Separation Point Granites 4.72, for the Maitai Group (sandstone variously bedded with siltstone/mudstone/limestone) 12.25, and for the Mt Arthur Marble 24.81 (Shirley *et al.*, 1979).

Vegetation can have a pronounced effect on water discharges in the Moutere Gravels (Johnston, 1979) and much of the research on the Moutere Gravels has focused on the hydrological implications of land-use change. Conversion of pasture or gorse into pine plantations tends to reduce annual flows, increase the number of days with zero flow and reduce flood peaks and volumes, once trees reach about 8–10 years of age (Duncan, 1979 and 1995). Two native forest catchments in the Moutere Gravels that were harvested and replanted in pines took 8 years for water yields to reduce to pre-harvest levels and 10 years for storm peak flows, quick flows and low flows to reach pre-harvest levels (Fahey and Jackson, 1997). Both these studies showed a similar time frame for recovery to a forest hydrological regime, even though the study sites lay within the upper and lower limits of the rainfall gradient across the Moutere Gravels.

The geology, hydrology and climate of the Moutere Gravels provide a contrast to that of the Hakarimata Ranges in the North Island, where similar studies of channel morphology in small-sized catchments have been carried out (Table 1).

Table 1 – Comparison of features between the Moutere Gravels, Nelson and the Hakarimata Ranges, Waikato (Chittenden *et al.*, 1966; Maunder, 1974; Ministry of Works and Development, 1975 a and b, 1978, 1979a and b; O'Loughlin *et al.*, 1978; Duncan, 1979; Quinn *et al.*, 1997; Boulton *et al.*, 1997; Hicks and McCaughan, 1997; Rattenbury *et al.*, 1998; New Zealand Meteorological Service, date unknown).

	Moutere Gravels	Hakarimata Ranges
Geology	silty clay-bound gravels	predominantly sedimentary sandstones, siltstones, mudstones, greywacke
Soils	shallow, stony, predominantly yellow-brown earths	well structured, free draining, predominantly yellow-brown earths
Hillslope	strongly rolling, moderately steep, steep (16–35°)	moderately steep to steep (21–35°)
Erosion potential	moderate, increasing in severity particularly on steeper slopes in pasture	slight to severe
Rainfall	mean 1347mm per annum, distribution fairly even throughout the year	mean 1627mm per annum, higher distribution in winter months, extreme hourly and daily rainfall intensities high compared to rest of NZ
Stream flow	usually ephemeral, low base flow 0–8 $l\ s^{-1}km^{-2}$	usually perennial, base flow 11–19 $l\ s^{-1}\ km^{-2}$

Methods

Site selection and description

A catchment comparison design similar to that of Quinn *et al.* (1997) was used for this study. Within the study area five catchments in pasture, five in pine plantation, and five in native forest were selected (Figure 2). The characteristics of each site are described in Table 2.

Catchments selected were restricted to those 2 km^2 (200 ha) or less in area, because other studies had indicated that riparian influences on channel morphology were more pronounced in smaller catchments (Zimmerman *et al.*, 1967; Quinn *et al.*, 1997, Davies-Colley, 1997). Catchment area was calculated from 1:50,000 NZMS 260 maps. Channel gradient was measured with an automatic level. A one-way analysis of variance found no significant

Table 2 - Site characteristics

Land use	Grid Ref (NZMS 260)	Area (ha)	Altitude (m)	Mean channel gradient ° (mm^{-1})		Stream order*
Pasture						
Pa1	N29 976 491	165	500	2.63	(0.046)	3rd
Pa2	N28 902 722	124	280	2.63	(0.046)	2nd
Pa3	N27 045 912	105	200	2.13	(0.037)	2nd
Pa4	N28 139 767	94	100	1.01	(0.018)	2nd
Pa5	N28 107 749	124	140	1.01	(0.018)	2nd
Pine plantation						
Pi1	N28 911 534	129	400	1.47	(0.026)	1st
Pi2	N28 030 641	60	340	2.28	(0.040)	2nd
Pi3	N28 978 585	128	440	2.63	(0.046)	1st
Pi4	N27 036 833	85	300	2.36	(0.041)	2nd
Pi5	N27 085 811	69	180	2.61	(0.046)	2nd
Native forest						
Na1	N29 917 482	137	480	2.36	(0.041)	2nd
Na2	M28 877 558	94	520	1.84	(0.032)	2nd
Na3	N28 024 757	127	280	2.24	(0.039)	2nd
Na4	N28 032 705	84	300	3.28	(0.057)	2nd
Na5	N28 968 608	101	420	1.81	(0.032)	1st

* Strahler, (1957), based on NZMS 260 1:50,000 maps

differences (at the 95% confidence level) in channel gradient and catchment area among catchments with the three land uses.

Pasture sites selected had all or most of the catchment in pasture. Catchment Pa1 had been in native pasture (*Rytidosperma sp.* and *Agrostis capillaris*) since the 1930's, with some reversion back to scrub. It had been in English pasture for the previous 15 years. Catchment Pa2 had been in pasture for about 50–60 years, although the head of this catchment (about 40% of the catchment area) was in 4-year-old *Pinus radiata*. Catchment Pa3 was established in native grass in the late 1800's and developed into English pasture in the 1960's. Catchment Pa4 has been in pasture with patches of gorse for at least 40 years. For catchment Pa5, the site history prior to 1969 is unknown, but the site was in half gorse, half pasture in 1969 and all in pasture since 1982. At catchment Pa5 deer were farmed on the lower catchment and sheep and cattle on the upper catchment, while the remaining four pasture catchments were grazed by both sheep and cattle.

Pine sites were selected in mature stands of *Pinus radiata* where streams are at their most stable in the production forest cycle and the influence of harvesting is minimal. Where possible, sites were selected in a second-rotation crop of trees to minimise the effects of previous land use on channel morphology. Of the 5 pine plantation catchments, one site (Pi1) was a first-rotation crop of 31-year-old *Pinus radiata* on reverting farmland; residual pieces of native wood were present in the stream channel. Three sites (Pi2, Pi4 and Pi5) were in second-rotation crops of *Pinus radiata* ranging from 19 to 26 years of age and had been in pine plantation forest for 46 to 55 years. Site Pi3 was in a third-rotation crop of *Pinus radiata* aged 27 years and had been in pine plantation forest for at least 60 years (the date of establishment of the first rotation crop is unknown).

Native forest catchments were selected to provide a benchmark for comparison with the pine plantation and pasture streams. However, most of the unmodified (i.e. unlogged) native forest was in Big Bush, in the southern and western areas of the Moutere Gravels. A compromise was made between selecting unmodified native catchments and ensuring that the native sites were spread throughout the study area. One native site was described by Wall (1985) as being modified with some logging (Site Na3); another site had been lightly logged (Site Na5). All of the sites are in varying types of beech forest.

Further details on the history and characteristics of each site are provided in Appendix 1 in Baillie (2001).

At each site, streams were visually assessed to select a representative 100 m reach (i.e. reaches with a similar channel pattern, channel confinement, streambed and bank materials) to ensure adequate sampling of sinuosity and channel bed units (Gordon *et al.*, 1992) and to compare with previous studies (Quinn *et al.*, 1997; Davies-Colley, 1997). The reaches were located at the bottom of the catchment, in areas where there were no major tributaries or significant changes in gradient, and away from any boundary influences e.g. fences across streams.

Field measurements

Geomorphically-based classification schemes for stream reaches and channel units are relatively new and undergoing refinement; no one classification system is universally accepted (Hawkins *et al.*, 1993; Hauer and Lamberti, 1996). The lack of consistent terminology and classification systems highlights the importance of giving detailed definitions and descriptions of the terminology being used. Measurements were selected that would characterise the channel morphology, provide information for statistical analysis, and allow comparisons among the three land uses and with other similar studies. These measurements are described below.

Cross-section measurements

Cross-section measurements were taken on transects located at 5 m intervals along a 100 m section of stream reach (21 transects in total). Bankfull width was defined as the horizontal distance between the tops of the channel banks at right angles to the orientation of the stream channel, measured to the nearest centimetre using a fibre tape. If the banks were at different heights, bankfull width was the horizontal distance between banks at the point at which overbank flow would occur (Murgatroyd and Ternan, 1983) (Figure 3).

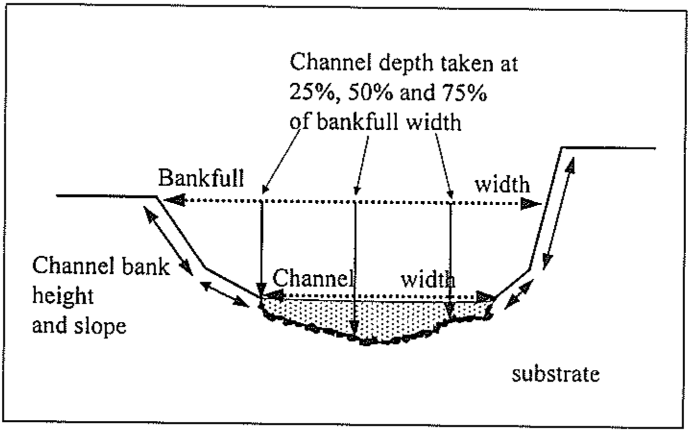

Figure 3 - Cross-section measurements at each transect

Channel width was defined as the width across the bottom of the channel, bounded on either side by the stream banks (Figure 3) and is the relatively level substrate plane over which the water column moves (Platts *et al.*, 1983).

Channel depth was assessed by measuring the vertical distance from bankfull height to the channel bottom, using a survey pole. Channel depth measurements were taken at 25%, 50% and 75% of bankfull width (Platts *et al.*, 1983) (Figure 3). Mean channel depth was calculated for each cross-section using the formula:

$$\text{Mean depth } (\underline{D}) = (D_2 + D_3 + D_4)/4$$

where D_2 = depth at 25% of bankfull width, D_3 = depth at 50% of bankfull width and D_4 = depth at 75% of bankfull width (Platts *et al.*, 1983).

True left and true right channel bank heights were measured to the nearest centimetre from the bottom of the bank (usually a distinct break in slope from the channel bottom) to the top of the bank, (see definition of bankfull width). Bank slope was determined to the nearest 5° using a clinometer placed on top of a rod (Platts *et al.*, 1983). Usually more than one measurement was taken, as there were often changes in the slope of the bank profile (Figure 3).

Channel substrate, a measure of both organic and inorganic particles on the streambed, was measured using Leopold's (1970) modification of Wolman's (1954) pebble count method. Samples were taken across the channel at evenly spaced intervals along the 21 transect lines until 150 pebbles had been measured. Each pebble was measured along its intermediate axis to determine its substrate class (Gordon *et al.*, 1992).

100-m stream reach measurements

Bank disturbances were assessed along both banks to provide a 'snap-shot' assessment of channel bank disturbance for the three types of catchment. The disturbances identified were those that were obviously recent, and lacked vegetation growth or a weathered surface. Disturbance types were classified using a modified version of Baillie *et al.* (1999) and are described in Table 3. The length and height of each disturbance were recorded, and where there had been a loss of bank material, depth was measured to estimate the volume lost.

Table 3 – Classification of channel bank disturbances.

Code	Description of channel bank disturbance
LS	Lateral scour—bank disturbance from fluvial scour, includes bank undercutting
SL	Bank slump, no discrete volume loss, bank material still intact
BC	Bank collapse, discrete volume loss
BS	Bank scuff, usually caused by animal disturbance/animal tracks

The three-level hierarchical classification system of Hawkins *et al.* (1993) was used to define the channel units for this study, although not all their channel units were applicable. Pools, riffles and runs were the main channel units identified in the field and are characteristic of mid-reach, medium- to low-gradient unconfined streams in low flow conditions (Gordon *et al.*, 1992). Channel units were measured to the nearest 10 cm, directly along the 100 m reach, using a fibre tape. Sinuosity, a measure of the 'wiggliness' of a stream, is commonly described by the sinuosity index (SI), which is the channel (thalweg) distance between two points divided by straight line distance between the same two points (Platts *et al.*, 1983; Gordon *et al.*, 1992).

Sinuosity was measured in the field to the nearest 10 cm by measuring a straight line between the start and end point of the 100 m section of stream channel.

Results

Unless stated otherwise, a one-way analysis of variance was used to compare results among the three land uses. Statistical significance was tested at the 95% confidence level.

Channel dimensions

There was no significant difference in either bankfull widths or channel widths of streams in catchments with the three land uses. However, mean bankfull width was wider in pasture streams than in forest streams, but not statistically significant. The variability of stream widths within catchments with a given land use was higher than the variability in widths among varying catchment types (Table 4).

Table 4 – Channel morphology characteristics of the three land uses (± 95%CI). Mean width-to-depth ratios with different letters are significantly different ($p<0.05$).

	Pasture (n = 5)	**Pine forest (n = 5)**	**Native forest (n = 5)**
Mean bankfull width (m)	4.57 ± 1.67	3.72 ± 1.71	4.00 ± 1.06
Mean channel width (m)	2.11 ± 0.55	2.20 ± 0.44	2.54 ± 0.31
Mean channel depth (m)	0.48 ± 0.26	0.73 ± 0.29	0.64 ± 0.25
Mean x-sectional area (m^2)	2.28 ± 1.32	2.91 ± 2.00	2.72 ± 1.89
Mean width : depth ratio	12*a*	5*b*	7*b*

Mean channel depths were shallowest in the pasture sites, deepest in the pine plantation sites, and of intermediate depth in the streams through native forest (Table 4). As with channel and bankful width, channel depths varied widely within catchments of a given land use and there was no significant difference in depths among the three land uses.

There was no significant relationship between bankfull width and catchment area. However, this is most likely due to the narrow range of catchment areas used in the study, which precluded a meaningful analysis of these two parameters.

Bankfull width and average channel depth for each transect were multiplied to give an estimate of cross-sectional area. There was a high degree of variability in cross-sectional area within each catchment type (Table 4). Although cross-sectional area was smaller in the pasture sites compared with the pine plantation and native forest sites, these differences were not significant.

The width-to-depth ratio (W/D) is a dimensionless index of cross-section shape and has been calculated using bankfull width and average channel depth measurements from each transect. The results (Table 4) show that width-to-depth ratios are significantly higher in the pasture streams in comparison with the pine plantation and native forest streams (one-way analysis of variance followed by a least significant difference (LSD) test) but not significantly different between the pine plantation and native forest streams. The low width-to-depth ratios in the forested streams, a result of narrower bankfull widths and increased channel depth, indicated that these streams were more entrenched than the pasture sites.

The sinuosity indices were similar among streams in catchments with the three land uses, averaging 1.30. 1.19 and 1.21 for the pasture, pine plantation and native forest sites respectively. There was no significant variation for the three land uses.

Estimated discharge

Annual discharge was estimated for each site using the formula:

$$\overline{Q} = 2 \times A^{0.8}$$

where $\overline{Q}$ = mean annual flood (m^3 s^{-1}), and A = catchment area (km^3) (McKerchar and Pearson, 1989). The 5-year and 10-year flood peaks were estimated at 1.46 and 1.83 times the annual flood peak respectively. The results are in Table 5 (see next page). There was no significant difference in peak discharge for catchments with the three differing land uses for these three flood peaks.

Condition of channel banks

The percentage of disturbed channel bank length was similar for the three land uses, ranging from 3–5% (Table 6, see next page). The average amount of bank material lost from disturbances in the plantation sites was twice that of the other two land uses, but this was influenced by the large amount of bank material lost at site Pi1. The remaining four pine plantation sites had losses of bank material similar to those of the pasture and native forest sites.

In the pasture sites, slumps and bank scuffs from animal movement were the predominant types of bank disturbance. Neither of these disturbances resulted in any significant loss of channel bank material. Bank collapses were the main type of channel bank disturbances in the pine plantation sites,

Table 5 – Estimated discharges for 1-year, 5-year and 10-year flood events

Land Use	1-year flood ($m^3 s^{-1}$)	5-year flood ($m^3 s^{-1}$)	10-year flood ($m^3 s^{-1}$)
Pasture			
Pa1	2.99	4.36	5.46
Pa2	2.38	3.47	4.35
Pa3	2.08	3.04	3.81
Pa4	1.90	2.78	3.48
Pa5	2.38	3.47	4.35
Pine plantation			
Pi1	2.45	3.58	4.49
Pi2	1.33	1.94	2.43
Pi3	2.44	3.56	4.46
Pi4	1.76	2.56	3.21
Pi5	1.49	2.17	2.72
Native forest			
Na1	2.57	3.76	4.71
Na2	1.90	2.78	3.48
Na3	2.42	3.54	4.43
Na4	1.74	2.54	3.18
Na5	2.02	2.94	3.69

Table 6 – Channel bank condition. BC = bank collapse, SL = slump, LS = lateral scour, BS = bank scuff.

	Channel bank slope (°)	Undercut profiles (%)	Channel bank disturbed (%)	Material lost (m^3)	Type of channel bank disturbances			
					BC	SL	LS	BS
Pasture								
Mean (total)	40	3	5	0.9	(5)	(8)	(4)	(8)
Pine plantation								
Mean (total)	60	16	3	2.0	(8)	(6)	(5)	–
Native forest								
Mean (total)	52	10	2	0.8	(3)	(1)	(2)	(5)

followed closely by slumps and lateral scour. Bank scuffs were absent from the pine plantation sites. Bank scuffs were the main source of channel bank disturbances in the native forest sites, however, largely due to pig rooting in one site (Na2).

Mean channel bank slopes were steepest in the pine plantation sites, followed by the native forest and pasture sites (Table 6). Although bank slopes differed by 8–20° among land uses, this difference was not significant ($P = 0.07$). However, a 5% LSD test showed mean channel bank slopes in the pasture sites were significantly lower than mean channel bank slopes in the pine plantation sites.

To compare bank undercuts for catchments with the three land uses, the number of bank profiles that were undercut was expressed as a percentage of the total number of bank profiles for each site (Table 6). While four of the native forest and all of the pine plantation sites had some degree of bank undercutting, bank undercuts were absent from three of the pasture sites. Bank undercuts tended to be quite stable and, particularly in the native forest sites, the roots of the streamside vegetation were holding the bank material in place. Undercuts were more frequent in the forest streams than the pasture streams, but this difference was not significant ($P = 0.08$). However, a 5% LSD test found the amount of undercuts in the pine plantation streams to be significantly higher than in the pasture streams.

Substrate analysis

The percentages of fines (<2mm) in the pasture, pine plantation and native forest streams were 30, 14 and 10% respectively. While a one-way analysis of variance showed no significant differences at the 5% level ($P=0.09$), a 5% LSD test showed the amount of fines in the pasture sites to be significantly higher than in the native forest sites. The results, however, were influenced by the high amount of fines at site Pa3 (74%). The median particle size for streams in each land use is shown in Figure 4. Median substrate size was significantly smaller in the pasture and pine plantation sites compared with the native forest sites (one-way analysis of variance; $P = 0.007$).

Channel units (pool/riffle/run)

Pool/riffle/run units were not measured at one of the pasture sites (Pa5), as most of the channel was dry. Riffles dominated the streams in catchments for all three land uses (Figure 5). The pool percentage in the pasture sites was dominated by a high percentage of pool length in one site, Pa4 (13% of the channel length, compared with 0%, 0%, and 5% at the other three sites). The lack of significant differences in the percentage of channel units between the pasture, pine plantation and native forest streams indicated that land use has little impact on the proportions of stream channel units.

Although the % length of the channel reach in pools was similar for the

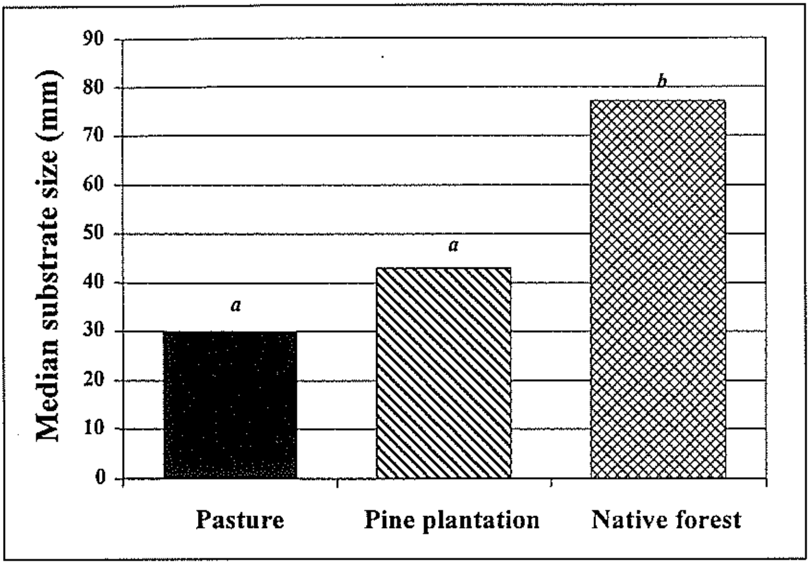

Figure 4 – Comparison of median substrate size for the three landuses (excludes bedrock and woody debris). Bars with different letters are significantly different.

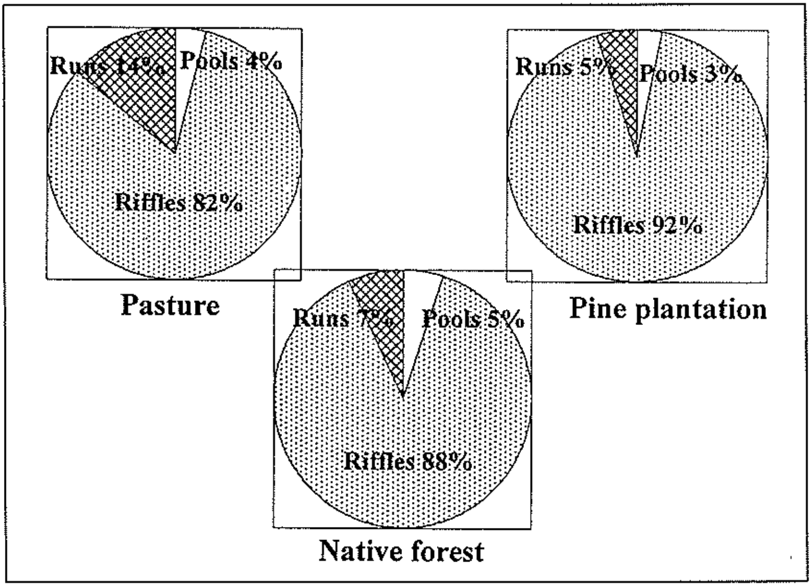

Figure 5 – Percentage of channel length in pool riffles and runs for the three land-uses.

three land uses (Figure 5) there were differences in the number of pools, even when taking into account that pools were assessed at only four pasture sites compared with five pine plantation and native forest sites. The total number of pools increased from pasture to pine plantation to native forest (5, 11 and 21 pools respectively). Large woody debris was absent in the pasture sites and had no influence on pool formation in these streams. In the forested streams large woody debris contributed to the formation of six pools in the pine plantation streams and nine pools in the native forest streams.

Discussion

The lack of significant differences in bankfull and channel widths and cross-sectional area for streams in catchments with varying land uses in the Moutere Gravels is in direct contrast to the results of similar studies elsewhere. Other researchers have found significant differences in bankfull widths and channel widths between pasture and forested sites, despite wide variation within the data sets (Zimmerman *et al.*, 1967; Murgatroyd and Ternan, 1983; Clifton, 1989; Sweeney, 1993; Trimble, 1997; Davies-Colley, 1997; Quinn *et al.*, 1997). Widths of forested streams were anything from 1.6 to 3 times those of pasture streams (Murgatroyd and Ternan, 1983; Sweeney, 1993; Davies-Colley, 1997; Quinn *et al.*, 1997) and cross-sectional areas of forest streams were greater than those of pasture streams (Murgatroyd and Ternan, 1983; Trimble, 1997; Dijkman, 1997). Zimmerman *et al.* (1967) attributed the wider and more variable channel widths of forest streams to woody debris in the stream channel and to tree root mats in the stream bank diverting channel flow. In the current study it was the pine plantation and native forest streams which showed the least variation of both bankfull and channel widths. Woody debris did not appear to be significantly influencing bankfull and channel widths or the variability of widths of the forest streams.

There were no significant differences in channel depths between the pasture and forest streams in the Moutere Gravels, a result similar to most other studies (Murgatroyd and Ternan, 1983; Trimble 1997; Dijkman 1997).

Results for the Moutere Gravels: discussion

For land in the Moutere Gravels it is possible that the small sample size and the inherent variability within the data sets used in between-catchment comparisons has obscured the effects of land use on channel morphology. If this is the case, then the land-use influence is significantly less than that found in other catchment studies. Both Zimmerman *et al.* (1967) and Quinn *et al.* (1997) still found significant differences in widths between pasture and forest sites, in spite of the background variation that exists when making between-catchment comparisons. Quinn *et al.'s* (1997) catchment study was similar to the present study, comparing five catchments each in pasture, pine plantation and native forest, with a similar range of catchment areas and gradients to those in the Moutere Gravels. Other factors must thus exert a greater influence on channel morphology than land use.

Hydrological studies in the small catchments of the Moutere Gravels indicate that sediment yields, particularly in forested catchments, are very low in comparison to yields at other sites in New Zealand and the USA (O'Loughlin *et al.*, 1978). However higher sediment yields have been recorded during high flows in recently harvested pine plantation streams (Graynoth, 1979), and two pasture catchments with 9-year-old *Pinus radiata* riparian areas produced higher sediment yields than a similar catchment entirely in pasture (Smith, 1992a). This contrasted with Hicks (1990), who recorded higher sediment yields from a pasture catchment when compared to a pine catchment. O'Loughlin *et al.* (1978) attributed the low sediment yields in small native catchments partly to the lack of storms during the study period and partly to the high degree of slope stability, which limits sediment supply to the stream. They suggest it would require infrequent high intensity storms, occurring approximately every 10 years, to produce flow and sediment in sufficient quantities to affect channel-forming processes in forest streams.

Channel-forming flows in the pasture steams are likely to be more frequent than this as pasture streams convey higher annual and flood peak flows than equivalent forest streams (Duncan, 1995). Lack of differences in channel width, depth, cross-sectional area, sinuosity and ratio of pools, riffles and runs for catchments with varying land uses indicates that, if pasture streams have more frequent high flows, they are of insufficient power, or are carrying insufficient sediment loads, to generate major differences in channel morphology.

It is possible then, that the low sediment yields in the Moutere Gravels, together with the infrequency of storms capable of delivering significant amounts of sediment to the stream and affecting channel morphology, are two factors influencing the lack of land use effects on stream morphology.

Pasture catchments in the Moutere Gravels have been in some form of pasture for at least 40–50 years, a similar time period to catchments in the Hakarimata Ranges (Quinn *et al.,* 1997), yet the channel narrowing observed in the Hakarimata Ranges is not evident in these streams. The processes hypothesised by Quinn *et al.* (1997) and Davies-Colley (1997), of sediment storage and build-up in the channel banks by pasture grasses, may occur in the Moutere Gravel catchments, but at a much slower rate due to the low sediment yields and infrequency of floods of sufficient magnitude to influence channel morphology. The soils that dominate Quinn *et al.*'s (1997) study sites are subject to moderate to severe sheet and soil slip erosion if vegetation is cleared (Hanchet, 1990). Erosion of these soils could be supplying far greater quantities of sediment to the streams than erosion of the Moutere Gravels. The Hakarimata Ranges have a higher mean annual rainfall compared to the Moutere Gravel areas, with more frequent extreme hourly and daily rainfall intensities, indicating they may be subjected to a higher frequency of channel forming events than the Moutere Gravel areas.

Another factor that may be influencing channel morphology in the Moutere Gravel areas is the composition of the bank materials. Composition of stream banks can have a strong impact on channel shape and width-to-depth ratios (Leopold *et al.*, 1964; Gordon *et al.*, 1992). Channels in non-cohesive sands and silts are usually wider and shallower, and have higher width-to-depth ratios, than channels in bedrock or more cohesive bank materials. Aggrading streams also tend to be wider and shallower and degrading streams deeper and narrower. Channels with high bank cohesion tend to deepen with increasing discharge, whereas channels with non-cohesive bank materials tend to widen. The low width-to-depth ratios in the Moutere Gravel streams indicate that these bank materials are cohesive.

The low levels of bank disturbance in these streams also tend to suggest that there was very little active erosion along the bank margins, regardless of land use. In contrast, Murgatroyd and Ternan (1983) found more active bank erosion along a forest channel in a 50-year-old coniferous plantation. Quinn *et al.* (1997) also recorded higher levels of unstable stream banks in a first rotation crop of 15-year-old pines planted on pastureland in the Hakarimata Ranges (40% of bank length) compared with pasture streams (20–40% of bank length). The low levels of bank disturbance in the mature pine plantation streams in the Moutere Gravels are similar to those found in a New Zealand-wide survey of 17 first- to third-order streams in mature pine plantations (crop age 22–34 years). Channel bank disturbances ranged from 0–36% of bank length, averaging 5% (Baillie *et al.*, 1999). It appears that while a first-rotation crop of young *Pinus radiata* on pasture land is undergoing active bank erosion (Quinn *et al.*, 1997), channel bank disturbance is much lower and channel banks are more stable in mature second-rotation *Pinus radiata* stands.

Stock grazing has also had little impact on bank disturbance in the pasture sites in the Moutere Gravels. Livestock can decrease bank stability and cause channel widening, although the widening is commonly confined to animal crossings. The degree of impact is related to the type of animal (cattle are more destructive than sheep), grazing intensity, and the cohesiveness and moisture content of the bank materials (Hackley, 1989; Williamson *et al.*, 1992; Trimble and Mendel, 1995; Myers and Swanson, 1992; Platts, 1979). While animals have influenced the type of channel bank disturbance in the pasture streams of the Moutere Gravels, animal tracks have not significantly destabilized the channel banks or caused significant losses of channel bank material.

Secondary influence of land use on channel morphology

There are indications that land use has some influence on the morphology of channels in the Moutere Gravels. The higher percentage of fines in the pasture streams and lower median substrate size in the pasture and pine plantation streams suggest that land use is influencing channel substrate. Farming and forestry practices are causing an aggradation of fine material in the stream channel that is absent from the native forest streams, a result similar to that of Quinn *et al.* (1997) for the Hakarimata Ranges.

Land use is also influencing width-to-depth ratios, which were significantly lower in the forest streams. There is disagreement among studies of the influence of tree roots and grass sod on channel bank stability in small streams. Keller and Swanson (1979) noted that living vegetation rooted in stream banks is particularly effective in increasing bank stability. In a forest stream in North Carolina, USA, tree roots protected 73% of the length of stream bank along the study reach. Tree roots extend along and into banks, therefore trees may be undermined considerably by bank erosion before they fall into the stream channel. Thus undercut stream banks are common where tree root protect stream banks.

This is in contrast to other studies, which propose that grass is a more effective retainer of sediment, stabilising and narrowing the channel banks (Zimmerman *et al.*, 1967; Murgatroyd and Ternan, 1983; Trimble, 1997; Davies-Colley, 1997; Quinn *et al.*, 1997). As a result, width-to-depth ratios were usually lower in pasture sites and higher in forest sites (Zimmerman *et al.*, 1967; Clifton, 1989; Trimble, 1997). Beschta and Platts (1986) suggested that while sod-forming grasses may adequately protect banks of low-gradient or ephemeral streams, for many small streams this type of vegetation alone is inadequate to resist the erosional forces of flowing water. Often vegetation with woody root systems provides a physical barrier to high velocities and turbulence, increasing surface roughness and relative bank stability.

In the Moutere Gravels it appears that riparian vegetation in the forest streams is more effective at consolidating and retaining this type of channel bank material than the grass in the pasture sites. This is reflected in the higher amount of bank undercuts, steeper bank slopes and the lower width-to-depth ratios in the forest streams. Although there was no significant difference among the varying land uses in channel depth, the width-to-depth ratios in the forest streams indicate that these streams tend to deepen in response to high flows. In the pasture streams, there was little evidence of stock damage to channel banks at the time of measurement. This does not discount the possibility that over time livestock have influenced the channel shape by reducing the amount of overhanging banks and lowering the bank slopes.

Land use also has some influence on the number of pools in the Moutere Gravel streams. The higher number of pools in the forest streams and the contributing influence of large woody debris to pool formation in these streams correspond to results from many other studies, particularly in the Pacific Northwest coast of America (Andrus *et al.*, 1988; Carlson *et al.*, 1990; Evans *et al.*, 1993; Montgomery *et al.*, 1995).

Conclusions

New Zealand studies to date on the effects of land use on channel morphology in small streams have all focused on one small geographical area, the Waikato Basin of the North Island. The differing results from areas underlain by the Moutere Gravels in Nelson highlight the variability within New Zealand's geological and climatic conditions and the risks inherent in extrapolating results to other areas. Conversion of pastures to pine plantations may not necessarily result in the degree or rate of channel widening observed in the Hakarimata Ranges. Factors other than land use may have a stronger influence on channel morphology. Landowners and managers considering conversion of land from pasture to pine plantations need to assess the local geology, climate and hydrology to determine whether channel widening is likely to occur in their area. However, the trend of wider streams under forest and narrower streams under pasture has been observed in New Zealand and in a number of other studies around the world, suggesting that the conditions in Moutere Gravel areas may be the exception rather than the rule.

There is very little information on sediment regimes in the Moutere Gravel areas, as most research has focused on the hydrological implications of converting pastures to pine plantations. Information on hillslope processes, erosion rates and sediment budgets in Moutere Gravel areas may provide a more definitive explanation for the differing channel morphology in this area. Other gravel deposits in New Zealand similar to the Moutere Gravels have plantation forests on them, for example the Old Man Gravels in Westland, the Kowhai Gravels in Canterbury and the Maniototo Conglomerate within the Hawkdun Group in Southland and Otago. A channel morphology study similar to this one may help validate whether these channel morphology characteristics are peculiar to the Moutere Gravels or are common to other similar gravel deposits.

This study also shows that we are a long way from understanding the complex geological and hydrological processes within catchments, how land-use practices influence these processes, and their impact on channel morphology and stream ecosystems.

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