The influence of stream bed stability and channel dynamics on lotic ecosystems: measurement and methodological advances

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Abstract

Stream bed instability is one of the major sources of physical disturbance to benthic invertebrate communities. Measurement of bed stability characteristics can be difficult and the multitude of assessment methods impedes comparability between ecological studies. This research investigated the efficiency of different measures of bed stability in characterising the relationship between disturbance and stream invertebrate community composition. It intended to provide recommendations for which technique is preferable under certain conditions and to develop and advance assessment methods of bed stability for use in stream ecology.

Bed stability was found to be highly variable within and between mountain stream reaches in the southern North Island of New Zealand. Channel dynamics are conditioned by intrinsic thresholds which reflect sediment supply and catchment connectivity. Although stream ecologists use a multitude of substrate stability measurements, each assessing a distinct subset of bed stability characteristics, a large array of methods has not yet been adopted. A literature review and subsequent empirical comparison found that the volume of scour derived from morphological budgeting, the bottom component of the Pfankuch Stability Index and distance travelled by in situ marked tracer stones had a strong link with invertebrate community composition and diversity. Consistent employment of morphological budgeting at a large number of reaches, highly variable in substrate and hydraulic conditions, requires selection of an appropriate DEM interpolation method. Amongst geostatistical and local neighbourhood approaches available in Surfer®, triangulation with linear interpolation was best suited to realistically represent channel morphology at various reaches.

The bottom component of the Pfankuch Stability Index is quick and cost-effective but is prone to observer-bias and examines only a small number of variables. Tracer stones were deemed the most suitable traditional method to measure stream bed stability relevant for invertebrate communities although it can be laborious and expensive when many sites are involved. Consequently a new descriptive survey protocol (SBSI) was developed that measures invertebrate community response to bed stability. Furthermore, a macroinvertebrate index for assessment of bed stability based on taxa abundance weighted composition of the entire community is proposed. These new methods can facilitate monitoring the effect of physical disturbance on lotic ecosystems and could serve as a powerful tool in river management.

Thesis structure and note on authorship

This thesis consists of a series of manuscripts, each written for publication in relevant journals. Thus, there is some repetition among the chapters, in particular in the methods sections and site descriptions. Also the numbering of figures and tables restarts for each chapter and some journal specific constrictions (e.g. length of abstract) were retained.

I carried out the entire field work on 48 sites and measured bed stability at six additional sites. I completely conducted the laboratory analysis of the collected samples and I wrote all texts compiled in this thesis. However, manuscripts are co-authored to acknowledge the input of others to the PhD project as appropriate. My supervisors Ian Fuller, Mike Joy and Russell Death contributed to developing the project concept, providing project funding and gear, editing manuscripts and giving general scientific advice. Jonathan Tonkin, a fellow PhD student and co-author of Chapter 5, contributed invertebrate data from six sites on the Central Volcanic Plateau to increase the database for development of a new bed stability measure.

Signed by all involved co-authors:

Russell Death 21/06/2010

Ian Fuller 25/06/10

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Table of Contents

Abstract		**iii**
Thesis structure and note on authorship		**v**
Acknowledgements		**vii**
General introduction		**1**
Chapter 1	The assessment of shear stress and bed stability in stream ecology	**7**
Chapter 2	Assessing DEM interpolation methods for effective representation of upland stream morphology for rapid appraisal of bed stability	**51**
Chapter 3a	Morphological dynamics of upland headwater streams in the southern North Island of New Zealand	**83**
Chapter 3b	Landscape connectivity in the eastern Ruahine Range	**113**
Chapter 4	Linking disturbance and stream invertebrate communities – how best to measure bed stability	**139**
Chapter 5	A new approach to assess bed stability relevant for invertebrate communities in upland streams	**167**
Chapter 6	A macroinvertebrate index to assess stream bed stability	**199**
Synthesis		**225**

Appendices **229**

Appendix 1: Study site coordinates and codes

Appendix 2: Periphyton biomass and habitat parameters

Appendix 3: Site averaged invertebrate data

Appendix 4: Bed stability measures

Appendix 5: Raw invertebrate data (CD-ROM)

Appendix 6: Published article derived from Chapter 1 (CD-ROM)

Appendix 7: Published article derived from Chapter 3 (CD-ROM)

General introduction

Lotic ecosystems are characterised by a strong longitudinal, lateral and vertical connectivity (Allan & Castillo, 2007). They are open systems, defined by downstream flow which shapes the habitat and provides transport for organisms, nutrients, and organic and inorganic particles (Angelier, 2003). Within these ecosystems benthic invertebrates play a key role as decomposers of organic matter and as an important link in the food web. They are sensitive to changes in environmental conditions that shape their habitat and thus invertebrate community composition is often used as an indicator for stream habitat health and water quality (Rosenberg & Resh, 1993; Statzner *et al.*, 2001). Disturbance is one of the fundamental determinants of structure and function of benthic communities in lotic ecosystems (Resh *et al.*, 1988; Lake, 2000). This includes physical and chemical alterations to the habitat. Physical disturbances are mainly caused by the shear stress exerted on the stream bed and its inhabitants by flowing water, particularly at elevated discharges. At a critical shear stress, depending on the constitution of the surface layer, particles are entrained, which may result in abrasion by suspended or rolling particles on the still largely stable substrate layer (Carling, 1987; Andrews & Smith, 1992). When the surface layer is disrupted large quantities of bedload can be transported and deposited at patches less affected by shear stress (Gomez, 1991). These channel dynamics can lead to spatial and temporal patterns in the composition of benthic communities via displacement, burial and mortality of plants and animals as well as alteration of habitat (Biggs *et al.*, 2001). Thus geomorphic processes such as sediment transport can be seen as a fundamental driver of lotic ecosystems (Rice, Greenwood & Joyce, 2001; Paola *et al.*, 2006; Rice, Ferguson & Hoey, 2006), in particular substrate stability is regarded as an important factor structuring benthic communities (Poff, 1992; Biggs *et al.*, 2001; Death, 2008). In turn channel forms are influenced by biological interactions (Fisher *et al.*, 2007) and consequently it is crucial for understanding lotic ecosystems to combine ecological, geomorphological and hydrological research methods (Dunbar & Acreman, 2001; Poole, 2010).

Reach-scale bed stability is controlled by a multitude of parameters ranging from the reach- to catchment scale. The flow regime which defines the energy available for substrate movement depends on climate, geology, vegetation and geomorphology of the catchment. Sediment availability is also determined by these parameters and the lateral and longitudinal connectivity within the catchment (Hooke, 2003; Fryirs *et al.*, 2007).

On a smaller scale reach gradient, channel form and substrate characteristics are effective. Bed stability of a reach can also fluctuate over time influenced by flood events and discrete sediment inputs (e.g. land slides) (Gomez, Naff & Hubbell, 1989; Hoey, 1992; Nicholas *et al.*, 1995). Thus identification of the morphological dynamics and their causes are fundamental to understand the implications for ecosystems which is addressed in Chapter 3a and b on the example of diverse New Zealand headwater stream reaches.

Bed stability comprises many aspects such as the entrainment, transport or deposition of particles. It can also be expressed as the effect of these processes, e.g. as abrasion of stable substrate by suspended or rolling particles. This leads to a multitude of measures of stream bed stability which are reviewed in Chapter 1 in respect of their relevance and suitability for research on ecological response of benthic communities to geomorphic dynamics. Investigations often focus on a number of stream reaches of varying hydraulic and substrate character to allow for comparisons between or within catchments. This might require methodological adjustments to some techniques such as the selection of an appropriate interpolation method for construction of Digital Elevation Models (DEMs) which are used in morphological budgeting (Chapter 2). Thus Chapter 2 provides the basis for application of the latter method during investigation of morphological dynamics in mountain streams leading to generation of two measures of stream bed stability (Chapter 3a). In Chapter 4 these are empirically compared with bed stability measures provided by three other methods, including *in situ* marked tracer stones, a flow competence calculation and the bottom component of the Pfankuch Stability Index, and their link to invertebrate community metrics is analysed. Chapter 4 extends the theoretical comparison of bed stability assessment methods in Chapter 1 while focussing on reach-scale measures efficiently applicable at numerous sites.

Research in stream ecology often requires assessment of many environmental parameters at a large number of reaches, e.g. when establishing a database for modelling composition and diversity of benthic invertebrate communities. In this situation efficient measurement of relevant stream bed stability characteristics is advantageous, however, currently used methods are either too laborious, do not reflect all necessary characteristics or suffer from other weaknesses (e.g. high invasiveness or observer-bias). To overcome this, a sophisticated *in situ* measurement of bed stability, as identified in Chapter 4, was applied to a large set of streams in the southern North Island of New Zealand to allow development of new approaches. Based on this dataset, Chapter 5 proposes an alternative time- and cost-effective method to assess response of invertebrates to substrate instability. Furthermore, Chapter 6 provides a macroinvertebrate index for bed stability that allows prediction of bed stability of a reach from which invertebrates have been sampled. These methods may facilitate future research in stream invertebrate ecology and can be used for monitoring of natural and anthropogenic substrate disturbances.

In summary this thesis has three main objectives:

- Investigation of the suitability of different methods to measure bed stability for research in benthic invertebrates and assessment of the link between these measures and community structure (Chapters 1 and 4),
- Assessment of channel dynamics in upland streams using appropriate techniques (Chapter 3a, 3b and 4) and, where necessary, adjustment of the methods for application on multiple streams of differing substrate and hydraulic character (Chapter 2) and
- Development of advanced methods to assess stream bed stability characteristics which are relevant to invertebrate community composition (Chapter 5 and 6).

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Chapter 1

The assessment of shear stress and bed stability in stream ecology


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ABSTRACT

Substratum stability and shear stress exerted by flowing water can have a strong influence on the structure of benthic communities. Bed stability can be characterised in a variety of ways, e.g. flow competence, threshold of particle entrainment, measures of erosion and deposition, particle transport distance, abrasion and bedload transport rate. This paper reviews methods for the quantification of bed stability and shear stress in streams and rivers that are relevant for the examination of the relationships between stream biota and bed stability.

The most suitable method for a research project depends mainly on the objectives. The targeted group of biota, spatial and temporal scale of investigation, as well as hydraulic conditions and substratum characteristics at the study site(s) determine the choice of a technique for the assessment of bed stability.

Indirect measurement of shear stress can be more accurate than calculations based on the DuBoys equation. However, the latter is preferred for reach-wide applications within the limits imposed by hydraulic conditions. The entrainment of the substratum is most effectively assessed using a combination of shear stress and competence equations, but the latter require careful parameterisation. At the patch-scale, direct measurement of entrainment force is a valid alternative.

Morphological budgeting is the most comprehensive and least invasive technique for the assessment of rates of erosion and deposition. The transport of substratum particles is efficiently monitored with *in situ* marked or active tracer particles which allow for rapid and non-invasive identification and high recovery rate. As the assessment of bedload transport rate by formulae can be inaccurate, direct measurement is preferred. However, bedload traps interfere with the substratum and continuity of measurement with samplers is limited. Thus developments in the sector of acoustic and piezoelectric devices offer a potential alternative.

The abrasive forces by suspended sediments on stream biota are effectively evaluated with artificial blocks that are fixed on the stream bed. Descriptive surveys that assess bed stability offer an alternative to direct measurement and calculations. They are straightforward and non-invasive but can be observer-biased. If single methods do not provide useful links with biological data this may be improved by the application of a multivariate approach.

Many of the methods assessed have not yet been applied in research on benthic communities, but these hydraulic and geomorphologic techniques offer considerable potential for the assessment of bed stability in stream ecology.

INTRODUCTION

Floods are an important controlling force on lotic ecosystems (Death, 2008) and influence the composition of benthic communities (Resh *et al.*, 1988; Reice, Wissmar & Naiman, 1990; Lake, 2000). Most stream ecologists agree that discharges exceeding some threshold act as a disturbance to benthic communities, although determining those values can be problematic (Poff, 1992; Death & Winterbourn, 1994).

Under low water velocity and shear stress sediment is not entrained and the impact on benthic organisms is limited to shear force (drag and lift) exerted by flowing water. This alone may cause the patchy distribution of benthic organisms and can lead to downstream displacement of macrophytes (Biggs *et al.*, 2001), periphyton (Biggs, Smith & Duncan, 1999; Suren & Duncan, 1999) and invertebrates (Lancaster & Hildrew, 1993a; Bond & Downes, 2000; Bond & Downes, 2003). As velocity and shear stress increase, phase-I bedload transport occurs when fine sediments may be winnowed (washed out) and rolled over a mostly stable coarser bed. This can lead to an additional impact on stream biota by abrasion (Downes *et al.*, 1998; Bond & Downes, 2003). At a critical flow velocity, the movement of larger particles is initiated (phase-II bedload transport). This usually involves disruption of any armour layer (see Appendix A for definitions) at the bed surface and can result in patchy areas of scour and deposition (Powell, 1998; Matthaei, Peacock & Townsend, 1999b). In more extreme events, the whole bed may be mobilised, altering the habitat structure dramatically. This can lead to displacement of plants and invertebrates (Giberson & Caissie, 1998; Matthaei, Arbuckle & Townsend, 2000; Bond & Downes, 2003) and mortality of invertebrates crushed by rolling stones. Thus floods which induce bedload transport are often associated with the most dramatic changes in the composition, density and biomass of benthic invertebrate communities (Holomuzki & Biggs, 2000; Death, 2008) and periphyton (Biggs *et al.*, 1999).

To examine the relationship between benthic biota and bed stability it is essential to quantify the latter accurately (Gordon, McMahon & Finlayson, 1992). There have been numerous attempts to do so, but most of the methods developed for stream hydraulics and fluvial geomorphology have yet to be adopted by stream ecologists. Furthermore, recent technological advances (e.g. acoustic and electronic sensors, active tracer particles and topographic survey methods) offer considerable potential for improving the measurement of bed movement for the study of stability-biota relationships.

This review presents methods that are used to assess different aspects of bed stability at different spatial and temporal scales, including: 1) shear stress, 2) entrainment, 3) erosion and deposition, 4) bedload transport and 5) abrasion. The techniques are evaluated not only for their potential to predict shear force and sediment movement *per se*, but also for their ability to explain biota-substratum stability relations.

CHARACTERISTICS OF BED STABILITY

Shear stress

When stream flow lacks sufficient energy to move bedload (non competent discharges), or where the bed is armoured or substratum particles are locked together (imbricated), the shear stress exerted on benthic biota by increased flows may be sufficient to alter the composition of benthic communities (Lancaster & Hildrew, 1993a; Bond & Downes, 2000; Bond & Downes, 2003). Shear forces exerted on organisms depend on their morphometry as well as kinematic viscosity and fluid velocity. Hence, the measurement of the latter can be used to determine shear stress. However, measurement of the velocity that affects small benthic organisms is difficult due to the steep velocity gradient in the boundary layer. Consequently indirect methods, like exposure to the flow of particles of known weight and/ or size, are employed to estimate the shear stress exerted at the channel bottom.

DuBoys equation

In stream ecology it is common to use the DuBoys equation (Eqn. 1) to gain an estimate of the mean boundary shear stress τ_o at the reach level (e.g. Statzner, Gore & Resh, 1988; Matthaei *et al.*, 1996; Duncan, Suren & Brown, 1999; Matthaei *et al.*, 1999b).

$$\tau_o = \rho_f \, g \, R \, S_f \qquad (1)$$

The friction slope S_f (see Appendix B for symbol annotation) differs from the bed slope S_b and the water surface slope S_w, because flow resistance is responsible for energy losses (Robert, 1990). S_f can be calculated using a backwater calculation if flow data and channel geometry are available. However, the observed differences between S_f and S_w are often slight, especially under conditions of high discharge (Powell & Ashworth, 1995; Milan *et al.*, 2001). Thus, the more easily measured S_w is an acceptable first-order approximation for S_f (Baker & Ritter, 1975; Lorang & Hauer, 2003). When the width-depth ratio of the channel is high (> 16.9 according to Giberson & Caissie, 1998), which is common in coarse bedload transporting streams, mean flow depth h may be substituted for the hydraulic radius R (Baker & Ritter, 1975; Powell & Ashworth, 1995; Downes, Glaister & Lake, 1997; Giberson & Caissie, 1998). The use of local bed slope and depth instead of R and S_f in Eqn. (1) might be preferable for the estimation of stream stability at the patch-scale, although actual shear stress is underestimated (Lorang & Hauer, 2003). Furthermore, it should be remembered that fluid density ρ_f is usually higher than the 1000 kg m^{-3} typically used because of suspended material, particularly during floods (Giberson & Caissie, 1998).

The DuBoys equation is strictly applicable only under uniform flow conditions (implying even bed topography and regular channel geometry) in wide channels (W/h > 20) (Gordon *et al.*, 1992; Gore, 1996). Three-dimensional flow effects (Milan *et al.*, 2001), bedform structures (e.g. pebble clusters and imbrication) (Carson & Griffiths, 1987) and the exposure to the thalweg (main thread of maximum velocity flow) are not accounted for. The values derived are high compared with local shear stress calculated from velocity profiles (Robert, 1990), but tend to underestimate the effective shear force (Carson & Griffiths, 1987).

The theoretical assessment of mean boundary shear stress is mostly based on the DuBoys equation. The choice of the parameters determines scale and accuracy of the calculation (Table 1). As the flow in natural rivers (especially shallow high gradient boulder- and gravel-bed rivers) is usually not uniform, the explanatory power of equations assuming the latter is limited (Campbell & Sidle, 1985). This may be enhanced by the inclusion of parameters like flow resistance, channel geometry and the energy slope (Lorang & Hauer, 2003). Thus shear stress estimations based on the DuBoys formula apply best under conditions of increased relative depth ($R/D_{84} > 4$, Hey, 1979), e.g. during high discharges, when flow is approximately uniform (Bhowmik, 1982; Milan *et al.*, 2001). However, mean boundary shear stress from the DuBoys equation has been linked with the distribution of benthic invertebrates in several studies under various discharges (Statzner *et al.*, 1988; Matthaei *et al.*, 1996). The equation provides a useful tool for reach-wide investigations of shear stress biota relationships.

Table 1. Methods for the assessment of shear stress (for annotations see Appendix B).

Method	**Scale**	**Constraints**	**Interference with substratum**	**Accuracy/ relation to biological data**
Du Boys equation	Reach	Uniform flow, W/h > 20	Low (measurement of parameters)	Overestimation of local shear stress (Robert, 1990) but underestimation of mean shear stress (Carson & Griffiths, 1987), recommended to assess the spatial distribution of invertebrates (Statzner *et al.*, 1988)
DuBoys equation (using h and S_b)	Patch	Uniform flow	Low (measurement of parameters)	Underestimation of local shear stress (Lorang & Hauer, 2003)
FST-hemispheres	Patch to reach, short-term	Usually normal flow conditions	Low	Related to invertebrate distribution (Dittrich & Schmedtje, 1995; Merigoux & Doledec, 2004), negative linear relationship with invertebrate taxon richness (Merigoux & Doledec, 2004) and with mussel density (Hardison & Layzer, 2001)
Point near-bed flow velocity	Patch	$h/D_{84} > 3$	Low	Related to invertebrate distribution (Effenberger *et al.*, 2006)
Depth averaged near-bed flow velocity	Patch	Simple flow geometry, logarithmic velocity profile	Low	Three times more accurate than point measurement (Wilcock, 1996)
Velocity profile	Patch	Simple flow geometry, logarithmic velocity profile	Low	Profiles least accurate compared to point and depth-averaged velocity, but no knowledge of bed roughness necessary (Wilcock, 1996)

FST-hemispheres

Calibrated **F**liesswasser**St**ammtisch (FST) hemispheres of different densities offer a measure of actual near-bed shear stress at a particular point in time (Statzner & Muller, 1989; Statzner, Kohmann & Hildrew, 1991). Despite some debate about the usefulness of FST-hemispheres for assessment of near-bed shear stress (Frutiger & Schib, 1993; Statzner, 1993; Dittrich & Schmedtje, 1995) they performed consistently well as indicators of ecologically relevant near-bed shear forces in hydraulically rough stream beds (Lancaster & Hildrew, 1993b; Scarsbrook & Townsend, 1993; Dittrich & Schmedtje, 1995; Hardison & Layzer, 2001; Merigoux & Doledec, 2004). However, Frutiger & Schib (1993) reported that only 50% of their benthic invertebrate taxa showed a relation between abundance and FST data. Statistical models based on FST measurements allow long-term characterisation of shear stress variability (Lamouroux *et al.*, 1992) that can be linked with variation in the density of invertebrate taxa in different hydraulic microhabitats (Doledec *et al.*, 2007). FST-hemispheres are a useful tool for investigating the spatial distribution of stream biota at base flow (Table 1). However, at higher discharges application is limited due to interference from bedload (impacts from saltating particles) and safety reasons (but see Gore *et al.*, 1994).

Near-bed flow velocity

Local shear stress can be estimated from measurements of flow velocity (e.g. single near-bed, vertical profile). Often a semi-logarithmic relationship between depth and velocity is assumed which is violated in reaches with high relative roughness (e.g. $h/D_{84} < 3$, Bray, 1980). Wiberg & Smith (1991) found that local shear stress calculated from depth averaged velocity derived from a profile was accurate for $h/D_{84} > 1$. In comparison, single point near-bed measurement allows a calculation of shear stress for the widest range of conditions, but is not as accurate as the depth averaged method. Estimations of boundary shear stress based on the relation of v and ln(1-h) in velocity profiles (e.g. Bhowmik, 1982) are the least accurate and apply in the most restricted flow conditions but require no estimate of bed roughness (Wilcock, 1996).

Effenberger *et al.* (2006) found a strong relationship between point measurements of near-bed flow velocity and the spatial distribution of invertebrates. Death & Winterbourn (1994) also found a strong positive correlation between the variability of near-bed flow velocity and the movement of marked stones.

Locally, indirect measurement of shear stress can provide more accurate results than the DuBoys approach. It may also give an indication of the impact of shear stress on stream biota (Table 1) although the small spatial and temporal extent of the measurements limits the use for larger reaches and/or long-term studies.

Substratum entrainment

Relationship between substratum grain size and tractive force

The proximal equality between mean boundary shear stress, calculated by the DuBoys equation, and the maximum diameter of entrained particles (rounded, non-cohesive, > 0.05 m) (Lane, 1955) has been widely exploited to define critical particle size for entrainment (Newbury, 1984; Death & Winterbourn, 1994; Muotka & Virtanen, 1995; Giberson & Caissie, 1998). Even for non-rounded particles comparable relationships have been developed (Newbury, 1984). Although this relationship can provide a good indication of habitat stability amongst sites within a stream (Giberson & Caissie, 1998), it can overestimate particle movement in steep or narrow rivers ($W/h < 16.5$) as well as underestimate it in wide and shallow channels ($W/h > 36.9$) (Hallisey & Belt, 1996). This approach is subject to the same constraints as the DuBoys equation and does not account for potential equal mobility due to hiding and protrusion of particles. Thus the applicability of this concept is constrained to rivers with a high relative depth ($h >> D_{50}$) (approx. 6 - 7, Newbury, 1984; > 10, Duncan *et al.*, 1999) and bed slopes less than 0.01, conditions which are more likely to be met in lowland rivers.

Not surprisingly, therefore, several authors found no significant relationship with other measures of bed stability when they applied this approach in steep and shallow streams (Death & Winterbourn, 1994; Duncan *et al.*, 1999). In contrast Cobb, Galloway & Flannagan (1992), Scarsbrook & Townsend (1993) and Muotka & Virtanen (1995) found a link between critical tractive force and the distribution of invertebrates and bryophytes. However, the relationship between tractive force and critical particle diameter cannot predict entrainment of the substratum consistently and applies in a limited range of rivers with gentle slope and high relative depth.

Shields equation

The Shields equation (Eqn. 2) (Shields, 1936) relates boundary shear stress to particle entrainment. It estimates the critical shear stress for a substratum grain size D_i at the point of incipient motion.

$$\tau_{crit} = \theta_{crit} (\gamma_s - \gamma_f) D_i \qquad (2)$$

The Shields coefficient θ_{crit} is a non-dimensional variable dependent on particle shape, substratum particle size distribution, exposure and other packing factors (Lorang & Hauer, 2003). It reaches a constant value for non-cohesive materials larger than 6 mm (Lorang & Hauer, 2003) for hydraulically rough beds (boundary $Re > 100$). θ_{crit} varies coarsely between 0.02 and 0.08, but more extreme values have been reported (Ashworth & Ferguson, 1989; Buffington & Montgomery, 1997; Shvidchenko, Pender & Hoey, 2001). Increasing channel slope (related to relative flow depth h/D_{50}), decreasing relative size (D_i/D_{50}) and substratum heterogeneity (size distribution) increases the Shields coefficient systematically (Bathurst, Graf & Cao, 1987; Buffington & Montgomery, 1997; Shvidchenko *et al.*, 2001). Furthermore, the definition of incipient motion (e.g. reference- or visual observation-based), grain shape, orientation, hiding effects (e.g. sheltering of smaller particles by larger), as well as discharge and bank vegetation influence θ_{crit} (Andrews, 1984). Values for θ_{crit} derived from visual-based studies (typically around 0.045) are recommended for analyses of incipient motion in discrete bed surface patches. In contrast, the usually higher reference-based θ_{crit} may give a better estimate of entrainment on a reach-average level because of its derivation from bedload transport measures and thus the integration of differential bed patch mobility (Buffington & Montgomery, 1997). Compared with the original Shields coefficient of 0.06, in gravel bed streams with a heterogeneous substratum, a lower θ_{crit} is expected, for instance down to 0.02 in high gradient rivers ($S_w > 0.002$), where $D_{Max}/D_{50} > 22$ (Lorang & Hauer, 2003) and the effects of form roughness and form drag resistance are considerable. A value of 0.045 for θ_{crit} has been used in many studies and is widely accepted for beds with coarse particles and high boundary Reynolds numbers (Miller, McCave & Komar, 1977; Yalin & Karahan, 1979; Komar, 1989; Duncan *et al.*, 1999).

There have been several attempts to improve the Shields equation and to widen its range of use (e.g. Komar, 1987; Thompson & Croke, 2008). Formulae such as Eqn. (3) incorporate the effects of hiding and heterogeneous beds in the Shields equation (Komar, 1989):

$$\tau_{crit} = 0.045\ (\gamma_s - \gamma_f)\ D_{50}^{\ 0.65}\ D_i^{\ 0.35} \qquad (3).$$

Duncan *et al.* (1999) also applied corrections to allow for small relative depths ($h/D < 2.5$) and high water surface slopes. Thompson & Croke (2008) incorporated the effects of bed form, microtopography and bed packing into the Shields equation. Lorang & Hauer (2003) found that critical shear stress calculated with a modified Shields equation overestimated the actual value for large cobble- and boulder-bed rivers by as much as an order of magnitude.

Andrews (1983) (cf. Parker, Klingeman & McLean, 1982) proposed the following relationship to calculate θ_{crit} for $0.3 < D_{isurface}/D_{50subsurface} < 4.2$:

$$\theta_{crit} = 0.0834\ (D_{isurface}/D_{50subsurface})^{-0.872} \qquad (4).$$

This highlights the fact that critical shear stress is influenced more by relative grain size than absolute grain size (Ferguson, 1994; Shvidchenko *et al.*, 2001). With the typical ratio of $D_{50surface}/D_{50subsurface} = 2.5$ for gravel bed rivers (Parker *et al.*, 1982) θ_{crit} can be estimated. However, in other studies the value for the first factor in Eqn. (4) lies between 0.019 and 0.087, whilst the exponent ranges from -0.32 to -1.25 (Buffington & Montgomery, 1997) and the values differ between riffles and pools (Sear, 1996).

A comparison between mean boundary shear stress (Eqn. 1) and critical shear stress for a particular grain size has been used to indicate zones of entrainment (Milan *et al.*, 2001), calculate the critical size of substratum particles moved (Duncan *et al.*, 1999) and define critical depth (Fuller *et al.*, 2002). Predictions of entrainment were well correlated with measurements of morphological change in most areas of a gravel bed stream (Milan *et al.*, 2001) and entrainment of *in situ* tagged particles (Biggs *et al.*, 2001). Bed stability measurements derived from a combination of Eqns.(1 & 3) showed a strong relationship with the composition of bryophyte communities (Duncan *et al.*, 1999) and periphyton biomass (Biggs *et al.*, 2001) (Table 2).

Table 2. Methods for the assessment of critical shear stress τ_{crit} and flow competence (for annotations see Appendix B).

Method	**Scale**	**Constraints**	**Interference with substratum**	**Accuracy/ relation to biological data**
$\tau_{crit} \approx D$ (Lane, 1955)	Reach	$h >> D_{50}$, $S_w < 0.01$, uniform flow, unarmoured bed	Low (measurement of D)	Weak relationship with other measurers of bed stability or bryophyte cover (Death & Winterbourn, 1994; Duncan *et al.*, 1999), linked to bryophyte (Muotka & Virtanen, 1995) and invertebrate distribution (Cobb *et al.*, 1992), negative linear to number of invertebrates (Death & Winterbourn, 1995)
$\tau_{crit} = \theta_{crit} (\gamma_s - \gamma_f) D_i$	Patch	Uniform flow, uniform bed, low h/D_i, low S	Low (measurement of parameters)	Depending on choice of θ_{crit}
$\tau_{crit} = \theta_{crit} (\gamma_s - \gamma_f) D_{50}^c D_i^d$	Patch	Uniform flow, low h/D_i, low S	Low (measurement of parameters)	Depending on choice of c, d, θ_{crit}
Combination of Shields equation and DuBoys equation (+ corrections, Duncan *et al.*, 1999)	Reach	Uniform flow, unarmoured bed	Low (measurement of D, R, S)	Related to actual entrainment (Milan *et al.*, 2001), negative linear relationship with bryophyte cover (Duncan *et al.*, 1999), related to periphyton biomass (Biggs *et al.*, 1999)
$\tau_{crit} = a D^b$	Patch	Site specific	Low (measurement of D)	Depending on parameters a, b
Spring balance	Patch	Subjectivity of particle choice	High	(Downes *et al.*, 1997)

Given the difficulties of selecting the most suitable parameters for empirical equations or the Shields coefficient, the calculation of the critical shear stress for entrainment is not straightforward, especially when a wide range of streams is being examined. However, for reach-scale investigations of the relationship between biota and bed stability a combination of the DuBoys formula and an advanced Shields equation (e.g. Duncan *et al.* 1999) may be useful.

Empirical equations of critical shear stress

Several studies have produced empirical entrainment equations of the type $\tau_{crit} = a\,D^b$ (Thompson & Croke, 2008), where a and b range from 26.6 to 110 and 0.38 to 1.21 respectively. The large range in parameter values is due to the difference in substratum assemblage between sites and differing methods used to define parameters (Lorang & Hauer, 2003). These empirical entrainment equations are thus too stream-specific to allow a general application of this approach.

Spring balance

Downes *et al.* (1997) used spring balances to measure the force necessary to initiate motion of particles in streams. This cannot be related directly to the critical shear stress but high forces will generally equate with high shear stresses as long as selective entrainment occurs (Downes *et al.*, 1997). This is a labour intensive methodology for reach-scale studies and the choice of particles can be subjective, but it will reflect actual shear stress to entrain particles better than indirect measurements.

Erosion and deposition

Scour chains and other buried devices

In both ecology and hydrology the deployment of metal scour chains is a common method for measuring scour and deposition of bed materials (Laronne & Duncan, 1992; Laronne *et al.*, 1992; Palmer, Bely & Berg, 1992; Matthaei *et al.*, 1999b; Matthaei, Guggelberger & Huber, 2003; Effenberger *et al.*, 2006). It allows quantification of the height of fill and the depth of scour with an accuracy ranging from < D_{25} to D_{84} (Laronne *et al.*, 1994; Matthaei *et al.*, 2003) on a patch-scale systematic grid. Installation is relatively rapid (33 chains per person per day, Matthaei *et al.*, 1999b) and causes little damage to sediment structure. Effenberger *et al.* (2006) observed no long-term effects on the invertebrate community. The chains proved to be resistant to dislocation and can be relocated after floods using coloured ropes or magnetic tracers. However, the assessment of temporal variation of scour and fill during bed moving events is limited and relocation is required after each event that is likely to result in substratum movement (Laronne *et al.*, 1994). As (phase-I) bedload transport occurs in patches in gravel bed rivers the suggested resolution of measurement is higher than one observation per square metre (Matthaei *et al.*, 1999b; Laronne, Garcia & Reid, 2001).

Scour chains were employed for the identification of stable bed patches which can serve as local refugia for benthic organisms during floods (Matthaei *et al.*, 1999b). Measures of scour and fill using scour chains have been related to density and vertical distribution of invertebrates (Palmer *et al.*, 1992; Effenberger *et al.*, 2006) as well as to the spatial distribution of benthic algae (Matthaei *et al.*, 2003) (Table 3).

Table 3. Methods for the assessment of erosion and deposition.

Method	**Scale**	**Constraints**	**Interference with substratum**	**Accuracy/ relation to biological data**
Scour chains	Patch/ reach, event-based	Substratum < boulders	Intermediate during installation	Related to distribution of algae (Matthaei *et al.*, 2003) and invertebrate taxa (Palmer *et al.*, 1992; Effenberger *et al.*, 2006)
Scour plates	Patch, event-based	Substratum < boulders	High	Related to vertical invertebrate distribution (Palmer *et al.*, 1992)
Dyed sand columns/ painted gravel	Patch, event-based	Substratum size	High	Related to vertical invertebrate distribution (Palmer *et al.*, 1992)
Pressure pillows	Patch, continuous	Substratum < boulders	High during installation	(Kurashige, 2002)
Morphological budgeting	Reach, event-based	Gravel/ cobble substratum	Low	Accuracy depends on surface roughness (Brasington *et al.*, 2000)

Alternatively, metal scour plates, buried at fixed depths can serve as measurement of scour depth and in sandy streams columns of dyed sand inserted in the top layer of the bed can replace scour chains (Palmer *et al.*, 1992). Wilcock (1997) measured the depth of entrainment with buried painted gravels. But both installation and retrieval require a disturbance of the substratum. Hence these methods are not appropriate for studies targeting benthic biota or for armoured and imbricated streambeds. Pressure pillows inserted into the surface of an artificial stream bed were used by Kurashige (2002) to measure sedimentation rates continuously but the construction was susceptible to damage during high bedload discharges.

Morphological sediment budget models

Movement of the substratum is reflected in changes of the morphology of the channel (Leopold, 1992). These changes can be assessed with repeated airborne surveys using digital photogrammetry or laser altimetry (e.g. Lane, 2001; Westaway, Lane & Hicks, 2001) or ground surveys employing tacheometry or photogrammetry (e.g. Ferguson & Ashworth, 1992; Lane, Chandler & Richards, 1994; Fuller *et al.*, 2002; Heritage & Milan, 2004).

Ground surveys have been conducted with a theodolite-electronic distance measurement (EDM) system (Chappell *et al.*, 2003; Fuller, Large & Milan, 2003b; Fuller *et al.*, 2005) but more recently also with Real Time Kinematic differential-GPS (RTK-dGPS) (Brasington, Rumsby & McVey, 2000; Fuller & Hutchinson, 2007). The difference in altitude of cross-sections or digital elevation models (DEM) between surveys is used to determine areas of quantified deposition or erosion (Brasington *et al.*, 2000; Brewer & Passmore, 2002). The calculation with DEMs is preferable because sediment budgets derived from planform and cross-section measurement underestimate the magnitude of volumetric change compared with DEM subtraction, nor do they permit identification of the spatial pattern of volumetric change (Fuller *et al.*, 2003a). Altitude measurements with RTK-dGPS or a theodolite-EDM system are, within the limits imposed by surface roughness (e.g. D_{50}) highly accurate and more than 2000 points with high spatial resolution can be obtained per day (Brasington *et al.*, 2000). The use of a GPS system is, however, limited at closed canopy sites and in deep valleys where satellite reception is critical.

Brasington, Langham & Rumsby (2003) indicate that ground surveys are much more precise than remote survey methods (especially at submerged zones; cf. Westaway, Lane & Hicks, 2000) and thus preferable for morphological budgeting. However, for very wide river beds or reaches of more than a few hundred metres in length, the use of photogrammetry should be considered (Lane, Westaway & Hicks, 2003).

Morphological budgeting has the advantage over scour chains to be less invasive and the ability to monitor an entire reach. However, scour chains may integrate effects of scour-fill compensation during single events. Both techniques give a lower bound estimate of the sediment flux because they do not account for substratum that is transported completely through the reach (Fuller *et al.*, 2003a). According to Martin & Church (1995) the morphological approach provides information of a quality comparable or superior to that of direct measurements of transport, yet requires less field effort. Its application is restricted to gravel- and cobble-bed rivers. To the best of our knowledge these measures have not been used in connection with biological data.

Bed load transport

Bedload is the sediment component that moves downstream by rolling or saltation. In rivers and streams where hydraulic conditions are generally unsteady (Lisle *et al.*, 2000) and spatial substratum grain size variability is high (Dollar, 2002), transport rate is highly variable in space and time (Gomez, 1991; Batalla, 1997; Ferguson, 2003; Vericat & Batalla, 2007). Bedload discharge also depends on the supply of sediments within the catchment and lateral and longitudinal connectivity of the river (Dietrich *et al.*, 1989; Hooke, 2003; Fryirs *et al.*, 2007). The transport of substratum can be expressed as volumetric change in sediment budgets, transport rate at a point, cross-sectional discharge or distance travelled by individual particles. Techniques for measuring bedload transport are ideally non-intrusive, flexible and representative for different types of transport (Ergenzinger & de Jong, 2003). To date most stream ecologists have only been interested in qualitative measures of bed stability. At the single particle-scale, qualitative assessment might be sufficient, but for whole reaches bedload transport occurs on a continuous graduation. For stream ecologists, quantitative measures of bedload transport can act as a superior indicator for the level of bed stability, particularly if only partial mobilisation of the bed occurs.

Tracer particles

Tracers are well suited for the stochastic and spatially variable nature of bedload transport because they reflect the movement of individual particles of known characteristics (Wilcock, 1997). Marked or tagged natural particles and artificial tracers are used to assess step length of movement (e.g. Habersack, 2001), proportion of the bed surface entrained (e.g. Laronne & Duncan, 1992), transport behaviour (e.g. Gottesfeld & Tunnicliffe, 2003) and transport rate (e.g. Ergenzinger & Conrady, 1982), or as an indicator of bed stability (e.g. Death & Winterbourn, 1994). Further they could facilitate the measurement of recolonisation periods of individual particles.

Stones coated with ordinary paint or fluorescent dye placed on the riverbed are often employed by ecologists and hydrologists (Death & Winterbourn, 1994; Townsend, Scarsbrook & Doledec, 1997; Ferguson & Wathen, 1998; Death, 2002; Ergenzinger & de Jong, 2003; Death & Zimmermann, 2005), but they have the disadvantage of a low recovery rate due to burial (Table 4). To overcome this, metal bars (Laronne *et al.*, 1992; Schmidt & Ergenzinger, 1992) or magnets (Hassan, Church & Schick, 1991; Laronne & Duncan, 1992; Bunte, 1996; Ferguson & Wathen, 1998) can be inserted into the particles and they are detected using a metal detector or a magnetometer respectively. Magnetic tracers usually have a larger detection range (McEwan, Habersack & Heald, 2001) than metal tracers. An easier but less durable alternative to the insertion of metal is the wrapping of stones with aluminium foil (Sear *et al.*, 2003). The transport rate and transport behaviour of particles marked with magnets or stones containing magnetic minerals can be monitored with a bar equipped with electromagnetic coils across the stream (Ergenzinger, 1985; Carling *et al.*, 1998; Froehlich, 2003) or with a longitudinal line of "Bed Movement Detectors" (Gottesfeld & Tunnicliffe, 2003). The overpassing of a magnetic particle induces an electric signal which is stored with high temporal resolution. The calculation of bedload discharge is possible using dispersion models (Sear *et al.*, 2000b).

Marking of tracer particles has been further advanced via insertion of radio transmitters into a particle. A signal is transmitted either continuously, at a programmed interval or when the particle is turned 180^o (Ergenzinger, Schmidt & Busskamp, 1989; Schmidt & Ergenzinger, 1992; Busskamp & Hasholt, 1996; Habersack, 2001). The tagged stones can be tracked from the banks with a set of antennae but application is restricted to shallow water and low conductivity (Ergenzinger & de Jong, 2003). Battery capacity (size) is a trade-off between life span and lower size boundary of particles (Habersack, 2003). These tags enable the monitoring of step length and transport behaviour as well as initiation of motion.

Radioactive tracers (e.g. ^{137}Cs) are an alternative to tags because they do not change density or centre of gravity (e.g. Bartnik, Madeyski & Michalik, 1992). However, they are no longer widely applied due to environmental issues (Ergenzinger & de Jong, 2003). The employment of tracers of differing lithology from the natural substratum (Mosley, 1978; Kondolf & Matthews, 1986) provides an effective and easy measure for event-based distribution of transport length, although recovery rate is low.

For the *in situ* marking of substratum particles Downes *et al.* (1998) and Matthaei, Peacock & Townsend (1999a) used chisels and drills with long drill bit extensions, but relocation is difficult and embeddedness may be disturbed during the marking process. Thus this method is more suitable for the qualitative measurement of entrainment. Barquin & Death (2006) used dyed quick curing concrete mix to mark embedded stones.

Table 4. Methods for reach-scale tracking of tracer particles.

Method	Constraints	Detection depth	Recovery rate	Relation to biological data and comments
Tracking of initially unembedded particles				
Painted tracer (visual)	Armour layer, burial	Surface	15 - 60%	Negative with periphyton biomass (Death & Zimmermann, 2005), negative linear with invertebrate species number and species richness (Death & Winterbourn, 1995; Death, 2002; Death & Zimmermann, 2005), quadratic with invertebrate taxon number (Townsend *et al.*, 1997)
Metal tracer (passive)	Armour layer, particle size	0.5 - 1 m	50 - 90%	
Stones wrapped in aluminium foil (passive)	Armour layer	0.25 m		
Magnetic tracer (passive)	Armour layer, particle size	0.5 - 1 m, usually higher than with metal tracer	50 - 90%	
Transmitters (active)	Armour layer, particle size, battery, low conductivity	Shallow water	Up to 100%	Battery life span: a few weeks to 10 months (size 0.01 m to 0.08 m respectively)
Radioactive tracer (passive)	Armour layer, environmental issues		ca. 5%	
Different lithology (visual)	Armour, burial	Surface	5 - 30%	
Artificial tracer (visual/ passive)	Armour layer, representativeness of substratum	Variable	ca. 35%	
DUMPLING (active)	Size (0.3 m), weight (37 kg)		100%	
Tracking of initially embedded particles				
Chiselled stones (visual)	Particle choice	Low	Low	
Dyed quick concrete mix (visual)	Particle choice	Surface		Distribution of invertebrates (Barquin & Death, 2006)

Artificial stones provide an alternative to natural particles and also give the opportunity to examine the influence of shape on transport length (Schmidt &

Ergenzinger, 1992). The use of cast aluminium forms avoids the insertion of metal bars in pebbles (Sear *et al.*, 2003). The collection of complex information about particle transport such as 3D-acceleration, differential pressure and impact of other particles, is also possible with artificial boulders like the DUMPLING (Ergenzinger & de Jong, 2003), although its size and weight restricts its application to bouldery streams (Table 4).

The measurement of bedload transport with tracers provides comparable results to direct measures but requires less effort and avoids large-scale intervention in the stream bed. For low transport rates, tracers are likely to be more accurate (Wilcock, 1997). However, the dominating influence of bed structure and channel morphology on the distribution of tracer stones and the weak relationship with stream power (Kondolf & Matthews, 1986; Hassan, Church & Ashworth, 1992) suggests that short-term studies with tracers are not sufficient to compute rates of bedload transport. In contrast, shorter-term studies are more suitable for investigating the movement of surface particles because the transport rate of tracer particles decreases due to vertical mixing (burial) and storage in less active zones of the system (e.g. floodplain, bars) (Ferguson *et al.*, 2002). If particles have to be removed from the stream for marking, bed structures and imbrication are destroyed and tracer particles placed on the bed surface may not represent the size characteristics of the substratum (Downes *et al.*, 1998; Biggs *et al.*, 1999). Longer-term studies can account for this, but they do not provide information about the frequency and magnitude of single disturbance events. The subjective choice and the shape of particles, as well as their number, may bias the results of tracer experiments (Schmidt & Gintz, 1995; Duncan *et al.*, 1999; Warburton & Demir, 2000; Ferguson & Hoey, 2002).

Nevertheless, a stability index derived from tracer experiments showed a strong negative relationship with invertebrate diversity and periphyton biomass (Death & Winterbourn, 1995; Death, 2002; Death & Zimmermann, 2005) (Table 4). *In situ* marked stones were also used to identify stable stones that can serve as refugia during floods (Matthaei *et al.*, 2000). They relate the shear forces to the local substratum and consequently give a better estimate of bed stability than unembedded tracers (Downes *et al.*, 1998; Matthaei *et al.*, 1999a). In combination with a non-invasive detection technique, *in situ* marked particles may be highly appropriate for ecological studies. Along with the objectives of a study, selection of an optimal tracer technique should consider representation of the substratum, tracer recoverability, longevity, durability, possibility of explicit identification of particles as well as labour and cost efficiency (Sear *et al.*, 2000b).

Bedload transport sampler and traps

The rate of bedload transport can be assessed with samplers and traps at various scales (Table 5). The most common handheld bedload transport samplers are of the pressure-difference type (Helley-Smith-, Vyzkum Ustav Vodohospodarsky (VUV)- and Arnhem sampler) with orifices up to 0.05 m^2 (Leopold, 1992; Hoey, Cudden & Shvidchenko, 2001; Hardardottir & Snorrason, 2003). Their sampling efficiency usually varies between 30% and 70%, but can be up to 100% (Helley-Smith sampler) (Gomez, 1991). A common constraint of these samplers is that the opening area needs calibration for hydraulic and substratum conditions (Gomez, 1991) but, much more critically, the sampling scheme should be sufficient to account for the cross-sectional substratum variability of the reach and the temporal variability in bedload transport (Ergenzinger & de Jong, 2003). This requires adjustment of the sampling period and may result in large sampling efforts in wide rivers. Therefore, predictions of bedload transport based on sampler measurements are often not very accurate (uncertainty of ±50%) (Wilcock, 2001). In conditions encountered in mountain streams (e.g. local high flow velocities and high surface roughness) bedload transport samplers are less applicable (Mizuyama, Fujita & Nonaka, 2003). Here portable net traps fixed to platforms on the stream bed may be used, delivering similar results to pit traps (Wilcock, 2001; Bunte & Abt, 2003; Bunte *et al.*, 2004). Bedload samplers are not frequently employed by stream ecologists perhaps because of the mentioned constraints and inaccuracy. However, for small-scale, event-based studies they constitute a potentially valid option for direct measurement of bedload transport rate.

Slot traps of various dimensions, inserted into the river bed, are used in many parts of the world (Salehi, Lagace & Pesant, 1997; Martin-Vide *et al.*, 1999; Hassan & Church, 2001; Sear *et al.*, 2003; Bond, 2004). They range from small sized pit traps, without continuous measurement, to Birkbeck samplers and large, stream-wide constructions for continuous monitoring. The latter is achieved with the employment of a weighing device (pressure cushion or load cell) below the sampling box or outside the channel (vortex tube, pump or conveyor belt) (Gomez, 1991; Sear *et al.*, 2000a; Ergenzinger & de Jong, 2003; Sear, 2003). Load cell systems are more reliable than pressure cushion devices because they are less susceptible to damage (e.g. puncture of pressure pillows) (Lewis, 1991). Smaller pit traps may fill rapidly during large events but are generally more accurate than handheld bedload transport samplers (Wilcock, 2001). Sampling efficiency for pit traps is up to 100%, decreasing with increasing fill (Laronne *et al.*, 2003). In particular at base flow, bedload transport traps may also sample suspended sediments (Batalla, 1997). The installation and maintenance of a bedload trap is expensive and involves a serious disturbance of the stream bed and biota. For this reason, bedload traps have not been used for investigations of benthic biota but for long-term projects they offer a useful tool for the assessment of ecologically relevant bedload discharge. As an alternative, monitoring of sediment volume accumulated in natural traps (basins), reservoirs or retention and diversion devices provides an opportunity to assess bedload transport rate, but calibration to exclude suspended sediments is difficult (Gomez, 1991).

Table 5. Methods for the assessment of bedload transport.

Method	**Scale**	**Constraints**	**Interference with substratum**	**Accuracy/ relation to biological data**
Pressure-difference sampler	Patch, short-term	Orifice area (up to 0.05 m^2), upscaling to stream width	Low	Sampling efficiency usually 30 – 70%, can reach up to 100%, small volume
Birkbeck slot sampler	Patch/ reach	Slot width, upscaling to stream width	High for installation	Continuous during smaller floods
Sediment trap	Cross-section, continuous		High for installation	Sampling efficiency up to 100%
Acoustic sensors	Patch/ reach	Calibration	Low – high for installation	Comparable accuracy as bedload traps (Downing *et al.*, 2003)
ADCP	Patch/ reach	Sandy substratum, high suspended load	None	
Electronic momentum sensor	Patch	Calibration	Low	Measures a combination of particle size and speed (Richardson *et al.*, 2003)
Piezoelectric sensors	Reach, long-term	Calibration	Low (installation)	Limited accuracy for single events (Rickenmann & McArdell, 2007)
Bedload transport formulae	Reach	Calibration site specific	Low (measurement of parameters)	Inaccurate for general application

Acoustic sensors

Acoustic sensors can be used to assess bedload transport intensity and the onset and cessation of movement (Ergenzinger & de Jong, 2003). In addition, estimates of transport rate using acoustic energy and estimates of transported particle size using the emitted frequency can be obtained (Bogen & Moen, 2003; Downing *et al.*, 2003; Froehlich, 2003; Mizuyama *et al.*, 2003). Hydrophones must be calibrated against actual bedload samples at each site. The sensor consists of a plate fixed horizontally on the bed (Bogen & Moen, 2003), a vertical pressure plate (Downing *et al.*, 2003) or horizontal steel pipes across the stream bed (Froehlich, 2003; Mizuyama *et al.*, 2003). Calibration limits the application at numerous sites, but the accuracy can be similar to a bedload trap. Acoustic Doppler Current Profiling (ADCP) allows the combined measurement of multi dimensional flow and velocity of bedload and suspended load (Rennie & Millar, 2004). Limitations of this technique include problems with the differentiation between near-bed suspension, bedload and fine grained bottom sediments as well as varying sensitivity to different particle sizes (Kostaschuk *et al.*, 2005).

Other sensors

Richardson, Benson & Carling (2003) presented an electronic sensor that allows detection of the momentum of impacting particles in bedrock channels. It gives a relative measure of bedload transport but needs to be calibrated. The latter can create some difficulties because the sensor measures a combination of grain mass and speed.

The piezoelectric bedload impact sensor employed by Rickenmann & McArdell (2007) can measure impacts of transported grains larger than 10 – 30 mm. These sensors are placed in an array over the whole stream width in a concrete bar. The measure is a reliable and continuous indicator of total bedload transport, but it needs to be calibrated and has limited accuracy for single events or small bedload volumes. Further it gives no information about the grain size distribution of the overpassing sediments (Rickenmann & McArdell, 2007).

Bedload transport formulae

Bedload transport formulae (e.g. Schoklitsch-type equation (Eqn. 5)) are generally based on four principal approaches: shear stress, stream discharge, stream power and a stochastic function for sediment transport (Gomez & Church, 1989).

$$q_b = X' \, S_f \, (q - q_{cr}) \tag{5}$$

In this example, bedload discharge q_b depends on excess water discharge and a sediment coefficient X'. Most bedload transport formulae originate from physical principles but their precision has been improved by the use of empirical datasets from flumes and streams. The formulae are consistent in that they employ in most instances the same hydraulic parameters (energy gradient, flow velocity, depth and discharge) which are in part intercorrelated (Gomez & Church, 1989; Martin & Church, 2000). Most formulae are well suited and parameterised for the dataset of their development, but fail when applied to other conditions (Knighton, 1998). They are based on limited basic assumptions which vary between streams and even within streams (e.g. selective entrainment). Characteristics like armouring, exposure to flow, equal mobility, variable sediment supply and pulsing cannot be fully accounted for, although some approaches try to incorporate these points (Parker, 1990; Duan & Scott, 2007; Thompson & Croke, 2008). Furthermore, the spatial variability within a stream is ignored because of the one-dimensional nature of the formulae (Hoey *et al.*, 2001; Ferguson, 2003; Martin & Ham, 2005). The result of comparative studies with bedload samplers/ traps (Gomez & Church, 1989; Batalla, 1997; Martin-Vide *et al.*, 1999; Habersack & Laronne, 2002; Barry, 2004) and morphological budgeting (Martin & Ham, 2005) show clearly that bedload transport formulae perform inconsistently (but see Bartnik *et al.*, 1992). Thus, bedload transport formulae need to be carefully selected according to the conditions for which they were developed, for instance turbulent and shallow mountain streams require other types of models than gravel-bed rivers (Biggs *et al.*, 2001; Mizuyama *et al.*, 2003; Ancey *et al.*, 2008). Additionally, empirical parameters and the entrainment threshold have to be determined to suit a new dataset, which is a difficult task (Wilcock, 2001; Habersack & Laronne, 2002). Thus the application of direct measurements of bedload transport is preferable to the use of bedload transport formulae (Gomez, 1991; Laronne *et al.*, 1992).

Abrasion by suspended sediments

Abrasion is an often neglected form of disturbance which can affect benthic flora and fauna. At normal flows the stream biota may be subjected to constant *in situ* abrasion by small suspended particles, which may represent a significant disturbance at higher discharges (Biggs, 1996; Peterson, 1996). It is unclear if sandblasting affects invertebrates (Rosenberg & Wiens, 1978; Culp, Wrona & Davies, 1986; Bond & Downes, 2003) but the effect on benthic algae is clearly recognised (Biggs *et al.*, 1999; Webb *et al.*, 2006).

The exposure of natural or artificial tracers to abrasion is an obvious opportunity for quantification (Table 6). The use of natural rocks that are cut in cubes or artificial blocks improves the visual monitoring of abrasion because the loss of edges and corners is simply detected. Furthermore, impact marks on the cube faces are subject to easy distinction and aide the interpretation of bedload moving events (Brewer, Leeks &

Lewin, 1992). Blocks that are of the same lithology as the river sediments have the advantage that they provide a better estimation of the actual abrasion in the channel. However, for the quantification of the impact on biota a measure of relative abrasion is sufficient. Thus ecologists prefer to use artificial tracers, like autoclaved lightweight aerated concrete blocks (Webb *et al.*, 2006). The latter have standardised material properties and abrade consistently proportional to the physical work performed on their surface. Moreover the abrasion rate is high enough to allow short deployment times (e.g. 2 months) which minimises mass loss by dissolution. Abrasion blocks need to be protected from the impact of bedload transport to gain a pure measure of abrasion by suspended particles. There is also the choice between blocks fixed on the stream bed or on bedrock, semi-mobile tethered blocks as well as loose tracer particles of known weight and size (Stott & Sawyer, 2000). For measurements relevant to stream invertebrates or periphyton it is preferable to place the blocks on the stream bed. Although fixed or tethered blocks may split and get lost or buried by sediments, the recovery rate can be high (Brewer *et al.*, 1992). These methods do not allow distinction between effects of sandblasting, overpassing bed materials and the physical impingement of fast flowing water. However, the practical consequences for ecologists are small because, in the field, biota are usually exposed to a combination of these effects (Webb *et al.*, 2006).

Table 6. Methods for the assessment of abrasion by suspended sediments.

Method	Scale	Constraints	Interference with substratum	Accuracy/ relation to biological data
Stone blocks	Patch	Absolute	Low	Actual abrasion of sediment
Artificial blocks	Patch/ months	Dissolution, high bedload transport	Low	Only relative measurement
Abrasion coefficients	Reach/ patch	Calibration	None	Underestimation of actual abrasion (Lewin & Brewer, 2002)

Abrasion coefficients derived from laboratory experiments are an easy alternative to field measurements but they generally underestimate the actual abrasion in rivers (Lewin & Brewer, 2002). Sklar & Dietrich (2004) presented a model to predict bedrock abrasion by saltating particles but it has not yet been applied in context with stream biota.

Descriptive surveys of substratum stability and multivariate approaches

Pfankuch Stability Index

The Pfankuch Stability Index is a qualitative measure that describes the probability of occurrence of substratum-moving discharges (Pfankuch, 1975). It consists of 15 variables representing properties of the upper and lower banks and the stream bed. Despite its subjectivity it shows a strong positive relation with the entrainment of painted stones (Townsend *et al.*, 1997), but not when the painted stones are used as an indicator of tractive force over time (Death & Winterbourn, 1994). If just the stream bottom component of the Pfankuch Index is employed, the relationship with other stability measures is considerably higher (Death & Winterbourn, 1994; McIntosh, 2000) and the assessment of stability at finer spatial scales might be possible (Winterbourn & Collier, 1987).

Descriptive approaches for the assessment of stream bed stability provide an easily applicable tool which has been widely exploited for investigations of biota in streams. Their major problem is the propensity to be observer-biased (Duncan *et al.*, 1999). Additionally, large temporal variation in scores can occur between surveys of the same reach by the same observer (A. C. Schwendel, unpublished data). Nevertheless, relations between bed stability assessed with the stream bed component of the Pfankuch Index and biological data have been established (Table 7).

Table 7. Descriptive surveys for the estimation of bed stability on a reach-scale.

Method	Constraints	Interference with substratum	Accuracy/ relation to biological data
Pfankuch Index	Subjectivity of perception	None	Related to other measures of bed stability, negative linear relationship with invertebrate taxon number (Townsend *et al.*, 1997)
Pfankuch Index bottom component	Subjectivity of perception	None	Positively related to other measures of bed stability (Death & Winterbourn, 1994), negative linear relationship with bryophyte cover (Suren, 1996; Duncan *et al.*, 1999), negative linear relation to invertebrate species richness, number and density (Death & Winterbourn, 1995; Death, 2002)

Multivariate approaches

Approaches that combine more than one measure of bed stability can have a stronger relationship with biological data because they can incorporate different aspects of substratum stability. Death & Winterbourn (1994) showed that a multivariate instability score consisting of hydraulic parameters (patch-scale), the movement of painted stones, water temperature and the bottom component of the Pfankuch index (reach-scale) had a stronger positive linear relationship with invertebrate species richness than with any of the constituent single variables.

CONCLUSIONS

The composition of benthic communities is a function of habitat and biotic interactions. Habitat stability in rivers is primarily determined by the forces of flowing water exerted on biota and substratum. Hence measurement of shear stress and substratum stability can indicate the distribution of benthic stream organisms, but they differ in precision and the aspect of bed stability they describe. Clearly there is no single technique suitable for all applications. Thus the selection of an appropriate method is subject to: (1) targeted fauna (mobility and range of activity), (2) spatial and (3) temporal scale of investigation (flood event-based or long-term), (4) hydraulic and (5) substratum conditions, and (6) research question of the study (e.g. range of flow, aspect of bed stability).

Most of the methods presented have been developed for research into stream hydraulics and fluvial geomorphology. Despite recent technological advances and development of new techniques only a few of them have been applied in ecological studies. Given the importance of bed stability for the biota of many streams and rivers and the multitude of ways to characterise that stability, we would like to encourage stream ecologists to consider also the potential of alternative techniques highlighted in this review for examining the links between stream stability and biota.

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Appendix A: Definitions

Armour layer	Coarse surface layer in streams that inhibits the entrainment of underlying finer material
Bed roughness	Relief of roughness elements on the channel boundary, normally a function of grain size and flow depth
Energy gradient	Difference in potential and kinetic energy per horizontal distance between two points in a stream
Flow competence	Ability of a stream velocity to move particles of a particular size as bedload
Imbrication	Overlapping and interlocking of particles
Incipient motion	Beginning of (grain) movement
Laser altimetry	Approach to obtain measurements of surface elevation with laser scanning techniques
Pebble cluster	Feature developed by stream flow over alluvial beds consisting of a group of particles
Photogrammetry	Approach to obtain measurements by means of photography
Reynolds number	Nondimensional parameter of fluid motion which determines the extent to which viscosity modifies flow
Stream power	Index for the erosive capacity of stream, defined as energy dissipation per unit area, stream length or mass of water
Tacheometry	Survey technique that produces rapid measurements of direction, elevation and distance using a kind of theodolite
Thalweg	Deepest continuous longitudinal line along a river

Appendix B: Symbol annotation

τ_o	Mean boundary shear stress (N m^{-2})
τ_{crit}	Critical shear stress at incipient motion (N m^{-2})
ρ_f	Density of the fluid (for pure water approx. 1000 kg m^{-3})
g	Gravity acceleration (9.81 m s^{-2})
R	Hydraulic radius (= A P^{-1}) (m)
A	Cross-sectional area (m^2)
P	Wetted Perimeter at a cross-section (m)
S_f	Friction slope (dimensionless)
S_w	Slope of water surface (m m^{-1})
S_b	Slope of stream bed surface (m m^{-1})
h	Water depth (m)
D_{50}	Substratum grain size for which 50% are finer (mm)
D_{84}	Substratum grain size for which 84% are finer (mm)
D_i	Substratum grain size for which i% are finer (mm)
D	Substratum grain size (mm)
γ_s	Specific weight of the sediment (= ρ g) (kg m^{-2} s^{-2})
γ_f	Specific weight of the fluid (= ρ g) (kg m^{-2} s^{-2})
θ_{crit}	Shields coefficient or dimensionless critical shear stress
v	Flow velocity (m s^{-1})
W	Stream width (m)
Re	Reynolds number
a, b, c, d	Empirical factors in entrainment formulae
q_b	Bedload discharge
q	Water discharge (m^3 s^{-1})
q_{cr}	Critical discharge (m^3 s^{-1})
X’	Sediment coefficient

Chapter 2

Assessing DEM interpolation methods for effective representation of upland stream morphology for rapid appraisal of bed stability

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ABSTRACT

Digital elevation models (DEMs) of river channels, built by interpolation between a sample of topographic survey points, are widely used to represent surfaces and to derive land-surface parameters. Differencing between successive DEMs permits quantification of change, which in gravel-bed rivers is used to construct a morphological budget of lower bound estimates of sediment flux and bed-stability surrogate. Choice of DEM interpolation method strongly influences DEM quality and realistic representation of channel forms. When comparing morphological budgets between multiple contrasting reaches, e.g. for rapid ecological appraisal, an effective and consistent means of DEM construction is required to avoid digitally generated inconsistencies. An appropriate interpolation method should be suitable for accurate representation of channels contrasting in substrate and hydraulic conditions, surveys of varying data density and distribution, and avoidance of site specific parameterisation. This paper investigates representation of channel form using a series of DEMs generated with the three-dimensional surface mapping software Surfer® by triangulation with linear interpolation, natural neighbours, point kriging, universal kriging, multiquadratic radial basis function, modified Shepard's method and inverse distance to a power on the example in 4 reaches of mountain streams in New Zealand. These reaches represent a diversity of channel forms, substrate and hydraulic properties. DEMs from triangulation with linear interpolation revealed consistently the best results and this method is recommended for geomorphological and ecological studies of multiple reaches. The main advantage over point kriging and radial basis function is better representation of channel margins and bedforms without introduction of breaklines, while it outperforms natural neighbours in honouring measured points.

INTRODUCTION

Fluvial geomorphology and hydrology can provide techniques and concepts that allow understanding of the complex hydrogeomorphological underpinnings of stream ecology (Poole, 2010). Consequently these disciplines share methods and tools, e.g. in geomorphology, hydrology and ecology digital elevation models (DEM) are often used to represent topography or derive land-surface parameters. DEMs of riverine landscapes are of particular interest for mapping (e.g. pattern of morphological change), modelling (e.g. flow routing) and calculating of sediment budgets. Morphological changes and sediment budgets are determined from the difference in surface elevation of subsequent DEMs. Morphological budgeting is a widely applied and accepted method for quantifying areas of deposition or erosion and for determining lower-bound sediment fluxes within a gravel- and cobble-bed river reach (e.g. Ashmore & Church, 1998; Brasington, Rumsby & McVey, 2000; Fuller *et al.*, 2005). In recent years the approach has shifted from budgets calculated from planform and/ or cross-sectional measurements (Martin & Church, 1995; Brewer & Passmore, 2002; Fuller *et al.*, 2002) to DEM based estimations (Lane, Chandler & Richards, 1994; Westaway, Lane & Hicks, 2000; Eaton & Lapointe, 2001; Brasington, Langham & Rumsby, 2003; Chappell *et al.*, 2003; Fuller *et al.*, 2003a; Fuller, Large & Milan, 2003b).

The pattern of scour and fill within a reach identified for instance by morphological budgeting can be used in ecology to assess intensity and spatial extent of physical disturbance, to examine spawning habitat quality and to investigate the availability of stable refugia for stream organisms during floods (Matthaei & Townsend, 2000; Wheaton *et al.*, 2010a). Additionally sediment budgets at various scales (e.g. patch, riffle or entire reach) can be employed as a measure of bed stability (Schwendel *et al.*, in press). Morphological budgeting also has the potential to replace scour chains in research on lotic ecosystems having the advantage of lower invasiveness and higher spatial resolution (Schwendel, Death & Fuller, 2010a).

Surveys to collect data used to create DEMs can be airborne (e.g. photogrammetry, laser altimetry) (Ham & Church, 2000; Lane, 2001; Westaway, Lane & Hicks, 2001; Brasington *et al.*, 2003; Lane, Westaway & Hicks, 2003) or ground based (photogrammetry, tacheometry, including, most recently, terrestrial laser scanning) (Lane *et al.*, 1994; Heritage *et al.*, 1998; Fuller *et al.*, 2002; Milan, Heritage & Hetherington, 2007) depending on the size of the reach and available technology. Measurement of 3D coordinates on a surface is afflicted with several kinds of error, notably precision, accuracy and reliability of measurements (Lane *et al.*, 1994).

Precision depends on the instruments used and surface roughness, while accuracy describes systematic errors such as verticality of the survey pole (Lane *et al.*, 1994). Gross errors or blunders control data reliability and are difficult to detect. Usually the irregular network of surveyed points is transformed to a regular grid (interpolation) which facilitates the comparison of DEMs from repeated surveys of the river bed. However, this involves error associated with DEM accuracy (sensu Wood & Fisher, 1993) which is affected by the interpolation algorithm, spatial structure of altitude as well as density and spatial distribution of data points (Desmet, 1997; Brasington *et al.*, 2000; Chaplot *et al.*, 2006; Fisher & Tate, 2006). Hence selection of an appropriate interpolation method can have a strong influence on resulting DEM quality (Kravchenko & Bullock, 1999; Wise, 2007; Yilmaz, 2007; Erdogan, 2009; Heritage *et al.*, 2009) but recommended methods vary with data density, scale and topography (Desmet, 1997; Chaplot *et al.*, 2006).

Environmental and ecological studies often require assessment of multiple reaches of sometimes highly contrasting nature (e.g. Schwendel *et al.*, in press). This requires a straightforward generation of DEMs, ideally using the same interpolation method for all reaches to provide consistency and improve comparability between DEMs and derived parameters. Thus an appropriate interpolation method should be suited to consistently generate DEMs that: (1) realistically and accurately represent channels having a range of contrasting substrate and hydraulic conditions; (2) are based on surveys of varying data density and distribution; (3) do not need time consuming site specific adjustments such as development of semi-variograms or introduction of breaklines; and (4) computation time should be manageable. This necessarily results in a trade-off between DEM quality of a single dataset and the suitability of a method for many datasets. The literature comprises many comparisons of site specific tailored interpolation methods (e.g. Desmet, 1997; Kravchenko & Bullock, 1999) and recent studies focus on development of new methodologies for data acquisition (e.g. Alho *et al.*, 2009; Hodge, Brasington & Richards, 2009), management of data uncertainty (e.g. Wheaton *et al.*, 2010a, b) and multi-scale data retrieval (e.g. McMillan & Brasington, 2007; Heritage *et al.*, 2009). In addition Heritage *et al.* (2009) have addressed the influence of survey strategy and performance of interpolation methods at a single site, but none of these studies has analysed the performance between contrasting channel environments. This study fills this gap which is important because it facilitates geomorphological and ecological research seeking to compare numerous, contrasting, river reaches and complies with the need of scientists to use morphological budgeting in applied and interdisciplinary studies.

This paper compares seven gridding methods on a range of topographic surveys of four diverse river reaches. DEMs were generated within Surfer®, a spatial analysis software widely used for this purpose in geomorphology and other disciplines (e.g. Takken *et al.*, 2001; Andrews, Gares & Colby, 2002; Fuller *et al.*, 2003b; Schmidt & Persson, 2003; Pilesjö, Persson & Harrie, 2006; Fuller & Hutchinson, 2007; Yilmaz, 2007). Dynamics of New Zealand headwater streams and processes responsible for the observed changes in topography are discussed elsewhere (Schwendel, Fuller & Death, 2010b).

SITES AND METHODS

Sites

Between October 2007 and February 2008 two topographic surveys were completed at four mountain streams in the Ruahine and Tararua Ranges which are located in the southern part of New Zealand's North Island (Fig. 1). The hydraulic properties of the reaches varied considerably in terms of slope, width and hydraulic radius as did sediment characteristics (Table 1). Topographic characteristics range from relatively smooth, clearly structured gravel-bed streams with low surface roughness (Tamaki) to very bouldery streams with highly structured surfaces (Pukeatua) (Fig. 2). Some reaches were laterally confined by vegetated banks (Manawatu) or valley topography (Pukeatua), whereas others migrated in wide floodplains (Tamaki, Waipawa). All catchments were dominated by native forest.

Table 1. Hydraulic and substrate characteristics of the study reaches.

Site	Stream order (Strahler, 1952)	Slope ($m\ m^{-1}$)	Mean hydraulic radius at bankfull (m)	Mean bankfull width (m)	Mean substrate D_{50} (mm)	Substrate composition (in order of relative proportion of g - gravel, c - cobbles, b - boulders)
Waipawa	3	0.032	0.481	48.6	58.5	g, c, b
Manawatu	3	0.047	0.232	7.4	64.9	c, g, b
Tamaki	2	0.021	0.195	19.0	35.2	g, c
Pukeatua	3	0.047	0.912	24.2	83.9	c, g, b

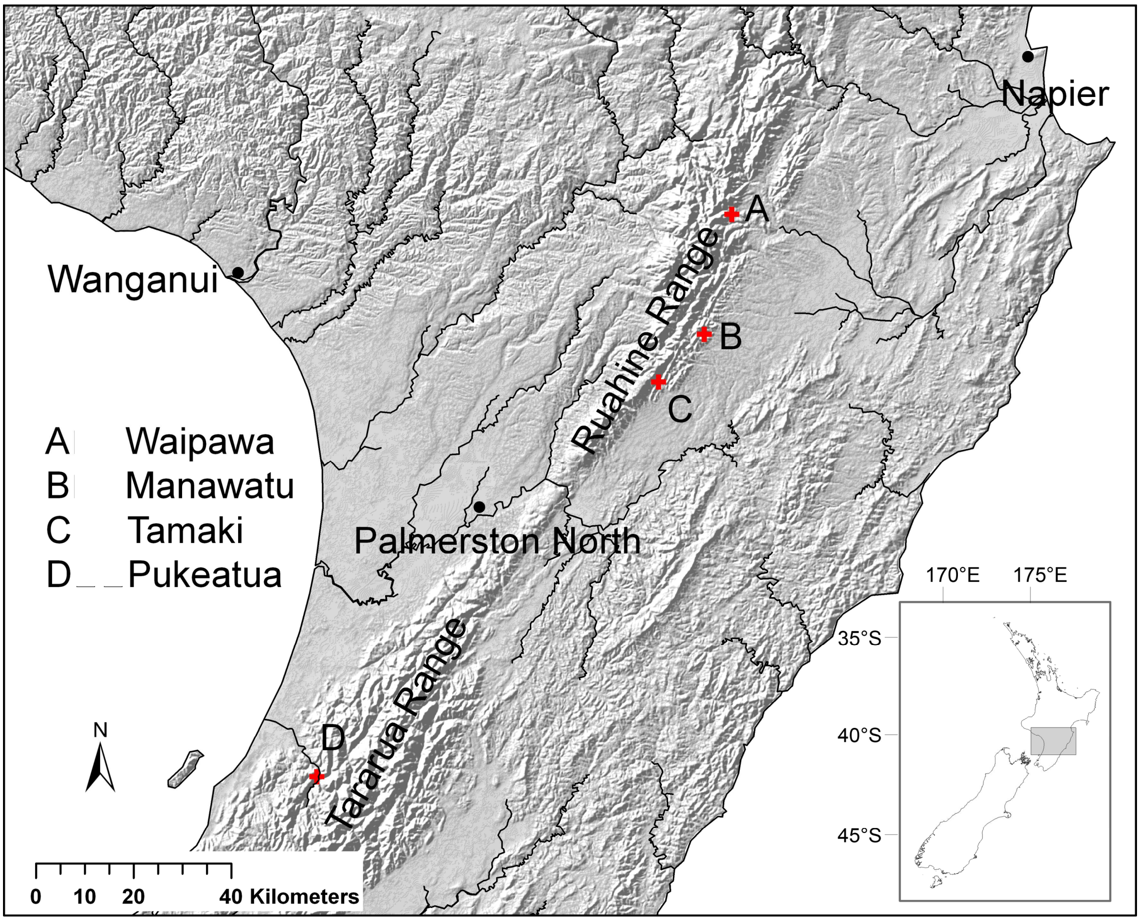

Figure 1. Study sites in the southern part of the North Island of New Zealand.

Figure 2. Study reaches: Waipawa (A), Manawatu (B), Tamaki (C) and Pukeatua (D).

For comparison of interpolation methods a sample of four surveys representing all four sites was selected (Table 2). They cover a wide range of survey area and point density. All reaches experienced at least one flood greater than bankfull stage and several spates (Schwendel *et al.*, 2010b).

Table 2. Point density and survey area of all surveys between October 2007 and February 2008 (datasets selected for testing interpolation methods are in bold).

Survey	**1 (October/ November 2007)**		**2 (January/ February 2008)**	
Site	**Area (m^2)**	**Point density (m^{-2})**	**Area (m^2)**	**Point density (m^{-2})**
Waipawa	**1897.22**	**0.58**	2437.94	1.54
Manawatu	131.84	9.41	**159.69**	**11.73**
Tamaki	902.64	2.05	**886.20**	**3.86**
Pukeatua	**613.49**	**1.95**	1002.41	2.11

Survey

The aim of the surveys was to generate DEMs from which morphological budgets of the gravel and cobble surface at a bedform scale could be constructed between successive dates. Budgets of this calibre of material are not only of commercial importance (e.g. gravel extraction) but also of ecological interest (e.g. providing an indication of stream bed stability, habitat change and physical disturbance).

Data were acquired using a differential GPS system (R8, Trimble Navigation Limited, Sunnyvale, USA) in RTK mode (cf. Brasington *et al.*, 2000). Where satellite reception was limited topographic data were retrieved with a electronic total station GTS 701 (Topcon Corporation, Tokyo, Japan). To prevent occurrence of multipath errors (Kennedy, 2002) the base station was installed some distance from each reach.

The survey was designed to be terrain sensitive, i.e. point density was highest at breaks in slopes and highly structured surfaces (Fuller *et al.*, 2005). Consequently in highly structured channels point density was higher than in smooth reaches. Substrates larger than cobbles require a grain scale resolution to be represented adequately in a DEM together with gravelly surfaces. As this is impractical for large survey areas, presence of boulders (b-axis >300 mm) was noted during the field survey and they were blanked in the DEM and thus not considered for budgeting. Concomitant tracking of boulders which were marked *in situ* with electronic tags showed that only 3% of them moved during floods (Schwendel *et al.*, 2010b). The surveyed surface reflects surface roughness, e.g. no attempt was made to measure at a grain-scale resolution and thus the survey pole was placed on top of stones as well as in gaps between particles. Surveyed areas vary between 132 m^2 and 2438 m^2 whereas average point density lies between 0.6 and 11.7 points m^{-2} (Table 2). Substrate composition was assessed with the Wolman pebble count method (Wolman, 1954) which measures the b-axis of > 100 randomly selected substrate particles. They were classified according to a modified Wentworth scale and particle size fractions were calculated (Table 1).

Precision of electronic theodolites or differential GPS systems is high, but due to satellite constellation, atmospheric interference or weather conditions larger errors can occur. These can be assessed with frequent measurements of independent check points during a survey (Brasington *et al.*, 2000) or more accurate data (Fisher & Tate, 2006). Internal quality control data generated by the survey device can also indicate precision of measurements (Fuller & Hutchinson, 2007). Here vertical precision calculated from a limited number of independent check points was 0.015 m which compares well to vertical error derived from internal quality control data ranging between 0.020 and 0.030 m. Survey error also depends on surface roughness and is often identified by a percentile of the substrate size distribution (Brasington *et al.*, 2000; Chappell *et al.*, 2003). Thus the 84^{th} substrate size percentile of the surveyed bed material assemblage (upper threshold 300 mm) (D_{84corr}) provided an indicator for the error induced by surface roughness. The latter is significantly larger than the above identified instrument precision.

Interpolation

Data were analysed, interpolated and visualised with Surfer 8.01 (Golden Software, Golden, USA). A grid size of 0.1 m was chosen which is suitable to account for small scale variation in densely surveyed areas, but still large enough (compared to surface roughness and mean point distances) to avoid the occurrence of spurious artefacts (Brasington & Richards, 1998; Fuller *et al.*, 2003a). Modern software packages offer a wide range of local neighbourhood and geostatistical interpolation methods of which seven were tested: triangulation with linear interpolation, natural neighbours, point kriging without drift, universal kriging, multiquadratic radial basis function, modified Shepard's method and inverse distance to a power. These methods are briefly described in Chaplot *et al.* (2006), Franke (1982), Fuller *et al.* (2003a) and Yilmaz (2007). For the inverse power weighting a power of 2 with a search radius including maximal 64 points and no smoothing was applied. The very similar modified Shepard's approach used default values calculated in Surfer® for the radii for quadratic fit and distance-weighting (Golden Software, 2002). Kriging was based on the default linear variogram with no nugget effect. All the tested interpolation methods except universal kriging are regarded as exact interpolators. This means the model honours the altitudes of surveyed points if these are lying on a grid node. Furthermore point kriging with linear drift (universal kriging) was also tested because a trend following the gradient of the stream was possible, at least for the larger surveys (cf. Fuller *et al.*, 2003a). However, generally no anisotropy was assumed because the length of the reaches was not much greater than the width. All methods are within limits appropriate for irregularly distributed data. For all interpolation methods the dataset specific default values generated in Surfer® were used to keep the analysis consistent and comparable. A specification of the gridding methods (e.g. development of variograms for kriging, introduction of breaklines) for each dataset might reveal better DEMs for a single survey but is not practicable with many datasets and beyond the scope of this particular paper.

Comparison of interpolation methods and DEM quality

Assessment of a DEM relative to the true surface requires more precise data of the surface topography (Wise, 2007), but this is often not available. However, independent topographic survey points can be used for total DEM error estimation if the error in measurement of the check method is accounted for (Brasington *et al.*, 2003). Where independent data are unavailable, DEM quality can be explored using split-sampling (Desmet, 1997; Chaplot *et al.*, 2006; Fisher & Tate, 2006), cross-validation (Erdogan, 2009) or residual analysis (Fuller *et al.*, 2003b; Fuller & Hutchinson, 2007; Yilmaz, 2007). Residual analysis uses non-independent data but has the advantage over split-sample approaches of not reducing DEM quality, which is important, since the survey was designed to be effective (terrain sensitive) and provide the best possible data for interpolation (cf. Fuller & Hutchinson, 2007). Quality assessment based on thinning of datasets works well with interpolation methods that estimate a local surface as a function of many points (e.g. kriging), but has disadvantages when a local surface depends only on a few neighbouring points (e.g. triangulation). DEM quality is not only defined in terms of vertical accuracy but also in terms of the desired application (e.g. DEM differencing) and derived properties (e.g. slope) (Lane *et al.*, 2003; Wise, 2007). Derivatives, like slope, curvature, estimation of change or flow routing (Brasington & Richards, 1998; Lane *et al.*, 2003; Wise, 2007; Erdogan, 2009), and comparisons between the DEM and visual observations of the actual surface in check areas with certain properties (e.g. planar surfaces, geometric bedforms) are often used to investigate shape reliability (Desmet, 1997). Visualisation allows semi-quantitative assessment of the DEM quality and is a common method to detect errors in DEMs (Wood & Fisher, 1993; Desmet, 1997). This is important regarding the purpose of the DEM (Fisher & Tate, 2006): unlike DEMs for erosion or hydrological modelling, where derivatives such as slope and flow routing are most important, DEMs for the purpose of mapping, analysing spatial patterns of change or reach-wide sediment budgets need to represent surfaces and channel shape realistically and close to the measured points. For this reason visualisation techniques were employed to compare the performance of different interpolation methods. In addition DEM error was investigated using residual analysis and comparison with independently surveyed cross-sections.

In a pre-selection phase models of all 4 datasets and each gridding method were visualised with shaded relief maps and contour maps (c.f. Wood & Fisher, 1993). These were qualitatively examined and interpolation methods that did not meet a minimum level of realistic surface representation were excluded from further analysis.

After consideration of linear drift in kriging models, a reduced number of interpolation methods were tested according to the following criteria:

(1) representation of relatively flat planes (e.g. depiction of sediment sheets or channel armour),
(2) representation of the surface of elevated grassy banks to depict their smooth and stable character,
(3) horizontal representation of straight lines (e.g. banks and bar margins),
(4) vertical representation of channel margins (e.g. for assessment of channel cross-profile),
(5) representation of the channel bottom (e.g. gravel bars, pools and steps),
(6) shape of contour lines to depict surface structure appropriately,
(7) representation of longitudinal elements (e.g. continuity of bars, trenches and banks) and
(8) residual analysis (honouring the elevation of measured points).

Additionally DEMs were compared directly (subtraction) with the triangulation model chosen as a reference, because its generation is most intuitive. Differencing of DEMs from two consecutive surveys was employed to investigate the use of different methods in application of morphological budgeting. During visualisation only the relative DEM quality between methods was assessed because survey precision was not accounted for, however, this uncertainty is considered in the discussion.

DEM quality was evaluated using mean error, standard deviation and mean absolute errors: The Mean Error (ME) is a commonly used measure which can account for the bias in data (systematic error) (Fisher & Tate, 2006) (Eqn. 1).

$$ME = \frac{\sum\left(Z_{survey} - Z_{DEM}\right)}{n} \tag{1}$$

The standard deviation of the Mean Error (SD) records the magnitude of scatter around zero (Eqn. 2).

$$SD = \sqrt{\frac{\sum\left[\left(Z_{survey} - Z_{DEM}\right) - ME\right]^2}{n-1}} \tag{2}$$

Alternatively the Root Mean Square Error (RMSE) or the Mean Absolute Error (MAE) (Eqn. 3) are used to assess the quality of a DEM. If the mean errors are close to zero RMSE and SD are similar, so only the MAE, ME and SD are discussed here.

$$MAE = \frac{\sum\left|Z_{survey} - Z_{DEM}\right|}{n} \tag{3}$$

It should be noted that the spatial variation in error was not accounted for in this study because for most methods only reach-averaged data were available.

RESULTS AND DISCUSSION

Pre-selection

Models of all four datasets and each gridding method were visualised with shaded relief maps and contour maps to rapidly appraise their representation of morphology relative to photographs. The triangulation, kriging, natural neighbours and radial basis function models show adequate representation of the channel surfaces. In contrast the modified Shepard’s method produces an overly smooth surface even when no smoothing factor was employed and it also shows poor representation of linear features like channel margins. This is illustrated in the Manawatu dataset compared to the triangulation model which served as a standard (Fig. 3A and B). The DEM created by inverse distance to a power has a very spiky surface (Fig. 3C). This can be adjusted by lowering the power, but again the result is an over-smoothed topography and some spikes still remain (Fig. 3D). Thus in the pre-selection phase the modified Shepard’s method and inverse distance to a power where excluded from further analysis.

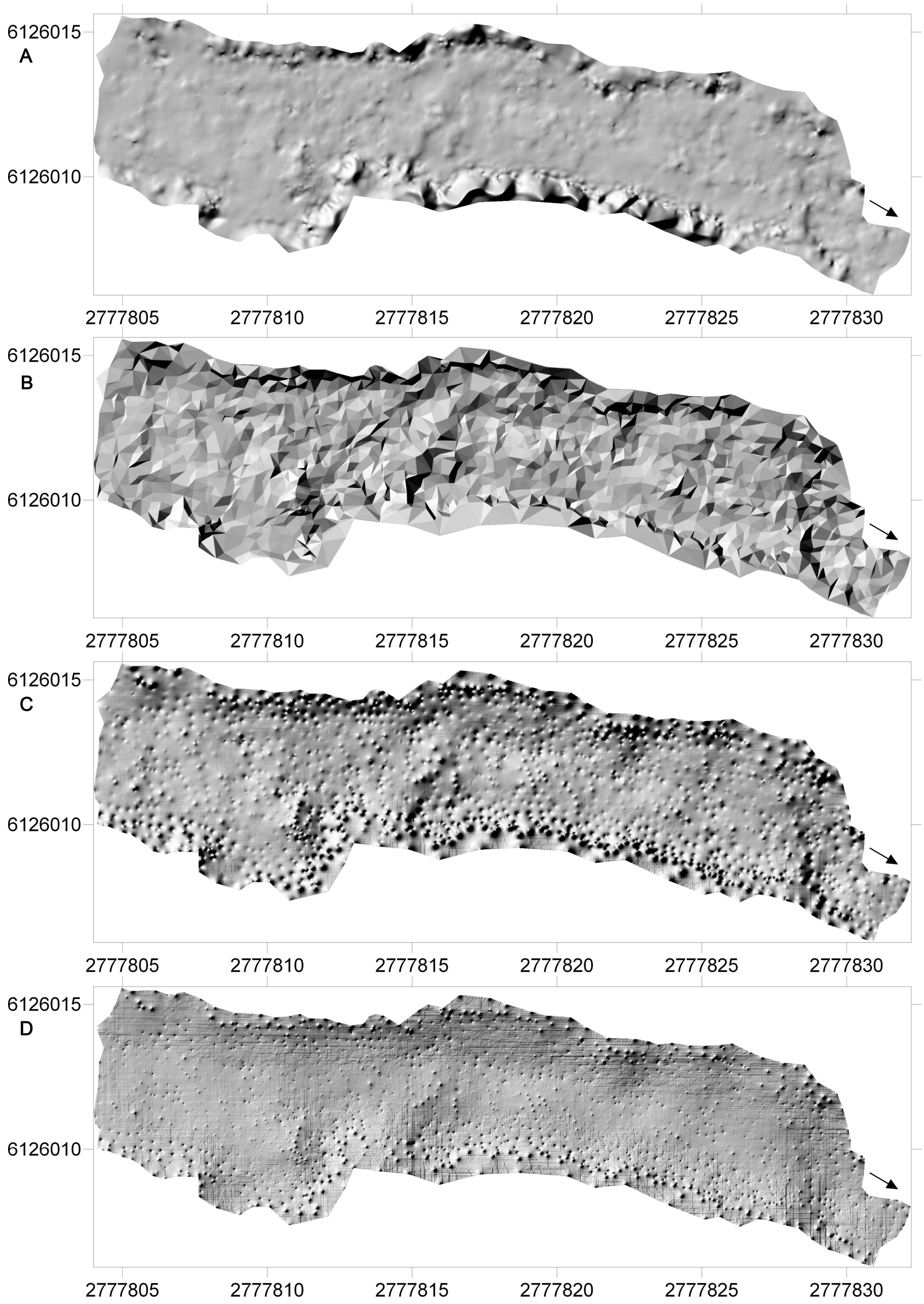

Figure 3. DEMs of survey Manawatu_2 generated with modified Shepard's method (A), triangulation with linear interpolation (B), inverse distance to a power of 2 (C) and inverse distance to a power of 1 (D). Arrow indicates flow direction and coordination axes denote easting and northing in m.

Universal kriging

In a second step the influence of linear drift versus no drift for point kriging DEMs was evaluated on all four datasets. The mean difference in residuals is only marginal (less than 21 nm). The mean vertical difference between models of the channel is less than ±1mm for the stronger small scale structured surveys Manawatu_2 and Pukeatua_1 and less than ±2 mm in the other two surveys. These differences lay far below surface roughness (cf. Table 1). This suggests that the influence of the slope of the valley floor is negligible for surveys of such small longitudinal extent (e.g. 5 – 7 times active channel width to include at least one riffle-pool sequence (Leopold, Wolman & Miller, 1964; Keller & Melhorn, 1978)). Hence only point kriging without linear drift is reported in the further evaluation of the methods to avoid unnecessary duplication and detail.

Criteria based comparison between methods

The remaining four interpolation methods triangulation with linear interpolation, kriging, natural neighbours and radial basis function were subject to criteria based analysis (Table 3).

(1) Representation of relatively flat planes. The active floodplain of Tamaki Stream comprises some reasonably flat patches (Fig. 2C in the background). There are no large differences between DEMs, although natural neighbours, kriging and to a certain extent radial basis function tend to create unrealistic island like concentric shapes (bull's eyes) (Fig. 4). The DEM generated with kriging seems to produce the most even surface and the triangulation model seems to be most realistic in terms of reproduction of longitudinal structures. No general ranking between these models could be established for this criterion.

(2) Representation of the ground surface of elevated grassy banks. Elevated grassy banks occur only on the Manawatu site (Fig. 2B). Their surface is not even but smooth. They were incorporated into the surveys to allow for lateral bank erosion and to define a stable boundary for surface interpolation. Point density is relatively coarse due to surface smoothness. Hence it is expected that DEMs represent a relatively flat surface between the points in order to avoid artificial differences between surveys of the same site.

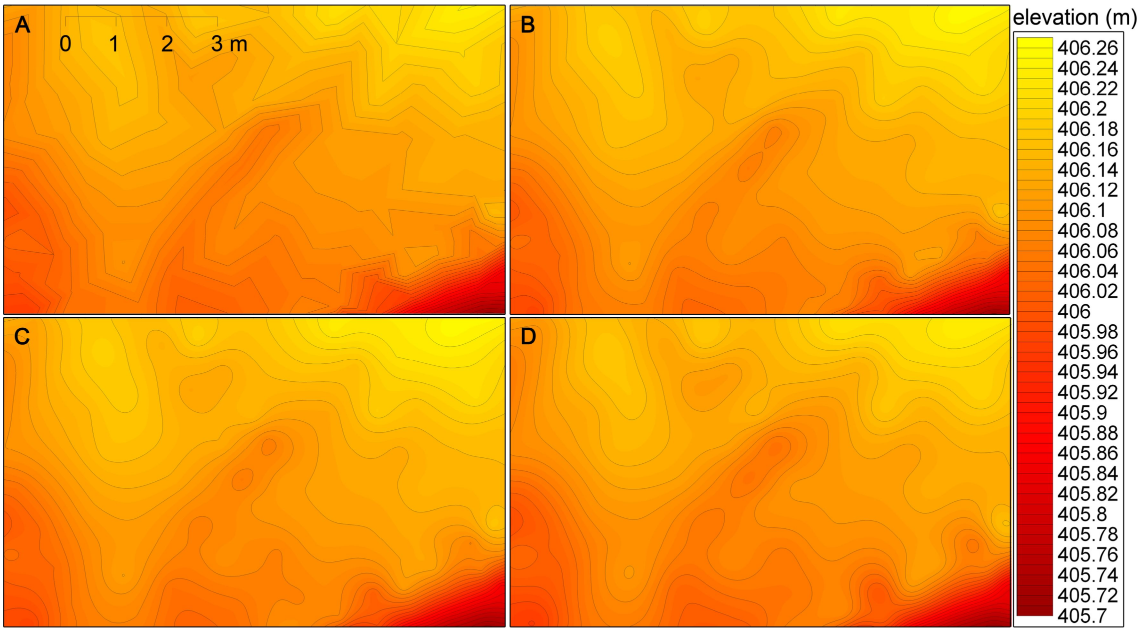

Figure 4. Comparison of representation of relatively flat patches of the Tamaki floodplain between gridding methods: triangulation (A), natural neighbours (B), kriging (C), radial basis function (D). The distance between contour lines is 0.02 m.

The triangulation model and the natural neighbours DEMs (Fig. 5A and B) give the impression of a plane bank as intended. In contrast the other two DEMs (Fig. 5C and D) show an undulating surface with higher elevations between points in the longitudinal direction, a classical scalloping effect, also found by Fuller *et al.* (2003b). The DEM created with radial basis function demonstrates this behaviour also in lateral direction, thus it is the least appropriate interpolation method according to this criterion.

(3) Horizontal representation of straight lines. When linear features like channel margins were surveyed a point was measured at each bend so that the lines in between should be represented as straight lines. The northern channel bank at the Manawatu site (Fig. 5) gives a good example of a very structured channel margin whereas the side walls of the Tamaki (Fig. 4) and Waipawa sites (Fig. 7) are straighter. The performance of the different gridding methods is consistent throughout all these examples. The triangulation DEM (Fig. 4A and Fig. 5A) connects neighbouring points with a straight line as intended, but looks unrealistic and angular. The natural neighbours DEM (Fig. 4B) produces slightly smoother shapes, which look more realistic and may have advantages with respect to the differencing of models over the edgy shapes of the triangulation DEM at the Manawatu site. The other two DEMs (Fig. 4 and Fig. 5) again show strong (radial basis function) and very strong (kriging) scallopy shapes between points and therefore do not represent linear features well.

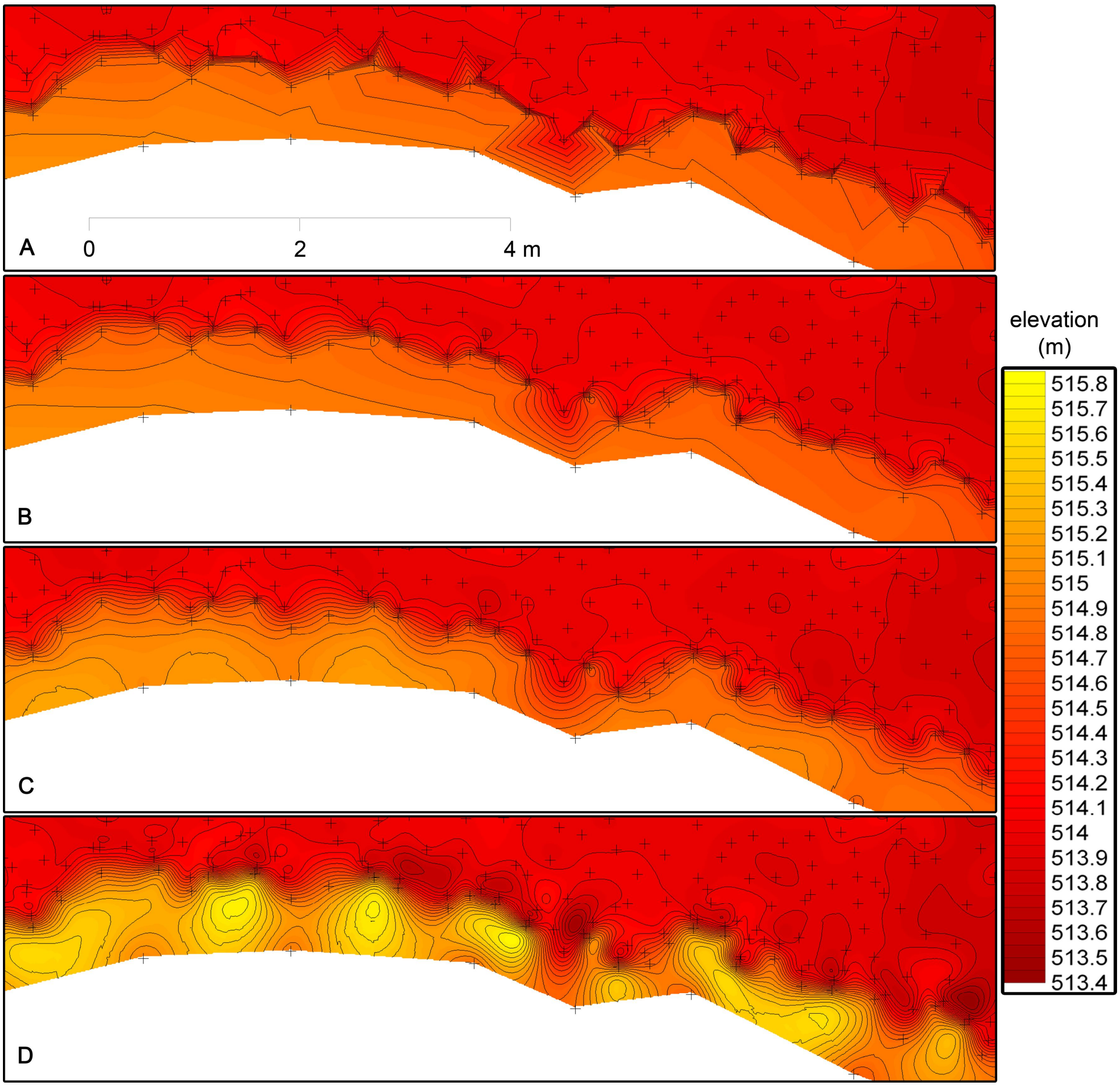

Figure 5. Comparison of representation of the banks and channel margins at the Manawatu site between gridding methods: triangulation (A), natural neighbours (B), kriging (C), radial basis function (D). The distance between contour lines is 0.1 m, measured points are displayed as crosses.

(4) Vertical representation of channel margins. The vertical profile of channel margins is usually not straight but has a concave shape with a steeper upper part and a lower gradient at the base. Often the upper point could not be measured directly on the edge because the substrate was over loose. Thus the measured gradient was often lower than the actual slope. If further smoothing of the profile is applied during modelling the displayed gradient might be too low and thus better represented by a DEM using straight connections between measured points. Following this assumption the triangulation DEM fits best (Fig. 6A). The DEM created with radial basis function gives the same gradient between points but it varies longitudinally along the channel (Fig. 6D). Kriging and natural neighbours generate slightly less steep contours between

points and kriging looks much smoother regarding the total channel profile (Fig. 6C and Fig. 7C). This leads to the suggestion that over the whole channel profile triangulation might give the best representation of actual cut-bank slope but may overestimate the volume below the surface, which should be recognised where bank erosion contributes to a morphological budget. Smoother bank sections that are predominantly formed by depositional processes will be best modelled with natural neighbours interpolation.

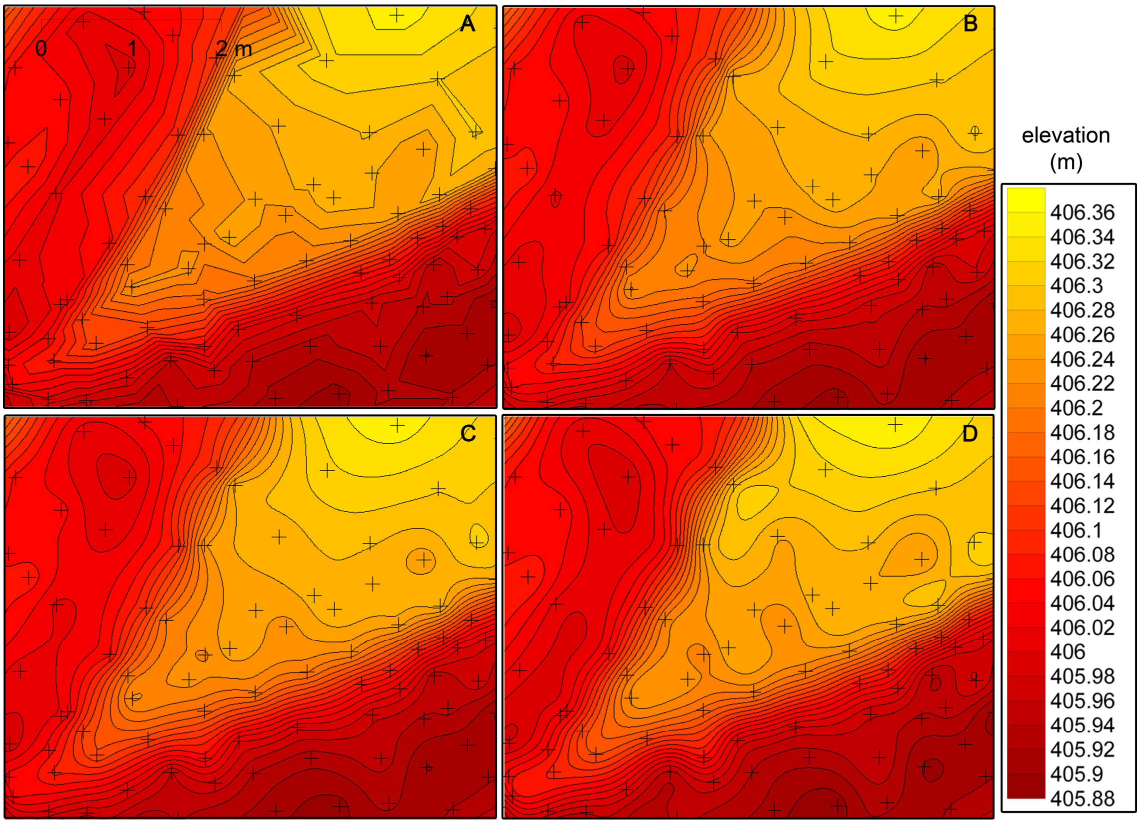

Figure 6. Comparison of representation of the channel margins at the Tamaki site between gridding methods: triangulation (A), natural neighbours (B), kriging (C), radial basis function (D). The distance between contour lines is 0.02 m, measured points are displayed as crosses.

(5) Representation of the channel bottom. Representation of the channel bottom is one of the most important criteria because here the main changes in sediment budget are likely to occur and bed stability can be detected. The channel bottom was often surveyed in a regular grid between breaklines in surface topography; gravel bars, banks and pools were accounted for with extra points. Thus a DEM should display the latter structures realistically and not add features where they were not surveyed. This is especially relevant for surveys with low point density (e.g. Waipawa_1).

The area in Fig. 7 depicts the wet channel and banks of the Waipawa River. This section consists of an upstream run which leads into a riffle with a longitudinal bar in the centre. Downstream follows an elongated pool. The model created with radial basis function differs strongly from the others. It shows unrealistic peaks and holes between measured points. Kriging and natural neighbours DEMs present some bull's eyes, but beside that their representation of the channel floor is relatively similar to that of the triangulation model. The longitudinal bar in the centre is best modelled with triangulation.

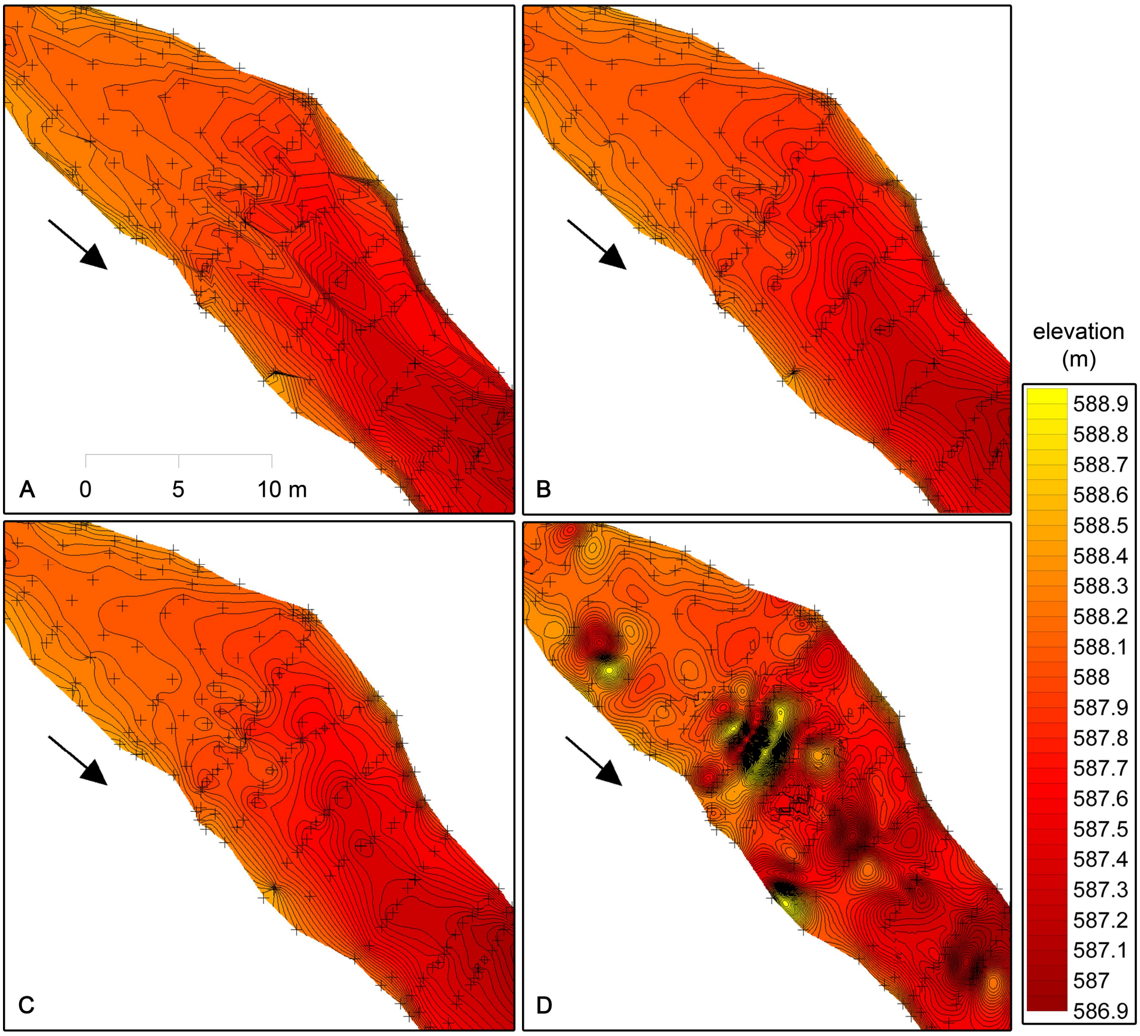

Figure 7. Comparison of representation of the channel bottom at the Waipawa site between gridding methods triangulation: (A), natural neighbours (B), kriging (C), radial basis function (D). The distance between contour lines is 0.05 m, measured points are displayed as crosses and an arrow indicates flow direction.

(6) Shape of contour lines. As contour line shapes reflect the surface structure, they should resemble natural shapes in a channel. Kriging, natural neighbours and radial basis function produce round shapes which are similar to real channel forms (Fig. 6). In case of the radial basis function derived DEMs the surface is often too pointy. The edgy appearance of the triangulated shapes shows little resemblance with natural surface shapes and reflects the process of the Delaunay-triangulation (see also Fig. 5).

(7) Representation of longitudinal elements. Longitudinal elements like bars, banks and trenches need to be modelled as continuous feature and not as unconnected rows of highs or lows. According to this criterion triangulation performs best, followed by radial basis function DEMs (bars in centre of Fig. 7A-D or bottom half of Fig. 4A-D). Natural neighbours and especially kriging often produce isolated bull's eyes instead of longitudinal elements.

(8) Analysis of vertical residuals. Deviation of the DEM surface from the measured points is used as a relative measure for how well the interpolation honours the input data. These DEMs showed generally very low deviations (Fig. 8). The mean error (Eqn. 1) was negatively biased for radial basis function, natural neighbours and triangulation whereas the values for kriging were weakly positive and the absolutely lowest in comparison. The standard deviation of the ME (Eqn. 2) varies considerably between sites with no clearly recognisable connection to survey or site characteristics. However, for each survey the magnitude of SD is similar for natural neighbours, triangulation and kriging whereas the dispersion around the ME is much lower for radial basis function. The mean absolute error (Eqn. 3) shows a comparable distribution with the exception that triangulation and kriging interchange their ranking. In summary the MAE and SD of radial basis function DEMs were significantly lower than these of the other models. Triangulation and kriging DEMs were close together followed by the natural neighbours DEMs. Thus the analysis of residuals suggests use of radial basis function as a preferential gridding method. It also shows that the methods, although each regarded as exact interpolator, honour survey points to varying degrees. Geostatistical methods such as kriging were suspected to perform less well but showed similar results to a mathematically simple model like triangulation. The spatial distribution of the residuals shows that the highest differences occur for all DEMs on the channel margins, where the modelling is most complicated (Fig. 9).

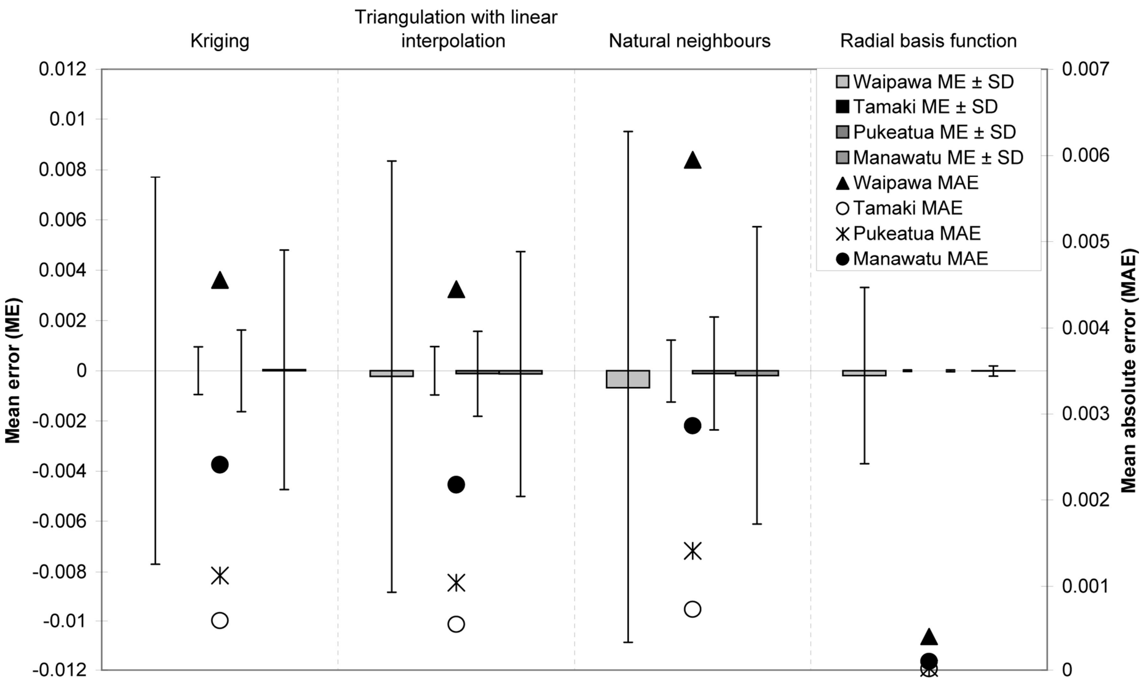

Figure 8. Residual analysis: mean error (ME) with error bars indicating the standard deviation (SD) and mean absolute error (MAE) (symbols) between sites and gridding methods.

Table 3. Summary of the evaluation of criteria and ranking in brackets (1 – most suitable, 4 – least suitable).

Criterion	Triangulation	Natural neighbours	Kriging	Radial basis function
(1) Planes	Flat (1)	Flat (1)	Flat (1)	Flat (1)
(2) Banks	Flat (1)	Flat (1)	Undulating (3)	Undulating (4)
(3) Horizontal lines	Straight (2)	Realistic (1)	Very scallopy (4)	Scallopy(3)
(4) Channel margins	Steep, straight (1)	Smooth (3)	Smoother (4)	Steep, smooth (2)
(5) Channel bottom	Realistic (1)	OK (2)	OK (2)	Poor (4)
(6) Contours	Angular (4)	Round (1)	Round (1)	Round, deep (3)
(7) Longitudinal elements	Realistic (1)	Isolated peaks (3)	Spiky (4)	Single peaks (2)
(8) Residuals	OK (2)	Highest (4)	OK (2)	Lowest (1)
Sum of ranks	13	16	21	20

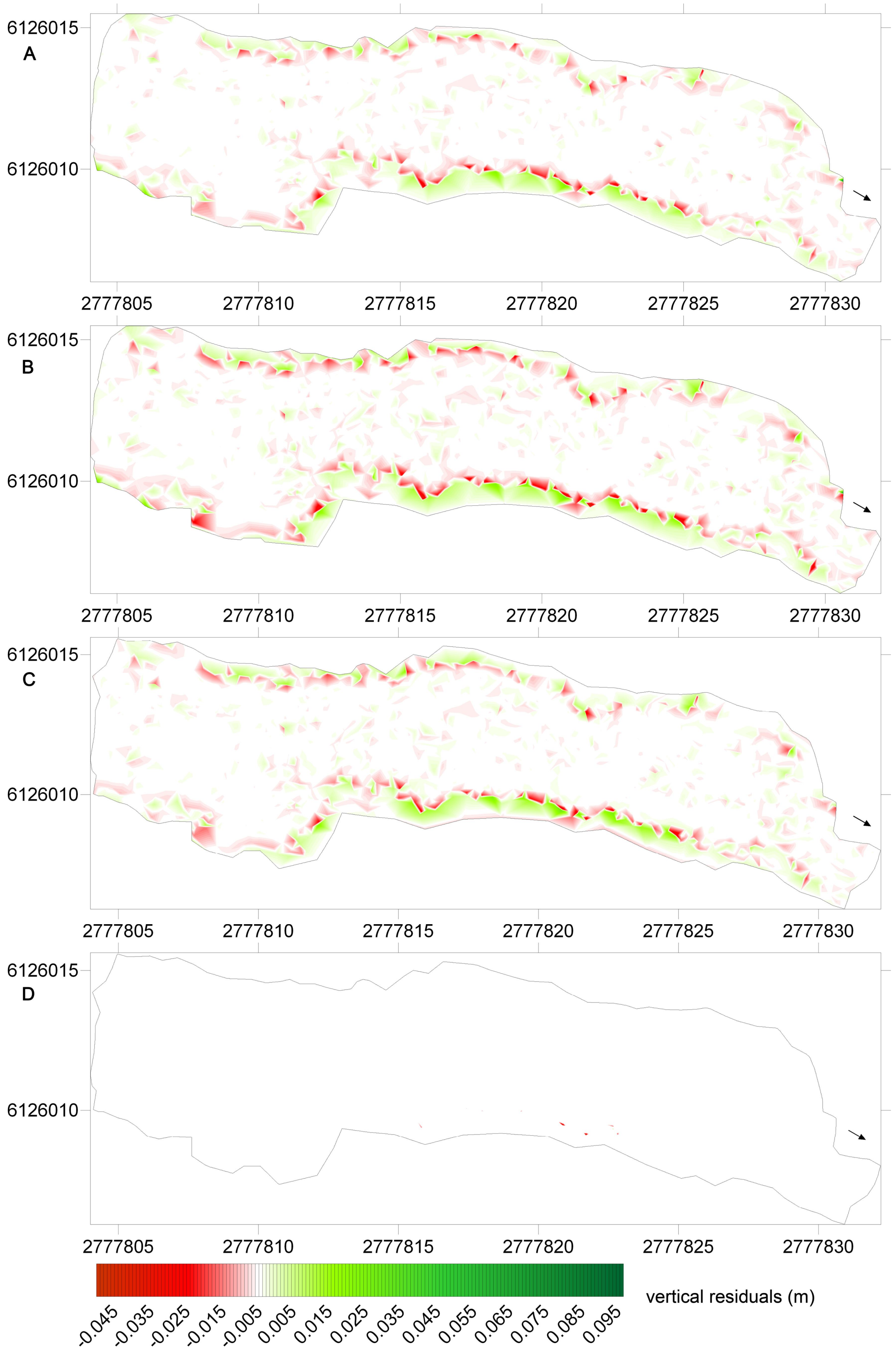

Figure 9. Spatial distribution of vertical residuals of models generated with triangulation (A), natural neighbours (B), kriging (C) and radial basis function (D) for the Manawatu_2 dataset. Arrow indicates flow direction and coordination axes denote easting and northing in m.

The criteria based on visualisation, rank triangulation with linear interpolation best (except for contour shape), followed by the natural neighbours method (Table 3). In contrast, if just the residuals are considered the radial basis function performs much better than the other methods. However, for the purpose of morphological budgeting it is crucial that surfaces are represented as realistically as possible, not only at survey points but also in between them. Thus triangulation with linear interpolation is the most suitable and consistent method for gridding in a range of streambed environments. This concurs with findings using different approaches to assess interpolation at a single site (Fuller & Hutchinson, 2007; Heritage *et al.*, 2009). Triangulation provides a robust technique which is unaffected by problems like over- and undershooting of surfaces near a jump discontinuity (Gibbs phenomenon) (Florinsky, 2002). Furthermore, triangulation with linear interpolation is favoured by a terrain sensitive survey that has high point densities at breaks in surface slope. An introduction of breaklines might have improved the performance of the other methods but when dealing with multiple sites and datasets this would be time intensive. However, the densification of survey points around breaks in slopes minimises this problem.

Direct comparison

The subtraction of the different DEMs from the triangulation DEM shows that the channel is represented most consistently with differences mainly below ±0.02 m between the triangulation and the natural neighbours DEM for the Tamaki (Fig. 10A-C), Pukeatua (Fig. 10D) and Manawatu sites. Kriging-generated DEMs often show more than 0.02 m difference whereas the radial basis function model exhibits the largest area of more than 0.02 m difference at these three sites. This is also mirrored in the volumes of the void between the DEMs and the comparison between cross-sections derived from DEMs and independent measurements (Fig. 11).

At the Waipawa site kriging is closest to triangulation with differences mainly below 0.05 m. The natural neighbours DEM lies within a vertical distance of mostly less than 0.1 m. In contrast the deviation of the radial basis function DEM is in some areas immense. As the Waipawa_1 survey has the lowest point density, the change in performance relative to triangulation could be related to that.

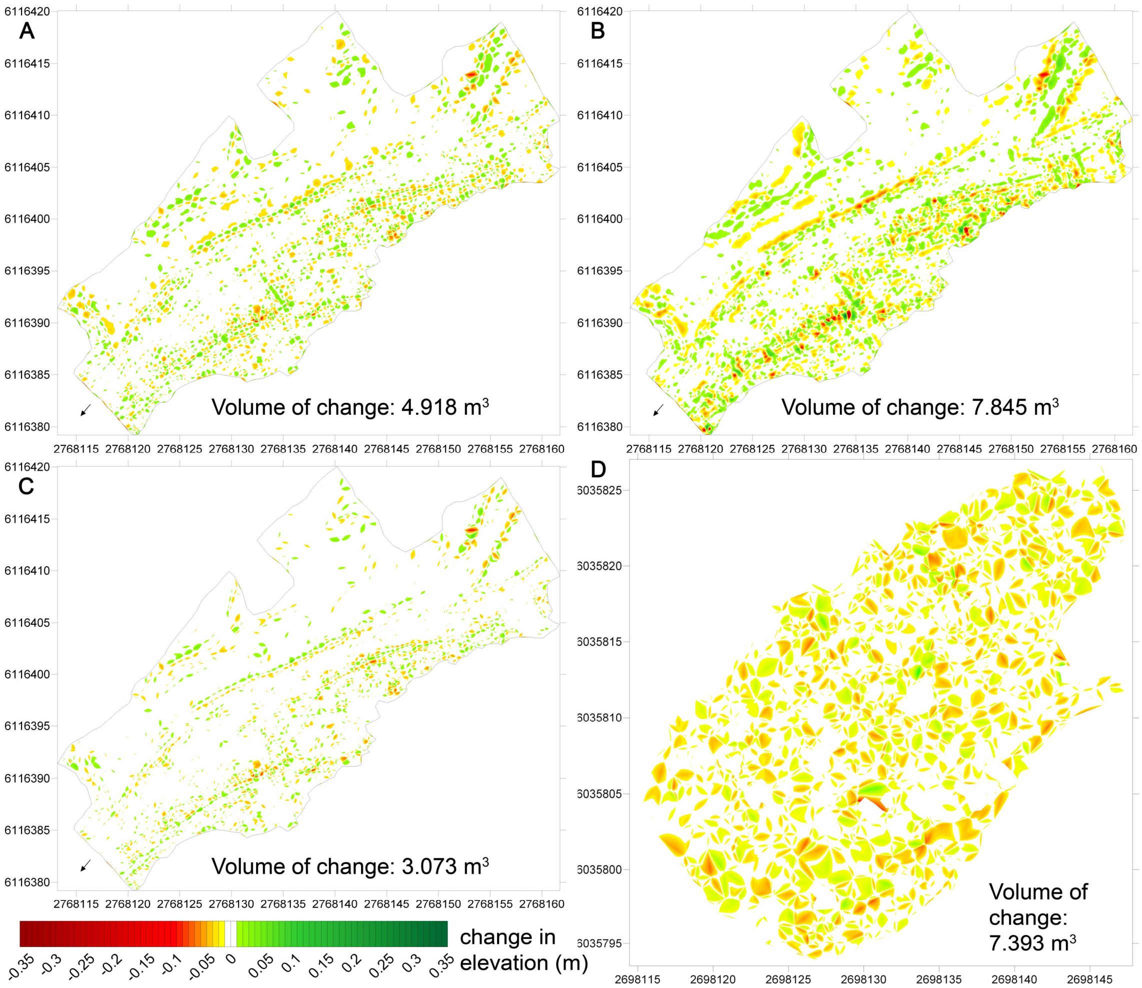

Figure 10. Subtraction of models generated with kriging (A), radial basis function (B) and natural neighbours (C, D) from triangulation model for Tamaki_2 (A-C) and Pukeatua_1 datasets (D). Arrow indicates flow direction and coordination axes denote easting and northing in m.

Overall the differences between models are smallest at the Tamaki site (Fig. 11) which possesses the lowest surface roughness and few small-scale structures. Here the deviations from the triangulation occur mainly at the channel margins and to a lesser extent on the channel bottom and floodplain (less than ±0.02 m) (Fig. 10A-C). In contrast differences between methods are more likely to appear at the channel bottom at reaches which are highly structured on a small scale like the Pukeatua site (Fig. 10D). This leads to the conclusion that there is no general bias between the methods although the residuals of the DEMs show a small variation in magnitude and direction. Differences between methods are consequently apparent only at small-scale structures and little when compared to surface roughness. The latter is the dominant error component afflicting data acquisition and of similar magnitude than interpolation errors (Schwendel *et al.*, 2010b). Thus an adequate detection threshold can to some degree account for inappropriate model choice.

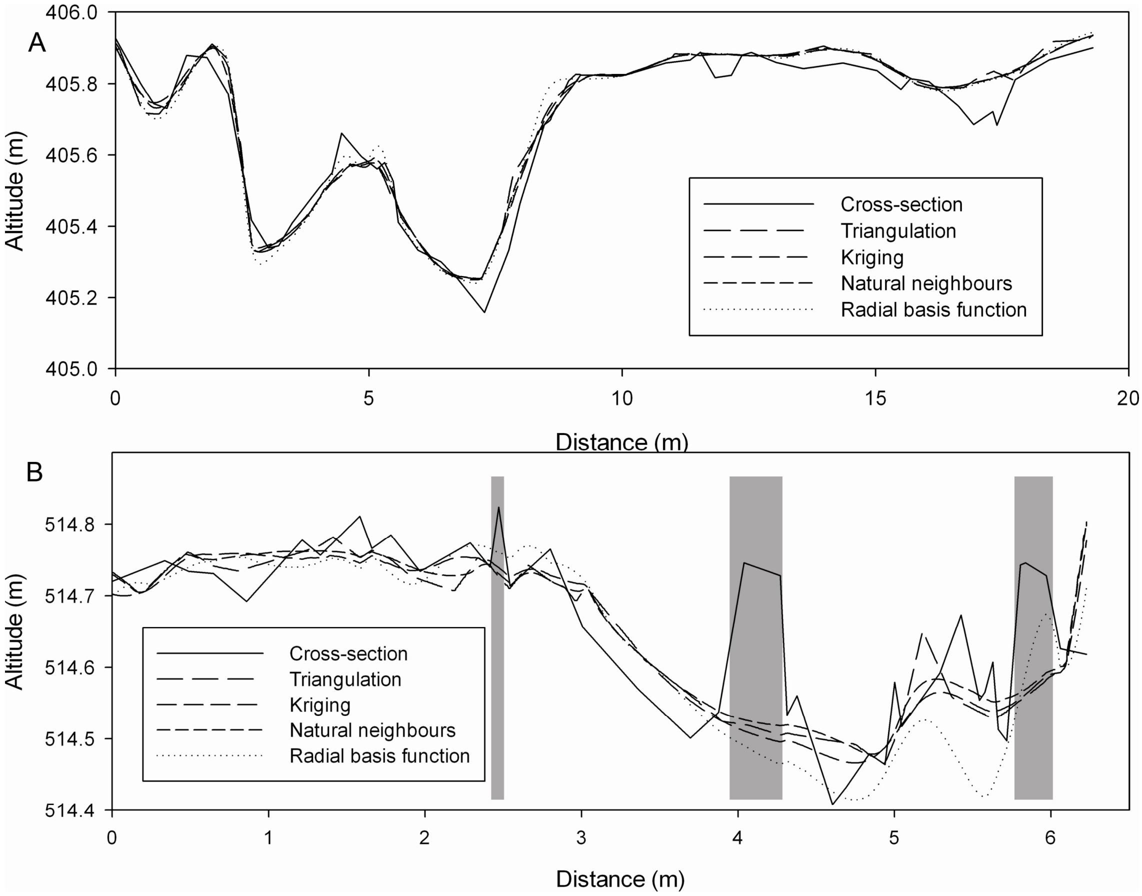

Figure 11. Cross-sections derived from different DEMs and independent topographic measurements ("cross-section"): Tamaki (A), Manawatu (B). Shaded areas depict blanked sections in the DEMs because of the presence of boulders (visible at the independent cross-section). Deviations between models and from independent surveys are more accentuated at small-scale structured sites (Manawatu) than at smoother surfaces (Tamaki) but are small compared to survey precision as defined by surface roughness (e.g. D_{84} is 0.058 m and 0.158 m at Tamaki and Manawatu respectively).

Comparison in application

The Tamaki and to a slightly lesser extent Waipawa sites can be regarded as showing responsive behaviour to small and intermediate floods reflecting a degree of intrinsic coupling. Abundant and highly erodible sediments from steep catchments with high erosion rates result in combination with frequent floods in a low channel and substrate stability (Schwendel *et al.*, 2010b). At these reaches DEM differencing is unlikely to detect effects caused by interpolation methods because it is masked by actual surface changes. Hence only the more stable Manawatu site is displayed (Fig. 12). All methods show the highest change in topography at the channel margins. This could be due to lateral erosion (often locally initiated by grazing cattle and sheep) or an artefact of interpolation. The fact that it appears almost on the entire southern bank, points towards the latter because no large scale bank erosion was visible there (Fig. 2B).

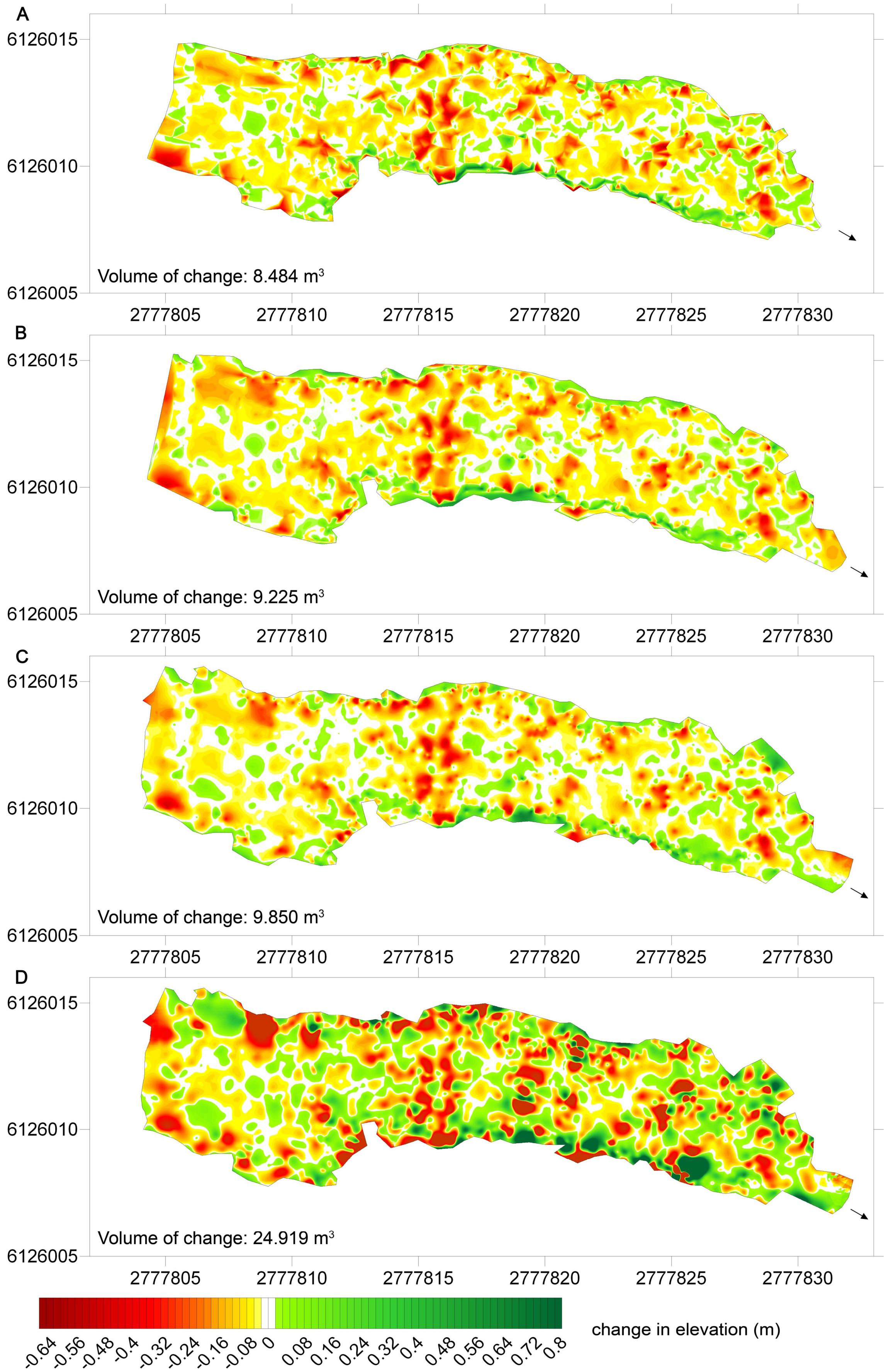

Figure 12. Models of change between the datasets Manawatu_1 and Manawatu_2 generated with triangulation (A), natural neighbours (B), kriging (C) and radial basis function (D). Arrow indicates flow direction and coordination axes denote easting and northing in m.

Patterns of scour and fill are similar between the methods with the exception that the radial basis DEMs exhibit less scour and fewer zones of no change in the channel. The triangulation DEM shows the smallest volume of change (Fig. 12) but within the same order as kriging and natural neighbours. The major source of this discrepancy seems to be representation of the channel margin.

CONCLUSIONS

Suggestions of optimal interpolation method from previous investigations are equivocal and subjective (Desmet, 1997) and are only valid for certain scales and surface characteristics. However, geomorphological and ecological studies that seek efficient and consistent comparison of sediment budgets derived by DEM differencing between numerous rivers require an interpolation method that allows a realistic representation of the topography of contrasting channels and can deal with varying data density and distribution. Furthermore, a large number of datasets favours approaches that do not need much site-specific parameterisation. This study accounts for these constraints at a river reach scale.

From the range of exact interpolation methods offered in Surfer®, triangulation with linear interpolation modelled the varying surfaces and channel shapes most realistically and consistently without the need to introduce breaklines or site specific parameters. It appears that this mathematically simple method is well suited for terrain sensitive surveys and the range of point densities investigated. If the data points are relatively regularly distributed triangular artefacts are rare and it produces superior results to geostatistical and other local neighbourhood approaches.

Triangulation with linear interpolation is commonly used for generation of DEMs of single sites (e.g. Brasington *et al.*, 2000; Brasington *et al.*, 2003; Fuller & Hutchinson, 2007; Heritage *et al.*, 2009) but it is also very suitable for comparative studies of multiple river reaches with contrasting channel topographies. This leads to the recommendation of triangulation with linear interpolation as a comprehensive and reliable method of DEM generation for environmental and ecological studies that aim to assess spatial variation in erosion and deposition at various scales and for investigation in bed stability between several varying coarse-substrate streams.

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Chapter 3a

Morphological dynamics of upland headwater streams in the southern North Island of New Zealand

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ABSTRACT

Short-term channel dynamics of mountain stream reaches in the southern North Island of New Zealand were assessed over two successive three-month periods using morphological budgeting. Response to floods varies between reaches, even when the catchments were located close to each other and had similar characteristics. The reaches on the Central Volcanic Plateau experienced least morphological change while streams with steep catchments and migrating planform in the Tararua and Ruahine Ranges showed frequent channel adjustments. Channel response is conditioned by intrinsic variables rendering reaches responsive or robust to the effects of floods and this is likely to reflect the degree of connectivity between slopes and channels and reaches.

INTRODUCTION

Mountain streams are commonly defined as having a steep gradient (e.g. > 0.002 m/m), gravel to boulder dominated substrate and spatially limited floodplain width (Wohl & Merritt, 2008). Tectonic activity, glacial history, large woody debris, and sediment input from hillsides and tributaries cause segmentation of the longitudinal profile (Chin & Wohl, 2005; Wohl & Merritt, 2005) and result in a variety of channel types that are not positioned in a typical sequence (e.g. cascade to riffle-pool in downstream direction). Evolution of these channel typologies is rather determined by transport capacity and sediment supply which reflect local lithology (grain size and shape), slope and land cover (Thompson *et al.*, 2006).

On a global scale New Zealand mountain streams are regarded as severely impacted by loss of biotic integrity (e.g. caused by water abstraction for hydroelectricity and irrigation or introduced species), and moderately impacted by anthropogenic channel alteration and land use (including past deforestation and mining) (Wohl, 2006). Despite human influence on channel dynamics headwater reaches in New Zealand are often perceived as having naturally unstable beds (e.g. Mosley & Blakely, 1977) which implies high rates of sediment transfer. This in turn suggests a sufficient supply of sediments from the catchment as well as competent flows to move them. The geologically young axial ranges in the southern part of the North Island consist of shattered and faulted rocks (Williams, 1991) and experience high rates of uplift and erosion (Whitehouse & Pearce, 1992). In addition earthquakes may trigger substantial mass movements in these catchments (Goff & McFadgen, 2002) and in the central plateau volcanic activity also contributes to the potential to provide large amounts of material to river systems (Manville *et al.*, 2009). Furthermore, high rainfall variability promotes not only weathering but can also cause frequent floods and flashy discharge regimes. Hence there is reason to believe that upland streams are morphologically dynamic. However, to date no research has compared short-term dynamics of different mountain stream systems in New Zealand.

This paper explores the morphological responses of twelve mountain streams to floods and spates over seven months. We focus on topographic changes of the stream channel rather than on bedload transport rate as an indicator of overall stream dynamic which incorporates both morphological change of banks and bed. Morphological budgeting is well suited for this purpose because it allows quantification of spatial patterns in sediment transfer within the channel (Ashmore & Church, 1998, Fuller *et al.*, 2003a; 2005) and provides a lower bound estimate of sediment flux (Fuller *et al.*, 2002;

Lindsay & Ashmore, 2002). Comparison of digital elevation models (DEMs) of river morphology before and after a flood event directly reveals processes such as erosion and deposition while the interpretation of DEMs of change in combination with site knowledge can lead to the identification of processes driving the topographic changes observed.

The factors influencing the morphological dynamics of a reach act on different spatial and temporal scales. While slope, substrate characteristics, connectivity and sediment supply vary between reaches (Hooke, 2003, Fryirs *et al.*, 2007), the influence of land cover (vegetation) on flood generation is higher at the catchment scale. The magnitude and recurrence interval characterises an event but the (long-term) processes occurring between events are also important for the morphological response to increased flows. We used catchment parameters from the Freshwater Environments of New Zealand (FWENZ) database (Wild *et al.*, 2005) to evaluate their importance to explain the differences in morphological dynamics between the 12 reaches investigated here.

SITES AND METHODOLOGY

Sites

Topographic surveys were carried out at 12 second to fifth order mountain rivers and streams in the southern part of the North Island of New Zealand. These reaches were chosen because their catchments have relatively low anthropogenic modifications and their position in terms of stream order or distance from the source within larger catchments is comparable. Within groups of sites geographical setting and catchment land cover are similar. They form part of the Manawatu, Tukituki, Ruamahanga, Otaki, Tongariro and Wanganui catchments which drain the eastern and western slopes of the northeast-southwest stretching Ruahine and Tararua Ranges and the Central Volcanic Plateau respectively (Fig. 1). Vegetation within the catchment upstream of the study reaches is dominated by native broadleaf-podocarp forest in the axial ranges and by tussock grassland and scrub around Mt. Ruapehu. Andesitic volcanic deposits constitute the bedrock on the Central Plateau whereas folded mesozoic greywacke and argillite of varying decomposition prevail in the Tararua and Ruahine Ranges (Mosley, 1978a).

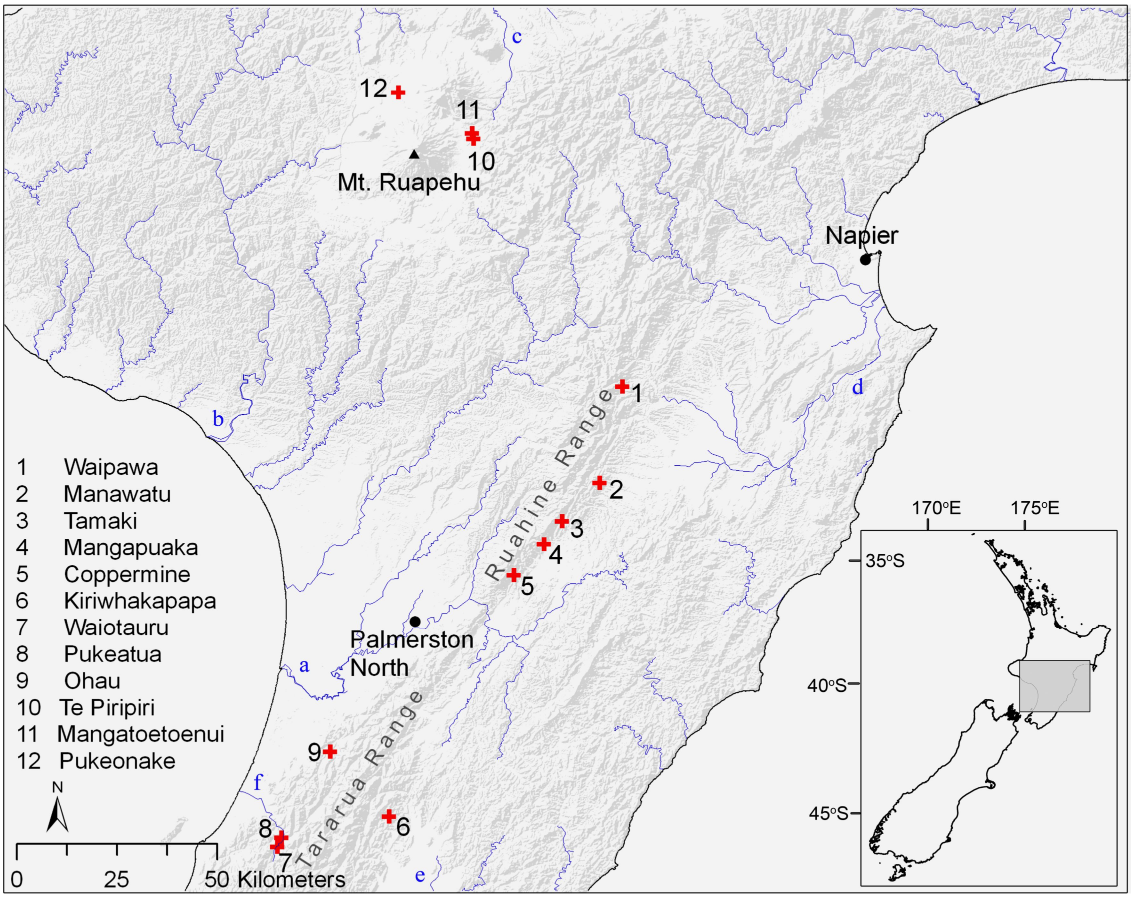

Figure 1. Study sites in the southern part of the North Island of New Zealand and important rivers: a – Manawatu, b – Wanganui, c – Tongariro, d – Tukituki, e – Ruamahanga and f – Otaki.

Table 1. Hydraulic and substrate characteristics of the study reaches.

Site	**Stream order (Strahler, 1952)**	**Slope (m m^{-1})**	**Mean hydraulic radius at bankfull (m)**	**Mean bankfull width (m)**	**Mean substrate D_{50} (mm)**	**Substrate composition** (in order of relative proportion of s - sand, g - gravel, c - cobbles, b - boulders)
Waipawa	3	0.032	0.481	48.6	58.5	g, c, b
Manawatu	3	0.047	0.232	7.4	64.9	c, g, b
Tamaki	2	0.021	0.195	19.0	35.2	g, c
Mangapuaka	2	0.029	0.129	25.5	28.0	g, c
Coppermine	3	0.042	0.328	7.0	51.2	g, c, b
Kiriwhakapapa	3	0.011	0.517	9.5	58.7	c, b, g
Waiotauru	5	0.012	0.803	42.8	84.4	c, g, b
Pukeatua	3	0.047	0.912	24.2	83.9	c, g, b
Ohau	4	0.012	0.701	18.0	64.0	c, g, b
Te Piripiri	3	0.014	0.198	2.8	34.9	g, c, (b, s)
Mangatoetoenui	4	0.025	0.369	11.5	97.2	c, g, b, (s)
Pukeonake	4	0.034	0.357	12.1	157.8	b, c, g

Hydraulic and substrate characteristics of the study reaches varied considerably representing the variety of mountain streams in the lower North Island (Table 1). Substrate composition ranges from heterogeneous assemblages with a relatively high proportion of boulders (e.g. Pukeonake) to well sorted gravel-dominated stream beds (e.g. Mangapuaka) (Fig. 2). The channels comprise distinctive features including step-pool sequences (e.g. Pukeatua), plane-bed sections (e.g. Tamaki), riffle-pool units (e.g. Manawatu) and bedrock confined sections (e.g. Ohau). Lateral confinements by stable banks or steep valley sides are common, although, at some sites channels could shift freely in a wide active floodplain (e.g. Waipawa).

Figure 2. Selection of the study reaches: Te Piripiri (A), Waiotauru (B), Coppermine (C), Ohau (D), Waipawa (E) and Mangapuaka (F).

Survey

Between October 2007 and May 2008 three topographic surveys at each of the twelve reaches were conducted. Three dimensional point coordinates were measured using a differential GPS system (R8, Trimble Navigation Limited, Sunnyvale, USA) in RTK mode (cf. Brasington, Rumsby & McVey, 2000) in combination with a electronic total station GTS 701 (Topcon Corporation, Tokyo, Japan) when satellite reception was limited. The GPS base receiver was installed some distance from each reach in order to prevent multipath errors (Kennedy, 2002). Survey point density was terrain sensitive, i.e. adjusted according to the surface complexity being highest at breaks in slopes (c.f. Fuller *et al.*, 2003a). Consequently total point density varied between very structured sites and relatively smooth reaches. Substrates larger than cobbles require a grain scale resolution to be represented adequately in a DEM together with gravelly surfaces. As this is impractical for large survey areas, boulders (b-axis > 300 mm) were not considered for the budgeting and were excluded from the DEM. Concomitant tracking of *in situ* marked boulders (Schwendel *et al.*, in press) showed that only 3% of them moved during floods (A. Schwendel, unpublished data). The surveyed length of stream ranges from 30 m to 200 m and was chosen to include all characteristic features of the reach. Survey area varies between 132 m^2 and 2942 m^2 and the average point density lies between 0.6 and 11.7 points per square metre (Table 2).

Table 2. Point density and survey area of all surveys between October 2007 and May 2008.

Survey	1 (October/ November 2007)		2 (January/ February 2008)		3 (May 2008)	
Site	Area (m^2)	Point density (m^{-2})	Area (m^2)	Point density (m^{-2})	Area (m^2)	Point density (m^{-2})
Waipawa	1897.22	0.58	2437.94	1.54	1467.79	1.89
Manawatu	131.84	9.41	159.69	11.73	162.84	7.48
Tamaki	902.64	2.05	886.20	3.86	917.70	3.01
Mangapuaka	1449.22	1.56	1515.63	2.04	1559.97	1.97
Coppermine	405.91	4.92	493.51	6.52	440.69	7.78
Kiriwhakapapa	278.21	1.29	310.87	1.77	259.15	3.15
Waiotauru	2892.44	0.73	2942.07	1.32	2601.62	1.20
Pukeatua	613.49	1.95	1002.41	2.11	792.17	2.17
Ohau	972.61	0.66	1113.24	1.03	1053.17	1.20
Te Piripiri	160.75	4.40	216.40	7.49	267.08	6.83
Mangatoetoenui	835.39	1.71	859.21	2.96	852.88	2.53
Pukeonake	439.74	2.85	511.57	5.24	161.21	6.31

Although, compared to errors induced by surface roughness, precision of dGPS and electronic theodolites is high (Brasington *et al.*, 2000), atmospheric interference and satellite constellation can be a problem. To assess this, frequent measurements of a limited number of independent check points during a survey were utilised (Brasington *et al.*, 2000) which revealed a vertical precision of 0.015 m. This compares well to the vertical error derived from survey-specific internal quality control data generated by the measurement device which ranges between 0.014 and 0.049 m (means per site in Table 3). The error induced by surface roughness, e.g. if the measuring pole is set on top of a particle or in a gap between grains, is often identified by a percentile of the substrate size distribution (Brasington *et al.*, 2000; Chappell *et al.*, 2003). We used the corrected substrate size (upper threshold 300 mm) of the surveyed bed for which 84% is finer (D_{84corr}) which for each survey and site significantly exceeds instrument precision (Table 3). Additionally, independent cross-sections and local temporary benchmark points were measured the same day as each survey. These were used for DEM quality analysis as recommended by Fisher & Tate (2006).

Table 3 Mean values per site for vertical survey precision and accuracy, vertical DEM accuracy and the level of detection (LOD) of genuine change (ME: mean error, SD standard deviation).

Error	Survey precision			Interpolation accuracy						LOD (m)
Source	Quality control		Sub-strate	Residuals		Independent checkpoints		Cross validation		
Site	ME (m)	SD (m)	D_{84corr} (m)	ME (m)	SD (m)	ME (m)	SD (m)	ME (m)	SD (m)	
Waipawa	0.024	0.017	0.132	-0.001	0.009	-0.014	0.049	0.012	0.111	0.187
Manawatu	0.020	0.018	0.158	-0.003	0.054	0.027	0.147	0.004	0.155	0.223
Tamaki	0.030	0.020	0.058	0.000	0.008	-0.004	0.060	-0.001	0.062	0.082
Mangapuaka	0.024	0.016	0.057	0.000	0.007	0.009	0.046	0.002	0.067	0.080
Coppermine	0.027	0.019	0.140	-0.001	0.019	0.038	0.084	0.005	0.100	0.198
Kiriwhakapapa	0.047	0.024	0.161	-0.000	0.008	-0.012	0.125	0.016	0.201	0.227
Waiotauru	0.015	0.008	0.177	-0.000	0.007	0.007	0.133	0.006	0.073	0.251
Pukeatua	0.029	0.017	0.145	-0.000	0.013	0.080	0.153	0.005	0.122	0.205
Ohau	0.030	0.019	0.149	-0.001	0.007	-0.010	0.071	0.009	0.089	0.210
Piripiri	0.014	0.006	0.097	-0.003	0.025	0.004	0.073	0.010	0.120	0.138
Mangatoetoenui	0.015	0.012	0.182	-0.001	0.012	-0.003	0.130	0.007	0.083	0.257
Pukeonake	0.025	0.018	0.177	-0.001	0.018	0.081	0.167	0.004	0.091	0.250

Substrate composition was assessed using the Wolman pebble count method (Wolman, 1954) which measures the b-axis of > 100 randomly selected substrate particles. The measurements were classified according to a modified Wentworth scale.

Interpolation

After a detailed check in order to eliminate gross errors and systematic errors, the data were interpolated to a regular gridded DEM with Surfer 8.01 (Golden Software, Golden, USA) using triangulation with linear interpolation and a grid size of 0.1 m. This grid width has been used in similar environments (Lane, Chandler & Richards, 1994) and is suitable to account for small-scale variation in densely surveyed areas. It is also sufficiently large compared with surface roughness to avoid the occurrence of spurious artefacts (Brasington & Richards, 1998). Preliminary analysis (Schwendel, Fuller & Death, in press) revealed that interpolation with triangulation was most effective amongst the exact interpolation methods available in Surfer in representing the surfaces of topographically variable stream reaches. In particular the modelling of longitudinal features (e.g. bars and trenches), channel side walls and the channel bottom was more realistic than using other interpolation methods without the need to introduce breaklines. The latter would be very time intensive when analysing a large number of datasets such as 36 in this study. Furthermore triangulation with linear interpolation is well suited for a terrain sensitive survey (Brasington *et al.*, 2000; Brasington, Langham & Rumsby, 2003; Fuller & Hutchinson, 2007) and is unaffected by problems like over- and undershooting of surfaces near a jump discontinuity (Gibbs phenomenon) (Florinsky, 2002). Effects of anisotropy (*sensu* Fuller *et al.*, 2003a) were found to be negligible because the length of the reaches was not much higher than the width (Schwendel *et al.*, in press).

Comparison of DEMs

For each site subtraction of DEMs from successive surveys revealed areas and volumes of change. However, DEMs and derived sediment budgets are affected by multiple sources of error (Lane, 1998) which need to be quantified in order to gain an estimate of a threshold of detectable change in topography (Wheaton *et al.*, 2007). This threshold accounts for propagated random errors emerging from measurement as well as interpolation errors. Thus a level of detection of genuine change was assessed considering precision of measurement as well as interpolation errors identified by residual analysis, independent data and cross-validation (quasi-independent data). Mean errors of all three measures are mostly small (e.g. < 0.02 m) and scattered around zero indicating little overall systematic bias whereas mean deviation from independent data is highest reaching up to 0.08 m (Pukeatua and Pukeonake) (Table 3). Standard deviations derived from independent and quasi-independent data are significantly higher than the standard deviation of the residuals and of similar size than the error emerging from data acquisition (D_{84corr}). In contrast, the precision between surveys (e.g. mean error ± 1 SD of all subsequent surveys is 0.023 ± 0.026 m) which was measured using local temporary benchmark points, is much lower. Surface roughness is at most sites the highest error component and was thus chosen as a rigorous means of assessing DEM quality and used for generating a level of change detection.

The propagation of error during the subtraction process was calculated using appropriate error propagation formula (Eqn. 1) where δ_u is the propagated error (level of detection) derived from the errors δ_1 and δ_2 of the input DEMs (cf. Brasington *et al.*, 2003; Lane, Westaway & Hicks, 2003):

$$\delta_u = ((\delta_1)^2 + (\delta_2)^2)^{0.5} \qquad (1).$$

The calculated level of detection ranges from 80 to 257 mm (Table 3) which compares well to other studies of gravel-bed rivers, e.g. 80 - 82 mm (Tamaki and Mangapuaka), 80 - 110 mm in Fuller, Large & Milan (2003b) and 100 mm in Brasington *et al.* (2000).

Tracer stones

As an independent indicator of substrate stability five tracer stones in each of three size classes (D_{50}, D_{70} and D_{90}) were marked in riffles with RFID tags (23 mm glass tags, Texas Instruments, Dallas, USA). The latter were attached *in situ* to the stones where turbulence and flow velocity permitted underwater application (89% of all particles) using wet curing epoxy-concrete (K273, Nuplex Construction Products, Hamilton, New Zealand). The remaining stones were removed from the river bed for tag attachment and afterwards carefully re-embedded. The percentage of entrained *in situ* marked tracer stones was significantly correlated with the percentage of entrained re-embedded stones (Spearman rank correlation, $r_S = 0.78$, $\alpha = 0.0001$). Tracer stones were relocated and identified up to a depth of 0.6 m in the substrate using a portable antenna and datalogger (OregonRFID, Portland, USA). Relocation surveys which took place approximately every two months or after high discharge events, encompassed the entire channel and active floodplain at least 50 m downstream of the last position of each tracer particle.

CHANNEL CHANGES

October/November 2007 to January/February 2008

Between the set of first surveys in October/ November 2007 and the set of second surveys in January/ February 2008 each catchment was influenced by at least one flood event that was competent to move at least part of the bed (Fig. 3). The areas and volumes of change varied considerably between sites (Table 4). Most of the reaches in the western Tararua Range showed high changes dominated by scour under influence of the 8 January flood. The high volume of scour at the Pukeatua site was mainly the erosion of a fan from a steep tributary stream at the north-western margin of the site and was therefore not representative for the entire stream bed of the relatively steep reach (Fig. 4). However, erosion was dominant throughout the entire site (64% of area scoured) with only a small area on the right side of the main channel being affected by deposition. At Waiotauru mainly the right bank was eroded, in particular at a steep medial bar upstream of the confluence with a side channel. The latter and the left side of the upper main channel experienced some aggradation. In the centre of the main channel, deep and swift flow prevented surveying (area excluded from the DEM and separated from surveyed areas by a hairline in Fig. 4), but few morphological changes adjacent to that zone indicate that no large scale sediment transfers occurred there. At the Ohau site scouring occurred in the central areas of the channel and the western side of the lower baseflow channel, while deposition took place only locally at the margins. In contrast at Kiriwhakapapa on the eastern side of the Tararua Range only few local morphological changes (mainly scour) could be detected reliably.

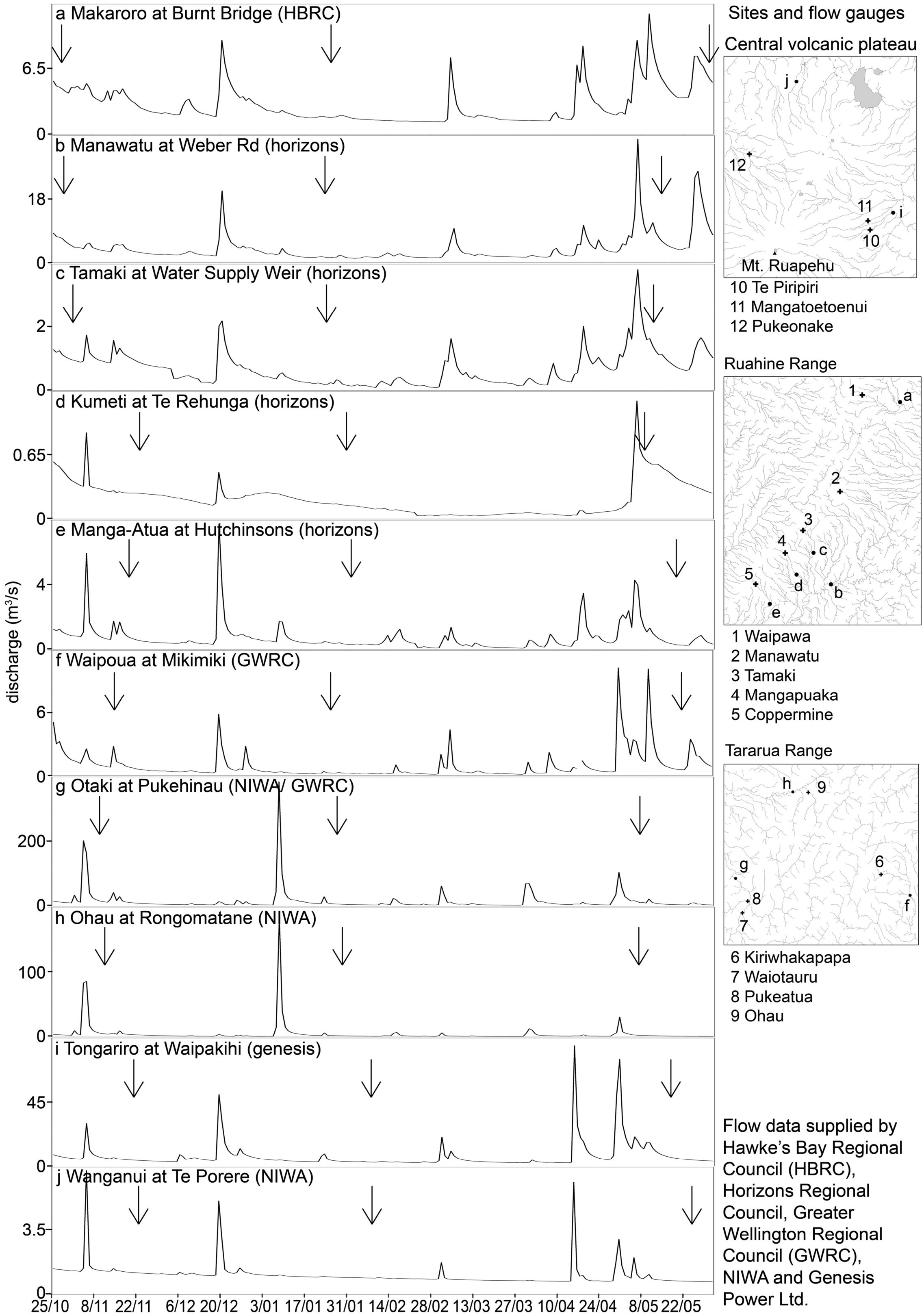

Figure 3. Flow hydrographs of gauges in neighbouring catchments or downstream of the study sites, arrows mark the survey dates at the respective reaches (site-gauge match: 1 – a, 2 – b, 3 – c, 4 – d, 5 – e, 6 – f, 7 and 8 – g, 9 – h, 10 and 11 – i, 12 – j).

Table 4. Volume and area of geomorphic change relative to the planar DEM area between October/ November 2007 and January/ February 2008 and between January/ February 2008 and May 2008 (bold).

	Volume				Area		
Site	**Fill (10^{-3} m^3 m^{-2})**	**Scour (10^{-3} m^3 m^{-2})**	**Net (10^{-3} m^3 m^{-2})**	**Total change (10^{-3} m^3 m^{-2})**	**Fill (%)**	**Scour (%)**	**Total change (%)**
Waipawa	15.529	31.114	-15.585	46.643	11.4	18.9	30.3
	1.469	**42.794**	**-41.325**	**44.264**	**3.3**	**23.7**	**27.0**
Manawatu	1.930	3.035	-1.105	4.965	1.3	3.9	5.2
	0.295	**0.625**	**-0.330**	**0.920**	**0.4**	**0.6**	**1.0**
Tamaki	54.202	15.025	39.177	69.228	32.3	13.7	46.0
	32.510	**14.568**	**17.943**	**47.078**	**27.6**	**17.1**	**44.7**
Mangapuaka	25.301	38.828	-13.526	64.129	22.8	23.5	46.3
	41.328	**5.068**	**36.260**	**46.395**	**25.1**	**5.8**	**30.9**
Coppermine	0.372	0.420	-0.048	0.793	0.7	0.6	1.3
	0.203	**0.513**	**-0.310**	**0.715**	**0.3**	**0.6**	**0.9**
Kiriwhakapapa	0.024	1.818	-1.794	1.842	0.1	2.7	2.8
	0.274	**0.000**	**0.274**	**0.274**	**0.5**	**0.0**	**0.5**
Waiotauru	3.801	26.532	-22.731	30.334	4.5	17.3	21.8
	3.762	**1.925**	**1.837**	**5.687**	**4.3**	**2.4**	**6.8**
Pukeatua	24.327	284.250	-259.922	308.577	10.8	63.6	74.4
	8.816	**10.362**	**-1.546**	**19.178**	**9.1**	**8.4**	**17.5**
Ohau	0.809	4.617	-3.808	5.426	2.5	8.5	11.1
	0.248	**0.400**	**-0.152**	**0.647**	**0.5**	**1.2**	**1.6**
Piripiri	0.867	0.762	0.105	1.629	1.1	0.8	1.9
	40.795	**5.252**	**35.543**	**46.048**	**39.6**	**5.6**	**45.3**
Mangatoetoenui	0.075	0.029	0.046	0.104	0.1	0.0	0.1
	0.000	**0.053**	**-0.053**	**0.054**	**0.0**	**0.2**	**0.2**
Pukeonake	0.282	0.102	0.181	0.384	0.5	0.1	0.6
	0.000	**0.003**	**-0.003**	**0.003**	**0.0**	**0.0**	**0.0**

Waipawa, Mangapuaka and Tamaki in the eastern Ruahine Range experienced substantial topographic changes whereas at Manawatu and especially the southernmost site there, Coppermine, few sediment transfers were detected (Fig. 5). Waipawa and Mangapuaka were dominated by erosion while Tamaki was aggrading. At Waipawa scour occurred throughout the reach but mainly at the channel margins, whereas some sections of the central channel showed deposition. These patterns point towards a widening of the riverbed, probably as an effect of previous aggradation (c.f. Grant, 1977). At both the Tamaki and Mangapuaka sites the shifting of the whole channel in the gravel body is clearly visible. The relative amount of change is probably underestimated because, compared with sites constrained by stable vegetated banks, a wider part of the floodplain was surveyed to capture all potential lateral migration. Some smaller topographic changes on the floodplain relatively distant to the active channel indicate that these zones were eventually inundated with competent flow to entrain surface materials. The Tamaki reach is less braided than at Mangapuaka and channel migration resulted in the abandoning and fill of an old side channel on the true left side. The complexity of the patterns at Mangapuaka suggests several phases of development. At the less dynamic sites of Coppermine and Manawatu, scour and fill is limited to small zones. Bank erosion is common but depositional areas on the southern channel margin of the Manawatu River result from bank collapse after being washed out during a previous flood. Fresh flood debris higher on the banks than bankfull level was found on both sides, which shows that potentially competent flows have occurred and the absence of sediment dynamics reflects a high degree of bed stability.

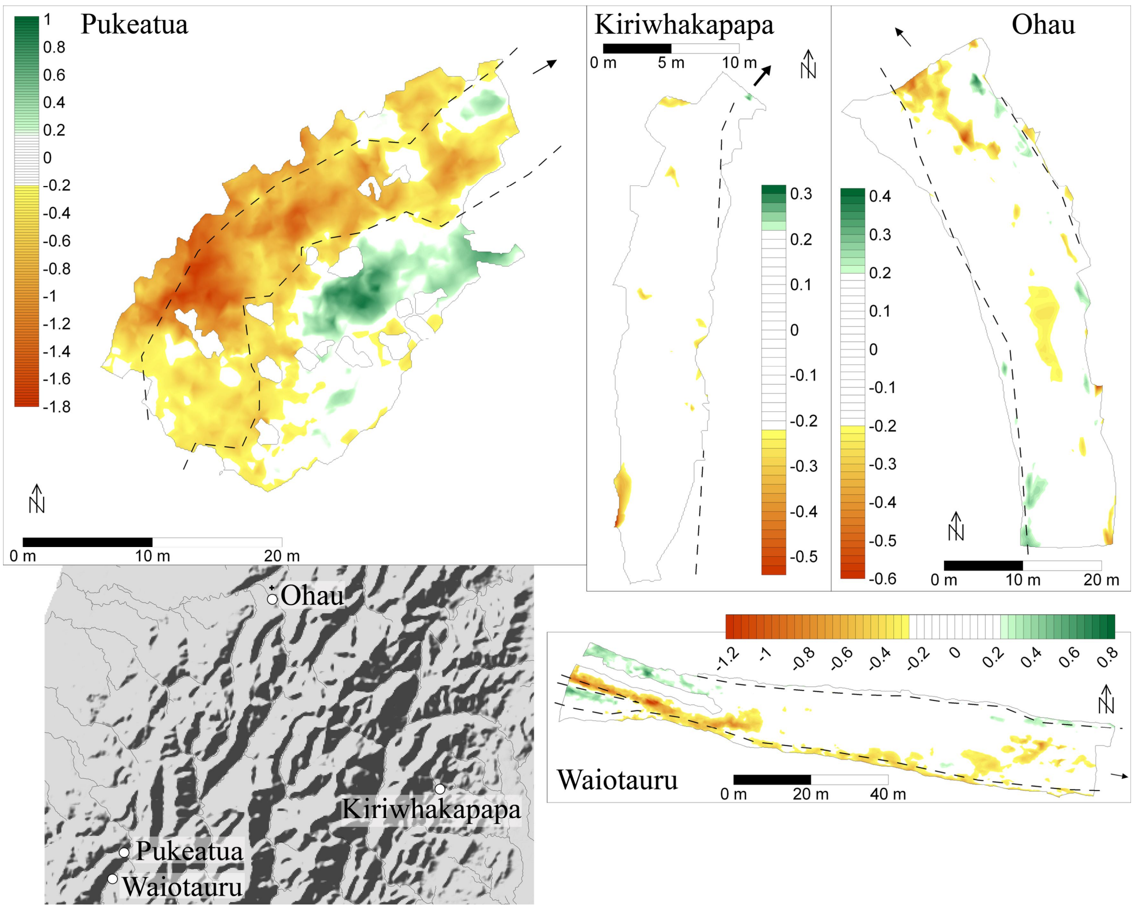

Figure 4. DEMs of topographic change (m) between October/ November 2007 and January/ February 2008 of the reaches in the Tararua Range with application of individual levels of detection, wetted channel zone at the more recent survey is outlined (broken line) and arrows indicate flow direction.

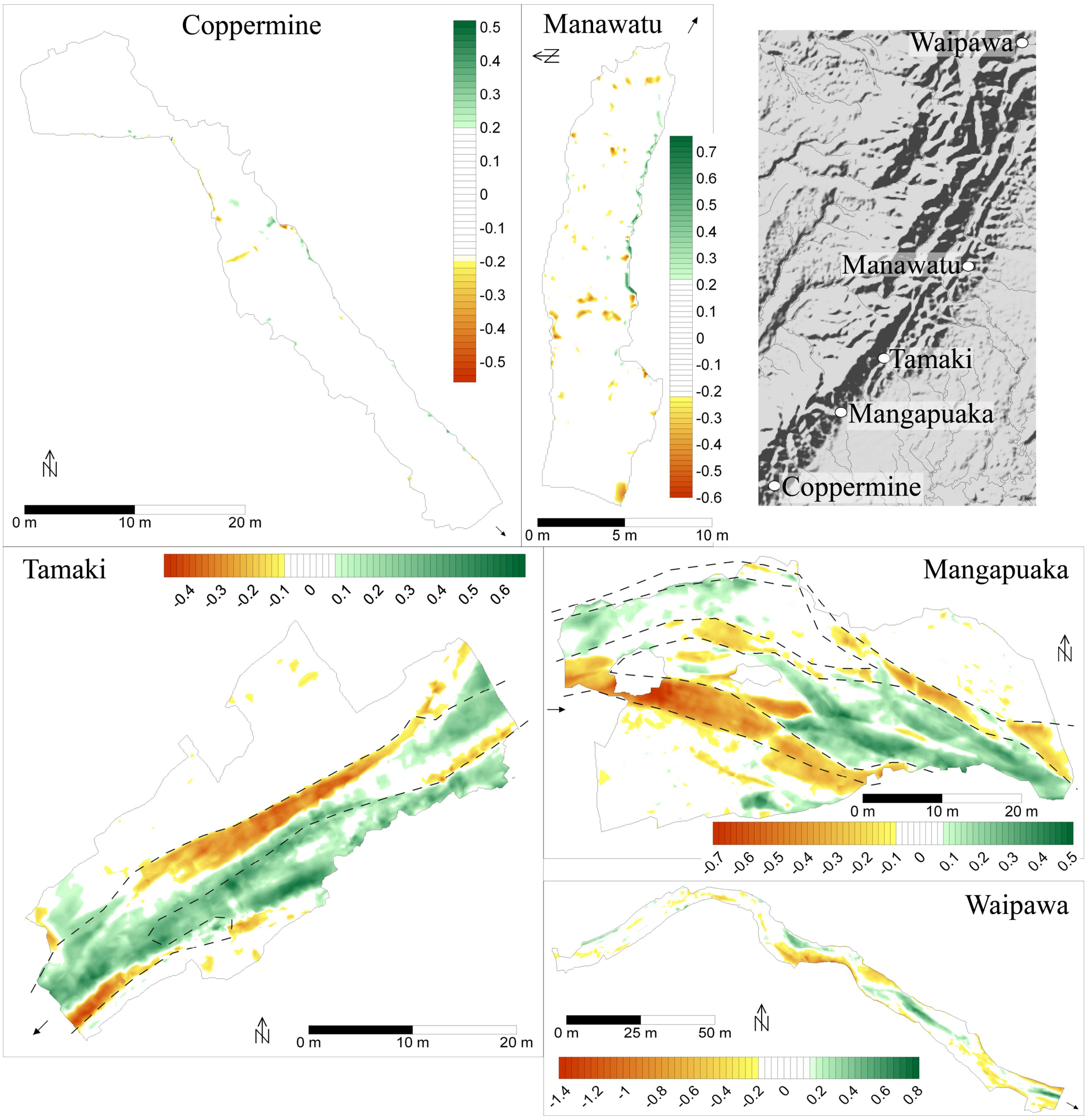

Figure 5. DEMs of topographic change (m) between October/ November 2007 and January/ February 2008 of the reaches in the Ruahine Range with application of individual levels of detection, wetted channel zone at the more recent survey is outlined (broken line) and arrows indicate flow direction.

All the sites on the Central Volcanic Plateau showed little detectable channel change (Fig. 6) although a gauge downstream (Te Piripiri and Mangatoetoenui) and in a neighbouring catchment (Pukeonake) experienced a considerable flood on 20 December (Fig. 3).

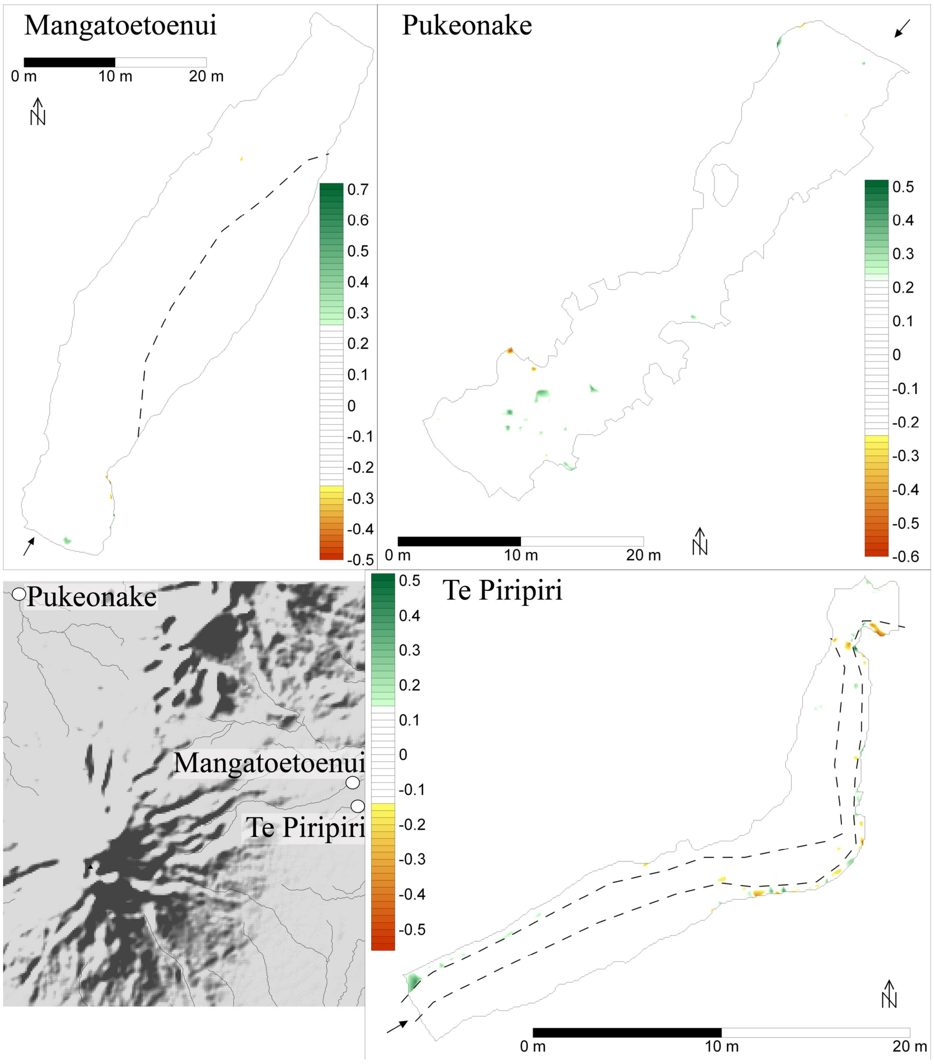

Figure 6. DEMs of topographic change (m) between October/ November 2007 and January/ February 2008 of the reaches on the Central Volcanic Plateau with application of individual levels of detection, wetted channel zone at the more recent survey is outlined (broken line) and arrows indicate flow direction.

January/February 2008 to May 2008

During the second period from January/ February to May 2008 several spates and floods occurred, many of them visible in the hydrographs of most catchments (Fig. 3). Hence in this second time period only the compound effects of all these events were captured. Morphological changes were greatest at the Waipawa, Mangapuaka, Tamaki and Te Piripiri sites (Table 4) and lowest at the remaining reaches on the Central Volcanic Plateau. Fill at one spot where a bank collapsed was the only topographic change registered at Kiriwhakapapa in the eastern Tararua Range (Fig. 7), although substantial tracer stone movement occurred (Table 5). The Ohau reach shows mainly small amounts of local erosion while erosion of the medial bar on the right of the upper main channel at Waiotauru continues. At the latter site some parts in the thalweg became scoured deeply which prevented high resolution surveying. In contrast, some deposition occurred in the centre of a shallow run between the two riffles of the reach, resulting in an overall positive sediment budget. At Pukeatua erosion of the aforementioned fan has nearly ceased and limited deposition appears in that zone. The material could be sourced from erosion of a riffle-pool unit further upstream causing movement of coarse substrate. This stream, also known as “Roaring Meg”, has a very flashy flood regime with longer periods of stable baseflow in between allowing growth of algae throughout the wetted channel. In contrast flood discharges and water levels can be high (drift wood deposited 1.5 m above baseflow stage; A. C. Schwendel, personal observation) which leads, when combined with high sediment supply from the many slope failures in the narrow valley, to a complex pattern of scour and fill. The patchy, but non-size selective entrainment of tracer stones points also towards a irregular pattern of highly competent discharge.

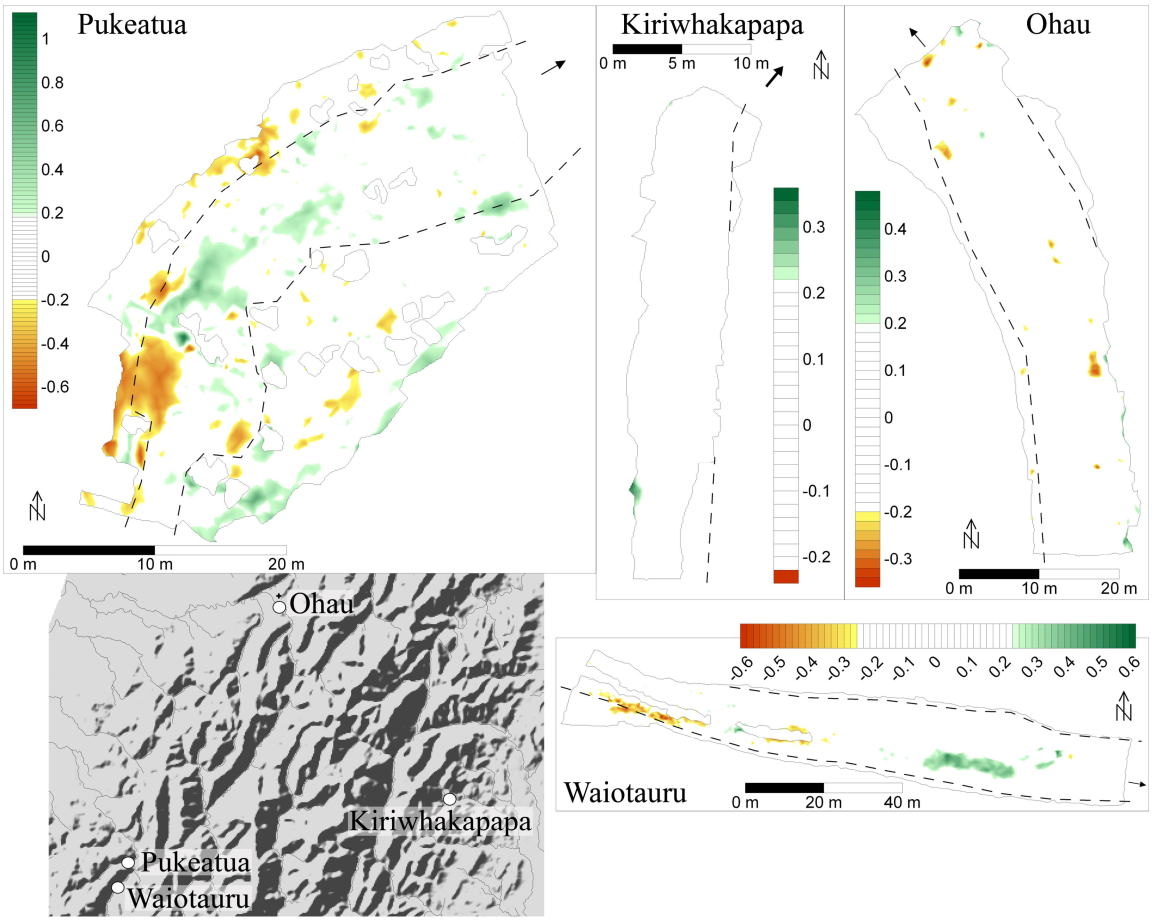

Figure 7. DEMs of topographic change (m) between January/ February and May 2008 of the reaches in the Tararua Range with application of individual levels of detection, wetted channel zone at the more recent survey is outlined (broken line) and arrows indicate flow direction.

Table 5. Mean percentage of entrainment and mean travelled distance of *in situ* marked tracer particles in each of the size classes D_{50}, D_{70} and D_{90} of the substrate.

	Entrainment (%)			Travelled distance (m)		
	D_{50}	D_{70}	D_{90}	D_{50}	D_{70}	D_{90}
Waipawa	100.0	100.0	100.0	85.3	76.3	79.2
Manawatu	50.0	40.0	0.0	19.8	5.3	0.0
Tamaki	100.0	100.0	100.0	68.3	72.6	59.0
Mangapuaka	87.5	75.0	33.3	25.9	28.1	16.7
Coppermine	88.9	70.0	20.0	22.6	11.0	0.2
Kiriwhakapapa	66.7	70.0	37.5	29.3	17.1	18.8
Waiotauru	100.0	75.0	87.5	40.2	41.3	36.6
Pukeatua	57.14	50.0	55.6	22.1	8.4	12.1
Ohau	100.0	60.0	20.0	43.6	28.0	1.3
Piripiri	40.0	20.0	40.0	5.8	1.1	3.4
Mangatoetoenui	83.3	62.5	55.6	37.2	31.9	6.6
Pukeonake	0.0	0.0	0.0	0.0	0.0	0.0

The characteristic dynamic morphologies of the first period are repeated between January and May at the reaches in the eastern Ruahine Range (Fig. 8). Manawatu and Coppermine are stable with only minor channel changes (mainly scour) close to the banks. In contrast the other sites show highly dynamic morphological change. At Waipawa erosion is dominant, again affecting point bars and the channel bottom, which causes an overall straightening of the reach. The upper middle part of the reach could not be surveyed for logistic reasons but the subjective impression was that scour prevailed here as well (A. C. Schwendel, personal observation). At Mangapuaka the channel system at the southern part of the site was filled and the flow was directed north of this zone with locally high erosion visible. Although surface flow ceased at this reach during summer, Mangapuaka has the highest fill dominated net budget among all sites (Table 4). The Tamaki reach showed considerable widening of the channel with lateral erosion and mid-channel deposition. This channel adjustment leads again to a positive net budget.

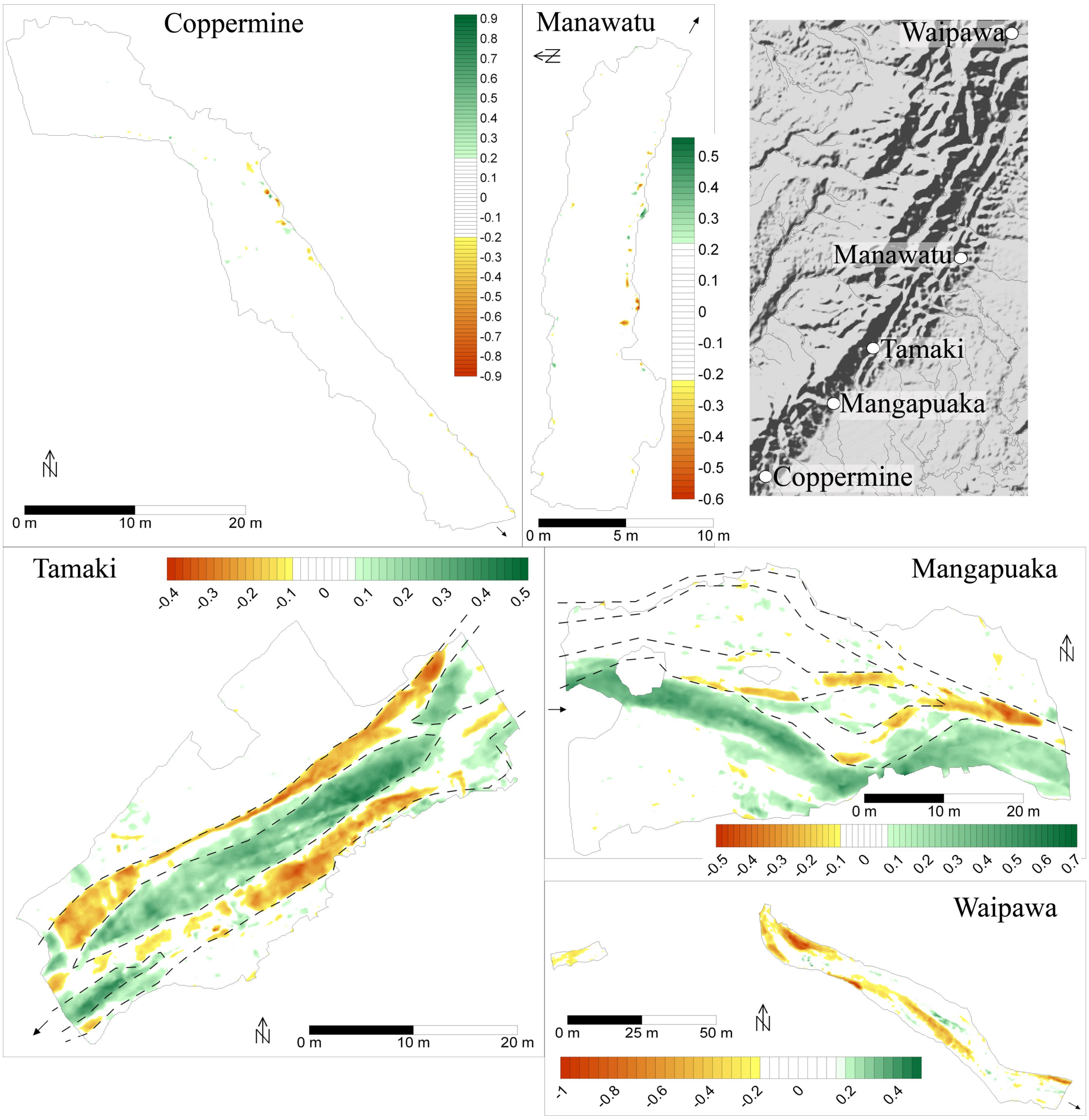

Figure 8. DEMs of topographic change (m) between January/ February and May 2008 of the reaches in the Ruahine Range with application of individual levels of detection, wetted channel zone at the more recent survey is outlined (broken line) and arrows indicate flow direction.

In contrast to the previous period the Te Piripiri experienced aggradation which affected nearly the entire baseflow channel (Fig. 9). The steep banks on the left of the upper part and the outside bend in the middle part of the reach were subject to some scour. The flow was relatively stable but flash floods can occur which lead to erosion of the scarcely vegetated banks of fine grained volcanic ash and provides the material for aggradation downstream. Again the Mangatoetoenui and Pukeonake sites experienced only few detectable topographic modifications. Especially for the Mangatoetoenui site this finding is surprising because more than 90% of tagged tracer stones moved during this period. It is reasonable to infer that the relatively high surface roughness which controls the level of detectable morphological change masks these sediment fluxes (see also at Kiriwhakapapa). In such a heterogeneous reach incorporation of the spatial variation in substrate composition into the level of detection might improve modelling of sediment budgets (Heritage *et al.*, 2009). However, this is beyond the scope of this paper. The Pukeonake reach cuts through lahar deposits and has a highly compacted bed, lined with allochthonous boulders. Its substrate can be characterised as very stable due to a strong embeddedness in a matrix of fine and coherent volcanic deposits. Additionally flow ceased at this site over short periods during summer resulting in ponds and puddles on the stream bed temporarily not connected by surface flow.

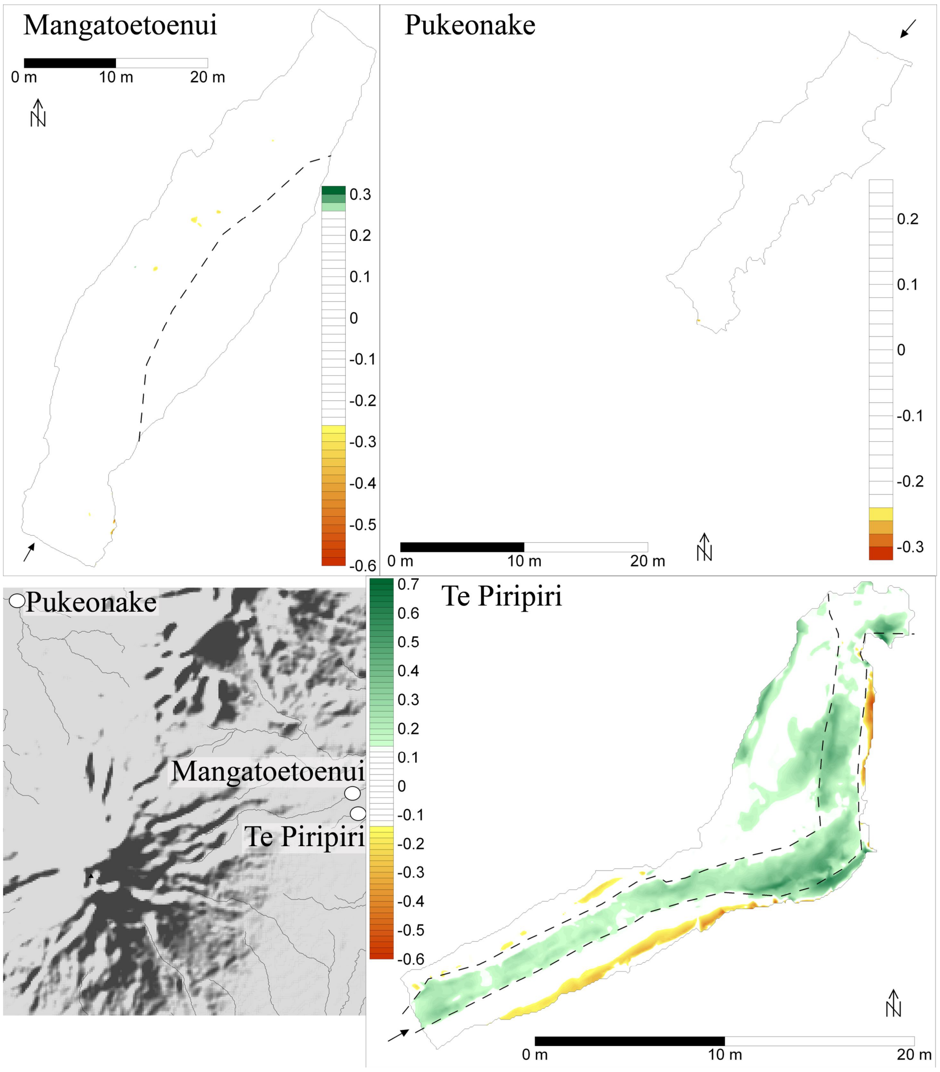

Figure 9. DEMs of topographic change (m) between January/ February and May 2008 of the reaches on the Central Volcanic Plateau with application of individual levels of detection, wetted channel zone at the more recent survey is outlined (broken line) and arrows indicate flow direction.

DISCUSSION AND CONCLUSIONS

Over both three month study periods, few sites showed any clear trends towards incision (e.g. Waipawa) or aggradation (e.g. Tamaki), which reflects the variability in flood characteristics and sediment supply within the region's upland headwater streams. Nevertheless, some groups of reaches with distinctive adjustment to floods can be identified over this timescale. There are highly active reaches which have high erosion rates in their steep catchments (e.g. up to 10 m^3 ha^{-1} a^{-1}) (Mosley, 1978a). Although most of these landslide derived sediments are momentarily stored in the upper catchment they provide an abundant long-term sediment supply (Grant, 1982; Dymond & Hicks, 1986). Some reaches respond dramatically by shifting channels even in smaller flood events (Mangapuaka and Tamaki) (c.f. Mosley, 1978b). However, the Waiotauru, Pukeatua, Ohau and Te Piripiri sites require larger floods to trigger channel changes which usually affect only parts of the bed. The Waipawa reach, which stands in between those groups in terms of channel stability, is less responsive to floods than Tamaki and Mangapuaka, probably because of the coarser substrate compared with streams of the first group. It maintains the position of its active channel relative to the floodplain, although considerable adjustments affecting the entire wetted channel occur. The stream beds of Manawatu, Coppermine and Kiriwhakapapa showed over the study period only local small scale response to floods in their laterally constrained channels, often associated with bank collapse (e.g. Mosley & Blakely, 1977). However, at some streams the latter might also be influenced by infrequent stock grazing on the banks, but even so they can be still classified as relative stable. It should also be noted that there can be considerable sediment flux within a reach (as measured with tracer stones), which is not necessarily expressed as morphological change (e.g. Kiriwhakapapa or Mangatoetoenui) because of scour-fill compensation. According to the calculated morphological change Mangatoetoenui and Pukeonake can be classified as very stable, although the question arises whether morphological budgeting without incorporating the spatial variance in error into the level of detection of genuine change is applicable for the former reach.

The different characteristics in sediment transfer between catchments are obvious, even when these catchments are located close to each other and experienced comparable flood events. Although no flow records were available from the study sites, hydrographs from further downstream exhibit parallel occurrence of major high-discharge events in neighbouring catchments (Fig. 3). Catchment scale parameters (Table 6) can explain the varying behaviour only partially. Average catchment slope is lowest on the Central

Volcanic Plateau where reaches are relatively stable. This is also apparent at the Ruahine sites which are probably most comparable due to their similar catchment characteristics, although slopes are generally higher there. Low bare ground and high tussock cover (Table 6) are typical for Pukeonake, but it is rather likely that the high bed stability there arises from the strong embeddedness of coarse substrate particles in a matrix of fine and coherent volcanic deposits. The Ruahine Range sites with high forest cover and less pasture (Table 6) are the least stable. An explanation would be that the steep catchments (e.g. 62% steeper than 30º at Waipawa) are less suitable for farming and the larger pasture land cover in the lower parts of the Manawatu and Coppermine catchments is a result of the availability of stable floodplain at these sites.

Table 6. Catchment characteristics of the study reaches derived from FWENZ database (Wild *et al.* 2005). Mean slope and land cover are runoff weighted within the catchment.

Site	Mean slope (degrees)	Bare ground (%)	Pasture (%)	Tussock (%)	Forest (%)	Catchment area (km^2)
Waipawa	30.4	10.0	1.0	9.0	77.0	15.1
Manawatu	23.2	0.0	33.0	0.0	66.0	5.2
Tamaki	27.8	0.0	0.0	0.0	99.0	14.8
Mangapuaka	28.8	0.0	0.1	0.0	99.0	6.5
Coppermine	23.1	0.0	16.0	0.0	82.0	4.5
Kiriwhakapapa	24.2	0.0	0.0	0.0	99.0	11.0
Waiotauru	28.1	0.6	1.0	3.0	94.0	244.0
Pukeatua	23.0	0.8	0.1	0.0	98.0	24.1
Ohau	28.5	0.2	0.2	0.9	98.0	84.6
Piripiri	5.5	48.0	0.0	51.0	0.0	13.6
Mangatoetoenui	13.8	84.0	0.0	13.0	1.9	62.6
Pukeonake	4.7	0.5	0.7	98.0	0.0	23.4

As to whether land use variables or slope can explain the differences in the Tararua Range, it is suggested that other factors such as connectivity and sediment supply (Fryirs *et al.*, 2007) are more important. Large landslips observed by the authors upstream of the Pukeatua, Waiotauru and Waipawa sites offer evidence to support this. These mass movements depend primarily on slope (Dymond *et al.*, 2006) and forest cover deterioration, which is in turn influenced by weather patterns, climate change, moisture stress and introduced mammals (Mosley, 1978a; Grant, 1989). However, well-developed downstream channel geometry relations found in some New Zealand headwater streams in similar geomorphic settings indicate that channel adjustment to discharge can be dominant despite substantial colluvial input (Wohl & Wilcox, 2005 and references therein).

This research indicates that reaches such as Tamaki and Mangapuaka could be considered as demonstrating responsive behaviour, adjusting form via sediment transfers accomplished by frequent and low magnitude flood events. These reaches are presumably primed for instability (*sensu* Brewer & Lewin, 1998) because availability of highly erodible substrate, frequent variation in local channel slope and frequent floods favour crosssing of intrinsic theresholds. In contrast, reaches where minimal change has been detected are best understood as being robust. Similar flood magnitudes and frequencies fail to result in detectable morphological change, and whilst sediment transport may still take place, it is not sufficient to register a morphological adjustment. The perception that mountain streams are generally characterised by instability is therefore inappropriate. As with any fluvial system, some systems will be primed for instability and exist close to thresholds of change (Brewer & Lewin, 1998) whilst others are far more robust (Werritty & Leys, 2001). Far more important to upland stream behaviour is likely to be the role of sediment supply from upstream reaches and slopes (Harvey, 1991), which in turn reflects the connectivity characteristics of the discrete system (Harvey, 2001). Strongly coupled systems which feed sediment efficiently from slope to channel and then from reach to reach (e.g. Hooke, 2003; Fuller & Marden, 2008) are much more likely to behave responsively to discrete and subtle flow events. This suggests that the catchments demonstrating such responsive behaviour are likely to reflect higher degrees of intrinsic coupling within the fluvial system above the reach. Robust behaviour with minimal detectable morphological change reflects a less strongly coupled system, with fewer sediment inputs contributing to and working their way downstream. This is based on the premise that channel morphology and morphological change is strongly conditioned by bedload flux (Leopold, 1992). This topic of responsive and robust behaviour in association with catchment coupling characteristics demands further attention than is feasible in this paper and is subject of further work in progress (Chapter 3b).

This study documents the high degree of variability between short-term channel dynamics and sediment transfers within mountain streams in the lower North Island of New Zealand. It finds no evidence for any consistent region-wide response of these reaches to flood events. Future research needs to better quantify the causes behind variable reach-scale sediment transfers, especially in conjunction with catchment connectivity characteristics. However, it is feasible to suggest that differing degrees of catchment connectedness may underlie the high degree of variability in reach behaviour identified.

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Chapter 3b

Landscape connectivity in the eastern Ruahine Range

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ABSTRACT

This study investigates the causes for the high variability in short-term channel dynamics and stream bed stability in mountain stream reaches of the eastern Ruahine Range in New Zealand's North Island. Despite similar geographical and geological characteristics of the catchments upstream of these reaches the morphological response to flood events ranges from almost none to frequent migration of the channel in a wide active channel zone. This study shows that these dynamics are mainly driven by sediment supply from slopes and gullies and from in-channel storage in particular where areas recently affected by erosion are limited. In the Waipawa catchment 22% of the area, dominantly gullies, could potentially supply sediment to the studied reach whereas in the Tamaki and Mangapuaka catchments 3.7% and 1.9% of area was affected by erosion and coupled to the respective study reaches. In contrast in the Manawatu and Coppermine catchments this figure was less than 0.3%. Connectivity between slopes and channel is also an important especially in catchments where sediment supply is scarce. In contrast reach to reach connectivity appears to be mostly given with transport barriers such as large woody debris having only a relatively short-term modulating effect on coarse sediment conveyance.

INTRODUCTION

Landscape connectivity is the physical coupling of landforms (Bracken & Croke, 2007), e.g. allowing exchange of water, solid material or air. Within water catchments terrestrial water and sediment transport is usually unidirectional downslope. Coupling between sediment sources on slopes and stream channels and the geomorphic processes involved as well as propagation of material through the channel network is critical to the functioning of sediment cascades and sensitivity of the landscape to change (Fryirs *et al*., 2007; Harvey, 2001; Hooke, 2003). The impact of flood events on sediment transfer is conditioned the degree of coupling between geomorphic units, e.g. sediment transport is maximised in strongly connected systems (Hooke, 2003; Lopez-Tarazon *et al*., 2009) which renders theses systems responsive to flood events and environmental change (Harvey, 2001; Macklin *et al*., 2010). Landscape elements which operate as buffers and barriers (Fryirs *et al*., 2007) may modulate and amplify sediment conveyance and thus control responsiveness of a system via energy expenditure and structural resistance (Brunsden, 2001).

Schwendel, Fuller & Death (2010) investigated short-term channel dynamics in New Zealand mountain streams and found that the responsiveness of reaches in terms of morphological adjustment to floods varied substantially between catchments. This contrasts with the widespread opinion that the Ruahine streams are generally inherently unstable (Schumm, 1977). Schwendel *et al*. (2010) suggested that channel dynamics are connected to the fraction of steep slopes within the catchments (see also Dymond *et al*., 2006) where sediment sources may be located, however, they did not quantify the extent of erosion on slopes and in gullies or the conveyance of sediments within the catchment. This needs to be addressed to understand the mechanisms and temporal pattern of sediment transport (Schumm, 1977). Although the short-term causes for varying morphological responsiveness of some reaches to floods may lay in local substrate and hydraulic characteristics (Schwendel *et al*., 2010), the latter are connected to catchment processes on longer time-scales. It has been suggested that rainfall pattern and resulting frequency and magnitude of floods as well as steepness of slopes, faulting and bedrock structure are the main influences on increased levels of erosion and bedload transport in these catchments (Grant, 1983; Marden, 1977; Stephens, 1975). Earthquakes may also trigger mass movements (Stephens, 1975) but this seems to be a minor variable compared to geological, geomorphological and climatic factors (Grant, 1983). The deterioration of podocarp-beech forest due to climatic change (Elder, 1965) and browsing mammals is not seen as a primary reason for increased erosion (Grant, 1989) but the impact on regeneration of forest cover after landslides is recognised (Hubbard, 1978). Thus rainstorm frequency and magnitude may be responsible for the long-term temporal variability in erosion while differences in reach-scale channel dynamics between catchments are a function of processes within the catchment, e.g. exceeding threshold slopes and erosion of stored alluvium (Schumm, 1977), backgrounded by geological and tectonic settings. Thus this study investigates the connectivity of geomorphic units for coarse sediments transport within five catchments in the eastern Ruahine Ranges upstream of the study reaches examined by Schwendel *et al*. (2010). The sites in the Ruahine Ranges were chosen as an example for very contrasting channel behaviour between catchments with similar geographical, geological and tectonic settings. Consequently this study extends the investigation of channel dynamics by researching the longer-term causes for the observed contrasting short-term behaviour. The selected catchments were subject to intensive research in the 1970s and early 1980s due to increased aggradation in piedmont areas (e.g. Mosley, 1978a; Neall, 1981). Erosion in the headwaters was aggravated by deforestation of the valley throats after 1870 which resulted in retrograding incision upstream, scour of old in-channel deposits and slope failure induced by bank erosion (Blakely, 1977). Substantial widening of the active channel zone and aggradation has been observed in the Tamaki catchment (e.g. between 1910 and 1940; Hubbard, 1978) and elsewhere, in particular after rainstorms such as cyclone Alison 1975 (Grant, Hawkins & Christie, 1978). For instance, Stephens (1975) recorded a 120% increase in eroded slopes between 1946 and 1974 in two catchments in the southern Ruahines. Grant (1981a) identified historic and recent periods of erosion in the Ruahine Ranges whereby the most recent period was by the time of publication still continuing. It is unclear whether this phase has ended and only few studies have assessed how these catchments developed since the 1980s. Furthermore, the mechanisms of sediment transport and coupling between geomorphic units has been investigated at individual catchments (e.g. Fuller & Marden, 2008) but to date we are not aware of a study which quantifies landscape connectivity for coarse sediment transport in a larger geographical context within New Zealand. This study fills this gap and temporarily extends local studies of catchments in the eastern Ruahines. A detailed understanding of what triggers morphologically responsive or robust behaviour of stream reaches to floods is important for instance regarding the ecological implications of substrate instability, gravel mining and flood control.

SITES

This study examined the headwater catchments of the Coppermine Stream, Mangapuaka Stream, Tamaki River, Manawatu River and Waipawa River in the eastern Ruahine Ranges, in New Zealand's central North Island (Fig. 1). These five catchments were chosen because previous investigation (Schwendel *et al.*, 2010) found strong differences in channel dynamics and stream bed stability in reaches situated where the streams emerge from the ranges (Fig. 1). The catchments have similar geographical settings, e.g. south-east orientation and comparable size (Table 1), and land cover consists dominantly of native broadleaf-podocarp forest with the Manawatu catchment having the highest fraction of low-intensity pasture (10.7%). The prevailing geology is folded mesozoic greywacke and argillite of varying decomposition (Mosley, 1978b). Steep valley slopes are common which can, in combination with high weathering rates, result in frequent slips and land slides after rain events.

METHODS

Reach-scale sediment budgets

Three topographic surveys were conducted in a stream reach at the lowest point of each of the investigated catchments between October 2007 and May 2008 (Schwendel *et al.*, 2010). These surveys were undertaken using a differential GPS system (R8, Trimble Navigation Limited, Sunnyvale, USA) in RTK mode or an electronic total station (GTS 701, Topcon Corporation, Tokyo, Japan). From these datasets DEMs were interpolated using a triangulation algorithm with linear interpolation in Surfer 8.01 (Golden Software, Golden, USA) (Schwendel, Fuller & Death, in press). Subtraction of DEMs from successive surveys revealed patterns of scour and fill beyond a minimal level of genuine change detection. Methodology of survey, interpolation and error analysis are given in detail in (Schwendel *et al.*, 2010).

Catchment connectivity

Geomorphological information was elucidated from geo-rectified aerial orthophotography with a resolution of 0.75 m. Aerial photos of the upper Waipawa were taken in summer 2008/09 while the other catchments were captured in January 2005. The aerial extent of recent (e.g. up to approximately 10 years old) erosional and depositional features such as slips and fans as well as recently reworked alluvial surfaces have been mapped in Arc Map 9.2 GIS (ESRI Software, Redlands, USA). The erosional features were classified according to age (active or not at the time of photograph) and state of coupling to the active channel zone. These classifications were verified during terrestrial surveys in October 2010 during which geomorphic landforms impeding reach to reach connectivity and slope-channel coupling were also investigated.

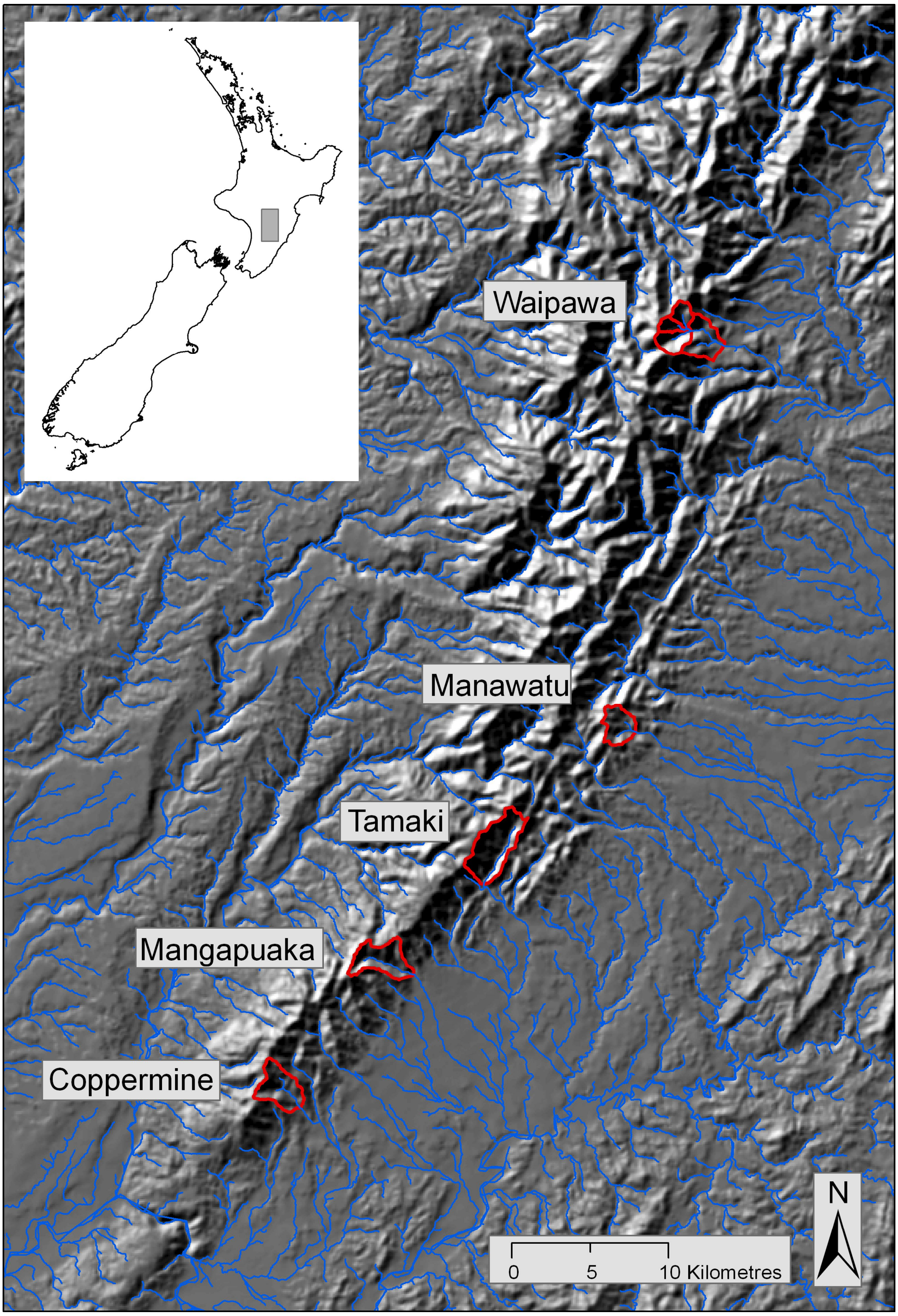

Figure 1. Studied catchments in the Ruahine Range, North Island, New Zealand.

Table 1. Areas affected by erosion and reworked channel area (in 10^3 m^2) and fraction of total catchment area (% in brackets) in the study catchments in the eastern Ruahine Ranges.

	Waipawa				**Mana-watu**	**Tamaki**	**Manga-puaka**	**Copper-mine**
	Upper	**N-Branch**	**Centre Branch**	**S-Branch**				
Catchment area	5316*	1614	1143	2560	3883	9337	6207	5885
Erosion area	1361 (25.6)	382 (23.6)	389 (34.1)	590 (23.0)	39 (1.0)	187 (2.0)	70 (1.1)	12 (0.2)
Disconnected	246 (4.6)	78 (4.9)	3 (0.3)	164 (6.4)	27 (0.7)	27 (0.3)	2 (0.0)	1 (0.0)
Coupled and connected	1114 (21.0)	303 (18.8)	386 (33.8)	425 (16.6)	11 (0.3)	159 (1.7)	68 (1.1)	11 (0.2)
Reworked channel area	75 (1.4)	3 (0.2)	31 (2.7)	41 (1.6)	0 (0.0)	191 (2.0)	49 (0.8)	0 (0.0)
Total sediment supply area	1190 (22.4)	306 (19.0)	417 (36.5)	466 (18.2)	11 (0.3)	350 (3.7)	117 (1.9)	11 (0.2)

*The area of the entire catchment upstream of the study reach is 10.0 km^2

RESULTS AND DISCUSSION

Short-term relative area and volume of change between Spring 2007 and Autumn 2008 were greatest at the Tamaki and Mangapuaka reaches and not much smaller at Waipawa (Table 2). In contrast this figure was at least an order of magnitude smaller at Manawatu and Coppermine. The balance between scour and fill varied with erosion prevailing at Waipawa, Manawatu and Coppermine while the Tamaki reach was predominantly aggrading.

Manawatu and Coppermine

The Manawatu and Coppermine reaches showed only locally small patches of scour or fill (Fig. 2B, C and 3B, C) and thus relative stability. Most parts of the Manawatu and Coppermine channels were armoured and although floods occurred in these periods (Fig. 4A and D) did not cause identifiable morphological change.

The Coppermine catchment comprises only 0.2% eroded area 89% of which was coupled to the main channel and the study reach (Table 1, Fig. 5). The slips were mainly isolated and ephemeral features (Fig. 3A). Since 2005 more shallow slides or slumps have occurred but the coupling of coarse material to the channel was limited. There was no reworked dry substrate identifiable from aerial photos.

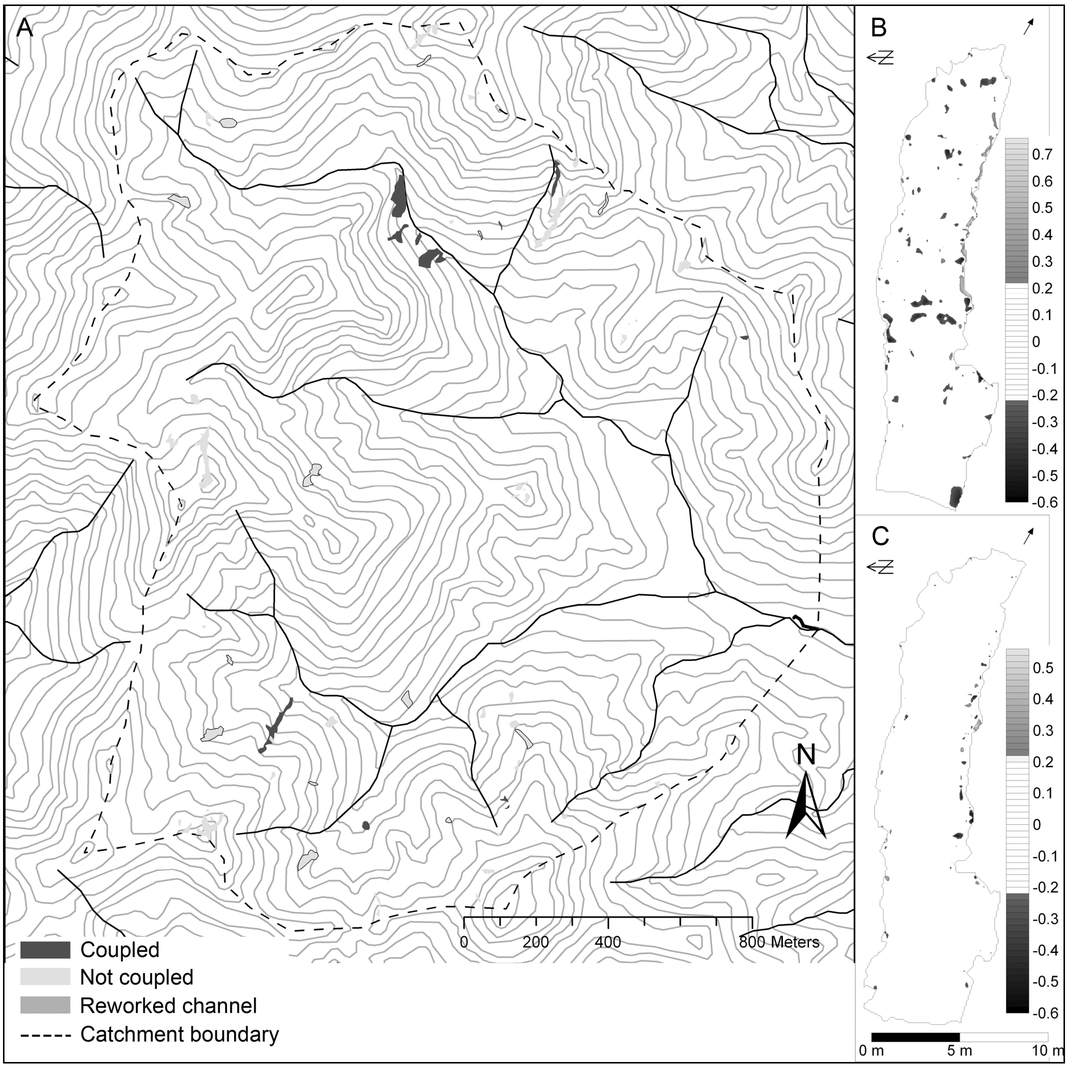

Figure 2. Areas of recent erosion and reworked channel within the Manawatu River catchment upstream of the study reach (A) and scour and fill (in m) at the study reach between October 2007 and January 2008 (B) and between January and May 2008 (C).

The upper Manawatu catchment is characterised by a mixture of scrub and grassland on the ridges and native bush on the valley slopes. The patches of erosion visible on the aerial photo are mostly on the ridges and disconnected from the channels (Fig. 2A). These erosion scars may date to previous landslide activity caused by deforestation and stock trampling, but their disconnection from the channels means that they have little or no influence on coarse sediment transport and channel dynamics. The largest recent, coherent slip connected to the channel was in the northern branch but was not active in 2005. Only 1% of the area or 38874 m^2 (Table 1) were subject to erosion in 2005 and only 30% of this was coupled to the channel (Fig. 5). As a result the single thread channel was armoured and the active channel zone was not much wider than the wet stream width.

Table 2. Volume and area of geomorphic change relative to the planar DEM area between October/ November 2007 and January/ February 2008 and between January/ February 2008 and May 2008 (bold).

	Volume				Area		
Site	**Fill (10^{-3} m^3 m^{-2})**	**Scour (10^{-3} m^3 m^{-2})**	**Net (10^{-3} m^3 m^{-2})**	**Total change (10^{-3} m^3 m^{-2})**	**Fill (%)**	**Scour (%)**	**Total change (%)**
Waipawa	15.529	31.114	-15.585	46.643	11.4	18.9	30.3
	1.469	**42.794**	**-41.325**	**44.264**	**3.3**	**23.7**	**27.0**
Manawatu	1.930	3.035	-1.105	4.965	1.3	3.9	5.2
	0.295	**0.625**	**-0.330**	**0.920**	**0.4**	**0.6**	**1.0**
Tamaki	54.202	15.025	39.177	69.228	32.3	13.7	46.0
	32.510	**14.568**	**17.943**	**47.078**	**27.6**	**17.1**	**44.7**
Mangapuaka	25.301	38.828	-13.526	64.129	22.8	23.5	46.3
	41.328	**5.068**	**36.260**	**46.395**	**25.1**	**5.8**	**30.9**
Coppermine	0.372	0.420	-0.048	0.793	0.7	0.6	1.3
	0.203	**0.513**	**-0.310**	**0.715**	**0.3**	**0.6**	**0.9**

At Coppermine Stream and Manawatu River coarse sediment supply from slopes to the wet channel was very low. Despite some substantial mass movements recently and in the past such as the Coppermine landslide 1976, these isolated events do not produce abundant coarse material (e.g. Mosley & Blakely (1977) reported a D_{50} of 19 mm at the Coppermine landslide 1976 compared to a D_{50} of 65 mm at the study reach (Schwendel *et al.*, 2010)) to have an measurable effect on reaches that are located at the trunk valley throat (Mosley & Blakely, 1977).

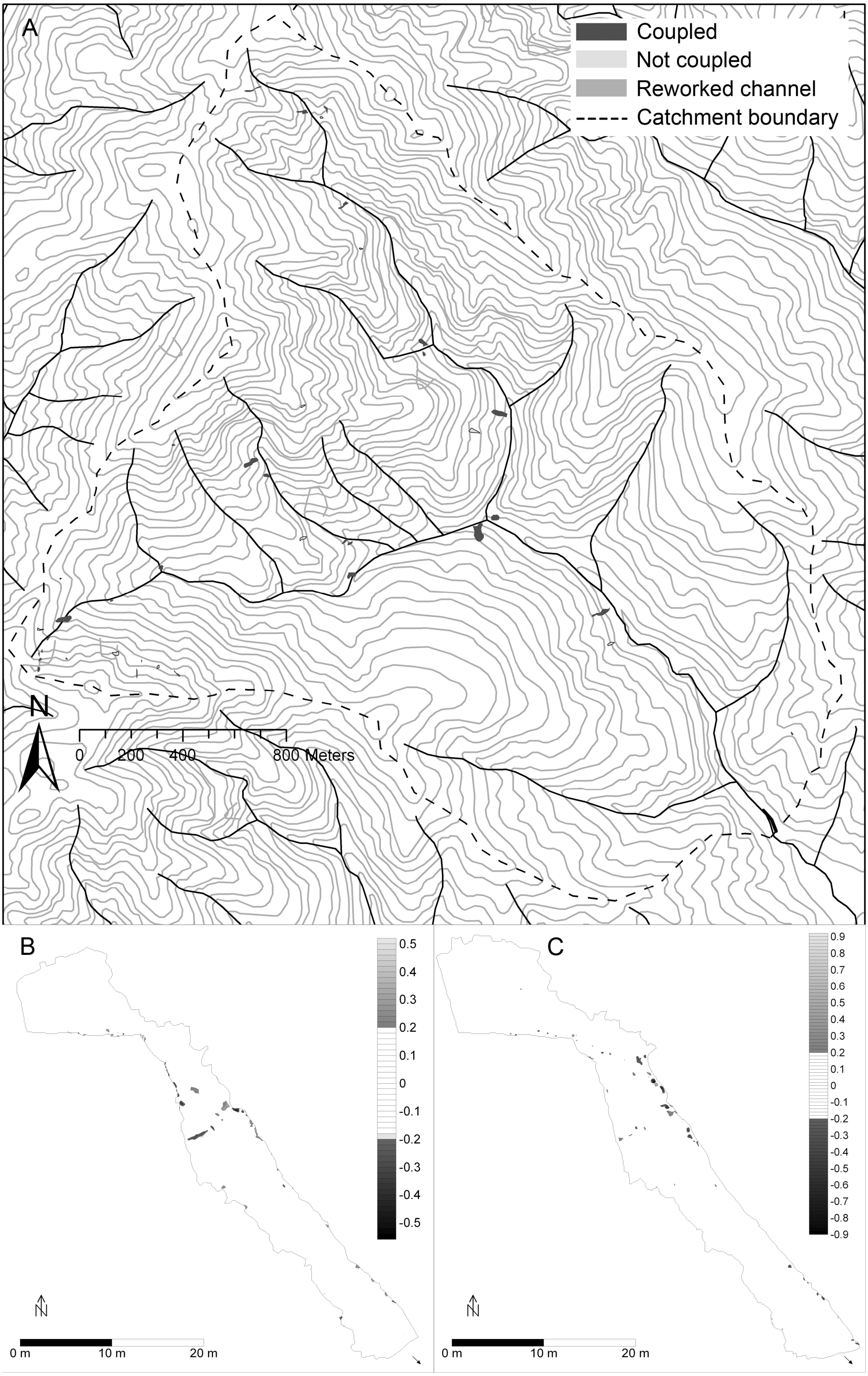

Figure 3. Areas of recent erosion and reworked channel within the Coppermine Stream catchment upstream of the study reach (A) and scour and fill (in m) at the study reach between November 2007 and February 2008 (B) and between February and May 2008 (C).

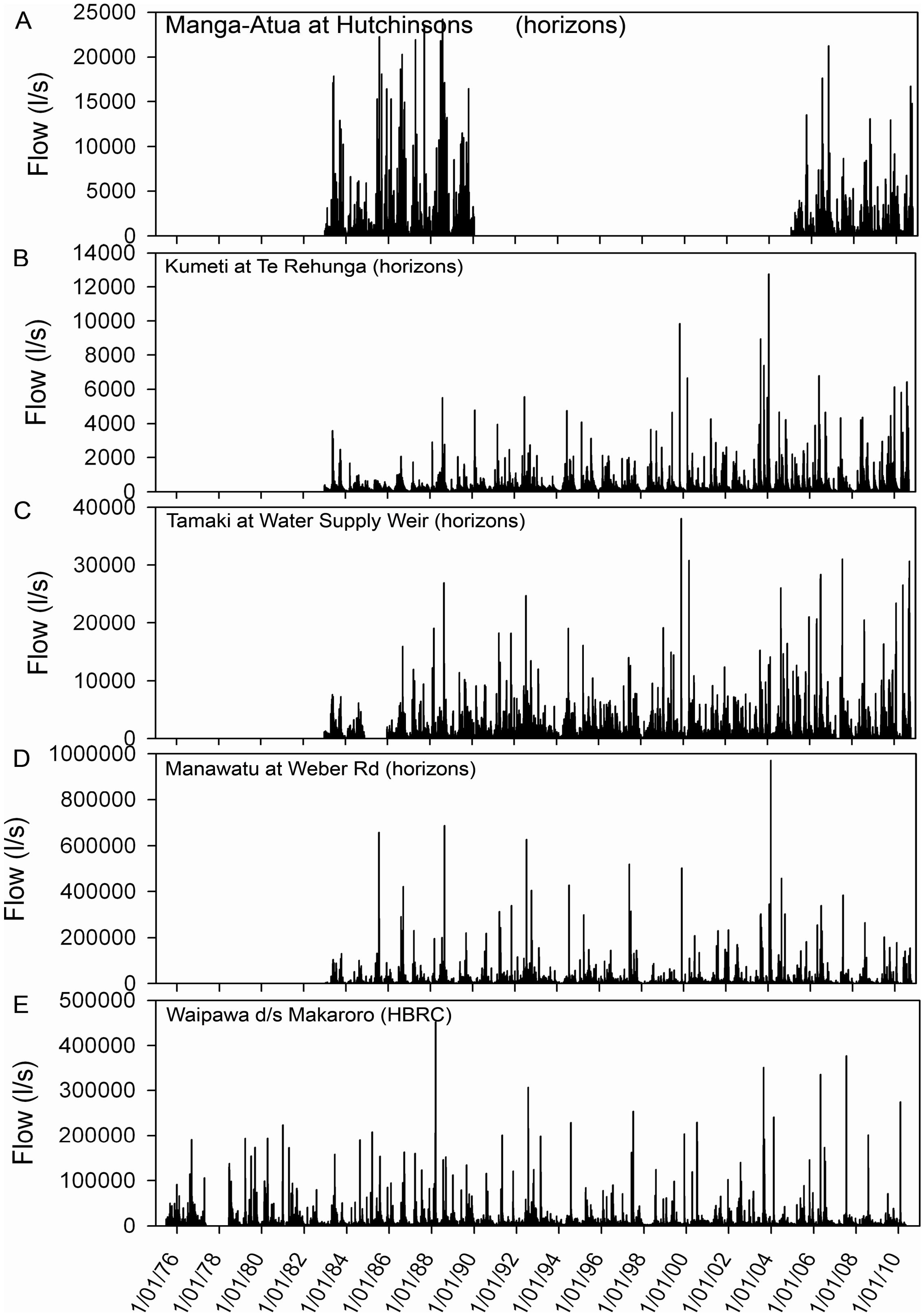

Figure 4. Flow hydrographs from gauges downstream of the study reaches Coppermine (A), Mangapuaka (B), Tamaki (C), Manawatu (D) and Waipawa (E). Flow data were provided by Horizons and Hawke's Bay Regional Councils.

Mangapuaka and Tamaki

In contrast at the other sites significant changes in channel alignment and geometry occurred and in the catchments a larger area is subject to erosion (Table 1). At the Tamaki and Mangapuaka reaches substrate size was much smaller than at the other sites and surface armouring was rare.

The multichannel Mangapuaka reach showed a complex pattern of change suggesting several phases of development (Fig. 6B). Here, the channel incised in the first period, followed by part infilling of previous channels (true right) in the second period (Fig. 6C). On the southern side of the active channel zone dense willow growth prevented surveying. Changes in absolute surface elevation were up to 0.7 m. The gravel retention structures downstream of the reach which were built in the 1950s (Blakely, 1977) are buried.

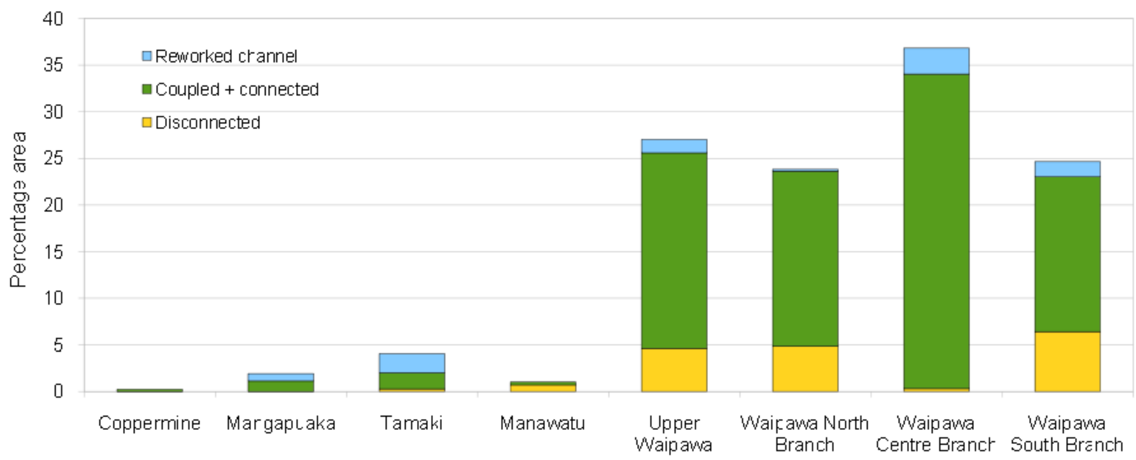

Figure 5. Percentage of catchment area subject to erosion or reworking connected and coupled or disconnected from the study reach at five mountain stream catchments in the eastern Ruahine Range.

At Mangapuaka 1.9% of the catchment area is identified as actively eroding (Table 1). This figure comprises 41% reworked channel area, 57% gullies and slopes connected to the main channel and only 2% disconnected erosion areas (Fig. 5). The main sediment sources are in a major true-left tributary approximately 1.5 km upstream of the study reach (Fig. 6A). Although its catchment area is approximately 3 times smaller than the main stem it is clearly responsible for the majority of the sediment supply to the main channel below the confluence, since the active channel dramatically widens from this junction, willows become restricted to the valley floor margins and the channel is often multi-threaded. The channel of this northern tributary was not incised in 2010 and appears to have been regularly reworked since 2005, actively transferring sediments. In contrast the main channel upstream of the confluence narrows significantly, was tightly encroached by willows and contained coarser substrate. It may still transport finer material form sources upstream but morphological activity is low. The sources of sediment are almost entirely coupled to the channel and evenly distributed throughout the catchment. However, at least since 2005, most coarse material that reached the main trunk channel was delivered from a single tributary. In contrast to many tributaries of the Tamaki River this channel has not incised and appears to transport regularly coarse sediments to the trunk channel, mainly as debris torrents during spates when transport capacity is sufficient.

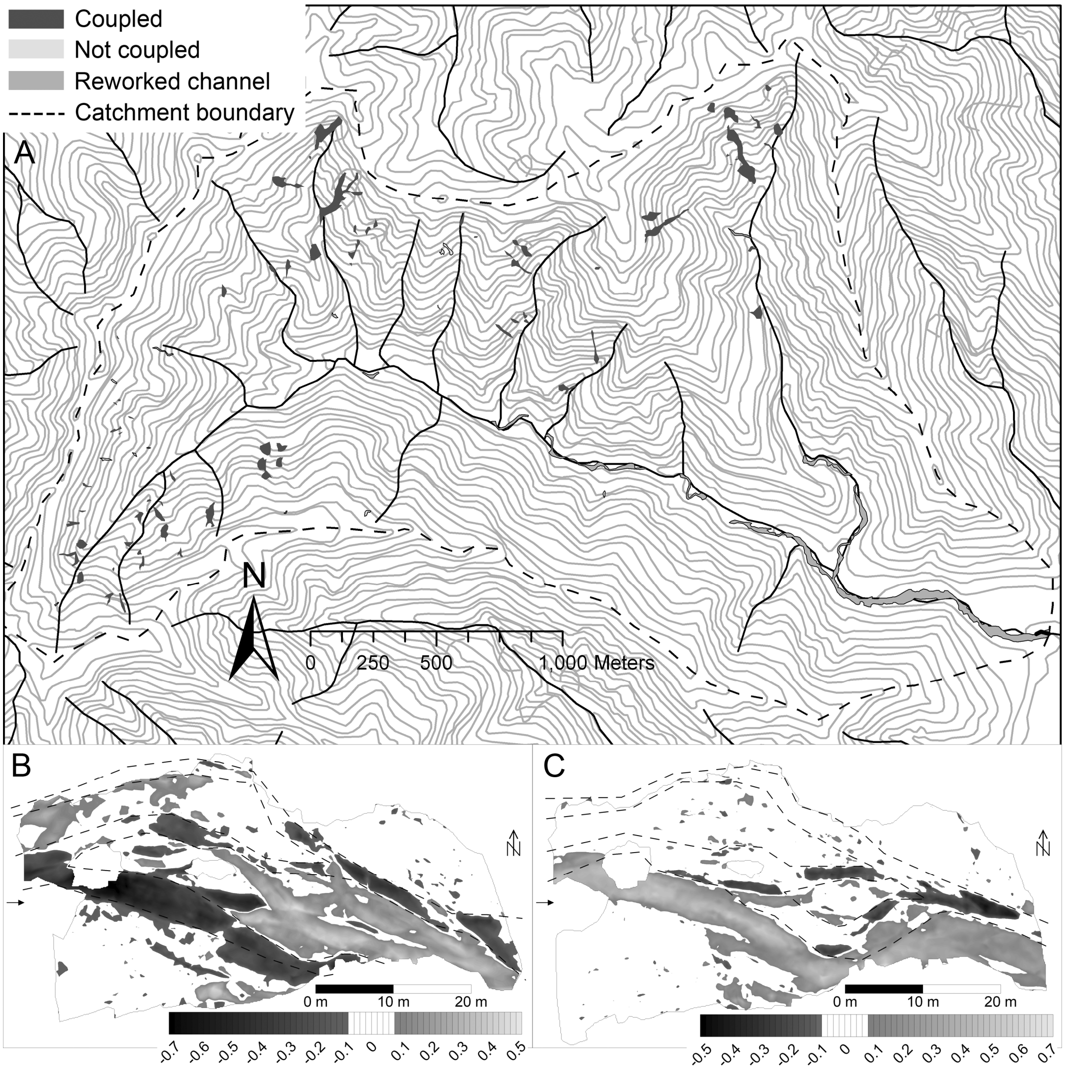

Figure 6. Areas of recent erosion and reworked channel within the Mangapuaka Stream catchment upstream of the study reach (A) and scour and fill (in m) at the study reach between November 2007 and January 2008 (B) and between January and May 2008 (C).

The channel of the Tamaki study reach was highly dynamic, first shifting to the true right and later considerably widening with lateral erosion and development of a mid channel bar (Fig. 7B and C). The active channel zone was constrained by willows which might have prevented fundamental channel migration.

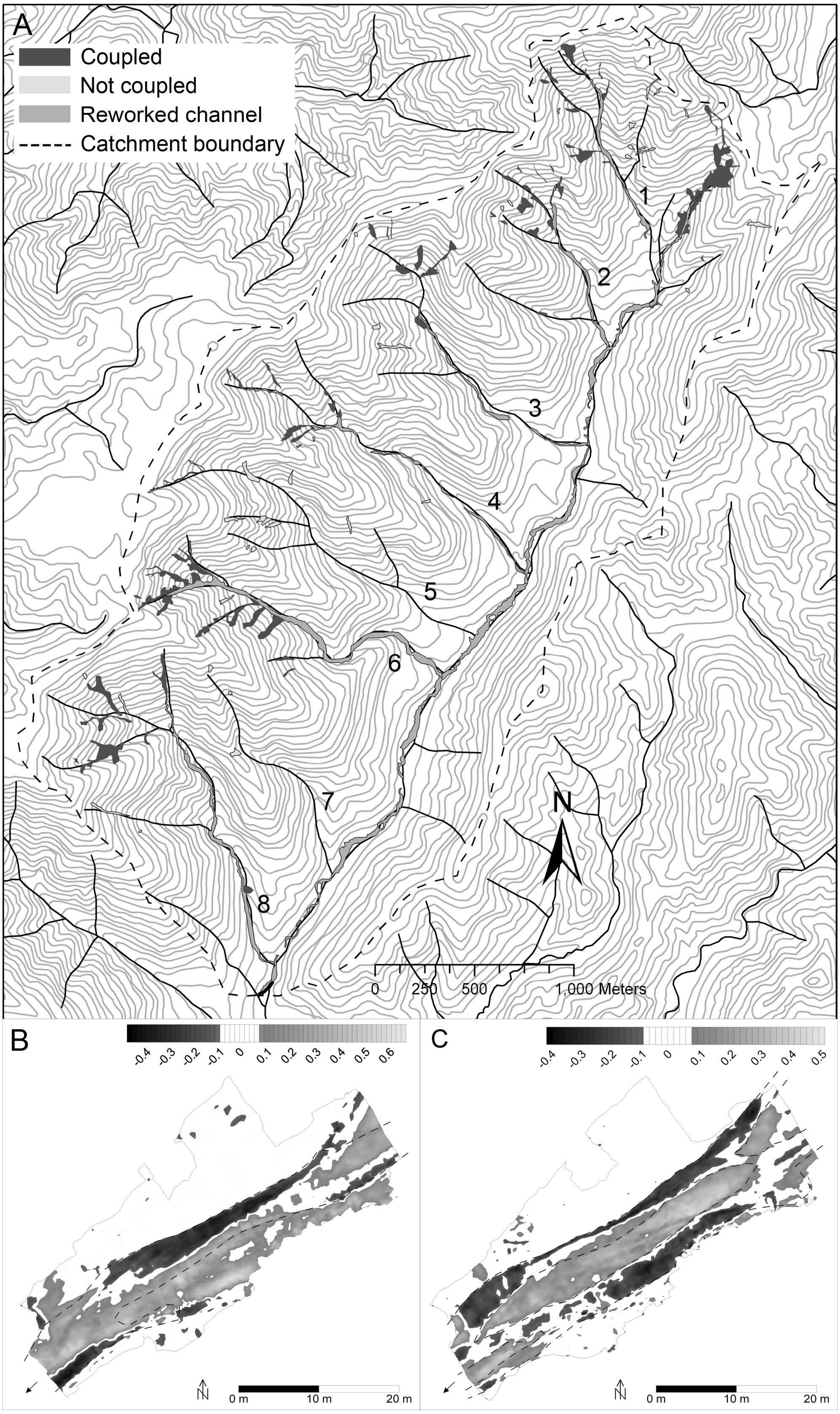

Figure 7. Areas of recent erosion and reworked channel within the Tamaki River catchment upstream of the study reach (A) and scour and fill (in m) at the study reach between November 2007 and January 2008 (B) and between January and May 2008 (C). True-right tributaries are numbered.

The Tamaki catchment consisted in 2005 of 186616 m^2 (2.0%) of eroded area 85% of which was connected to the main channel (Table 1). The area affected by erosion has decreased since 1974 (495000 m^2) to almost the level measured in 1946 (174000 m^2) (Stephens, 1977). The main sources of sediment were situated in the true right tributaries and the headwaters of the main stem (Fig. 7A). The latter sub-catchment is characterised by substantial gully erosion and unstable slopes regularly delivering large amounts of debris and large woody debris to the channel. Tree trunks and boulders constitute temporary barriers for sediment transport in the narrow valley but over longer timescales sediment input appeared to be continuous. The second true right tributary was in 2005 strongly connected to the main stream. Cut banks of up to 6 m height at the confluence and slips in the headwaters give evidence of previous accumulation of debris layers (sheet deposits), probably during the 2004 flood, given the age of vegetation growing on this upper surface. Since then incision dominated and in 2010 the bed was armoured and the gravel banks were partly vegetated. An older and higher fan surface of this tributary to the north of the current confluence has been deposited around 1880 (Grant, 1981b). At the first and third tributaries the situation is similar although the old channel fill is not as deep and sediment supply less substantial. The fourth tributary to the right conveyed sediment mainly sourced from the headwater gullies to the main channel, in particular fine material. In contrast the fifth tributary showed to sign of recent (within the last 10 years) connectivity although sediment deposits of up to 2 m height from earlier more morphologically active phases are present. This sub-catchment contains also only a few, small, active slips. The sixth tributary had a very steep catchment dominated by gully erosion. Debris torrents produced substantially amounts of sediment that were actively conveyed to the main channel. The seventh tributary showed no evidence of recent sediment conveyance to the main channel while the eighth generated an alluvial gravel fan indicating strong connectivity between the substantially eroded areas in the headwaters and the tributary although the fan acts as a buffer to the main stem. Since 1946 erosion in this sub-catchment was always high ranging between 3.4% (1946) to 5.6% area (1974) (Hubbard, 1978). A considerable amount of the finer substrate material deposited and reworked in the study reach appeared to be sourced from this tributary. The tributaries to the true left played only a minor role in sediment production and were not well connected to the main channel (Fig. 7A). The channel itself migrated within a wide active zone which was frequently reworked and constituted 2.0% (191000 m^2) of the catchment area (Table 1). Thus it more than doubled the area potentially supplying sediment to the study reach. This figure declined from 455000 m^2 in 1974 but was higher than in 1946 (135000 m^2) (Stephens, 1977). Multi-thread planform was common and reach to reach connectivity implied, given there are no obvious long-term barriers to downstream conveyance of material, although willow and poplar plantings in the lower valley have probably increased sediment storage and limited channel migration.

In the Tamaki catchment the situation is similar to Mangapuaka although zones of erosion are here mostly confined to the headwater gullies and steep convex creep slopes below the summit plateau. Although the extent of erosion was higher the 1970s the mechanisms and location of erosional features has not much changed and it has been suggested that erosion occurs repeatedly at the same sites (e.g. reactivation of old slips) (Hubbard, 1978). These deliver sediment periodically, triggered by rainstorms and, potentially, by seismic events. The Ruahine fault zone borders the catchment to the west and the main valley follows the Mohaka fault zone (Marden, 1977). Between those numerous splinter faults cause crush zones with high susceptibility for erosion (e.g. fourth and sixth right tributary). In both, the Mangapuaka and Tamaki catchments in-channel storage and reworking of this material with strong reach-reach connectivity is probably a significant sediment source for the respective study reaches on the main stem channel. The few observed barriers to sediment transport along the main stem appeared to be only of temporary nature, having a modulating effect on sediment supply to the study reach.

Waipawa

At the Waipawa reach the principal position of the channel was maintained, although over longer periods (e.g. 2008 to 2010) it migrated within the wider active channel zone. However, in between all surveys channel margins and point bars experienced some scour while, especially in the lower part, channel morphology was highly dynamic with alternating deposition and erosion of longitudinal bars and an overall widening and straightening of the channel (Fig. 8B and C). Nevertheless, some sections of the channel bottom were armoured and relatively stable within the reach during the survey period. Historically this reach experienced substantial widening (e.g. 43 m in active channel width between 1950 and1975) and aggradation (e.g. 1.1 m in mean bed level between 1960 and 1975) since the 1930s (Grant, 1977).

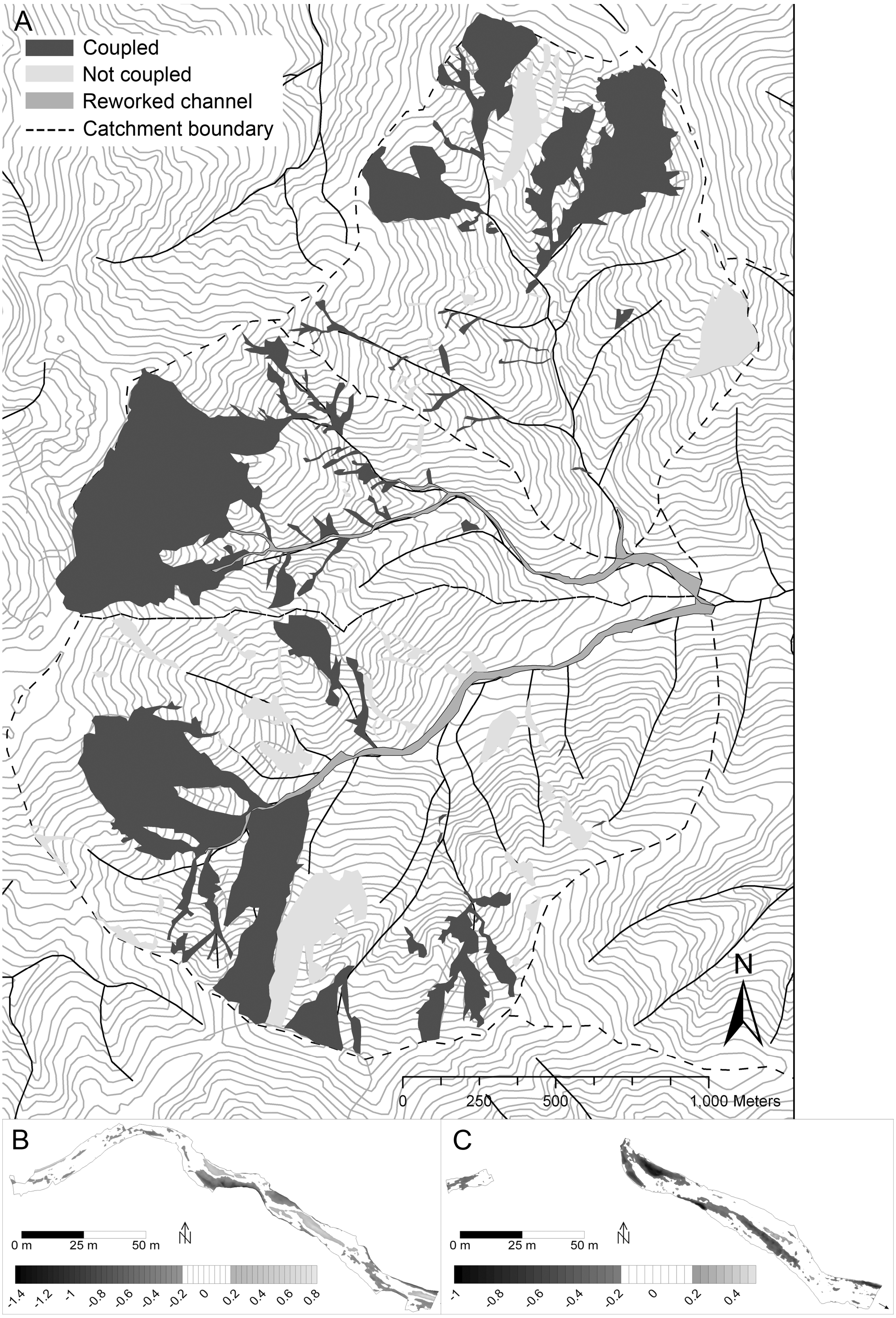

Figure 8. Areas of recent erosion and reworked channel within the Waipawa River catchment upstream of Waipawa Forks (A) and scour and fill (in m) at the study reach between October 2007 and January 2008 (B) and between January and May 2008 (C).

The Waipawa catchment was divided into four sub-catchments: South Branch, Centre Branch, North Branch and the lower part of the investigated catchment (Fig.

8A), following Grant's (1982) description. For the latter sub-catchment no detailed aerial photography was available, however lower resolution imagery and field reconnaissance showed that there were no major sediment sources connected to the channel and that sediment conveyance was unimpeded in the main channel, even in the gorge sections (Fig. 9). A single-thread channel planform prevailed, although branching occurred occasionally.

The South Branch drains the largest of the three upper sub-catchments where landslides and gully erosion occupied 23% of the planimetric catchment area (Fig. 5). Of this fraction 72% or 425220 m^2 (Table 1) were coupled to the South Branch channel. In particular the true left headwater gullies and slopes were highly active and constantly supplying gravel- to boulder-sized sediment to the system. Although substantial erosion occurred in their headwaters, two true-right tributaries were disconnected, in one case by a spectacular waterfall. At the time of investigation the main channel of the South Branch consisted of mainly boulders and was armoured, but the active channel zone contained plenty of finer sediment that appeared to be frequently reworked during floods (1.6% of sub-catchment area).

The Centre Branch has the smallest area of the three upper sub-catchments. It consisted of 34.1% eroded area of which 99% was connected to the channel (Fig. 5). The entire east-facing slopes of Teatuaparapara can be described as a big gully complex which had in some parts a thin vegetation cover but sufficiently frequent erosion appears to prevent stabilisation and establishment of higher vegetation. The channel course lacked any barriers or buffers that would impede sediment transport. It contained huge boulders and tree trunks and appeared to change course frequently. At the confluence between North and Centre Branch the latter tributary was morphologically more active with a wider active channel zone and a higher sediment load. Cut-banks made up of unconsolidated gravel-size sediments were up to 6 m high and interspersed with boulders and large woody debris. Thus the area of active reworked channel was 2.7% of the entire sub-catchment (Table 1).

Figure 9. Gorge section of the Waipawa showing both storage and conveyance of finer alluvium. Recent activity has filled the valley floor which the stream is currently reworking and incising (note the presence of fresh, unvegetated terraces and coarse lag in the current wetted channel where finer material has been flushed, consistent with Grant's (1982) observations in the upper catchment). Photo: ICF 2nd October 2010.

In contrast the North Branch gives the appearance of being less connected to the main channel, at least under normal flow conditions. The valley floor upstream of the confluence with the Centre Branch was rather narrow with only small reworked areas outside the wet channel (0.2% of sub-catchment) (Fig. 8A). The latter was strongly armoured. In the headwaters of this sub-catchment, however, sediment supply was plentiful (23.6% area) and the majority of these gullies and slips were connected to the channel (79%) (Fig. 5). In particular the Armstrong tributary was characterised by intensive gully erosion in combination with shallow debris slides which in some parts reached up to the ridge. The substrate was fine greywacke fragments and soil particles originated from volcanic ash deposits on top of the surrounding ranges (Grant, 1977). The boulder, armoured nature of North Branch suggests that the fine material supplied from the Armstrong tributary is rapidly flushed through this steep upper section of channel during storms, which both convey the fine scree from the gully source and flush it through the upper reach.

The situation encountered in the Waipawa catchment stands out because of the vast area subject to erosion which has decreased by 7% and 38% in North Branch and Upper Waipawa respectively since the impacts of cyclone Alison in 1975 (Grant, 1982) (0.409 km^2 in North Branch, 1.81 km^2 in Upper Waipawa, c.f. Fig. 5). Gully erosion is dominant in the upper catchment. Coarse sediment supply from the North Branch is buffered under normal flow conditions while fine material originating from the eroded regolith is rapidly flushed through as suspended load leaving a boulder lag in the channel. Coarser sediments are stored in reaches with lower hydraulic energy gradient, e.g. upstream of the confluence with the Centre Branch where sediment deposits from the latter lead to additional choking of the North Branch (Grant, 1982). Grant (1982) identified a flood stage of 12.4 m at Fletcher's Crossing as a lower threshold to enable coarse sediment to be transported from the North Branch into the main channel. Flood events of this magnitude have occurred approximately 20 times since 1975 (Fig. 4E) and since the other two upper sub-catchments are well connected to the study reach there has been substantial sediment supplied to contribute to the rapidly changing main stem study site. High rates of sediment supply and throughput are reflected in the dynamics of this reach. However, it is likely that finer bedload is transported beyond the study reach which corresponds with the observation of armoured stream beds in parts of the catchment. Thus larger flood events than at Tamaki or Mangapuaka may be necessary to lead to the observed responsive channel behaviour at the Waipawa study reach. It is reasonable to infer that coarse bedload transport is limited by transport capacity rather than sediment supply (Grant, 1983). Although some sediment sources have not been coupled to the channel in the last 10 years and some tributaries are disconnected from the trunk channel the large amount of sediment supplied from other parts of the system, including reworked channel areas, provide a plentiful source of sediment over the long term. However, conveyance speed of material from single sources through the catchments has not yet been established and thus it is difficult to determine which source of sediment and which transport pathway leads to observed sediment budgets in a particular reach.

CONCLUSIONS

The high variability in reach-scale morphodynamics at New Zealand mountain streams (Schwendel *et al.*, 2010) appears to be mainly driven by differences in sediment supply rate and controlled by coupling of sediment sources on slopes and gullies to channels. Reach to reach connectivity can be limiting in small headwaters, but at a catchment-scale it has a rather modulating effect on sediment conveyance to the studied reaches. The five studied catchments showed a high variation in relative aerial extent of sediment sources connected to the study reaches which were situated at the lower end of these catchments (Fig. 5). Areas of erosion appear to remain the same over time, e. g. rather reactivation of older supply areas than erosion of previously vegetated areas, although their extent has to a varying degree decreased since the 1970s. Catchments strongly and frequently affected by erosion such as Waipawa or some East Cape catchments (Fuller & Marden, 2008) are primed for research in transport mechanisms and controls as well as assessment of sources and storage areas within the catchment. Hence future research should focus on sediment tracing and routing through these catchments to connect erosion and transport processes with local channel morphologies.

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Chapter 4

Linking disturbance and stream invertebrate communities – how best to measure bed stability

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ABSTRACT

Substrate stability is a key determinant of stream invertebrate community composition, however its measurement can be problematic. Consequently stream ecologists often use different approaches and techniques to quantify bed stability making comparison between studies difficult. This study examines the link between six reach-scale measures of substrate stability and invertebrate community metrics in 12 New Zealand mountain streams.

The strength of the link between different metrics of community composition and bed stability varied with the employed method to define the latter. Using morphological budgeting to measure spatial patterns and volumes of scour and fill we found that as erosion of sediments increases, invertebrate diversity declines exponentially. In particular, increases in the volume of scour reduced taxa richness, while pure deposition of coarse sediments was less relevant for invertebrate communities. Overall the distance travelled by *in situ* marked tracer stones had the strongest link with all invertebrate community metrics while the bottom component of the Pfankuch Index related very well to diversity. Both showed near linear declines in diversity with decreasing stability. In contrast the link between invertebrate communities and the proportion of bed area affected by entrainment was weak.

Consequently, tracer-based indices and the Pfankuch bottom component are proposed as the most suitable measures for research involving invertebrate substrate stability relationships. Measures derived from *in situ* marked tracer stones reflect only entrainment and transport of particles. In contrast the bottom component of the Pfankuch Index encompasses the widest range of bed stability characteristics but is prone to observer-bias. An objective method that combines the efficiency of the Pfankuch Index with the characteristics measured using tracer stones could serve as a powerful explanatory tool in stream ecology.

INTRODUCTION

Lotic ecosystems can be strongly influenced by floods (Resh *et al.*, 1988; Reice, Wissmar & Naiman, 1990; Lake 2000, Death 2008). High discharges can result in coarse substrate movement, which is a potential source of physical disturbance for periphyton (Biggs, Smith & Duncan, 1999), invertebrate (Cobb, Galloway & Flannagan, 1992; Death & Winterbourn, 1995; Holomuzki & Biggs, 2000) and bryophyte communities (Suren & Duncan, 1999). Many diversity-disturbance models predict low diversity at severely disturbed sites. At intermediate levels of disturbance diversity might peak (Grime, 1973; Connell, 1978), but most studies of lotic ecosystems do not support this hypothesis (Vinson & Hawkins, 1998; Death, 2008). Inclusion of habitat productivity, for example shifting the intermediate disturbance peak relative to productivity, may improve the fit of physical disturbance-diversity models for lotic environments (Huston, 1979; Hildrew & Townsend, 1987; Death, 2002). Substrate movement causes habitat alteration and can lead to displacement and death of stream invertebrates as well as to changes in their food sources. Thus it is widely recognised that bed stability has a significant effect on the composition of benthic stream invertebrate communities (e.g. Townsend, Scarsbrook & Doledec, 1997b; Matthaei & Townsend, 2000; Effenberger *et al.*, 2006; Death, 2008). We are thus starting from the premise that stream bed stability affects invertebrate community composition and we are investigating how best to measure the relevant aspects of bed stability.

Bed stability can be characterised by entrainment, transport and deposition of particles at different scales (Schwendel, Death & Fuller, 2010a). Most techniques however only assess a limited subset of these aspects. The entrainment of coarse particles is difficult to assess because particles may be imbricated, sheltered by other particles or have varying properties (e.g. shape or density) (Richards, 1990; Gomez, 1991). Furthermore, the hydraulic conditions that determine entrainment, such as relative depth or the available flow energy, are highly variable within a reach. Substrate entrainment is usually calculated using various modifications of the Shields equation (e.g. Komar, 1989). Direct measurements of the force necessary to move particles with a spring balance (Downes, Glaister & Lake, 1997) can account for substrate assemblage and particle properties but are very labour-intensive for reach-wide application.

Areas of the stream bed where erosion and deposition occur have been identified by stream ecologists using scour chains (Palmer, Bely & Berg, 1992; Matthaei, Peacock & Townsend, 1999a; Matthaei, Guggelberger & Huber, 2003; Effenberger *et al.* 2006). However, tacheometric or GPS-based channel surveys, combined with morphological budgeting, can provide high resolution surveys of an entire reach and allow the calculation of volumetric budgets (Lane, Chandler & Richards, 1994; Brasington, Rumsby & McVey, 2000). Real-Time Kinematic differential GPS systems permit surveying of up to 4000 points per day (Schwendel, Fuller & Death, 2010b), although when satellite coverage is low due to overhanging vegetation or valley topography, theodolite-electronic distance measurement (EDM) systems provide an alternative. However, maintaining a direct line of sight between the theodolite and the reflector can be laborious and non-robotic total stations require two operators. Surveys should ideally be flood event-based to account for scour-fill compensation (Lindsay & Ashmore, 2002), e.g. patches that are scoured during a first flood may be refilled in the following event, resulting in no observed change when assessed over a multi-event scale.

Substrate transport is often assessed with tracer particles of various kinds (e.g. Laronne & Duncan, 1992; Sear *et al.*, 2000), bedload samplers (e.g. Bunte & Abt, 2003) or acoustic devices (e.g. Bogen & Moen, 2003). When benthic communities are to be sampled concomitantly these techniques ideally should not interfere with the substrate, which is probably why most stream ecologists have preferred the less invasive tracer methods. Alternatively subjective visual evaluations of stream bed stability like the Pfankuch Index (e.g. Death & Winterbourn, 1994; Townsend *et al.*, 1997b; McIntosh, 2000) theoretically should encompass all aspects of bed stability. They are popular because of their cost-effective, straightforward and quick application but can suffer from observer-bias.

This large range of potential measures of substrate stability combined with the variety of community characteristics (diversity, abundance or community composition) makes it difficult for ecologists to readily identify an appropriate technique. This paper investigates the relationship between six bed stability measures derived from four assessment techniques and invertebrate community metrics in 12 mountain streams. These methods each characterise a distinctive set of bed stability aspects. They include morphological budgeting, flow competence calculation at bankfull discharge, transport of initially embedded tracer stones and the bottom component of the Pfankuch Index. The aim of this paper is to identify the most useful and applicable reach-scale measure of bed stability for research on benthic stream invertebrate communities.

STUDY SITES

The study was carried out from October 2007 to September 2008 in 12 reaches of mountain rivers and streams in the southern part of the North Island of New Zealand

(Fig. 1). The reaches were located on the eastern and western slopes of the northeast-southwest trending Ruahine (5 sites) and Tararua Ranges (4), and the Central Volcanic Plateau around Mt. Ruapehu (3). The geology of the latter is dominated by Quaternary andesitic volcanic deposits whereas the former ranges consist of Mesozoic greywacke and argillites of varying decomposition. The reaches were chosen to represent a wide range of anticipated bed stability. The composition of the substrate ranged between gravels and cobbles although some sites contained a considerable proportion of boulders. Some of the study reaches were laterally confined by vegetated banks, whereas others migrated within a wide active channel zone. None had a closed forest canopy but shading from riparian vegetation did occur occasionally. The streams varied considerably in terms of slope, width, conductivity, and sediment supply. There is relatively little anthropogenic influence in the mountainous catchments where the vegetation is dominated by native broadleaf-podocarp forests in the Tararua and Ruahine Ranges and tussock grassland and scrub on the Central Volcanic Plateau.

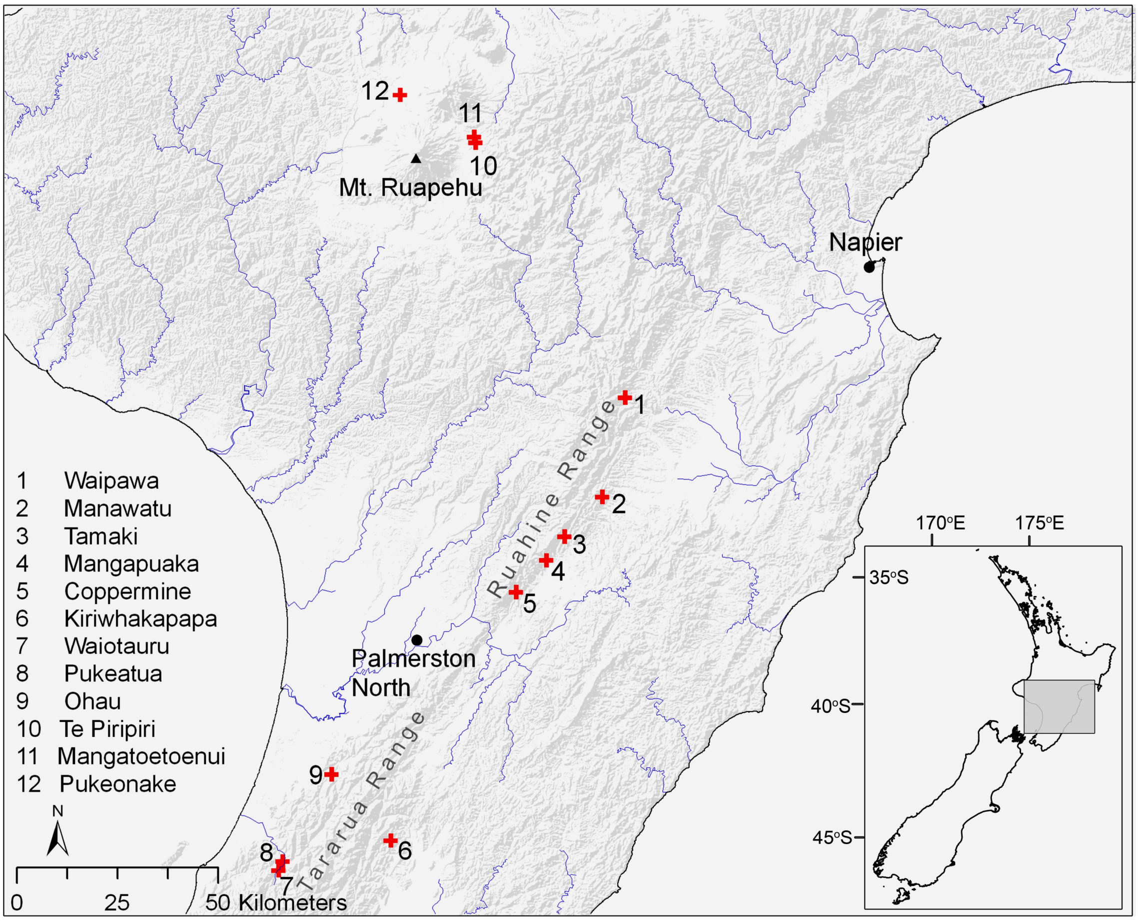

Figure 1. Study sites investigated between October 2007 and September 2008 in the southern North Island of New Zealand.

METHODS

Invertebrates

Five Surber samples (500 µm-mesh, 0.1 m^2) were collected from riffles at three times throughout a year (Austral spring, late summer and winter). Samples were stored in 4% formalin or > 60% isopropyl alcohol. Abundant groups of taxa/ families (> 300 individuals per sample) (e.g. Chironomidae, Leptophlebiidae or Conosucidae) underwent a subsampling process following Vinson & Hawkins (1996). They were identified to the lowest possible taxonomic level (usually species level) using the keys in McFarlane (1951), Winterbourn (1973), Towns & Peters (1996) and Winterbourn, Gregson & Dolphin (2006). Invertebrate abundance was significantly correlated between sampling dates (r_S = 0.34 - 0.99, *df* = 17 - 54, $p < 0.05$) at each site. Constancy of taxa abundance between seasons as indicated by Kendall's coefficient of concordance W was significant (W = 0.28 - 0.72, *df* = 26 - 59, $p < 0.05$). Because of this and the generally low seasonal variability in New Zealand stream invertebrate communities (Towns, 1981; Winterbourn, 2004), three sample occasions through the year were deemed sufficient to represent community composition between flood events.

Periphyton and physicochemical characteristics

Wetted stream width and depth were measured at each invertebrate sampling point (Table 1). Flow velocity (averaged over 60 s) was recorded with an electromagnetic flow meter (Model 801, Valeport Ltd., Devon, UK) 0.05 m above the stream bottom. At each sampling site pH, conductivity (temperature corrected) and temperature were measured using Eutech pHtestr2 and ECScan Low+ (Eutech Instruments, Singapore). Degree of substrate embeddedness was subjectively assessed by dislodging stones and classified into 4 categories ranging from tight to loose (Death & Joy, 2004). Composition of the riparian environment (characterised as percentage aerial cover of native riparian vegetation – NRV or active channel – DAC) was also estimated.

Periphyton biomass was measured concurrently to examine the interacting effects of bed stability and periphyton on benthic invertebrate communities. Five gravel-size stones were collected beside the invertebrate Surber samples. They were transported in the dark in cooled stream water before being stored at -18°C. Pigments were extracted in 90% acetone for 18 h at 5°C in the dark before chlorophyll *a* absorption was measured using a Cary 50 Conc UV-Visible spectrometer (Varian, Mulgrave, Australia). Chlorophyll *a* pigment concentration was calculated (Steinman & Lamberti, 1996; APHA, 1998) and corrected for stone surface area which was estimated based on measurement of the a-, b- and c-axes of the gravels with a sliding calliper following Graham, McCaughan & McKee (1988).

Table 1. Abiotic characteristics of the study sites. Depth, width, velocity, conductivity, temperature and pH measurements are seasonally averaged one-off readings taken concomitantly with invertebrate sampling between October 2007 and September 2008. Depth, width and velocity were measured at each of the 5 invertebrate sampling points per site.

Site	Stream order (Strahler, 1952)	Mean depth (m)	Mean width (m)	Mean flow velocity (m s^{-1})	Mean conductivity (µS cm^{-1})	Mean temperature (°C)	Mean pH	Slope (m m^{-1})	Substrate D_{50} (mm)
Waipawa	3	0.20	5.4	1.000	103	8.8	8.2	0.032	59
Manawatu	3	0.20	4.3	0.603	66	9.4	7.8	0.047	65
Tamaki	2	0.17	3.3	0.811	64	10.8	7.6	0.021	35
Mangapuaka	2	0.09	2.3	0.584	69	8.6	6.7	0.029	28
Coppermine	3	0.13	4.4	0.592	90	13.5	7.4	0.042	51
Kiriwhakapapa	3	0.15	6.5	0.603	64	9.7	7.2	0.011	59
Waiotauru	5	0.26	17.4	0.716	68	11.3	7.7	0.012	84
Pukeatua	3	0.18	9.7	0.720	80	12.4	7.7	0.047	84
Ohau	4	0.24	14.0	0.694	72	12.7	7.6	0.012	64
Te Piripiri	3	0.19	2.0	0.742	69	8.5	7.7	0.014	35
Mangatoetoenui	4	0.26	8.6	0.597	139	7.1	8.0	0.025	97
Pukeonake	4	0.17	6.8	0.398	23	8.2	7.0	0.034	158

Morphological budgeting

Three topographic surveys of the river beds and the adjacent floodplain were undertaken in Austral spring, summer and autumn with a Trimble R8 differential GPS system (Trimble Navigation Limited, Sunnyvale, USA) in RTK mode (Brasington *et al.*, 2000). Where satellite reception was limited topographic data were retrieved with a Topcon electronic total station GTS 701 (Topcon Corporation, Tokyo, Japan). The GPS base station was installed some distance from the reach in order to prevent the occurrence of multipath errors (Kennedy, 2002). The survey was designed to be terrain sensitive, e.g. point density was highest at breaks in slopes and highly structured surfaces (Fuller *et al.*, 2005). Reach length was defined as approximately 5 - 7 times active channel width and included, where present at least one riffle-pool sequence (Leopold, Wolman & Miller, 1964; Keller & Melhorn, 1978). Thus the area of the surveys varied between

132 m^2 and 2942 m^2 whereas the average point density was between 0.6 and 11.7 points per square metre.

The datasets comprising three-dimensional coordinates were triangulated and linearly interpolated on a regular quadratic grid with a width of 0.01 m using Surfer 8.01 (Golden Software, Golden, USA) (Schwendel, Fuller & Death, in press). For the larger reaches (Waipawa and Waiotauru) a larger grid width of 0.02 m was preferred. The resulting digital elevation models (DEMs) of two consecutive surveys were subtracted from each other to produce a DEM of topographic change. To account for propagated errors in representation of the real surface, precision of measurement and accuracy of the DEMs, a level of minimal detection of genuine change was identified and applied to the DEMs when the area and volume of scour (VOS) and fill (VOF) relative to the survey area were calculated (Schwendel *et al.*, 2010b).

Flow competence

The percentage of substrate that would move at bankfull discharge (flow competence bankfull – FCB) was calculated following Duncan, Suren & Brown (1999). This approach employs a modified Shields and the DuBoys equation to relate mean boundary shear stress to entrainment of particles. It is assumed that all clasts on the river bed smaller than the critical grain size move under these conditions. The composition of the substrate (Table 1) was assessed with the Wolman pebble count method (Wolman, 1954) which measures the b-axis of > 100 randomly selected substrate particles. They were classified according to a modified Wentworth scale. The necessary measurements of cross-sections and water surface slope were attained with RTK-dGPS or a tacheometric EDM-system (see above). At each site around 20 random particles were collected and density measured while fluid density was assumed to be 1000 kg m^{-3}, both necessary for calculation of specific weights in the Shields equation.

Tracer stones

To assess the stability of the surface layer five randomly selected stones in each of three size classes (D_{50}, D_{70} and D_{90}) were marked with electronic RFID tags (23 mm glass tags, Texas Instruments, Dallas, USA) which were attached *in situ* to randomly selected stones using underwater curing epoxy-concrete (K273, Nuplex Construction Products, Hamilton, New Zealand). Where an underwater application was impossible due to swift current, stones were removed from the river bed and after the tag was attached were carefully re-embedded. This appeared to have relatively little effect on substrate stability assessment as the percentage of entrained re-embedded and *in situ* marked stones were correlated (r_S = 0.77, *df* = 11, *p* = 0.005). Marked stones were relocated and identified without interference by their unique coded tags using a portable antenna and datalogger (OregonRFID, Portland, USA). Compared to the number of tracers stones used for assessment of reach-scale bed movement in other studies (e.g. 400 in Matthaei, Peacock & Townsend, 1999b) the number of marked stones is low and the full spatial variability in bedload transport might not be accounted for. However, experience from previous studies (e.g. Death & Zimmermann, 2005) suggested that 15 stones are sufficient to provide a meaningful estimate of ecologically relevant bed stability.

Positions of the stones were measured using tacheometric ground survey or from marked locations on riparian vegetation and stable banks. Mean recovery rate was 71% and ranged between 41% and 100% across all sites. The distance travelled was recorded and converted to an index of bed stability. The latter comprises the weighted (by geometric mean of the size class) sum of travelled distance. Stones that were not recovered were assigned a travel distance between 50 m and 200 m depending on estimated stream power. Two surveys were conducted to relocate the stones within six months after marking, which resulted in two measures of tracer stone movement: the initial behaviour (ITM) until the first relocation (after on average 81 days) and the travelled distance over the entire period (after on average 161 days) (TTM).

Pfankuch Stability Index

The Pfankuch Stability Index is a visual evaluation method of stream bed and bank stability and of the capacity for morphological adjustment to floods (Pfankuch, 1975). The bottom component was used as it has been shown to relate best to biological data (Death & Winterbourn, 1995). It involves allocation of an observer’s subjective evaluation of six attributes, including substrate brightness, angularity, consolidation, percentage of stable materials, scouring and amount of clinging aquatic vegetation, to four predetermined categories to which scores are weighted according to their perceived importance. The sum of the scores results in a stability index, where high values represent low stability. It was assessed twice at each site by the same observer within a few months and the results averaged (bottom component Pfankuch – BCP).

Data analysis

As data were not normally distributed the non-parametric Spearman rank correlation r_S (Statistix 9.0, Analytical Software, Tallahassee, USA) was used to investigate the connection between measurements of bed stability and invertebrate community metrics. The latter included total number of individuals, total number of taxa, evenness (Berger-Parker dominance index), taxa richness (Margalef's Index) (cf. Death & Winterbourn, 1995) and rarefied species richness (ES20). The latter allows comparison of taxa richness between samples with differing number of individuals and was calculated in PRIMER v6 (Plymouth Marine Laboratory, Plymouth, UK) following Sanders (1968) and Hurlbert (1971). Significance from the multiple correlations was adjusted using false discovery rate correction (Benjamini & Hochberg, 1995). The nature of the established relationships between measures of bed stability and community metrics was subsequently examined with regression analysis in Statistix 9.0. The use of regression techniques is not entirely appropriate because of the non-normal data distribution of some variables, thus the derived results need to be interpreted carefully when indicating a non-monotonic link. While diversity metrics describe only community structure the community composition at each site was characterised by non-metric multidimensional scaling (NMDS) of standardised (by maximum) species abundance in PRIMER v6 using Bray-Curtis similarity among sites. The link between bed stability measurements, specific invertebrate taxa and NMDS-axes was examined using Spearman rank correlation.

RESULTS

Bed stability

Bed stability was generally highest at the sites on the Central Volcanic Plateau, in particular at Pukeonake Stream. In contrast the Waipawa site was rated amongst the least stable sites by almost all measures, except volume of fill (Fig. 2). The assessment of bed stability using the bottom component of the Pfankuch Index, tracer stones and the calculated percentage of bed in motion at bankfull discharge also characterised some streams in the eastern Ruahine Ranges and Pukeatua Stream as unstable, although ranking of the sites varied considerably between the methods. The measurement of topographic change using morphological budgeting techniques resulted in assessment of both relative volume and area of scour and fill. Area and volume were highly correlated for scour and fill (r_S = 0.95 and 0.98, df = 11, p = 0.0001), thus only volumes are reported here. Relative volume of scour was maximal at Pukeatua whereas the most sedimentation per reach area occurred at the Te Piripiri site (Fig. 2). The bottom component of the Pfankuch Index was significantly correlated ($r_S > 0.73$, $df = 11$, $p < 0.01$) with all the other bed stability measures except volume of fill and the flow competence calculation. In contrast the latter showed only weak correlation with the other measures ($r_S < 0.66$, $df = 11$, $p > 0.02$). The two tracer measures were highly intercorrelated ($r_S > 0.94$, $df = 11$, $p < 0.001$).

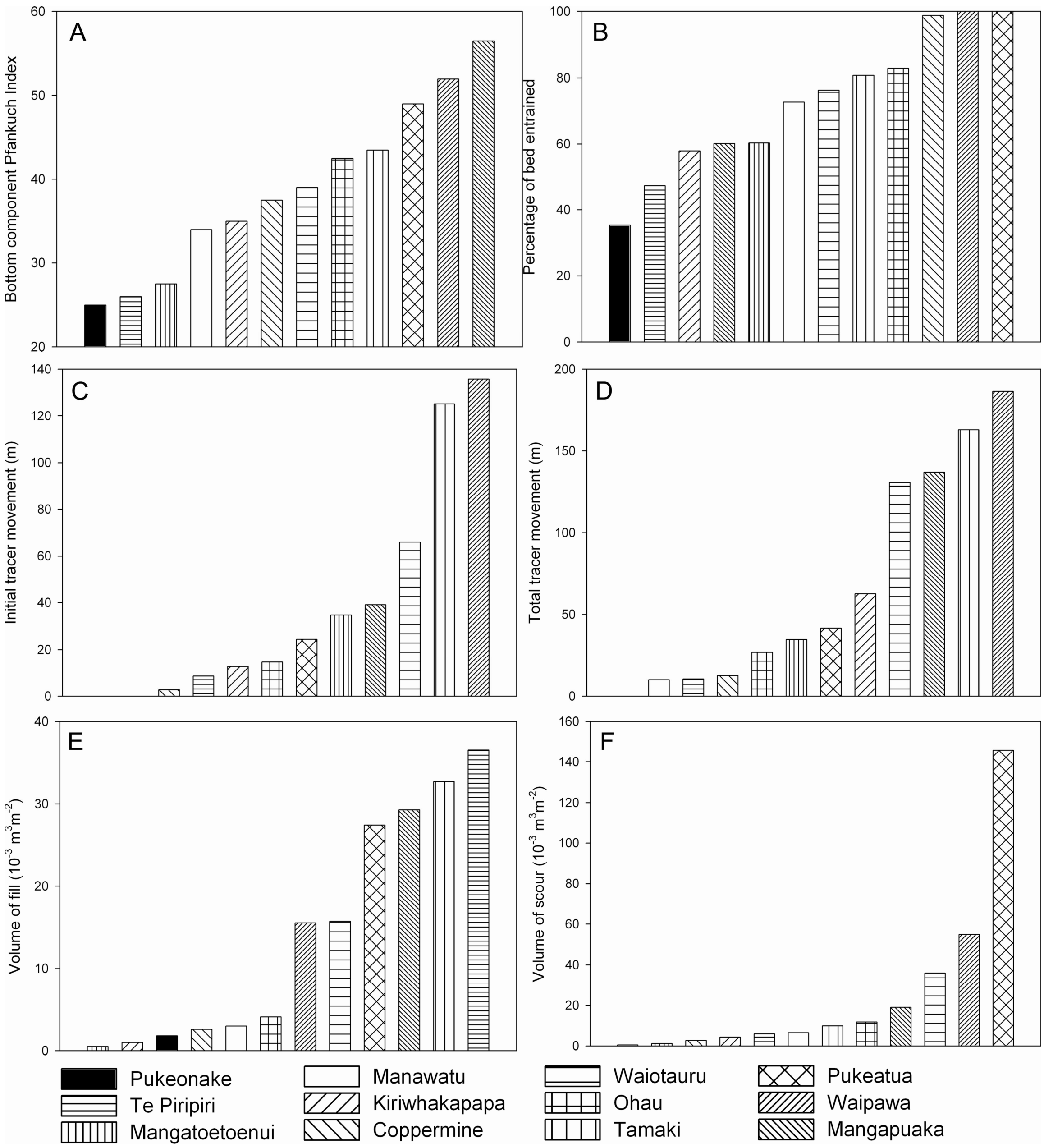

Figure 2. Bed stability assessed at 12 study sites using six measures. The sites are ranked from high stability (left) to low stability.

Invertebrate communities

Taxa number

The composition of the invertebrate communities at each site was relatively constant over the ten month study period. The total number of taxa from all sites was 110, with each site containing between 27 and 60 taxa. The Tararua and Ruahine sites were dominated by Trichoptera, Plecoptera and Ephemeroptera (85 - 94% of individuals and 43 - 69% of taxa) whereas the sites on the Central Volcanic Plateau had a smaller fraction of individuals in these orders (18 - 70%) and more Diptera. Total number of taxa was not significantly correlated with any measure of bed stability, but it was strongly correlated with percentage of native riparian vegetation (Table 2).

Table 2. Correlation of invertebrate community characteristics (evenness = Berger-Parker Index, taxa richness = Margalef's Index) and periphyton biomass with six measures of bed stability (BCP – bottom component Pfankuch Index, FCB – flow competence at bankfull discharge, ITM – initial tracer stone movement, TTM – total tracer movement, VOS – volume of scour, VOF – volume of fill) and biotic and abiotic parameters (NRV – native riparian vegetation area, DAC – dry active channel area) from 12 North Island, New Zealand rivers. Samples and measurements were collected between October 2007 and September 2008. Significance from multiple correlations (for each column) was adjusted using False Discovery Rate and is indicated by * for $\alpha = 0.1$ and ** for $\alpha = 0.05$.

	Taxa no.	**No. of individuals**	**Evenness**	**Taxa richness**	**Rarefied taxa richness**	**NMDS axis 1**	**NMDS axis 2**	**NMDS axis 3**	**Periphyton biomass**
Bed stability									
BCP	-0.19	-0.16	0.59*	-0.64*	-0.63	0.15	0.80**	0.00	-0.42
FCB	-0.08	-0.11	0.08	-0.22	-0.18	0.26	0.33	-0.09	-0.08
ITM	-0.54	-0.46	0.58*	-0.56*	-0.43	0.05	0.59*	0.36	-0.54
TTM	-0.38	-0.30	0.65*	-0.59*	-0.46	0.00	0.68*	0.20	-0.66
VOS	-0.08	-0.04	0.42	-0.71*	-0.57	0.22	0.62*	0.08	-0.11
VOF	0.05	-0.01	0.33	-0.36	-0.32	0.35	0.26	0.10	0.16
Periphyton	0.52	0.34	-0.53	0.50	0.42	0.01	-0.64*	-0.08	
Abiotic parameters									
Depth	-0.38	-0.25	-0.23	-0.15	0.04	-0.10	-0.13	0.34	0.12
Velocity	-0.13	-0.12	0.06	-0.35	-0.08	0.19	0.13	0.18	-0.13
Conductivity	-0.21	-0.30	-0.24	0.14	0.29	-0.34	-0.09	0.34	0.16
pH	-0.19	-0.17	-0.36	0.02	0.19	-0.27	-0.27	0.30	0.22
NRV	-0.69*	-0.64*	0.09	-0.22	-0.01	0.18	0.18	0.69*	-0.27
DAC	-0.51	-0.38	0.64	-0.54	-0.54	0.01	0.55	0.40	-0.34

Total number of individuals

The mean number of individuals of all samples at each site ranged from 21.2 at Mangatoetoenui Stream to 625.8 at Manawatu River. The strongest link with the measured environmental variables was with native riparian vegetation (Table 2). In contrast no significant monotonic relationship with any bed stability measure could be established.

Diversity Indices

Community evenness (Berger-Parker Index) had the highest significant positive correlation with total tracer movement, followed by the bottom component of the Pfankuch Index and initial tracer movement (Table 2). Margalef's Index was significantly correlated with the volume of scour, the bottom component of the Pfankuch Index and the tracer measures. Rarefied taxa richness showed no significant correlation with any bed stability measure or abiotic parameters. Regression analysis revealed that the relationship between diversity measures and volume of scour was best explained by logarithmic or power functions (Fig. 3). For the remaining measures of bed stability linear models were of similar quality than curvilinear models (Table 3).

Table 3. Comparison of regression models of invertebrate community metrics and measures of bed stability (BCP – bottom component Pfankuch Index, ITM – initial tracer stone movement, TTM – total tracer movement, VOS – volume of scour). Models are compared by their Akaike's Information Criterion for small samples (AICc) whereas the lowest value (bold) signifies the best model. Significance indicated by * for $\alpha = 0.1$ and ** for $\alpha = 0.05$.

	Linear	**Polynomial (2nd order)**	**Logarithmic**	**Exponential**	**Power**
Evenness (Berger-Parker Index)					
BCP	-40.39**	-35.89	-39.91**	**-40.56****	-40.31
ITM	**-36.42**	-32.56	-34.59	-36.31	-34.63
TTM	**-40.11****	-35.64	-34.43	-39.91**	-34.43
Taxa richness (Margalef's Index)					
BCP	0.98**	4.69*	0.45**	0.83**	**0.35****
ITM	3.77	6.54	**3.44***	3.70*	3.52*
TTM	0.35**	2.75**	3.79*	**0.19****	3.87*
VOS	6.00	3.70**	1.42**	5.99	**1.14****

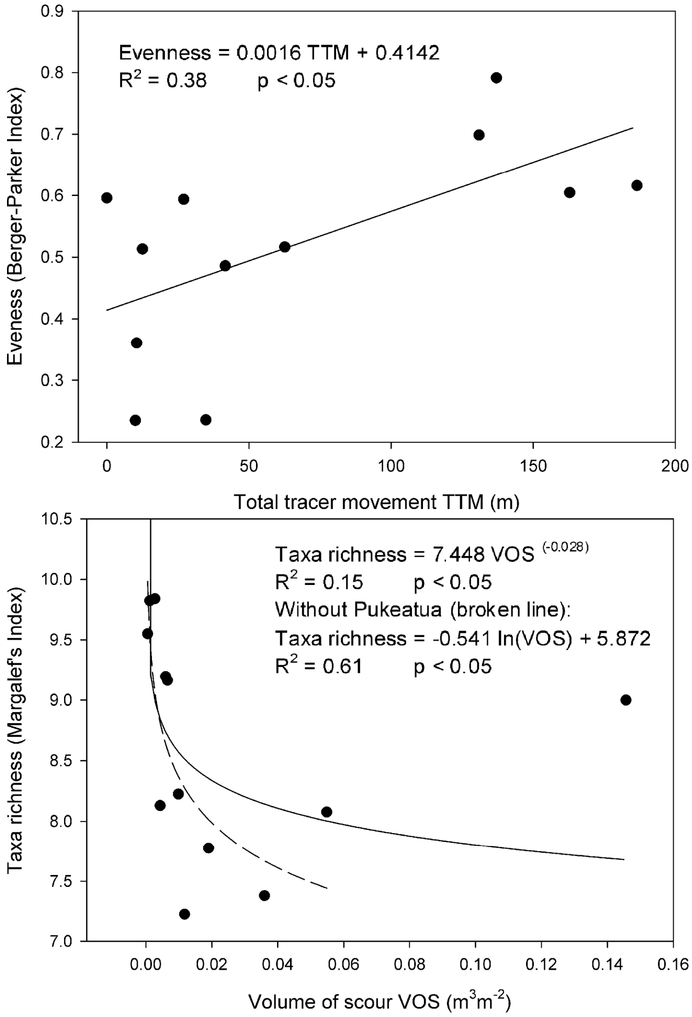

Figure 3. Invertebrate community metrics as a function of bed stability (highest correlated measure and best regression model). For the taxa richness the relation improves when the Pukeatua site with its high local sediment supply from a tributary is omitted (broken line).

Community composition

The second axis from the NMDS (stress 0.06; Fig. 4) was correlated with the bottom component of the Pfankuch Index, bed stability measured by tracer particles, volume of scour and periphyton biomass, while the third axis was strongly connected with native riparian vegetation (Table 2). The first and third axes were not significantly correlated with any bed stability measure.

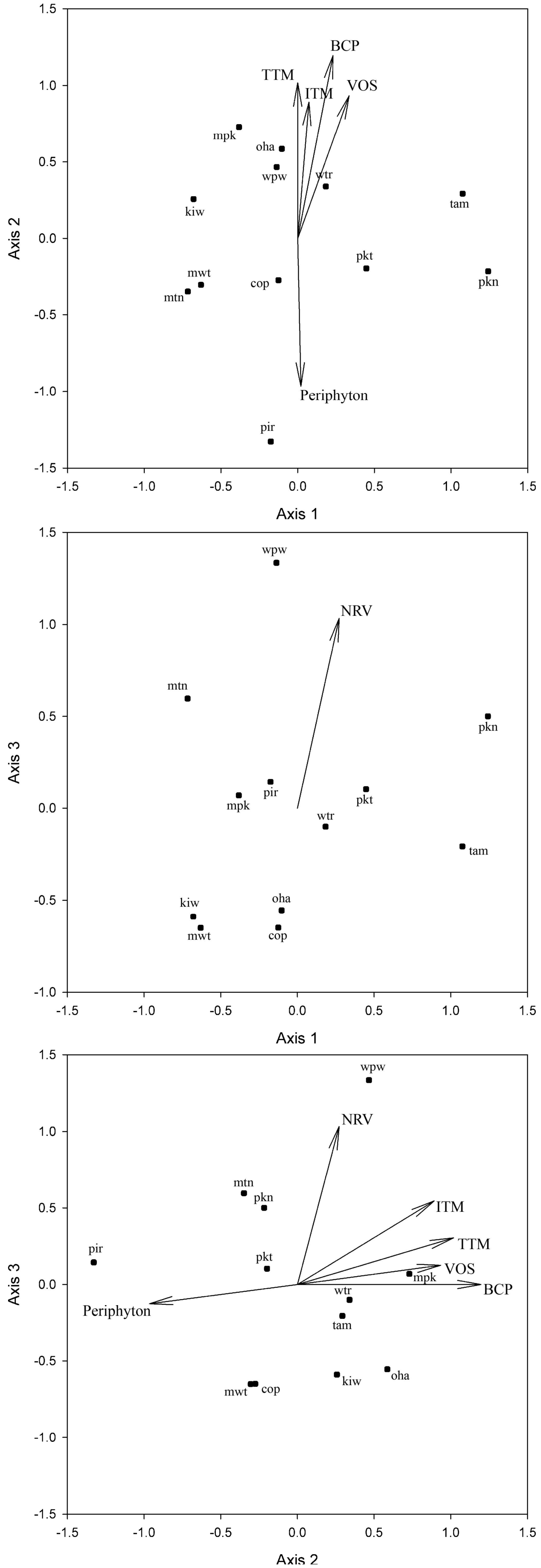

Figure 4. Location of invertebrate communities (wpw = Waipawa, mwt = Manawatu, tam = Tamaki, mpk = Mangapuaka, cop = Coppermine, kiw = Kiriwhaka-papa, wtr = Waiotauru, pkt = Pukeatua, oha = Ohau, pir = Te Piripiri, mtn = Mangatoetoenui, pkn = Pukeatua) relative to three non-metric multidimensional scaling axes and correlated measurements.

Larvae of the mayfly *Austroclima sepia*, the caddisfly *Pycnocentria gunni*, Diptera of the family Empididae and Platyhelminthes were only found at sites that were identified as being relatively stable (e.g. low values on second NMDS axis). The first two taxa are often associated with moss (Winterbourn *et al.*, 2006) on stable substrates. Diamesinae, Orthocladiinae, *Chironomus zelandicus*, the caddisfly *Neurochorema* spp. and Simulidae were also much more abundant at these sites compared to less stable reaches. In contrast Hydrophilidae beetles were exclusively collected at more unstable sites which correspond with data from other New Zealand studies (Sagar, 1986; Townsend, Doledec & Scarsbrook, 1997a).

Periphyton

Periphyton biomass was negatively correlated with the second NMDS-axis. There was no significant relationship between periphyton biomass and any measure of bed stability, but high biomass was usually found at stable sites with high and intermediate invertebrate diversity.

DISCUSSION

The assumption that bed stability is one of the principal abiotic factors influencing stream invertebrate community composition is supported by our findings. However, the strength and form of the correlation between invertebrate community structure and bed stability varied with the particular measure of bed stability employed. Distance travelled by *in situ* marked tracer stones was consistently the best predictor for the influence of bed stability on the composition and diversity of invertebrate communities. It longitudinally integrates bedload transport over the entire reach and *in situ* tagging incorporates entrainment of particles. The bottom component of the Pfankuch Index which allows, to a certain degree, incorporation of other aspects of bed stability such as sedimentation, also related well to diversity and community composition. However, entrainment and particle transport appear to be more relevant for communities than pure deposition of coarse sediments. Diversity of invertebrate communities and number of individuals declined linearly with decreasing bed stability measured with both techniques. Periphyton biomass opposed bed stability on the second NMDS-axis, which is typical for open canopy streams where the effects of substrate stability on invertebrates and their food source are difficult to distinguish (Suren, 1993; Death & Zimmermann, 2005). Although other aspects contributing to the growth of periphyton communities such as partial shading and valley orientation were not factored out separately, no evidence of a strong overriding effect of different levels of periphyton biomass on the relationship between bed stability and the composition of invertebrate communities was given.

Morphological budgeting

Volumes of scour and fill derived from the subtraction of DEMs were not linearly related to the abundance of individuals or the number of taxa. In contrast there was a strong link between taxa richness and volume of scour, which was best described by curvilinear functions. However, removing the Pukeatua site, where the highest volumes of scour were found, dramatically improved linear relations, which show a steeper slope (Fig. 3). The exclusion of this site is reasonable since excessive scour was mainly due to lateral erosion of a fan from a steep tributary stream at the margin of the site and was thus not representative for the entire stream bed of the reach. The strong link between volume of scour and the second NMDS axis points towards a more important influence of entrainment on community composition compared with sedimentation processes. Morphological budgeting permits identification of such spatial patterns of scour and fill and is a well established method for the assessment of changes in morphology in gravel-bed rivers (e.g. Fuller *et al.*, 2002). Coarseness of the substrate (e.g. Pukeonake reach) may impede the survey which is designed to measure topography at a bedform scale. Boulders and large cobbles require a grain size resolution which is impracticable for large reaches. Thus the survey can be designed to exclude bouldery sections of the riverbed, but in cases of occasional movement of large-sized substrate, this can result in errors. Application of a rigorous level of change detection minimises the influence of errors associated with substrate size, measurement and interpolation. However, a spatially uniform (reach-scale) level of detection may prevent registration of subtle erosion or deposition to which invertebrate communities might be sensitive. Thus measurement of topographical change on a riffle-scale or application of spatially variable error assessment might relate better to invertebrate community metrics. Morphological budgeting also cannot account for sediment that is completely transported through the reach or scour-fill compensation during a single event (Fuller *et al.*, 2003).

Flow competence calculation

The calculation of the maximum entrained substrate size at bankfull discharge and the resulting percentage of bed surface in motion have been successfully used to show that periphyton biomass (Biggs *et al.*, 1999) and bryophyte cover (Duncan *et al.*, 1999) increase with bed stability. However, our study showed no link between this measure and invertebrate community composition or periphyton biomass. This may be a result of our definition of bankfull discharge. We estimated bankfull stage as the level below which no perennial vegetation occurs, or according to flood trash lines and indicative channel forms. However, this concept bears some uncertainties depending on the magnitude of recent floods. A comparison with mean annual flood (MAF) data (Pearson & McKerchar, 1989) showed that for all sites, except Waipawa, the estimated bankfull water level was considerably lower than MAF stage. We did not use the MAF data for calculation of the proportion of entrained substrate (cf. Duncan *et al.*, 1999) because channel cross-sections were only measured to bankfull stage and extrapolation beyond this is likely to generate error. Furthermore, use of a higher water level would have increased the percentages of substrate entrainment and resulted in an upper truncation.

Tracer stones

Tracer particles can be used to quantify entrainment, transport length and path of surface stones. The bed stability measures derived from their transport distance was consistently well related with diversity metrics and invertebrate community composition. The initial movement measure seems more relevant to predict the number of taxa and individuals present. Compared with total movement, initial tracer movement is more sensitive to fine gradations in bed stability at relatively unstable sites because initial transport of a large fraction of stones beyond the search distance (e.g. Tamaki) might result in domination of few immobilised particles in subsequent measurement periods. This can lead to a disproportionately low total tracer movement relative to more stable sites which have shorter transport distances over all periods. On the other hand tracer monitoring over a longer period characterises the flood regime better.

The strong link between tracer measures and community composition emphasises the importance of the transport and entrainment components of bed stability for benthic communities. Negative linear relations between taxa number and measures of tracer stone movement have been recorded in many studies (Robinson & Minshall, 1986; Death & Winterbourn, 1995; Death, 2002; Death & Zimmermann, 2005), but quadratic relations had occasionally similar (Death, 2002; Death & Zimmermann, 2005) or higher explanatory power (Townsend *et al.*, 1997b) or no relationship was observed (Reice, 1985; Englund, 1991). However, Townsend *et al.* (1997b) measured only entrainment of tracers rather than transported distance, whereas other studies focused on smaller scales (e.g. single stone, Robinson & Minshall, 1986). The connection between invertebrate density and tracer stone movement was also found by Death & Winterbourn (1995) and Matthaei, Arbuckle & Townsend (2000), but other studies found no correlation (Death, 2002; Death & Zimmermann, 2005). However, most studies agree that invertebrate abundance decreases with increasing physical disturbance (Vinson & Hawkins, 1998; McCabe & Gotelli, 2000). Strong links between diversity (e.g. Berger-Parker dominance index, rarefied taxa richness and Margalef's Index) and tracer movement are supported by many studies (Boulton, Spangaro & Lake, 1988; Englund, 1991; Death & Winterbourn, 1995; Rosser & Pearson, 1995; Death, 2002; Death & Zimmermann, 2005) although the nature of the noted tracers varied (e.g. unembedded stones).

Presence of *in situ*-marked stones after floods can provide information about the patchiness of disturbance (Matthaei *et al.*, 1999b; Downes *et al.*, 1998) and availability of refugia for invertebrates on stable surface stones (Matthaei *et al.*, 2000). In this study stones were marked *in situ* in order to reflect actual entrainment more realistically (Downes *et al.*, 1998), compared with tracers placed on the riverbed. Under conditions of strong imbrication (e.g. Pukeonake), low sediment supply (e.g. Manawatu) and/ or the presence of a bed armour layer, differences in entrainment between *in situ*-marked particles and stones placed on the channel bottom could be expected to be immense. However, the form of the connection between community characteristics and movement of *in situ*-marked stones found in this study corresponds with the relations observed using initially unembedded stones (e.g. Death & Winterbourn, 1995; Death, 2002; Death & Zimmermann, 2005). A frequently observed weakness of this method is the decrease in transport rate with time due to immobilisation (burial, storage on bars and floodplain) of tracers (Ferguson *et al.*, 2002), especially when the number of tracers is low. Another complication with a relatively low number of tracers is that the spatial variability of bedload transport within the reach might not be fully accounted for (Ferguson, 2003; Vericat & Batalla, 2007). Malfunction or loss of the RFID tags can be a further, albeit rare, constraint of this method. Nevertheless, low cost of RFID tags (e.g. US$ 2.61 per tag), high recovery rate, the possibility of non-invasive relocation and identification of invisible tracer stones proved to be major advantage of this technique.

Pfankuch Index

The bottom component of the Pfankuch Index is a bed stability measure that incorporates entrainment, deposition and transport of the substrate. It was linked with invertebrate community composition and diversity, in particular taxa richness, but there was no link with the number of taxa and individuals. In contrast Death & Winterbourn (1995) and Death (2002) found a strong negative linear relationship between taxa number and the bottom component of the Pfankuch Index, whereas Townsend *et al.* (1997b), using the full Pfankuch Index recorded only a weak correlation. Death & Winterbourn (1995) also show a strong negative linear connection between invertebrate density and the bottom component of the Pfankuch Index, but weaker relations with evenness and taxa richness, which contrast with our findings here. A potential cause for these differences could be that the visual assessment of stream characteristics is prone to subjectivity. Large differences between evaluations of the same reach by the same observer under varying conditions (e.g. weather) can occur (A. C. Schwendel, unpublished data). However, the approach is straightforward, quick and cost-effective.

CONCLUSIONS

Although the Pfankuch Index or a limited number of tracers do not fully account for the spatial variability in substrate stability they provide relevant bed stability measures for invertebrate communities. As employment of tracer stones requires frequent site visits and is more laborious than the potentially observer-biased Pfankuch Index, future research needs to focus on the development of a straightforward surrogate for the measurement of tracer stone movement that is less affected by subjectivity than the Pfankuch Index. Such a method could facilitate assessment of ecologically relevant stream bed stability characteristics and would serve as an effective tool for research in abiotic effects on benthic communities.

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Chapter 5

A new approach to assess bed stability relevant for invertebrate communities in upland streams

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ABSTRACT

Composition and structure of lotic ecosystems can be affected by substrate instability. Consequently stream ecologists have used various methods to determine bed stability characteristics. However, the link between community composition and these measurements varies because benthic biota often respond to combinations of bed stability characteristics. This paper presents a protocol to determine reach-scale stream bed stability in mountain streams which is relevant for invertebrate communities (Stream Bed Stability for Invertebrates, SBSI). The approach is calibrated on community composition response to bed stability but does not measure any single bed stability characteristic *per se*. It consists of 13 parameters that are assessed once at each reach with minimal instrumentation and low interference with the substrate. These 13 parameters cover aspects of sediment supply from banks, transport capacity and substrate erodibility as well as effects of particle transport on channel bottom structures, substrate assemblage and single grains. Application of the SBSI protocol improved the relationship between bed stability and community diversity compared to when conventional bed stability measures were employed. The SBSI protocol provides a cost- and time-effective assessment method for bed stability and its application can facilitate research on invertebrate community response to physical disturbance.

INTRODUCTION

Flow influences many important structural attributes of stream ecosystems such as substrate stability, habitat volume and channel morphology (Poff & Ward, 1989). Variation in discharge is recognised as one of the fundamental determinants of structure and function of benthic communities in lotic ecosystems (Resh *et al.*, 1988; Reice, Wissmar & Naiman, 1990; Lake, 2000; Death, 2008). Floods can cause movement of coarse bed substrate which can affect composition of periphyton (Biggs, Smith & Duncan, 1999), invertebrate (Cobb, Galloway & Flannagan, 1992; Death & Winterbourn, 1995; Holomuzki & Biggs, 2000), bryophyte (Suren & Duncan, 1999) and macrophyte communities (Riis *et al.*, 2008). However, different groups of biota respond to different aspects of bed stability on a range of scales. For instance the reaction to patchy scour or fill varied between invertebrate taxa while on a larger scale stable patches might migitate the effects substrate instability (Matthaei & Townsend, 2000). Bed stability is a characteristic feature of alluvial channels comprising aspects like entrainment, transport and deposition of substrate as well as abrasion by suspended material on scales ranging from a single particle to an entire reach. These bed stability characteristics might affect sessile organisms in different ways than more mobile groups of biota (Downes, 1990; Englund, 1991; Holomuzki & Biggs, 2000; McAuliffe, 1984). Consequently some methods to quantify bed stability perform well with one group of organisms but show only a weak relationship with other groups (Duncan, Suren & Brown, 1999; Schwendel *et al.*, in press). This in turn is reflected in the wide variety of bed stability measurements used by stream ecologists to examine the effects of flow disturbance (Schwendel, Death & Fuller, 2010).

The effects of substrate movement on stream invertebrate communities via habitat alteration, displacement and death of individuals, and changes in their food sources are widely recognised (e.g. Townsend, Scarsbrook & Doledec, 1997; Matthaei & Townsend, 2000; Effenberger *et al.*, 2006; Death, 2008). Different levels of bed stability, e.g. apparent in depth and pattern of disturbance or in transport distance of particles, are reflected in invertebrate community composition for instance via recolonisation abilities of individual taxa (Death, 2008). The methods employed to assess bed stability in relation to invertebrate community metrics are reviewed in Schwendel *et al.* (2010) and include calculation of critical shear stress (Newbury, 1984; Cobb *et al.*, 1992; Death & Winterbourn, 1995), FST-hemispheres (Dittrich & Schmedtje, 1995; Merigoux & Doledec, 2004), scour chains (Palmer, Bely & Berg, 1992; Matthaei & Townsend, 2000; Effenberger *et al.*, 2006), scour plates (Palmer *et* *al.*, 1992), tracer stones (Death & Winterbourn, 1994; Townsend *et al.*, 1997; Death & Zimmermann, 2005; Barquin & Death, 2006), morphological budgeting (Schwendel *et al.*, in press) and the Pfankuch Stability Index (Death & Winterbourn, 1995; Townsend *et al.*, 1997; Death, 2002). Each of these methods can only assess a distinct set of bed stability characteristics and the strength of the relationship with invertebrate diversity and community composition varies (Schwendel *et al.*, in press). The need of site specific calibration (e.g. bedload transport formulae and acoustics sensors) and interference with the substrate (e.g. scour plates and bedload traps) can constrain application for multi site studies and concomitant invertebrate sampling respectively (Schwendel *et al.*, 2010). Insufficient spatial (e.g. bedload samplers) or temporal coverage (e.g. FST-hemispheres) for reach-wide, long-term bed stability assessment can be an additional problem. Further, time and cost constraints can often prevent application of elaborate methods. Visual surveys of stream bed properties such as the Pfankuch Stability Index can circumvent some of these limitations but they can potentially be biased by observers or regional factors such as substrate lithology.

Thus a technique that combines the strengths of elaborate bed stability measurements with the easy application of a visual approach would facilitate research on stream invertebrates and increase comparability between studies. Consequently, this paper presents a straightforward survey protocol specifically calibrated for the assessment of reach-scale stream bed stability relevant for invertebrate community composition (SBSI). It needs to be pointed out that the SBSI survey does not measure any single aspect of bed stability *per se* but determines a characteristic response of invertebrate community composition to a combination of bed stability characteristics. The SBSI was validated at independent sites using *in situ* marked tracer stones and the bottom component of the Pfankuch Index, two techniques that were shown to be well related to invertebrate community metrics (Schwendel *et al.*, in press). Additionally the relationship between bed stability measured with SBSI and community metrics was explored.

Application for the SBSI method may include scientific studies of disturbance-diversity relationships and habitat characteristics as well as assessment of the potentially confounding effects of bed instability on invertebrate community composition when the latter is employed to determine water quality or environmental status of a stream.

METHODS

Study sites

Data for calibration and validation of SBSI protocol were collected between October 2007 and March 2010 from 54 mountain stream reaches in the southern part of the North Island of New Zealand. They were located in the axial Tararua (n = 12) and Ruahine Ranges (n = 11), the Central Volcanic Plateau (n = 13) and around Mt. Egmont (n = 18) (Fig. 1). The former ranges consist of uplifted folded and faulted Mesozoic greywacke and argillite whereas the other mountains are composed of Quaternary andesitic volcanic deposits. Catchment vegetation was dominated by native broadleaf-podocarp forests, scrub and tussock grassland and anthropogenic influence is relatively small (e.g. < 0.1% urban land use, 0 – 45% non-intensive pasture and no infrastructure upstream of sites). Consequently water quality was expected to be relatively unimpaired. The studied stream reaches varied considerably in substrate assemblage, width and channel form (Table 1). Substrate composition ranged between gravels and cobbles although some sites contained a considerable proportion of boulders. Riparian vegetation was variable with native forest, willows and poplars, native scrub, non-intensive pasture, tussock and bare ground present. Some of the reaches were laterally confined by vegetated banks, whereas others migrated within a wide active channel zone.

Invertebrate communities

Five Surber samples (500 µm mesh, 0.1 m^2) were collected from riffles during periods of baseflow at least two weeks after the last spate to ensure a characteristic species assemblage was collected. Seasonal variability in New Zealand stream invertebrate communities is generally low (Towns, 1981; Winterbourn, 2004) however, this was tested and confirmed at 18 of the sites where samples were taken three times throughout the year (Schwendel *et al.*, in press and J. Tonkin, unpublished data). Samples were stored in 4% formalin or > 60% isopropyl alcohol and later sorted. Very abundant taxa (> 300 individuals per sample) were subsampled following Vinson & Hawkins (1996): samples expected to contain large numbers were divided in equal subsamples of which one was initially searched for invertebrates. Only those taxa which number of individuals did not exceed 300 in the first subsample were searched for in the second subsample. Invertebrates were identified to the lowest possible taxonomic level using the keys in McFarlane (1951), Winterbourn (1973), Towns & Peters (1996) and

Winterbourn, Gregson & Dolphin (2006). Invertebrates were sampled where applicable from riffles because community composition there is likely to reflect gradations in substrate stability and on a larger scale instability in riffles affects also pools, e.g. via bedload transport.

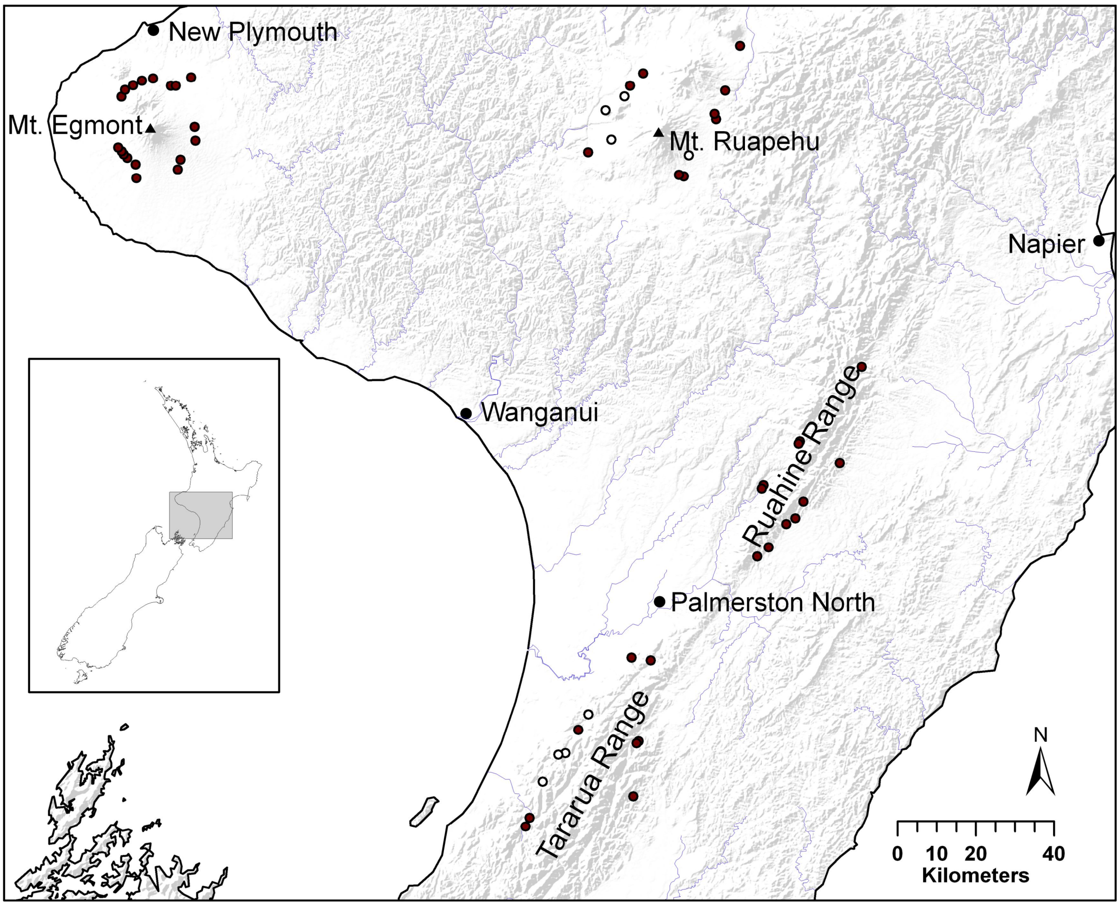

Figure 1. Stream reaches in the southern North Island of New Zealand studied for calibration of the Stream Bed Stability for Invertebrates protocol. Open circles denote the sites used for validation.

Periphyton and habitat parameters

At each invertebrate sampling point depth, wetted stream width and near-bottom flow velocity were measured. The latter was recorded over 60 s with an electromagnetic flow meter (Model 801, Valeport Ltd., Devon, UK) 0.05 m above the stream bed. At each site pH and temperature corrected conductivity were measured using Eutech pHtestr2 and ECScan Low+ (Eutech Instruments, Singapore) respectively. Percentage aerial cover of riparian land use categories (native vegetation, pasture and willows) within a strip of approximately 5 m and the fraction of dry active channel bare of vegetation under base flow conditions was estimated visually.

Table 1. Abiotic characteristics of the study sites assessed between October 2007 and March 2010. Depth, width, velocity, conductivity, temperature and pH measurements are averaged from 5 readings taken concomitant with invertebrate sampling; TTM is an index of bed stability calculated from the movement of *in situ* marked tracer stones. Sites used for validation are in italics. This table is continued on the following page.

Site	Stream order (Strahler, 1952)	Mean depth (m)	Mean width (m)	Mean flow velocity (m s^{-1})	Mean conductivity (µS cm^{-1})	Mean temperature (°C)	Mean pH	Substrate D_{50} (mm)	TTM (m)
Tararua Range									
Waitohu	4	0.20	6.8	no data	84	11.5	7.5	86	39.94
Waiotauru	5	0.26	17.4	0.716	68	11.3	7.7	84	38.57
Waikawa	4	0.18	6.1	no data	76	13.2	7.5	99	36.78
Panatewaewae	3	0.11	7.0	no data	74	13.1	7.6	103	31.21
Kiriwhakapapa	3	0.15	6.5	0.603	64	9.7	7.2	59	20.43
Ohau	4	0.24	14.0	0.694	72	12.7	7.6	64	14.30
Pukeatua	3	0.18	9.7	0.720	80	12.4	7.7	84	12.50
Makahika	4	0.17	6.3	no data	66	19.4	7.4	82	11.18
Mangatainoka	4	0.17	11.7	0.694	52	13.3	7.1	108	7.67
Rawnsley	2	0.11	5.1	0.422	48	13.5	6.9	159	4.74
Tokomaru	4	0.14	14.6	0.707	81	17.5	6.9	85	3.07
Kahuterawa	4	0.15	3.5	0.616	68	14.1	6.5	85	0.06
Ruahine Range									
Waipawa	3	0.20	5.4	1.000	103	8.8	8.2	59	79.56
Tamaki	2	0.17	3.3	0.811	64	10.8	7.6	35	64.46
Mangapuaka	2	0.09	2.3	0.584	69	8.6	6.7	28	21.51
Konewa	3	0.10	6.5	0.575	133	13.0	7.5	72	15.36
Rokaiwhana	3	0.22	3.1	0.887	66	14.7	7.1	58	14.96
Makawakawa	4	0.21	27.6	0.630	58	14.3	7.0	83	12.03
Raparapawai	3	0.17	7.0	0.931	72	13.3	7.3	84	8.44
Makiekie	2	0.19	5.7	0.646	51	10.9	7.3	109	4.86
Coppermine	3	0.13	4.4	0.592	90	13.5	7.4	51	4.43
Manawatu	3	0.20	4.3	0.603	66	9.4	7.8	65	3.85
Cone	2	0.16	4.5	0.588	50	11.0	7.2	107	0.53
Central Plateau									
Mangatoetoenui	4	0.26	8.6	0.597	139	7.1	8.0	97	18.70
Waikato	3	0.14	3.2	no data	66	10.0	7.8	18	11.38
Te Piripiri	3	0.19	2.0	0.742	69	8.5	7.7	35	2.09
Wahianoa	3	0.26	6.3	0.967	70	12.8	7.4	145	1.73
Whakapapaiti	4	0.28	15.8	0.976	138	11.8	8.2	125	1.02
Oturere	4	0.42	9.4	0.859	112	10.2	8.6	131	0.59
Makomiko	3	0.13	5.3	no data	27	11.3	7.5	107	0.07
Makotuku	2	0.13	5.7	no data	30	9.2	7.4	116	0.03
Waiharakeke	3	0.23	3.5	0.965	159	10.7	8.1	104	0.01
Mangahuia	2	0.20	8.6	no data	38	9.9	7.1	147	0.01
Poutu	5	0.44	7.7	1.053	71	10.6	8.0	80	0.00
Orautoha	3	0.24	2.5	0.548	128	12.8	8.3	166	0.00
Pukeonake	4	0.17	6.8	0.398	23	8.2	7.0	158	0.00

Table 1 (continued). Abiotic characteristics of the study sites assessed between October 2007 and March 2010. Depth, width, velocity, conductivity, temperature and pH measurements are averaged from 5 readings taken concomitant with invertebrate sampling; TTM is an index of bed stability calculated from the movement of *in situ* marked tracer stones. Sites used for validation are in italics.

Site	**Stream order (Strahler, 1952)**	**Mean depth (m)**	**Mean width (m)**	**Mean flow velocity ($m\ s^{-1}$)**	**Mean conductivity ($\mu S\ cm^{-1}$)**	**Mean temperature (°C)**	**Mean pH**	**Substrate D_{50} (mm)**	**TTM**
Mt. Egmont									
Waiwhakaiho	3	0.25	13.8	0.614	109	16.6	7.9	100	50.00
Timaru	2	0.12	3.6	0.295	69	14.6	6.9	213	34.04
Kaiauahi	3	0.17	11.8	0.756	159	17.5	7.9	172	26.68
Manganui	2	0.15	14.7	1.022	56	18.9	6.7	142	20.77
Waiongana	2	0.13	8.9	0.684	112	15.6	7.7	164	17.74
Kapuni	3	0.14	10.7	0.649	61	14.2	7.2	82	14.46
Punehu	4	0.21	4.9	0.706	98	13.4	7.7	77	11.91
Mangorei	2	0.12	6.2	0.715	82	15.2	7.3	>300	10.07
Katikara	2	0.11	2.6	0.403	55	15.5	6.8	168	8.81
Waiaua	3	0.16	6.7	0.727	130	11.9	7.7	50	8.36
Oakura	3	0.14	7.8	0.412	77	14.0	7.2	239	3.14
Kiri	3	0.17	7.9	0.647	51	17.0	7.2	159	2.60
Waiaua Forks	3	0.14	6.5	0.890	124	10.7	7.7	146	1.63
Kaupokonui	3	0.18	7.4	0.580	79	18.1	7.5	150	1.56
Oaonui	2	0.12	5.1	0.796	102	13.7	8.0	73	1.06
Cold	1	0.21	3.4	0.797	80	10.0	7.3	74	0.98
Patea	3	0.21	8.4	0.486	72	12.3	7.0	192	0.31
Waiaua trib.	3	0.19	4.3	0.751	113	11.0	7.5	133	0.02

Chlorophyll *a* pigment concentration on five gravel-sized stones that were collected beside invertebrate samples was assessed as a measure of periphyton biomass. The stones were transported in the dark in cooled stream water before storing them at -18°C. Pigments were extracted in 90% acetone for 18h at 5°C in the dark before the chlorophyll *a* absorption was measured using a Cary 50 Conc UV-Visible spectrometer (Varian, Mulgrave, Australia). Chlorophyll *a* pigment concentration was calculated (Steinman & Lamberti, 1996; APHA, 1998) and corrected for stone surface area which was estimated based on measurement of the a-, b- and c-axes of the gravels with a sliding calliper following Graham, McCaughan & McKee (1988).

Substrate composition of riffles was assessed by measuring the b-axis of > 100 randomly collected particles (Wolman, 1954) and classifying them according to a modified Wentworth scale.

Bed stability

Substrate stability was assessed with two established reference measures including tracer particles and the Pfankuch Stability Index. For the development of the new approach a set of 38 candidate variables (Table 2) were selected from a large array of parameters potentially related to stream bed stability (Knighton, 2008; Petts & Foster, 1985) in respect to importance and practicability of assessment with minimal instrumentation in the field. These candidate variables were evaluated at stream sections with a length of approximately 5 – 7 times stream width to include, where present at least one riffle-pool unit (Keller & Melhorn, 1978).

Candidate variables were associated with the riparian environment (denoted A), the cross (B) and longitudinal profile (C) of the channel, the channel bottom structure (D) and the substrate (E). The density and composition of the riparian vegetation within a 5 m-strip along the active channel zone (A1, A3) reflected bank stabilisation by roots, pressure from land use and frequency and magnitude of flood disturbance. Together with bank erosion (B2) and deposition of derived fine sediments (B3) these parameters indicated sediment supply from banks and slopes. These processes influenced substrate characteristics (E3-6) which can be relevant for bed stability. Transport capacity was assessed in terms of available potential energy (slope) (C1), expenditure on roughness elements (D6), channel adjustments (C2, D4) and flood regime (A2). The channel dynamics resulting from sediment supply and transport capacity were reflected in channel form (B1), structures (D1, D3-5), aquatic vegetation (D2) and substrate characteristics (E1-4, E7). Additionally lithology of the substrate, weather (sunny, overcast or rain) and state of the floodplain substrate (dry or wet) were recorded because these factors could potentially interfere with visual evaluation methods such as the Pfankuch Index (A. C. Schwendel, unpublished data).

Table 2. Assessed properties of the channel, banks and riparian environment potentially related to bed stability, categorical variables were rated at a scale from 1 (associated with stable substrate) to 4 (associated with substrate instability), * variable removed because of intercorrelation.

Variable	**Description**
Riparian environment	
A11	Fraction of pasture on riparian strip (%)
A12	Fraction of native forest on riparian strip (%)
A13	Fraction of exotic vegetation on riparian strip (%)
A14	Fraction of scrub on riparian strip (%)
A15	Fraction of other land cover (none, tussock, etc.) on riparian strip (%)
A21	Ratio of floodplain width to active channel width (m/m)
A22*	Ratio of floodplain width to wet channel width (m/m)
A23	Ratio of active channel width to wet channel width (m/m)
A31	Percentage of high bank surface covered with vegetation (%)
A32	Variation in species and age of high bank vegetation (categorical)
Channel cross profile	
B11	Channel incision, ratio of width to depth (m/m)
B21	Bank erosion (categorical)
B22	Number of recent bank collapses
B31	Number of recently deposited lateral bars of fine material (< coarse gravel)
Channel longitudinal profile	
C11	Bed slope (m/m)
C21	Sinuosity (categorical)
Channel bottom	
D11	Fraction of area affected by erosion and deposition (%)
D21	Occurrence and form of aquatic vegetation (categorical)
D31	Number of multiple barforms
D32	Fraction of area occupied by multiple barforms (%)
D41	Number of riffle-pool and step-pool sequences
D51	Occurrence of bedform clusters (categorical)
D61	Fraction of area with supercritical flow (%)
Substrate	
E11	Grain angularity (categorical)
E21	Constitution of grain surface (categorical)
E31	Interlock and overlap between particles (categorical)
E41	Packing and compaction of particles (categorical)
E51	Fraction of sand and smaller grain size (% area)
E52	Fraction of gravels (% area)
E53	Fraction of cobbles (% area)
E54	Fraction of boulders (% area)
E55	Homogeneity (% area of most abundant size class/ number of size classes present)
E56*	Size index (Sum of fractions weighted by their geometrical mean size of their size class)
E57*	Mean size index (Size index/ number of size classes present)
E58*	Fraction of cobbles and gravels (% area)
E61	Fraction of stable material (large boulders and bedrock) (%)
E71	Occurrence of an armour layer (categorical)

Tracer particles were used to assess stream bed stability. Five randomly selected tracer stones in each of three size classes (D_{50}, D_{70} and D_{90}) were marked with RFID tags (23 mm glass tags, Texas Instruments, Dallas, USA) which were attached *in situ* to stones in riffles using wet curing epoxy-concrete (K273, Nuplex Construction Products, Hamilton, New Zealand). When high turbulence or fast flow velocity prevented underwater application (11% of particles), stones were removed from the river bed for tag attachment and afterwards carefully re-embedded. The percentage of entrained *in situ*-marked tracer stones and re-embedded tracers was significantly correlated (Spearman rank correlation, r_S = 0.70, df = 26, p = 0.0001). Relocation and identification of each tracer stone was carried out contactless using a portable antenna and datalogger (OregonRFID, Portland, USA). Initial and subsequent positions of tagged stones were surveyed using high precision differential GPS or marked on riparian vegetation and stable banks. Relocation surveys took place approximately every two months or after high discharge events over a total period of six months. The entire bed and active channel downstream of the last position of each tracer particle was searched intensively to the next local sediment trap (e.g. riffle) beyond a minimal distance of 50 m. Stones that could not be recovered were assigned a travel distance of 50 m. Although this was less then usually searched it accounted for tracers lost by deep burial (> 0.6 m), storage in inactive parts of the floodplain, tag damage and malfunction. The travelled distance of the tracer particles was converted to an index of bed stability (TTM = sum of tracer movement) using the following approach:

$$TTM = (d_{50}\, s_{50}/n_{50} + d_{70}\, s_{70}/n_{70} + d_{90}\, s_{90}/n_{90}) / (d_{50} + d_{70} + d_{90}) \qquad (1).$$

The sum of the moved distances s of stones of a size class between the surveys is divided by the counted recoveries n and weighted by the geometric mean particle size d of that class.

As a second independent measure of bed stability the bottom component of the Pfankuch Stability Index (BCP) (Pfankuch, 1975) was employed once at each site. The bottom component was preferred over the total index because in previous studies it showed a better relationship with other measures of bed stability (Death & Winterbourn, 1994) and is well related to biological data (Death & Winterbourn, 1995; Suren, 1996). It involves allocation of an observer’s subjective visual evaluation of six attributes, including substrate brightness, angularity, consolidation of particles, percentage of stable materials, evidence of scouring and state of clinging aquatic vegetation, to four predetermined categories to which scores are weighted according to their perceived importance. The sum of the scores results in a stability index, where high values represent low stability.

Data analysis

The collected data were examined in four steps: (1) analysis of invertebrate community composition and structure, (2) development of the SBSI protocol, (3) exploration of the relationship between SBSI, other measures of bed stability and community metrics and (4) validation of the SBSI protocol at independent sites in respect to other bed stability measures and relevance for invertebrate communities.

The composition of the invertebrate community at 46 calibration sites (Fig. 1) was explored with non-metric multidimensional scaling (NMDS) in PC-ORD 5.0 (MjM Software, Gleneden Beach, USA) using standardised (by maximum) invertebrate taxa abundance. Association of the derived axis scores with measured environmental parameters and selected variables from the Freshwater Environments of New Zealand (FWENZ) database (Wild *et al.*, 2005) was assessed using Pearson's correlation. The axis that was best correlated to conventional bed stability measures was selected for calibration of the SBSI. Community diversity (Brillouin Index), taxa number, rarefied taxa number (for 200 individuals following Sanders (1968) and Hurlbert (1971)) and mean number of individuals per 0.1 m^2 were calculated for all sites in PRIMER v6 (Plymouth Marine Laboratory, Plymouth, UK).

The SBSI was developed with linear best subset regression (Statistix 9.0, Analytical Software, Tallahassee, USA) using the selected NMDS axis as dependent variable and the 38 parameters assessed in the field (Table 2) as independent variables. Adjusted R^2, residual mean square error, Mallows' Cp, predicted residual sum of squares and Akaike's Information Criterion for small samples (AICc) were used to compare models.

The relationship between the SBSI site scores, bed stability measured with tracer stones and the bottom component of the Pfankuch Index, and invertebrate community metrics was assessed with Spearman rank correlation to account for the non-normal distribution of variables. This was accomplished for the 46 sites used for SBSI calibration to show the relevance of the SBSI for invertebrate communities and separately for the eight randomly selected validation sites. Significance from the multiple correlations was adjusted using false discovery rate correction (Benjamini & Hochberg, 1995).

RESULTS

Invertebrate community

A total of 127 invertebrate taxa were collected across the 46 SBSI calibration sites with a mean number of individuals per 0.1 m^2 of 194 consisting of on average 33 taxa. Overall Trichoptera comprised the largest number of taxa (35%), followed by Diptera (25%) but the samples were numerically dominated by Ephemeroptera larvae (45% of individuals) of which *Deleatidium* spp. was most common (100% of sites) and abundant (42% of individuals).

Ordination (2D stress 0.16) revealed that only one axis was strongly correlated with bed stability measured with tracer stones and the bottom component of the Pfankuch Index (Table 3). This axis was also associated with periphyton biomass and the fraction of the active channel bare of vegetation (Fig. 2). It was subsequently used to calibrate the SBSI. Sites associated with low bed stability were found in the Ruahine Ranges and around Mt. Egmont and were dominated by *Deleatidium* species. In contrast very stable sites were located mostly on the Central Plateau and had a richer fauna and higher number of individuals.

SBSI protocol

Any intercorrelated variables of assessed reach properties were removed from further analysis (Table 2). Weather and substrate surface wetness were not significantly correlated with other variables but substrate lithology (andesite and greywacke) was significantly correlated to grain angularity (E11) (r_S = 0.82, df = 45, p = 0.0001). Andesitic stones were more rounded than greywacke clasts prior to fluvial transport. Consequently scores for grain angularity were raised by one class at sites with greywacke dominated substrate. Best subset regression, using the NMDS axis best correlated to bed stability measures as dependent variable and the refined set of reach properties as independent variables, led to the identification of an optimal model (Table 4). This model of stream bed stability relevant for invertebrates (SBSI) comprises 13 variables which reflect mostly direct effects of channel dynamics observed on the banks and at the channel bottom. Sediment supply and transport capacity are represented with two variables each which are assessed on the banks and the longitudinal channel profile. Substrate parameters (size and compaction) constitute a second group mirroring effects of sediment dynamics such as sorting. Low variance inflation factors (*VIF*) indicated that collinearity between the variables is low.

Table 3. Correlation of bed stability measurements (total tracer movement – TTM, bottom component Pfankuch Index – BCP), measured (marked with *) environmental parameters and periphyton biomass and downstream variables, segment variables and runoff-weighted upstream catchment variables from the FWENZ database (Wild *et al.*, 2005) with NMDS axes, significant correlations are marked bold ($p < 0.01$).

Axis	**1**	**2**
	r	***r***
Width*	-0.06	0.06
Depth*	0.33	-0.20
Velocity*	0.12	-0.19
Conductivity*	0.22	-0.03
Temperature*	-0.17	0.13
pH*	0.33	-0.09
Riparian Pasture*	0.18	0.25
Riparian bare floodplain*	**-0.44**	-0.33
Periphyton biomass*	**0.44**	0.13
Average slope of *downstream* network	-0.31	0.09
Maximum slope of *downstream* segments	0.18	-0.10
Maximum *segment* slope based on 30 m grid	0.03	0.17
Segment sinuosity	-0.05	0.07
Average *segment* slope	-0.26	-0.12
Shaded fraction of *segment*	-0.02	0.06
Percentage of the *segment* riparian area covered in scrub	0.20	0.13
Upstream mean January air temperature	0.06	**0.49**
Upstream catchment rain days > 15 mm/month	-0.27	0.13
Upstream lake index	0.19	0.00
Percentage of *upstream* catchment annual runoff from alluvium	0.12	0.13
Percentage of *upstream* catchment annual runoff from peat	-0.12	-0.03
Upstream average of calciferous regolith	-0.19	0.14
Upstream catchment average of regolith hardness	-0.10	-0.06
Upstream catchment average of particle size	-0.05	0.04
Percentage of *upstream* catchment consists of bare ground	0.15	**-0.62**
Percentage of *upstream* catchment covered in exotic forest	0.25	-0.10
Percentage of *upstream* catchment covered in indigenous forest	-0.08	**0.39**
Percentage of *upstream* catchment with pastoral landuse	0.17	0.09
Percentage of *upstream* catchment covered in tussock	-0.04	-0.25
Percentage of *upstream* catchment consist of wetland	0.10	0.10
Segment stream order	0.18	-0.02
TTM	**-0.53**	0.04
BCP	**-0.57**	0.09

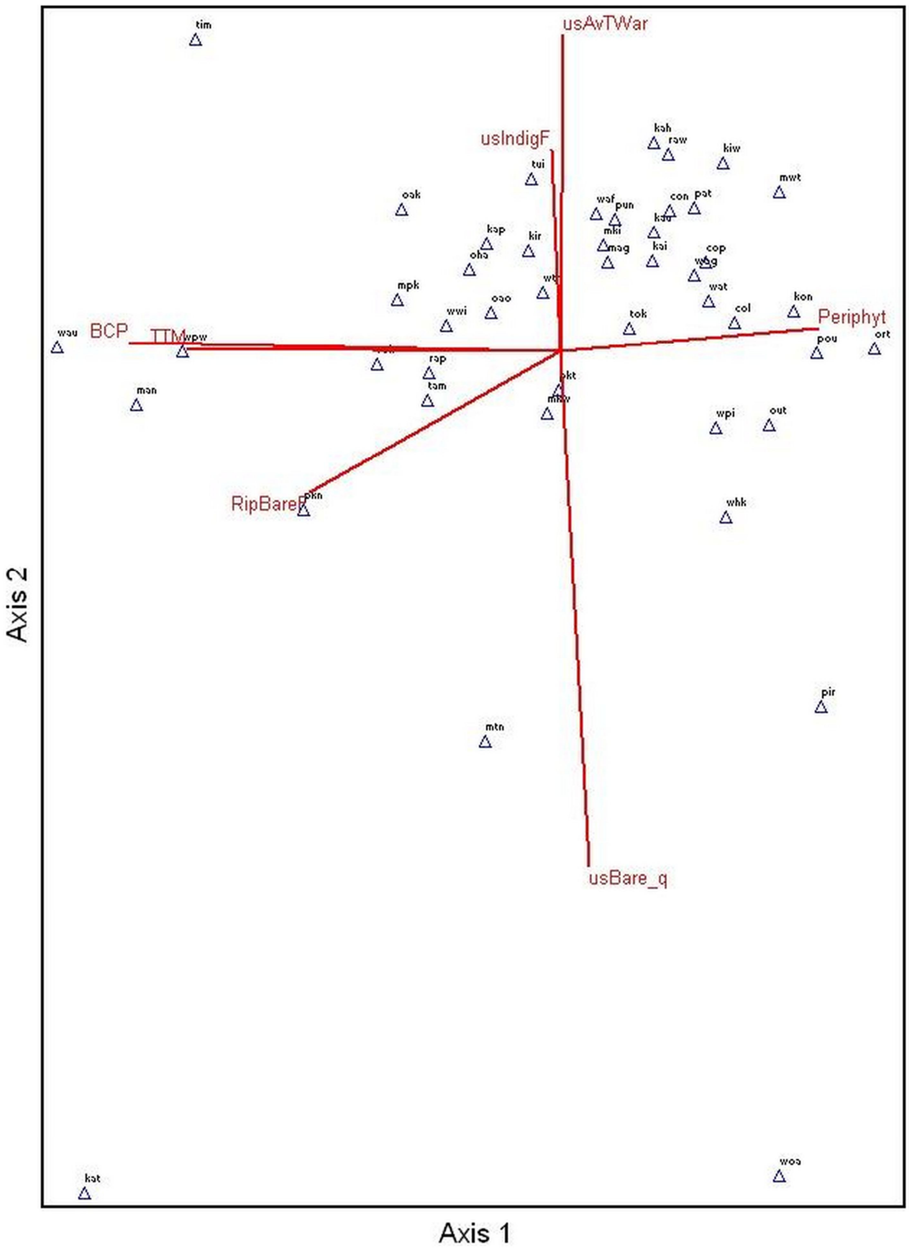

Figure 2. Non-metric Multidimensional Scaling axes of 46 mountain stream invertebrate communities and correlated parameters ($p < 0.01$). Periphyt – periphyton biomass, usAveTWar - Upstream mean January air temperature, usIndigF - Percentage of upstream catchment covered in indigenous forest, TTM – total tracer movement, BCP – bottom component of Pfankuch Index, RipBareF - Dry active channel bare of vegetation under base flow conditions, usBare_q - Percentage of upstream catchment consisting of bare ground.

Based on the regression model a field sheet (Appendix A) was designed that facilitates recording of the variables and allows with the help of a pocket calculator rapid on-site assessment of bed stability. Channel, bank and substrate properties are to be recorded, noted in relevant fields and multiplied with their respective coefficient. The sum for each compartment (e.g. banks, longitudinal profile, channel bottom and substrate) is recorded on the right hand side of the sheet and this column is than added up to result in the SBSI site score.

Table 4. Results of the regression analysis of the NMDS axis against 39 characteristics of the channel and the riparian environment (R^2 = 0.805, adjusted R^2 = 0.726), *VIF* – variance inflation factor

Variables	Coefficient	Std error	T-test if slope ≠ 0	*P* value	*VIF*
Constant	-6.31006	1.00297	-6.29	0.0000	0.0
A23	0.21652	0.06028	3.59	0.0011	2.1
A31	0.01239	0.00375	3.31	0.0023	1.8
B21	0.26123	0.06495	4.02	0.0003	2.0
C11	0.05583	0.02096	2.66	0.0120	1.3
D11	0.29004	0.09619	3.02	0.0050	3.2
D31c	0.28711	0.07222	3.98	0.0004	3.0
D32	0.01200	0.00556	2.16	0.0385	1.9
D51c	0.27049	0.07771	3.48	0.0015	1.6
E11	0.24180	0.12253	1.97	0.0572	1.5
E21	0.16677	0.09457	1.76	0.0874	2.6
E41	0.25041	0.11964	2.09	0.0444	1.7
E51	0.02885	0.00937	3.08	0.0042	2.2
E55	0.05240	0.02019	2.60	0.0141	3.1

Bed stability and community metrics

Correlation between the SBSI site scores and community diversity (Brillouin Index), taxa number, rarefied taxa number and mean number of individuals was highly significant (Table 5). These community metrics were also correlated with bed stability measured with tracers (except taxa number) or the bottom component of the Pfankuch Index but the relationship was always weaker than with the SBSI.

The three measures of bed stability were intercorrelated with the strongest relationship apparent between the bottom component of the Pfankuch Index and SBSI site scores (Table 6).

Validation at independent sites

At eight randomly selected sites a linear relationship was found between bed stability assessed with the bottom component of the Pfankuch Index and the SBSI protocol (Table 6). In contrast the tracer measure was not correlated with any of the two former, however, correlation coefficients were similar or higher than at the sites used for SBSI calibration and the failure of detection of a significant relationship might be due to the low number of sites. Correlation between the Brillouin Index and SBSI site scores was stronger than with any of the other bed stability measures (Table 5). In contrast taxa number, rarefied taxa number and the mean number of individuals were slightly better related to the bottom component of the Pfankuch Index.

Table 5. Correlation of invertebrate community metrics with bed stability assessed with the SBSI protocol, *in situ* marked tracer stones (TTM) and the bottom component of the Pfankuch Stability Index (BCP) at 46 New Zealand streams used for SBSI calibration and at eight independent sites from the same regions for validation. Significance from multiple correlations was adjusted using False Discovery Rate and is indicated by * for α = 0.05, ** for α = 0.005 and *** α = 0.001.

	SBSI calibration sites			**Validation sites**		
	SBSI	**TTM**	**BCP**	**SBSI**	**TTM**	**BCP**
Brillouin Index	-0.75***	-0.52***	-0.68***	-0.81*	-0.78*	-0.73*
Taxa number	-0.56***	-0.27	-0.54***	-0.73*	-0.34	-0.82*
Rarefied taxa number for 200 individuals	-0.77***	-0.51***	-0.55***	-0.73*	-0.40	-0.82*
Mean number of individuals	-0.75***	-0.35*	-0.45**	-0.74*	-0.34	-0.86*

Table 6. Correlation of bed stability assessed with the SBSI protocol, *in situ* marked tracer stones (TTM), the bottom component of the Pfankuch Stability Index (BCP), and the first NMDS axis at 46 New Zealand streams used for SBSI calibration and at eight independent sites from the same regions for validation. Significance from multiple correlations was adjusted using False Discovery Rate and is indicated by * for α = 0.05, ** for α = 0.005 and *** α = 0.001.

	SBSI calibration sites			**Validation sites**	
	TTM	**BCP**	**NMDS axis 1**	**TTM**	**BCP**
SBSI	0.48***	0.66***	-0.86***	0.47	0.75*
TTM		0.46**	-0.56***		0.67
BCP			-0.59***		

DISCUSSION

The presented protocol for assessment of bed stability relevant for invertebrates (SBSI) produces site scores highly related to invertebrate community diversity and structure. This relationship is stronger than that of any traditional bed stability measure with community metrics at the calibration sites. The SBSI method is calibrated on the response of invertebrate communities, signified by a NMDS axis, to varying degrees of bed stability as measured with traditional techniques and compares well to the NMDS calibration axis (Table 6, Fig. 3). The NMDS axis used for calibration of the SBSI is strongly associated with bed stability measures and periphyton biomass. Periphyton as a potential food source for invertebrates influences invertebrate community composition

(Death, 2002) but biomass itself is affected by bed movement and can consequently be seen as a proxy for bed stability. The link of the NMDS calibration axis with the percentage of bare active channel reflects the flood regime which influences bed stability. Lack of vegetation on the banks can indicate regular inundation with flows competent to strip vegetation and to prevent perennial plant growth. Alternatively it can be caused by active bank erosion during lower discharges when undercutting of banks can lead to failure. This reflects a high degree of channel activity and sediment input and accordingly bed disturbance. Hence it is reasonable to interpret the NMDS axis as being dominated by bed stability.

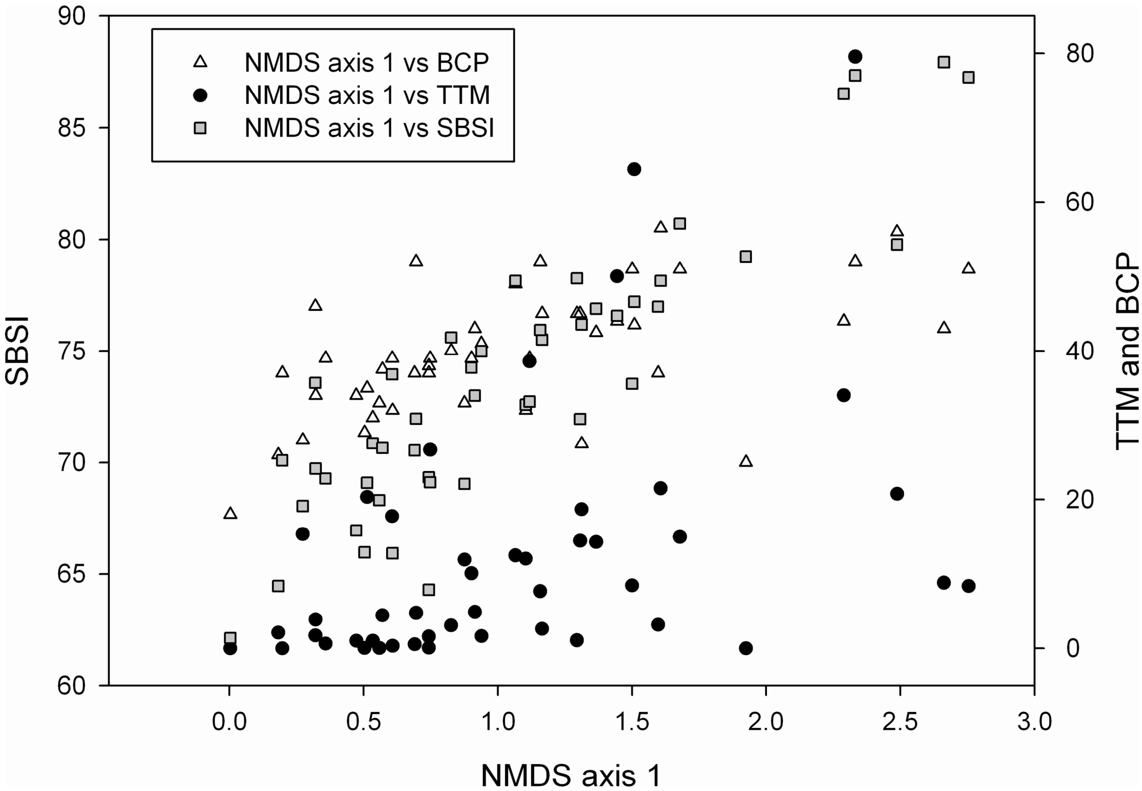

Figure 3. Stream bed stability assessed with the Stream Bed Stability for Invertebrates Index (SBSI), *in situ* marked tracer stones (TTM) and the bottom component of the Pfankuch Stability Index (BCP) plotted against the NMDS axis used for calibration of the SBSI.

Validation at independent sites showed the applicability of the SBSI approach and its relevance for invertebrates. Connection with community diversity is improved when the SBSI is used compared to other bed stability measures but the bottom component of the Pfankuch Index performs slightly better with number of taxa and individuals (Fig. 4). However, the SBSI approach can account for regional variation in parameters such as lithology and should be less affected by observer subjectivity than the purely visual assessment of the Pfankuch Index.

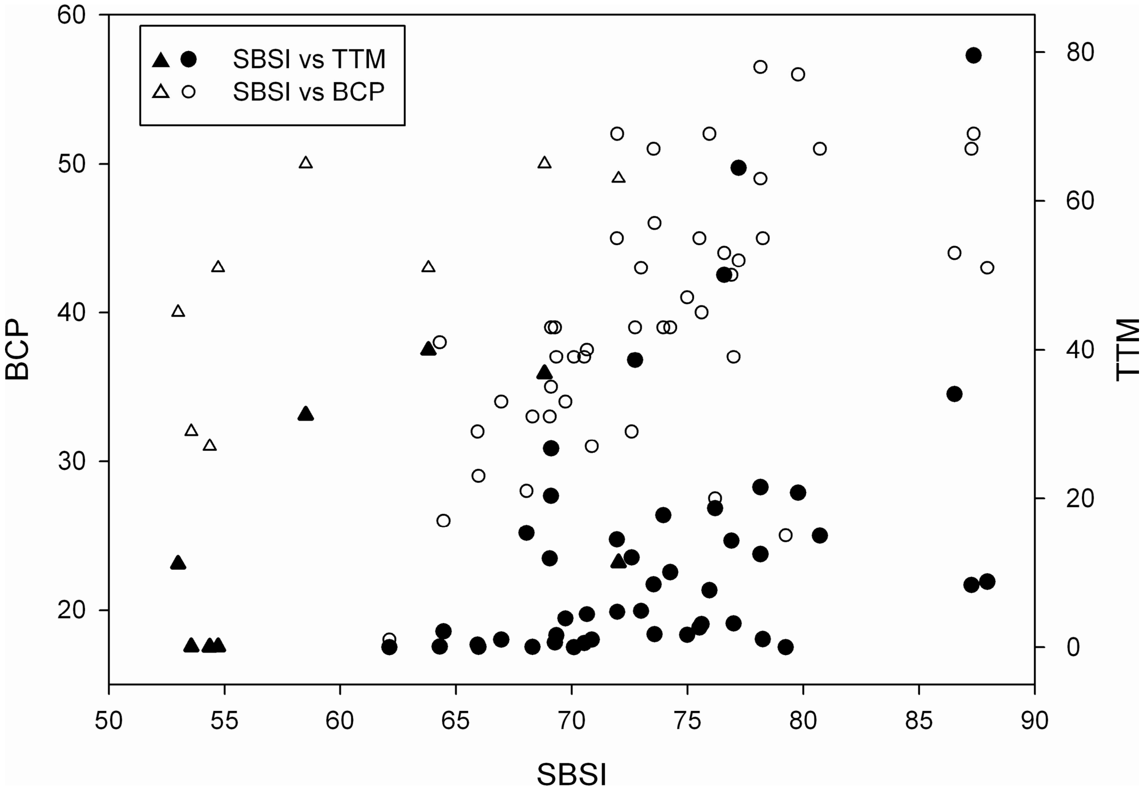

Figure 4. Site scores of the Stream Bed Stability for Invertebrates Index (SBSI) plotted against conventional measures of bed stability: *In situ* marked tracer stones (TTM, filled symbols) and the bottom component of the Pfankuch Stability Index (BCP, open symbols). Sites used for validation are shown as triangles.

The parameters of the SBSI model are summarised in Table 7. Theoretically the total SBSI score ranges between 19 (stable) and 201 (unstable) when extreme values for all parameters are assumed. However, the calibration sites which according to the bed stability measurements include both very stable and unstable reaches, cover a range of only 62 to 88. Thus values higher than 80 represent sites with low bed stability whereas SBSI smaller than 70 indicates high bed stability. The substrate sand fraction and homogeneity are potentially the most powerful parameters but their extreme values seldom occur in mountain streams. At the calibration sites bank vegetation cover and abundance of multiple barforms had the highest mean scores (10.8 and 9.1 respectively) while slope, area of multiple barforms and sand fraction achieved lowest mean scores (< 2.3). In the following section for each parameter the link with bed stability is explored and assessment in the field with the help of the provided field sheet (Appendix A) is described.

Friction slope determines the total energy available for transport and entrainment of particles in a stream. Water surface or stream bed gradient is often used a as a surrogate because it is easier to measure (Schwendel *et al.*, 2010). When the ratio of flow depth to roughness element height is high (e.g. during high discharge) this is an acceptable first-order approximation. Bed slope can be estimated in the field, if necessary with the help of an Abney level.

Table 7. Parameters of the stream Bed Stability for Invertebrates (SBSI) survey with weights and potential range of values (*extreme values estimated) and scores.

	Parameter	Weight	Range	Minimum score	Maximum score
C11	Bed slope	0.56	0.0001* – 1*	0.00006	0.56
A23	Active /wet channel	2.17	1 – 10*	2.17	21.70
B21	Bank erosion	2.61	1 – 4	2.61	10.44
A31	Bank vegetation cover	0.12	0 – 100	0.00	12.00
E51	Sand fraction	0.29	0 – 100	0.00	29.00
E55	Substrate homogeneity	0.52	4 – 100	2.08	52.00
E41	Packing and compaction	2.50	1 – 4	2.50	10.00
E21	Particle surface	1.67	1 – 4	1.67	6.68
E11	Grain angularity	2.42	1 – 4	2.42	9.68
D11	Reworked area	2.90	1 – 4	2.90	11.60
D31	Multiple barform number	2.87	0 – 5	0.00	14.35
D32	Area of multiple barforms	0.12	0 – 100	0.00	12.00
D51	Bedform clusters	2.70	1 – 4	2.70	10.80
	Total SBSI			19.05	200.81

The active channel includes the zone that is dry at baseflow stage but is subject to regular inundation. It is well coupled to the channel and it is involved in processes of sediment transport. In the field this zone can be determined by the absence or scarcity of perennial vegetation and the presence of recent flood debris. The ratio of the active channel width to wetted baseflow channel width is low (e.g. close to 1) for hydrologically stable streams with small variation in flows (e.g. lake fed). With increasing frequency and magnitude of floods a higher ratio is expected although local geomorphology can interfere (e.g. narrow valleys, bedrock constrictions and bank composition). Both, this parameter and stream bed slope quantify potential transport capacity and are expressed on a continuous scale. Considering the potential range of values, bed slope has much less weight than the active channel to baseflow channel width ratio in the regression model.

The sediment supply from banks and lateral channel erosion is represented by the categorical parameter bank erosion. It is evaluated in the field on a scale ranging from none over weak and moderate to strong. Strong bank erosion means that eroded surfaces or collapsed banks are present throughout the reach and that lateral erosion is severe. Moderate bank erosion depicts a state where either light and discontinuous bank erosion is common or locally bank erosion is strong. The category "weak bank erosion" is chosen when only patchy and light bank erosion occurs. Extrinsic causes for bank collapse such as trampling cattle or human interference are included in this parameter and are not separately assessed.

The percentage of riparian vegetation cover of the upper banks (above bankfull stage) specifies average vegetation density of the understorey (e.g. stems per m^2), not the canopy cover along both sides of the reach. It was expected to be positively related to bed stability because vegetation reduces surface erosion and dense roots stabilise the banks. However, regression showed an inverse relationship to bed stability which can be explained by land use, altitude aspects and bank composition. The sites with low bank vegetation cover were either in high altitude locations on the Central Volcanic Plateau or natural vegetation was scarce. Anthropogenic land use practices like forestry or gravel mining on floodplains can cause low density of bank vegetation. They are only profitable on relatively stable ground thus reflecting bank stability. Altitude mirrors catchment size and is thus related to stream power. Hence high altitude sites above the tree line with low vegetation cover have usually more stable upper banks than low altitude sites. This parameter combines these two causes of bank vegetation cover while bank protection by roots is obviously of less importance on the infrequently flood-affected upper banks. We used an accuracy of 5% for bank cover estimations.

Substrate size distribution reflects erosion, sedimentation and transport processes. Fine particles require less shear force for selective entrainment than coarse grains. Hiding and protrusion effects can prevent selective entrainment but visual surface substrate assemblage assessment does usually capture only patches dominated by sand and not hiding sand grains between larger particles. Thus the percentage of sand and smaller grain sizes present and the associated low critical shear stress can indicate high sediment mobility given sufficient transport capacity. Erosion and sedimentation of sandy substrate and associated changes in habitat can cause shifts in invertebrate community composition (Palmer *et al.*, 1992; Downes *et al.*, 2006).

Substrate size homogeneity can be caused by sorting (e.g. downstream fining) but depends also on catchment substrate lithology and sediment sources (reworking of older alluvial deposits, hillslope collapses or fresh tributary inputs). However, in mountain streams where substrate variety is usually limited by catchment size sorting can be instrumental for substrate size composition. Because sorting processes require substrate movement the parameter “substrate homogeneity” is positive related to instability. In the field it requires estimation of the percentage cover of the size classes silt (< 0.063 mm), sand (0.063 mm – 2 mm), gravel (2 mm – 64 mm), cobble (64 mm – 256 mm) and boulder (> 256 mm). Then the aerial cover fraction of the dominant size class is divided by the number of classes present.

Packing and compaction of particles is highly developed in stable substrate channels. It can be an effect of incompetent flows or lack of sediment supply. This parameter should not be confounded with overlap of particles because of the stone shape of some lithologies. It can easily tested by walking in the bed and four categories are distinguished. Tight packing means that in the entire channel stones move only minimally when full body weight is applied and includes bedrock. Wedged packing depicts conditions where only parts of the channel have tight packing or where the entire substrate moves under the foot but does not principally change position (e.g. is entrained afterwards). The “moderately loose” category includes a mix of all four categories throughout the channel skewed towards looser conditions. Stones may change position when stepped on but should not be entirely dislodged. Loose packing means that the foot sinks into the substrate and particles move easily.

The categorical parameter “Constitution of particle surface” has been modified from the categories of brightness defined by Pfankuch (1975). It incorporates surface roughness and brightness which can be effects of particle movement. However, it needs to be distinguished between different lithologies (e.g. limestone and volcanic rocks) which have varying spectra of colours and brightness. Particles of different geological origin can have variable surface roughness after the same transport length. Stains and plant growth on stones are dependent on temperature, light, nutrient levels and mineralisation. It is also advisable to allow for weather conditions and surface moisture when stones on the floodplain are investigated: Wet surfaces on a rainy day can appear much duller than in dry and sunny conditions. The categories range from more than 95% of stained particles with considerable organic film and growth, over “65 – 95% dull” and “35 – 65% dull” to “less than 35% dull”.

The parameter “Grain angularity” was also adopted from the Pfankuch Index. It ideally expresses the amount of work performed on a particle during fluvial transport but the characteristic depends very much on lithology in terms of hardness, cleavability, stratification and mineral content as well as distance from source. Thus adjustment of the scores of sharp and angular rock types such as mudstone greywacke to the scores of particles that are already rounded prior to fluvial transport (e.g. some volcanic rocks) by the observer is recommended. The categories include particles well rounded in all dimensions with smooth surfaces, corners and edges well rounded in two dimensions, corners and edges rounded combined with flat surfaces and sharp edges and corners with roughened surfaces.

The percentage of reworked area describes the amount of obvious recent erosion (e.g. bright sections) and sedimentation (bars of fines, filled pools) of the channel bottom. A fraction of more than 80% is rated as very high, 50 – 80% as high, 20 – 49% as intermediate and less than 20% as low.

Multiple barforms are a feature of dynamic channels able to adjust to changing sediment supply and floods. However, over short-term they can be relatively stable channel structures creating various habitats and providing potential refugia during smaller spates. Surprisingly, the number of multiple barforms is positively related to bed stability in the SBSI model which might reflect habitat heterogeneity. In contrast their size as a fraction of the total bed area decreases with SBSI bed stability because large areas of multiple barforms indicate substantial channel dynamics. The number of multiple barforms is classified in six categories which are indexed from 0 to 5.

Bedform clusters locally influence flow turbulence causing expenditure of energy which is not available to entrain substrate. They are commonly thought to be resistant to entrainment during high-discharge events (de Jong, 1992; Reid, Frostick & Brayshaw, 1992) but depending on flood magnitude bed form clusters can be as unstable as single surface stones (Matthaei & Huber, 2002). Thus their suitability as refugia for invertebrates and periphyton varies and they do not necessarily support richer invertebrate faunas because of increased habitat heterogeneity (Biggs *et al.*, 1997; Francoeur, Biggs & Lowe, 1998; Matthaei & Huber, 2002). For the SBSI protocol abundance of bedform clusters is estimated in the field visually and categorised in four classes ranging from none to abundant (e.g. > 5% aerial cover).

CONCLUSIONS

The presented method for the reach-scale assessment of bed stability relevant for invertebrate communities in upland streams seeks to combine statistical derived relationships between bed stability characteristics and the invertebrate community and causal connections. This distinguishes it from other approaches which aim to measure characteristics of bed stability *per se* but often are not very well related to responses of different groups of biota. The SBSI protocol provides a similar or stronger relationship with community diversity and composition than traditional bed stability measures.

Index calibration was conducted in upland streams to avoid the confounding effects of water quality on invertebrate communities but potentially the SBSI protocol could be applied to a wide range of streams. The SBSI method is straightforward, cost- and time-effective and requires minimal instrumentation (Abney level and pocket calculator) and only one site visit is necessary. Interference with the substrate is low which facilitates concomitant invertebrate sampling and the stability score can be calculated on-site. It should suffer less from difficulties of purely visual assessments (such as the Pfankuch Index) and can account for regional differences (e.g. in lithology). However, observer bias potentially can be a problem. This and applicability at numerous independent sites need to be tested to allow analysis of deficits and adjustments.

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Appendix A: SBSI field sheet

Stream Bed Stability relevant for Invertebrates

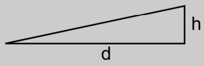
River ____ Date ____ Observer ____

Reach ____ Koordinates ____ ____ Altitude ____

Weather: sunny overcast rain Surface conditions: dry wet Lithology ____

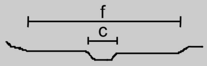
banks + longitudinal profile

Bed slope



h ____ m
d ____ m
s = h/d = ____

Floodplain



active channel width
f ____ m
wetted channel width
(baseflow) c ____ m
r = f /c = ____

Bank erosion

	b
strong	4
moderate	3
weak	2
none	1

Bank vegetation cover

v = ____ %

s * 0.56 = ____ r * 2.17 = ____ b * 2.61 = ____ v * 0.12 = ____ SUM ____

substrate

Substrate composition

s1 silt ____ %
(<0.063 mm)
s2 sand ____ %
(<2 mm)
s3 gravel ____ %
(2 - 64 mm)
s4 cobble ____ %
(64 - 256 mm)
s5 boulder ____ %
(> 256 mm)

Substrate heterogeneity

number of fractions
present n ____
% of dominant
fraction m ____
u = m/n = ____

Packing + compaction

	p
loose	4
moderatly loose	3
wedged	2
tight	1

Particle surface

	d
<35% dull	4
35-65% dull	3
>65% dull	2
dark, stained	1

Grain angularity

edges & corners:

	a
well rounded in 3D	4
well rounded in 2D	3
rounded	2
sharp	1

s2 * 0.29 = ____ u * 0.52 = ____ p * 2.50 = ____ d * 1.67 = ____ a * 2.42 = ____
SUM ____

channel bottom

Reworked area

	e
>80%	4
50-80%	3
20-49%	2
<20%	1

Multiple barforms

number	g
0	5
1	4
2	3
3	2
4	1
5+	0

area

k ____ %

Bedform clusters

	t
abundant	4
common	3
some	2
none	1

e * 2.90 = ____ g * 2.87 = ____ k * 0.12 = ____ t * 2.70 = ____ SUM ____

SBSI ____

SBSI 1.3 May 2010

Chapter 6

A macroinvertebrate index to assess stream bed stability

This chapter has been accepted for publication in *Marine & Freshwater Research*:

Schwendel A. C., Joy M. K., Death R. G. & Fuller I. C. (in press) A macro-invertebrate index to assess stream bed stability. *Marine & Freshwater Research.*

ABSTRACT

Biotic indices based on community composition and calculated from sensitivity scores assigned to individual taxa are commonly used as indicators for ecological integrity of fluvial ecosystems. Macroinvertebrate indices can assess water quality but invertebrate community composition also responds to other environmental factors including stream bed disturbance. This study presents a biotic community index that assesses stream bed stability in stony riffles. This Macroinvertebrate Index of Bed Stability is calibrated on transport and entrainment of in situ-marked tracer stones in 46 streams in New Zealand's North Island, representing a wide range of substrate stability. Scores were investigated for 67 common invertebrate taxa using Indicator Species Analysis based on taxa abundance at varying levels of substrate stability. The resulting site score, weighted by taxa abundance, improved a predictive model of bed stability, generated with model trees, when added to the pool of habitat variables and explained 69% of the variation in bed stability. Site scores were strongly correlated with measured bed stability at the development sites, but not at eight independent validation sites, suggesting the need for further testing on a larger dataset including streams in other regions of New Zealand, and overseas.

INTRODUCTION

Stream invertebrate communities are subject to a multitude of environmental influences on varying geographical scales that affect community composition and relative abundances of taxa (Winterbourn, 1981; Quinn & Hickey, 1990). Thus, they are often used to assess environmental characteristics of waterways, in particular water quality (Rosenberg & Resh, 1993; Hynes, 1994; Boothroyd & Stark, 2000). Amongst these influences, fluctuations in discharge, particularly floods, can have strong effects on habitat and community structure (Resh *et al.*, 1988; Reice, Wissmar & Naiman, 1990; Lake, 2000). Increased shear stress exerted by flowing water alone can displace animals and plants. At a certain threshold of flow velocity, fine sediments may be washed out, and with increasing discharge the entire substrate may be eventually entrained, causing habitat alteration, death and dislocation of invertebrates (Lancaster & Hildrew, 1993; Bond & Downes, 2000; Bond & Downes, 2003) and scour of food sources such as periphyton (Biggs, Smith & Duncan, 1999). Invertebrates may be washed downstream (Poff & Ward, 1991) or seek refuge in stable parts of the channel (Townsend & Hildrew, 1994) or temporarily on the floodplain (Matthaei & Townsend, 2000). Within the channel, the hyporheic interstitial zone (DoleOlivier, Marmonier & Beffy, 1997), stable surface stones (Matthaei, Arbuckle & Townsend, 2000), patches of low shear stress (Lancaster & Hildrew, 1993) and stream margins (Rempel, Richardson & Healey, 1999) can all act as refugia during floods. Ecologically meaningful measurement of bed stability can be difficult because the variety of available techniques assess only a specific subset of bed stability characteristics, such as entrainment, particle transport, deposition or abrasion (Schwendel, Death & Fuller, 2010a), and the relationship between these measures and invertebrate community structure may differ (Schwendel *et al.*, in press). However, most studies agree that invertebrate abundance and diversity decreases with increasing bed disturbance (Vinson & Hawkins, 1998; Death, 2008, but see Townsend, Scarsbrook & Doledec, 1997a). Furthermore, bed stability assessment can be time-consuming and/or observer-biased (Schwendel *et al.*, 2010a). Thus, determination of substrate stability based on biological monitoring may be a more cost-effective alternative than traditional measurements, especially if the invertebrate community has already been sampled, for example to assess water quality. Stream invertebrate communities can indicate habitat condition over longer time scales (e.g. life cycle) and can account for a combination of factors influencing stream habitats.

Influence of substrate stability on community composition may complicate biological assessment of water quality and thus confound stream health monitoring using invertebrates (Stark, 1993). A macroinvertebrate index of bed stability may provide background information to improve interpretation of water quality based on biological criteria. A macroinvertebrate index of bed stability could also be used to monitor the impacts of anthropogenic physical disturbance, such as when river beds are modified for flood control or for gravel extraction. In studies of invertebrate ecology, it can be used to account for the habitat parameter stream bed stability, and could make direct measurement redundant. Consequently, in this paper we develop an index of bed stability for common invertebrate taxa of stony riffle communities in New Zealand. The resulting site scores were compared with measured bed stability at independent sites, as well as with modelled data from streams in the southern North Island of New Zealand.

MATERIALS AND METHODS

Study sites

For development and validation of the Macroinvertebrate Index of Bed Stability, 54 upland stream reaches in the southern North Island of New Zealand were investigated between October 2007 and March 2010. Sites were located in the Tararua Range, Ruahine Range, Central Volcanic Plateau and around Mt. Egmont (398040S to 408540S; 1738570E to 1768120E) (Fig. 1). The 46 sites used for development of the index were interspersed with eight randomly selected validation sites. The catchments are dominated by native vegetation and natural land cover (51 - 100%, in average 87%) and anthropogenic influence is generally low (e.g. < 0.1% urban landuse (Wild et al., 2005) and no infrastructure upstream of sites). Thus water quality was expected to be within a natural range. Substrate size as assessed on > 100 randomly collected stones (Wolman, 1954), ranged between gravels and cobbles although some sites contained a considerable proportion of boulders or sand (Table 1).

Invertebrates and habitat variables

At each site five Surber samples (500 µm mesh, 0.1 m^2) were collected from riffles under baseflow conditions, at least two weeks after the last spate (discharge larger than three times median flow but not exceeding bankfull stage) to ensure the species assemblage characteristic for the site was sampled. Seasonal variability in New Zealand stream invertebrate communities is generally low (Towns, 1981; Winterbourn, 2004) and seasonal influences on biotic indices are minor (Stark & Phillips, 2009). To test for seasonal variation in invertebrate assemblage, at 18 sites samples were collected three times throughout the year and community composition was found not to vary significantly (Schwendel *et al.*, in press and J. Tonkin, unpublished data). Samples were stored in 4% formalin or 60% isopropyl alcohol. Very abundant groups of taxa (> 300 individuals per sample) were subsampled following Vinson & Hawkins (1996): samples expected to contain large numbers were divided in equal subsamples of which one was initially searched for invertebrates. Only those taxa which number of individuals did not exceed 300 in the first subsample were searched for in the second subsample. Invertebrates were identified to the lowest possible taxonomic level using the keys in McFarlane (1951), Towns & Peters (1996), Winterbourn (1973), Winterbourn, Gregson & Dolphin (2006) and an unpublished key for Hydrobiosidae (B. Smith, NIWA, Hamilton, New Zealand).

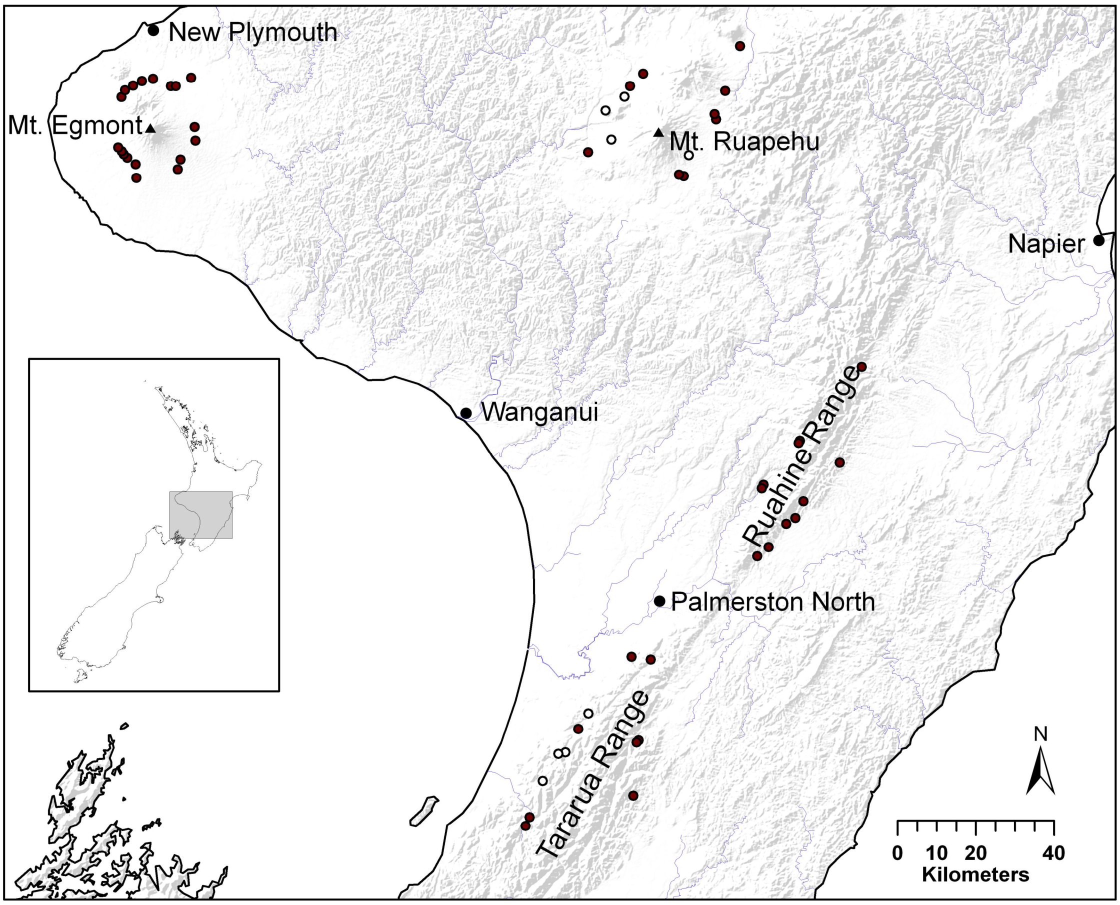


Figure 1. Stream reaches in the southern North Island of New Zealand used for development (filled circles) and validation (empty circles) of the Macroinvertebrate Index of Bed Stability.

Stream width, flow depth, near-bed flow velocity were measured at each invertebrate sampling point (Table 1). Flow velocity (averaged over 60 s) was recorded with an electromagnetic flow meter (Model 801, Valeport Ltd., Devon, UK) 0.05 m above the stream bottom.

Table 1. Abiotic characteristics of the study sites measured between October 2007 and March 2010 at 54 North Island, New Zealand rivers. Depth, width, velocity and conductivity measurements are averaged one-off readings taken concomitant with invertebrate sampling, reach gradient, stream order and altitude are derived from the FWENZ database (Wild *et al.*, 2005), TTM is an index of bed stability calculated from the movement of *in situ* marked tracer stones, sites used for validation are in italics. This table is continued on the following page.

Site	Stream order (Strahler, 1952)	Mean depth (m)	Mean width (m)	Mean flow velocity ($m\ s^{-1}$)	Mean conductivity ($\mu S\ cm^{-1}$)	Reach gradient (%)	Altitude (m)	Substrate D_{50} (mm)	TTM (m)
Tararua Range									
Waitohu	4	0.20	6.8	no data	84	2.0	137	86	39.94
Waiotauru	5	0.26	17.4	0.716	68	1.0	118	84	38.57
Waikawa	4	0.18	6.1	no data	76	1.0	190	99	36.78
Panatewaewae	3	0.11	7.0	no data	74	1.0	186	103	31.21
Kiriwhakapapa	3	0.15	6.5	0.603	64	1.0	313	59	20.43
Ohau	4	0.24	14.0	0.694	72	1.0	138	64	14.30
Pukeatua	3	0.18	9.7	0.720	80	4.0	136	84	12.50
Makahika	4	0.17	6.3	no data	66	2.0	174	82	11.18
Mangatainoka	4	0.17	11.7	0.694	52	2.0	360	108	7.67
Rawnsley	2	0.11	5.1	0.422	48	6.0	348	159	4.74
Tokomaru	4	0.14	14.6	0.707	81	0.2	40	85	3.07
Kahuterawa	4	0.15	3.5	0.616	68	0.3	322	85	0.06
Ruahine Range									
Waipawa	3	0.20	5.4	1.000	103	2.0	598	59	79.56
Tamaki	2	0.17	3.3	0.811	64	4.0	413	35	64.46
Mangapuaka	2	0.09	2.3	0.584	69	3.0	398	28	21.51
Konewa	3	0.10	6.5	0.575	133	2.0	212	72	15.36
Rokaiwhana	3	0.22	3.1	0.887	66	2.0	368	58	14.96
Makawakawa	4	0.21	27.6	0.630	58	2.0	195	83	12.03
Raparapawai	3	0.17	7.0	0.931	72	2.0	318	84	8.44
Makiekie	2	0.19	5.7	0.646	51	3.0	560	109	4.86
Coppermine	3	0.13	4.4	0.592	90	4.0	292	51	4.43
Manawatu	3	0.20	4.3	0.603	66	5.0	521	65	3.85
Cone	2	0.16	4.5	0.588	50	3.0	552	107	0.53
Central Plateau									
Mangatoetoenui	4	0.26	8.6	0.597	139	2.0	917	97	18.70
Waikato	3	0.14	3.2	no data	66	1.0	1076	18	11.38
Te Piripiri	3	0.19	2.0	0.742	69	2.0	989	35	2.09

Table 1 (continued). Abiotic characteristics of the study sites measured between October 2007 and March 2010 at 54 North Island, New Zealand rivers. Depth, width, velocity and conductivity measurements are averaged one-off readings taken concomitant with invertebrate sampling, reach gradient, stream order and altitude are derived from the FWENZ database (Wild *et al.*, 2005), TTM is an index of bed stability calculated from the movement of *in situ* marked tracer stones, sites used for validation are in italics.

Site	Stream order (Strahler, 1952)	Mean depth (m)	Mean width (m)	Mean flow velocity (m s^{-1})	Mean conductivity (µS cm^{-1})	Reach gradient (%)	Altitude (m)	Substrate D_{50} (mm)	TTM (m)
Central Plateau (continued)									
Wahianoa	3	0.26	6.3	0.967	70	3.0	939	145	1.73
Whakapapaiti	4	0.28	15.8	0.976	138	1.0	886	125	1.02
Oturere	4	0.42	9.4	0.859	112	2.0	776	131	0.59
Makomiko	3	0.13	5.3	no data	27	2.0	776	107	0.07
Makotuku	2	0.13	5.7	no data	30	2.0	830	116	0.03
Waiharakeke	3	0.23	3.5	0.965	159	2.0	887	104	0.01
Mangahuia	2	0.20	8.6	no data	38	2.0	881	147	0.01
Poutu	5	0.44	7.7	1.053	71	1.0	506	80	0.00
Orautoha	3	0.24	2.5	0.548	128	0.6	715	166	0.00
Pukeonake	4	0.17	6.8	0.398	23	3.0	842	158	0.00
Mt. Egmont									
Waiwhakaiho	3	0.25	13.8	0.614	109	2.0	364	100	50.00
Timaru	2	0.12	3.6	0.295	69	5.0	364	213	34.04
Kaiauahi	3	0.17	11.8	0.756	159	2.0	366	172	26.68
Manganui	2	0.15	14.7	1.022	56	2.0	466	142	20.77
Waiongana	2	0.13	8.9	0.684	112	1.0	251	164	17.74
Kapuni	3	0.14	10.7	0.649	61	3.0	476	82	14.46
Punehu	4	0.21	4.9	0.706	98	2.0	267	77	11.91
Mangorei	2	0.12	6.2	0.715	82	3.0	344	> 300	10.07
Katikara	2	0.11	2.6	0.403	55	7.0	419	168	8.81
Waiaua	3	0.16	6.7	0.727	130	2.0	349	50	8.36
Oakura	3	0.14	7.8	0.412	77	5.0	395	239	3.14
Kiri	3	0.17	7.9	0.647	51	7.0	575	159	2.60
Waiaua Forks	3	0.14	6.5	0.890	124	3.0	341	146	1.63
Kaupokonui	3	0.18	7.4	0.580	79	2.0	393	150	1.56
Oaonui	2	0.12	5.1	0.796	102	3.0	314	73	1.06
Cold	1	0.21	3.4	0.797	80	4.0	444	74	0.98
Patea	3	0.21	8.4	0.486	72	3.0	518	192	0.31
Waiaua trib.	3	0.19	4.3	0.751	113	3.0	350	133	0.02

At each sampling site, conductivity was measured using Eutech ECScan Lowþ (Eutech Instruments, Singapore). Five gravelsized stones were collected concurrently with invertebrate sampling to measure periphyton biomass by measuring chlorophyll *a* absorption using a Cary 50 Conc UV-Visible spectrometer (Varian, Mulgrave, Australia), and calculating chlorophyll a pigment concentration on the upper side of the gravels (Schwendel *et al.*, in press). Reach gradient measurements were attained with high-precision differential GPS (R8, Trimble Navigation Limited, Sunnyvale, USA) or a tacheometric Electronic Distance Measurement system (GTS 701, Topcon Corporation, Tokyo, Japan).

Bed stability

Stream bed stability was assessed at each site over a period of six months, which included the invertebrate sampling date(s), by monitoring the movement of 15 tracer particles, with five representing each of the size classes D_{50}, D_{70} and D_{90}. These tracer stones were located in riffles and marked *in situ* with RFID tags (23 mm glass tags, Texas Instruments, Dallas, USA) which were attached to stones using wet curing epoxy-concrete (K273, Nuplex Construction Products, Hamilton, New Zealand) without altering erodibility (Schwendel *et al.*, submitted). During the study periods, all sites experienced several spates and at least one flood event (e.g. Schwendel, Fuller & Death, 2010b). Approximately every two months, or after high discharge events, the entire bed and active floodplain at least 50 m downstream of the last position of a tracer particle was searched intensively with a portable antenna connected to a datalogger (OregonRFID, Portland, USA), which allowed contactless relocation and identification of tracer stones. Initial and subsequent positions of tagged stones were surveyed accurately using high-precision differential GPS and Total Station ground surveys, or marked on riparian vegetation and stable banks. Stones that could not be recovered were assigned a travel distance of 50 m. Although 50 m was less than the length of stream that was usually searched, it accounted for tracers lost by deep burial (> 0.6 m), storage in inactive parts of the floodplain, tag damage and malfunction. The travelled distance of the tracer particles was converted to an index of bed stability (TTM = sum of tracer movement) using the following approach:

$$TTM = (d_{50}\, s_{50}/n_{50} + d_{70}\, s_{70}/n_{70} + d_{90}\, s_{90}/n_{90}) / (d_{50} + d_{70} + d_{90}) \qquad (1)$$

The sum of the moved distances s of stones of a size class between surveys is divided by the counted recoveries n and weighted by the geometric mean particle size d of that class. For further analysis sites were grouped in 4, 7 and 11 classes according to their bed stability (Table 2). Class boundaries were chosen according to natural breaks in the data structure identified by a univariate cluster analysis algorithm using Euclidean distances between log-transformed TTM values. Each class contained a similar number of sites.

Table 2. Classification of total tracer movement (TTM) in 11, 7 and 4 classes of bed stability which were used as input variables for Indicator Species Analysis; the number of sites contained within a group are given in brackets.

<table>
<tr><th>TTM</th><th>11 classes</th><th>7 classes</th><th>4 classes</th></tr>
<tr><td>0</td><td>0 (3)</td><td rowspan="2">0 (6)</td><td rowspan="3">0 (9)</td></tr>
<tr><td>>0 – 0.09</td><td>1 (3)</td></tr>
<tr><td>0.1 – 0.89</td><td>2 (3)</td><td rowspan="2">1 (6)</td></tr>
<tr><td>0.9 – 1.4</td><td rowspan="2">3 (6)</td><td rowspan="4">1 (14)</td></tr>
<tr><td>1.5 – 1.9</td><td rowspan="2">2 (5)</td></tr>
<tr><td>2 – 2.9</td><td rowspan="2">4 (8)</td></tr>
<tr><td>3 – 4.9</td><td>3 (6)</td></tr>
<tr><td>5 – 9.9</td><td>5 (4)</td><td rowspan="2">4 (8)</td><td rowspan="4">2 (14)</td></tr>
<tr><td>10 – 12.4</td><td rowspan="2">6 (7)</td></tr>
<tr><td>12.5 – 14.9</td><td rowspan="3">5 (9)</td></tr>
<tr><td>15 – 19.9</td><td>7 (3)</td></tr>
<tr><td>20 – 24.9</td><td rowspan="2">8 (4)</td><td rowspan="4">3 (9)</td></tr>
<tr><td>25 – 29.9</td><td rowspan="3">6 (6)</td></tr>
<tr><td>30 – 49.9</td><td>9 (2)</td></tr>
<tr><td>50+</td><td>10 (3)</td></tr>
</table>

Macroinvertebrate Index

Of the total 132 collected taxa, only those present at more than 5% of all sites (67 taxa) were considered for development of the Macroinvertebrate Index of Bed Stability. This dataset was used in the indicator species algorithm in PC-ORD (Version 5.0, MjM Software, Gleneden Beach, USA), which is based on the method from Dufrene & Legendre (1997). It combines information on the concentration of taxa abundance and the faithfulness of occurrence of taxa to a particular class (McCune & Mefford, 1999). The method produces indicator values ranging from 0 (no indication) to 100 (perfect indication) for each taxon in each class, which are subsequently tested for statistical significance using comparison with a randomised dataset generated by a Monte Carlo technique.

Taxa were then manually arranged according to their indicator values along the bed stability gradient, whereas taxa with high indicator values exclusive to the class representing highest bed stability were on top, and those only indicative for the class with lowest bed stability on the lower end. Taxa that indicated intermediate bed stability were placed in the centre. This manual sorting process was guided by a relative variable that combined exclusiveness and high indication for a particular class. We determined this variable for each taxon and each class by subtracting neighbouring indicator values, weighted increasingly with growing distance from the class for which it was calculated, from the indicator value of that class. In the next step, scores, ranging from 10 to -10, were allocated to the taxa for each of the three bed stability classifications. Criteria are outlined in Table 3, however, taxa that indicated bed stability over a range of classes were assigned a score relative to these criteria according to their skew and position in the table and the significance of the indicator values. This process, from Indicator Species Analysis to score assignment, was performed for all three bed stability classifications. The resulting three scores for each taxon were averaged and rounded to form the overall score for each taxon. This practice minimised the potential problem of classifying bed stability during the Indicator Species Analysis algorithm. Indicator species analysis and development of the invertebrate index was performed both with absolute abundance data and relative abundances. The resulting invertebrate indices of the two datasets were strongly correlated and the ranking of taxa was similar ($r_S = 0.94$, $p < 0.0001$, $df = 66$). Hence only the index based on absolute invertebrate abundance is reported and discussed in this paper. The index for bed stability for each site was calculated by multiplication of abundance with the score for each taxon, and dividing the sum of these through the total number of individuals present.

For validation, the index of bed stability was also calculated for eight randomly selected independent sites and compared with measured bed stability, using Spearman rank correlation in Statistix 9.0 (Analytical Software, Tallahassee, USA). As a second test of the applicability of the developed index, bed stability was modelled with habitat characteristics and optionally the invertebrate index of bed stability to establish whether the inclusion of the index improved the model prediction of substrate movement. Habitat characteristics were extracted from either the Freshwater Environments New Zealand (FWENZ) database (Wild *et al.*, 2005) or measured concomitantly with invertebrate sampling. Before bed stability was modelled, the 74 variables were reduced to a subset of highly predictive and non-redundant variables in WEKA 3.6.1 (The University of Waikato, Hamilton, New Zealand) using correlation-based evaluation of feature subsets (Hall & Smith, 1998) with the BestFirst search method. Of the 14 selected parameters in this process, the estimated percentage of dry active channel not covered in vegetation was the only measurement taken at the sites (Table 4).

Table 3. Criteria for assignment of scores to taxa according to their indication values (IV) for three classifications of bed stability (4, 7 and 11 classes), when taxa are not exclusively indicative for one particular class, the score was chosen according to the IV in the dominant class relative to IVs of all other classes from the range given in the last three columns.

Criterium	**Almost exclusively indicative for a class and IV > 40**			**Almost exclusively indicative for a class and IV > 20**			**Dominant in a class**		
No. of classes	**11**	**7**	**4**	**11**	**7**	**4**	**11**	**7**	**4**
Score									
10	10	6	3						
9				10	6	3	10	(6)	
8	9						10	6	(3)
7		5		9			10	6	3
6	8				5		10/9	6	3
5				8			9	5	3
4	7	4	2				9	5	3
3				7	4	2	9/8	5	2
2	6						8	4	2
1				6			7/6	4	2
0	5	3		5	3		5	3	2/1
-1				4			4/3	2	1
-2	4						2	2	1
-3				3	2	1	2/1	1	1
-4	3	2	1				1	1	0
-5				2			1	1	0
-6	2				1		1/0	0	0
-7		1		1			0	0	0
-8	1						0	0	(0)
-9				0	0	0	0	(0)	
-10	0	0	0						

The Macroinvertebrate Index of Bed Stability was modelled in WEKA 3.6.1 with M5P model trees (Quinlan, 1992) using 46 sites for model development and eight sites for correlative validation. M5P model trees are an extension of regression trees in a sense that leaves are associated with multivariate linear models. Model trees were chosen because they are not based on assumptions about the form of relationships and can deal with continuous variables. M5 model trees were introduced by Quinlan (1992) and improved to the M5′ model tree algorithm by Wang & Witten (1997). The latter first constructs a regression tree by recursively splitting the instance space and hence minimising the intra-subset variability, measured by the standard deviation in the values down from the root to the node. Attributes are tested at each node resulting in calculation of an expected reduction in error. The attribute that maximises the latter is chosen and splitting stops if the values of all instances that reach a node vary slightly or only a few instances remain. After generation of a tree, M5′ computes a linear multiple regression model for every interior node using only attributes associated with that node and those tested in the sub-tree rooted at that node. Attributes will be dropped and the tree will be pruned if that results in a lower estimated error. After pruning, the adjacent linear models will be sharply discontinuous at the leaves. M5 applies a smoothing process combining the model at a leaf with the models on the path to the root to form the final model at a leaf which substantially increases the accuracy of predictions (Wang & Witten, 1997).

Table 4. Parameters used to model the Macroinvertebrate Index of Bed Stability sourced from direct measurement at 54 North Island, New Zealand rivers between October 2007 and March 2010 and databases (FWENZ – Freshwater Environments NZ, LCDB – Land Cover Data Base).

Parameter	**Description**	**Source**
SegSinu	Segment sinuosity (m m^{-1})	FWENZ database
SegSlope	Average segment slope (m m^{-1})	FWENZ database
SegExoticForest	% of riparian area in category exotic forest	FWENZ database
UsRaindays50_q	Mean number of runoff weighted catchment rain days with precipitation greater than 50 mm per month	FWENZ database
UsLake	Lake index	FWENZ database
UsSteep	Proportion of catchment with slope > 30°	FWENZ database
UsExoticForest_q	Fraction of annual runoff from land cover category exotic forest	FWENZ database
UsIndigForest_q	Fraction of annual runoff from land cover category indigenous forest	FWENZ database
UsMiscLandCover_q	Fraction of annual runoff from land cover category other than LCDB category 1 - 9	FWENZ database
UsPastoral_q	Fraction of annual runoff from land cover category pastoral	FWENZ database
UsWetland_q	Fraction of annual runoff from land cover category wetland	FWENZ database
SegOrder	Stream order (Strahler, 1952)	FWENZ database
UnvegActiveChannel	Percentage of (dry) active channel not covered in vegetation (%)	Estimate at site
Invertebrate Index for bed stability	Index for the assessment of stream bed stability in stony riffles	Based on macroinvertebrate community composition

RESULTS

Bed stability measured as total tracer movement (TTM) ranged between zero (no entrainment, e.g. Orautoha, Pukeonake and Poutu) and 79.6 (Tamaki). High values were a result of either loss of all particles in the first flood event (e.g. Waiwhakaiho) or large transport distances (e.g. Tamaki and Waipawa). The reaches on the Central Volcanic Plateau generally had the most stable substrate, and only the Mangatoetoenui and Waikato sites experienced substantial bed movement (Table 1).

Bed stability scores were assigned to 60 taxa, whereas 7 taxa did not indicate a particular range of substrate stability. The Trichoptera species *Zelolessica cheira*, *Triplectides* sp., *Confluens hamiltoni*, *Orthopsyche* sp. and *Hydrobiosis spatulata* were the taxa most indicative of stable substrate conditions (score ranging from 9 to 10) whereas the mayfly *Zephlebia* sp., the Coleoptera family Ptilodactylidae and the dipteran *Mischoderus* sp. had the highest scores amongst the other taxa (Table 5). The number of taxa indicative of unstable substrates was lower and there was no taxon that had exclusively high indicator scores at the lowest bed stability sites. However, taxa such as the caddisflies *Hydrobiosis umbripennis*, *Psilochorema bidens*, *Hydrochorema* spp., *Hydrobiosis charadraea*, *H. clavigera* and larvae and adults of the Coleoptera family Hydrophilidae indicated relatively unstable substrate conditions and have been assigned the highest negative scores (-6.5 to -3.5).

The resulting invertebrate index of bed stability for each site ranged between -0.04 (Timaru) and 5.35 (Wahianoa). It was significantly correlated with the bed stability measurement TTM (r_S = -0.60, p < 0.001, df = 45) at the sites used to develop the index and at all sites (r_S = -0.58, p < 0.001, df = 53) whereas the correlation at the validation sites only was weaker (r_S = -0.50, p = 0.216, df = 7). The index at the validation sites was lowest (unstable) at Waitohu and Waikawa (0.89 and 0.93) and had its maximum at Waikato (3.70) (Fig. 2). The validation sites represented a wide range of bed stability as assessed by the tracer technique. TTM values reached from 0.01 (Mangahuia) to 39.94 (Waitohu) with the more stable sites located on the Central Volcanic Plateau.

Table 5. Scores for New Zealand stream macroinvertebrates according to their indication for substrate stability in stony riffles for the use of calculating the Macroinvertebrate Index of Bed Stability by adding the abundance-weighted scores of taxa and dividing them by the total number of scored individuals.

Taxon	Score	Taxon	Score
Ephemeroptera		**Trichoptera**	
Austroclima sepia	7.5	*Aoteapsyche colonica*	4.5
Coloburiscus humeralis	7	*Beraeoptera roria*	4
Deleatidium spp.	n/a	*Confluens hamiltoni*	9
Ichthybotus hudsoni	n/a	*Costachorema callistum*	5
Mauiulus luma	7	*Costachorema psaropterum*	0.5
Neozephelbia_scita	6.5	*Costachorema xanthopterum*	1
Nesameletus_ornatus	n/a	*Helicopsyche albescens*	2.5
Zephlebia spp.	8.5	*Hudsonema* spp.	-1.5
Plecoptera		*Hydrobiosella mixta*	-1
Austroperla cyrene	1.5	*Hydrobiosis charadrea*	-2.5
Megaleptoperla grandis	5	*Hydrobiosis clavigera*	-2.5
Stenoperla prasina	0.5	*Hydrobiosis frater*	1
Zelandobius confusus	2	*Hydrobiosis parumbripennis*	4
Zelandoperla spp.	3.5	*Hydrobiosis spatulata*	9
Diptera		*Hydrobiosis umbripennis*	-6.5
Aphrophila neozelandica	2	*Hydrochorema* spp.	-3.5
Austrosimulium spp.	-1.5	*Neurochorema* spp.	8
Chironomid pupae	5	*Olinga feredayi*	0
Chironomus zealandicus	4.5	*Orthopsyche* spp.	9
Diamesinae spp.	6	*Oxyethira albiceps*	6.5
Empididae	1	*Plectronemia maclachlani*	0.5
Eriopterini (excl. *Aphrophila* sp.)	n/a	*Psilochorema bidens*	-4
Hexatomini	2.5	*Psilochorema macroharpax*	n/a
Limonia sp.	n/a	*Psilochorema nemorale*	-1
Mischoderus spp.	8	*Pycnocentria* spp.	7
Molophilus sp.	n/a	*Pycnocentrodes* spp.	1
Muscidae	5	*Triplectides* sp.	9.5
Neocurupira sp.	5.5	*Zelolessica cheira*	10
Orthocladiinae	4.5	**Megaloptera**	
Polypedilum spp.	0	*Archichauliodes diversus*	2
Tanypodinae	7	**Crustacea**	
Tanytarsini	0	Amphipoda	-2.5
Coleoptera		**Mollusca**	
Elmidae	0.5	*Potamopyrgus antipodarum*	7
Hydraenidae	-2	**Oligochaeta**	4.5
Hydrophilidae	-5	**Platyhelminthes**	4.5
Ptilodactylidae	8.5		

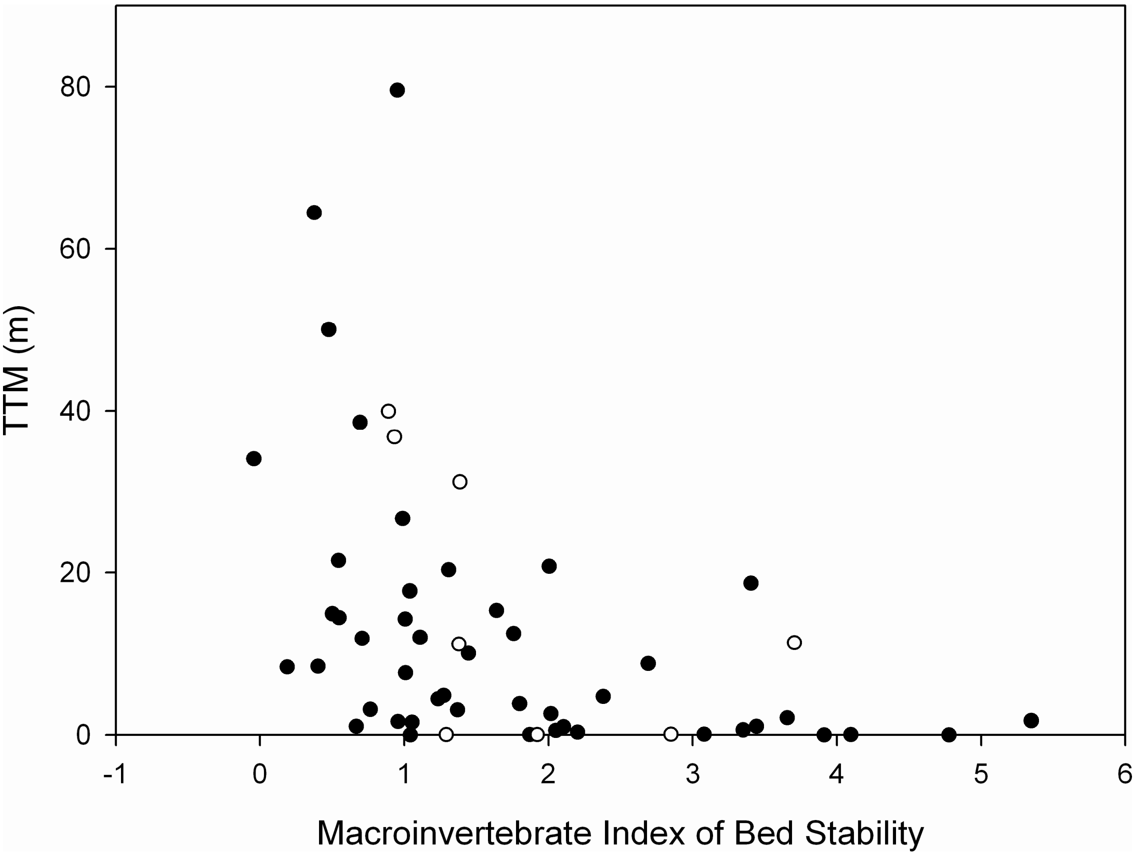


Figure 2. Total transported distance of tracer particles (TTM) in relation to the Macroinvertebrate Index of Bed Stability at 54 upland streams in New Zealand, empty circles denote sites used for validation.

Modelling bed stability with M5P trees resulted, after pruning, in relatively simple one-branch regression models in which the variables fraction of steep sloped catchment, Macroinvertebrate Index of Bed Stability and fraction of annual runoff from indigenous forest were used (Table 6). The correlation coefficients between modelled and measured data were 0.830 and 0.809 for the models that respectively included and excluded the invertebrate index. Thus the former model explained 69% (R^2) of the variation in bed stability compared to 65% with the latter model.

Table 6. Variables and regression coefficients for models to predict bed stability generated with pruned M5P model trees from 13 habitat characteristics derived from direct measurement and the FWENZ database and optionally the Macroinvertebrate Index of Bed Stability.

Inclusive Macroinvertebrate Index of Bed Stability		**Exclusive Macroinvertebrate Index of Bed Stability**	
57.0734	UsSteep_q	67.0933	UsSteep_q
-2.8854	Macroinvertebrate Index of Bed Stability	8.6869	Usindigforest_q
8.7473	Constant	-1.7840	Constant

DISCUSSION

Site scores

The developed Macroinvertebrate Index of Bed Stability has potential to offer a new perspective on monitoring of substrate stability because it is based on community response. Statistical models generated from habitat variables were enhanced when site scores calculated by the index were included in the pool of variables. The latter consisted of a wide range of habitat characteristics, which mostly showed a potential causal relation to bed stability (e.g. catchment land use parameters can influence sediment supply and flow regime, whereas reach slope and sinuosity are related to the energy available for erosion). Hence, the M5P model that excludes the index can explain already 65% of the variation in bed stability, but for the improved model, in which the site score was one of the selected variables, this figure increased to 69%. Although this enhancement appears small, the practical improvement is immense because invertebrate data can be collected at more regular intervals than those at which the FWENZ database is updated (e.g. for changes in land use). Thus, temporal fluctuations in bedload transport, for instance as a result of changes in sediment supply (Wathen & Hoey, 1998), and the biotic response to these fluctuations, might be better reflected in the model that includes site scores.

Site scores of the Macroinvertebrate Index of Bed Stability were well-related to measured stream bed stability at the development sites only and at all sites combined. However, at the eight independent validation sites, no significant connection could be established, although the correlation coefficient between these two parameters was fairly high, and similar to the coefficient at the development sites. Failure to find a significant connection at independent validation sites may be partly attributable to the small sample size in this study but means also that the index needs to be evaluated on a larger dataset (including sites from other regions in New Zealand) and, if necessary, adjusted. Internationally, the applicability of the index is limited by the distribution of the scored taxa, which are mostly endemic to New Zealand. However, the methodology of index development is transferable to other countries where local taxa might be assigned scores in the same way.

Scores of individual taxa

The sensitivity of many New Zealand invertebrate taxa to substrate movement is largely unknown, although several studies indicate that Ephemeroptera (in particular

Deleatidium spp.), Chironomidae and Simuliidae are resilient to bed disturbance (Mackay, 1992; Death, 1996; Francoeur, Biggs & Lowe, 1998), whereas Mollusca, Amphipoda and platyhelminths are more likely to be affected by floods. However, for other taxa evidence is equivocal or information is lacking. Cased caddisflies are generally thought to be susceptible to the effects of floods (Death, 2008), although *Pycnocentrodes* spp., for example, appear relatively unaffected by increased flow (Irvine & Henriques, 1984). However, most of these studies did not measure bed stability. Townsend, Doledec & Scarsbrook (1997b) suggest that species traits such as small body size, high adult mobility, habitat generalist, clinging ability, streamlined shape and having two or more non-aquatic life stages influence resilience and resistance to substrate instability. *Deleatidium* spp. possess all of these traits and are often dominant in unstable rivers (Sagar, 1986; Death, 1996). However, they can also be abundant under stable conditions, *Deleatidium* spp. are not particularly good indicator species, which is reflected in the assignment of no stability score (Table 5). Apart from *Hydrochorema* spp. and *Hydrobiosis charadraea*, the taxa indicating low stability are not typically associated with unstable upland streams, and are generally found in a wider range of altitudes on stony substrates with varying degrees of aquatic vegetation (Winterbourn et al., 2006). *Zelandobius* sp., Elmidae, *Pycnocentrodes* spp., *Hydrobiosis umbripennis* and some Hydrophilidae (*Berosus* sp.) were found in unstable rivers and have some of the above-mentioned advantageous traits associated with this habitat (e.g. strong clinging ability) (Sagar, 1986; Townsend et al., 1997b), but their scores range between -6.5 and 2 (Table 5). This suggests that low bed stability is better indicated by community composition (e.g. absence of certain taxa), and taxa with the most negative scores need not necessarily be very well-adapted to low bed stability, but might prefer habitat characteristics or ecological conditions common in unstable streams (e.g. water chemistry, limited predation). Also, taxa might be tolerant of low bed stability, but that may not exclude them from more stable sites. At intermediate levels of bed stability, the influence of other habitat parameters might be more pronounced (Lancaster & Downes, 2010). The broad habitat range of tolerant taxa suggests that competition with taxa restricted to stable streams is not overly strong, which is in accord with the general perception that competition and niche specialisation is not very strong in New Zealand stream invertebrates (Winterbourn, 2004).

Taxa found on the other end of the bed stability spectrum, such as *Zelolessica cheira* and *Confluens* sp. are associated with moss, liverwort and algae growth on stones and wood (Winterbourn et al., 2006), indicating stable substrates. *Triplectides* sp. is also associated with wood as food and case material, whereas *Orthopsyche* spp., *H. spatulata* and the shredders Ptilodactylidae are often found in small forested, stony streams with abundant leaf litter. The presence of leaf litter in riffles will be associated with relatively stable substrate. This is because when the substrate in riffles is unstable (e.g. is regularly entrained) leaves and twigs cannot accumulate there and are swept away with the substrate. Under base flow conditions tractive force is usually higher in riffles compared to pools (e.g. Milan et al., 2001). *Zephlebia* spp. is also associated with leaf litter and can be abundant in slow-flowing lowland streams (Winterbourn et al., 2006). Taxa that are considered as potentially good indicators for stable substrate such as *Helicopsyche*, *Hydrobiosella*, *Pycnocentria*, *Ichthybotus*, *Neozephlebia* and *Austroperla* (I. Henderson, pers. comm.) have scores ranging from -1 to 7.0 owing to their tolerance of intermediate conditions of bed stability (Table 5). However, the concept of a certain taxon alone indicating a narrow range of habitat conditions does not apply for New Zealand invertebrate communities (Winterbourn, 1981). 'Indicator communities' are not clearly defined, and relative species abundance and community composition are subject to gradual changes in response to a multitude of environmental variables that do not allow habitat specialists and biotic interactions to develop.

The Macroinvertebrate Index of Bed Stability reflects the response of invertebrate communities to stream bed stability without discriminating between direct and indirect (e.g. via other correlated habitat variables) influence of bed stability. On an individual taxon level, a limit-response model (Lancaster & Downes, 2010) might be able to explain tolerance of extreme levels of substrate stability better because it accounts for the interfering effects of other habitat variables at a range of intermediate bed stabilities. However, because the tolerance levels vary between taxa, the Macroinvertebrate Index of Bed Stability draws together empirical community response to the bed stability gradient without inferring a causal link exclusively based on bed stability.

As many New Zealand invertebrates are generalists, biotic indices that incorporate the abundance of all taxa within a community are a more suitable approach to assess habitat characteristics biologically than the consideration of single indicator taxa. Furthermore, the substantial number of common stony-stream taxa within New Zealand's regions facilitates the country-wide application of such an index (Winterbourn, 1981). Biotic indices can evaluate community structure and make use of the indicator species concept without placing undue emphasis on the presence of uncommon species. Thus, the usefulness of such an approach is best evaluated based on the quality of the derived index compared with the actual measured environmental variable, rather than the validity of individual taxon scores.

Potential applications

Past studies in stream invertebrate ecology often lack assessment of the habitat parameter substrate stability, and results are consequently difficult to compare between studies. The cost- and time-effort for elaborate bed stability measurements might have deterred some researchers from direct measurement in favour of theoretical approaches (e.g. critical shear stress to entrained particle-size relations), which may lack accuracy and relevance for biota (Schwendel *et al.*, 2010a). Hence, the Macroinvertebrate Index of Bed Stability provides an effective and ecologically relevant alternative to elaborate direct bed stability measurements, especially if invertebrate community composition is already known. This may lead to inclusion of stream bed stability as a habitat parameter in more studies. The Macroinvertebrate Index of Bed Stability could also be employed as a biological measure of bed stability for assessment and monitoring of the impact of anthropogenic disturbance on lotic ecosystems such as gravel extraction, river engineering and fording of vehicles and stock. This can help to make ecologically informed management decisions regarding regulation of impacts such as promoting fencing of waterways. Furthermore, the index can also widen the applicability of other biotic indices such as EPT, MCI (Stark, 1985) or UCI (Suren, Snelder & Scarsbrook, 1998), which require community composition as a function of water quality only rather than of other habitat variables. Consequently, Stark (1985) suggests careful selection of sampling sites, or additional assessment of habitat parameters, to account for their inter-site variability. The Macroinvertebrate Index of Bed Stability can be used here to quantify comparability of sites. It may help interpretation of biological water quality assessment and thus allow sites previously unsuitable for the MCI to be investigated.

Future research needs to be carried out to calibrate the Macroinvertebrate Index of Bed Stability for other regions of New Zealand beyond the southern North Island, to generally validate the index, and to account for regionally restricted taxa. Widening of the geographical context can also lead to improvement in the sensitivity of the index to subtle changes in bed stability. Furthermore, extending the index to include assessment of other substrates besides gravel, cobbles and boulders, e.g. silty or sandy lowland rivers, would dramatically increase the range of sites that could be assessed. To a lesser extent, this also applies to the inclusion to other geomorphic units besides riffles. The approach and methodology of the index potentially have global relevance but, owing to endemism, the actual taxa scores might be restricted to New Zealand.

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Synthesis

The aim of this thesis was to review and extend the current knowledge of the effects of stream bed stability on invertebrate communities from a methodological perspective. This included investigation of the suitability of bed stability measurement methods for application in research on stream invertebrates, one of the most important functional groups of lotic ecosystems. It also incorporated test and application of previously not used methods in this perspective and the development of new and advanced techniques. These objectives have been fully attained.

Short-term channel dynamics and sediment transfers were found to be highly variable within mountain streams in the lower North Island of New Zealand (Chapter 3a). This was mainly driven by sediment supply from slopes and the active channel zone, and differing degrees of connectivity between geomorphic units within the catchment than by a consistent region-wide response to flood events (Chapter 3b). A multitude of approaches to measure these varying degrees of stream bed stability is used and each technique measures different characteristics of substrate stability, e.g. entrainment, transport or deposition of particles. A review of the existing literature (Chapter 1) could not identify a single generally preferential method of stream bed stability assessment in stream ecology because suitability depends on research objectives, targeted group of biota, temporal and spatial scale of investigation, and site characteristics. However, at a reach-scale entrainment of substrate is most efficiently assessed with a combination of shear stress and flow competence equations while particle transport is best monitored with *in situ* tagged tracer particles. A lower bound estimate of sediment flux and patterns of erosion and deposition can be obtained with morphological budgeting. Descriptive visual surveys such as the Pfankuch Stability Index that theoretically incorporate many bed stability characteristics can also provide ecologically relevant measurement. Consequently these four techniques were selected for practical comparison.

However, prior to comparison and due to the planned application of the most suitable method at a large number of sites, the use of morphological budgeting required first some research into an appropriate DEM interpolation method (Chapter 2). The latter should not need much site specific parameterisation and allow a realistic representation of the topography of contrasting channels. Triangulation with linear interpolation is well suited for terrain sensitive surveys, can deal with varying data density and distribution and meets the above requirements best amongst geostatistical and other local neighbourhood approaches offered in Surfer®.

The relationship of bed stability measures derived from morphological budgeting, tracer stone movement, a flow competence calculation and the bottom component of the Pfankuch Index with invertebrate community structure and composition was explored at an initial set of 12 sites (Chapter 4). Increasing reach-wide volume of scour derived from morphological budgeting reduced taxa richness exponentially. The distance travelled by *in situ* marked tracer stones and the bottom component of the Pfankuch Index had the strongest link with invertebrate community composition, and diversity declined almost linearly with decreasing stability. The bottom component of the Pfankuch Index is cost- and time-effective but visual evaluation is prone to observer-bias. Thus tracer-based measures were proposed as the most suitable technique for research involving invertebrate substrate stability relationships and were applied to 42 additional stream reaches in the southern North Island of New Zealand. This database was used to develop new and advanced methods to assess stream bed stability characteristics because tracer techniques can be arduous and time-intensive when applied at many sites. It requires frequent site visits and the number of tracers necessary to account for the spatial variation in bed stability within a reach can make it a laborious and expensive approach to measure substrate stability.

Thus a straightforward survey to measure “Stream Bed Stability relevant for Invertebrates” (SBSI) was designed that combines the efficiency of the Pfankuch Index and the characteristics measured with tracer stones (Chapter 5). It assesses 13 substrate and channel properties and was calibrated on the response of invertebrate community composition to variation in stream bed stability measured with tracers. This approach provides an alternative bed stability measure, which is less subjective and time-consuming than the Pfankuch Stability Index or tracer stones respectively, and can facilitate research on disturbance effects on benthic communities at a large number of sites. The SBSI measure is highly relevant for invertebrate community structure, to which it was stronger related than any of the traditional stream bed stability measures.

Finally, an invertebrate index was developed which assesses stream bed stability based on the composition of the entire community (Chapter 6). The Macroinvertebrate Index of Bed Stability can be employed when community composition is already known, e.g. for biological monitoring of water quality. Site scores were highly correlated to bed stability measured with tracer stones, however, at a limited number of validation sites this connection was not significant. Thus future work is required to validate this approach on larger datasets, preferably from other regions in New Zealand to account for potential regional variation. Nonetheless, this biological measure of bed stability has potential application for monitoring of the impact of anthropogenic disturbance on lotic ecosystems such as gravel extraction or river engineering and should lead to ecologically informed management decisions.

While the Macroinvertebrate Index of Bed Stability shows the response of invertebrate communities to a measured gradient of stream bed stability, the SBSI protocol was developed on a gradient in invertebrate community composition that reflects to a high degree stream bed stability. However, it may also incorporate other known and unknown, potentially intercorrelated habitat parameters such as primary productivity or temperature. Thus the SBSI must be seen as an invertebrate specific tool, that assesses a range of parameters related to aspects of stream bed stability and not as a measure of any single bed stability characteristic. For instance, it may assess only indirect consequences of substrate entrainment to invertebrates such as concomitant dislocation of leaf litter. However, it can predict independently measured bed stability well and reflects different metrics of invertebrate community structure.

This structure of a community can be captured in various ways, e.g. as a mathematical axis, number of animals or taxa and various indices of diversity. Within this thesis a large number of different metrics, commonly used in stream ecology is applied because there is no single best measure of community structure. Different indices capture various aspects of community composition which might be of interest for ecological research. Thus the wide range of metrics was chosen deliberately to show the wider relevance of the analysis and the general applicability of the methods.

Bed stability is also a very complex attribute of streams that can be divided into many aspects on a range of scales (Chapter 1). Its definition depends very much on substrate characteristics (e.g. regarded size fraction), scale (e.g. grain or reach), mode of transport (e.g. bedload and washload) and process (e.g. erosion, transport or sedimentation). Further, the effects of instability can be distinguished from the process that implies instability (e.g. abrasion versus transport). However, in streams, in particular in mountainous regions where heterogeneity of channel topography is high, single aspects of bed stability occur hardly ever in isolation and the effect on ecosystem usually compounds. Thus in stream ecology the definition of bed stability is often diffuse and subject to the research question but for measurement of bed stability (or rather instability) a distinction between bed stability characteristics is necessary.

This thesis provides advice for scientists, particularly stream ecologists wishing to measure stream bed stability in respect of selection and application of appropriate methods. For assessment of reach wide patterns of fill and scour and analysis of channel dynamics with morphological budgeting it suggests triangulation as a robust and efficient DEM interpolation method. The thesis recommends three approaches for investigation of ecologically relevant stream bed stability, each for application under different conditions. If time and cost is not an issue, *in situ* marked tracer stones provide a robust and replicable measure of stream bed stability. On the other hand the newly developed SBSI protocol provides an efficient alternative that is well related to invertebrate community structure. In case bed stability is preferred to be assessed biologically the Macroinvertebrate Index of Bed Stability can be used. Collecting and analysing invertebrate samples might require even more effort than direct bed stability measurement with tracer stones, but in biological or environmental studies there might be synergies with other objectives. In particular the two latter methods need to be applied in future in order to validate and, if necessary, refine and adjust them. Stream bed stability is an important habitat variable for lotic ecosystems and I hope that the presented thesis leads to increased inclusion of substrate stability measurement in studies on rivers.

Appendices

Appendix 1. Studied rivers and streams in the southern North Island of New Zealand with site coordinates (NZMG) and site codes.

Site	Code	Northing	Easting
Waipawa River	wpw	6150590	2783340
Manawatu River	mwt	6125950	2777940
Tamaki River	tam	6116350	2768140
Mangapuaka Stream	mpk	6110420	2763680
Coppermine Stream	cop	6102330	2756360
Kiriwhakapapa Stream	kiw	6041190	2724710
Waiotauru River	wtr	6033520	2697140
Pukeatua Stream	pkt	6035780	2698100
Ohau River	oha	6057570	2710230
Te Piripiri Stream	pir	6213890	2745920
Mangatoetoenui Stream	mtn	6215250	2745780
Pukeonake Stream	pkn	6225640	2727050
Oaonui Stream	oao	6206430	2592640
Waiaua River	wau	6205320	2593460
Waiaua Fork Stream	waf	6204400	2593630
Waiaua River tributary	wat	6203960	2595110
Cold Stream	col	6201910	2597030
Punehu Stream	pun	6198780	2597390
Kaupokonui Stream	kau	6200980	2608130
Kapuni Stream	kap	6203020	2608920
Patea River	pat	6208360	2612640
Manganui River	man	6211960	2612550
Waiongana Stream	wog	6224450	2611550
Waiwhakaiho River	wwi	6222200	2607490
Kaiauahi Stream	kai	6223180	2606610
Mangorei Stream	mag	6224220	2601800
Kiri Stream	kir	6223670	2598910
Oakura River	oak	6222470	2596620
Timaru Stream	tim	6221360	2594530
Katikara Stream	kat	6219610	2593640
Cone Creek	con	6131760	2767220
Makiekie Creek	mki	6131270	2766930
Konewa Stream	kon	6120560	2757790
Makawakawa Stream	mkw	6119680	2757540
Rokaiwhana Stream	rok	6111970	2766210
Raparapawai Stream	rap	6104660	2759410
Rawnsley Stream	raw	6055280	2725980
Mangatainoka River	tui	6055140	2725410
Kahuterawa Stream	kah	6076180	2729310
Tokomaru River	tok	6076780	2724190
Wahianoa River	woa	6199150	2737520
Waiharakeke Stream trib.	whk	6199540	2736340
Orautoha Stream	ort	6205440	2713060
Whakapapaiti Stream	wpi	6222480	2723710
Poutu Stream	pou	6232590	2751900
Oturere Stream	out	6221050	2748170
Waitohu Stream	wth	6046250	2697075
Waikawa Stream	wkw	6049650	2701755
Panatewaewae Stream	ptw	6049855	2701925

Appendix 1 (continued). Studied rivers and streams in the southern North Island of New Zealand with site coordinates (NZMG) and site codes.

Site	Code	Northing	Easting
Makahika Stream	mhk	6060900	2712620
Upper Waikato Stream	wkt	6208850	2744920
Mangahuia Stream	mha	6221880	2723440
Makomiko Stream	mkm	6215290	2716630
Makotuku River	mkt	6204630	2717480

Appendix 2. Periphyton biomass, composition of riparian environment, substrate embeddedness (tight – 1, good – 2, moderate – 3, loose – 4) and size classes (a – 16-22.6 mm, b – 22.6-32 mm, c – 32-45.3 mm, d – 45.3-64 mm, e – 64-90.5 mm, f – 90.5-128 mm, g – 128-300 mm, h – >300 mm) containing the 50th, 70th and 90th percentile of the substrate size distribution assessed between October 2007 and March 2010 at the sampling sites in the southern North Island of New Zealand. * denotes measurements taken by J. Tonkin. This table complements Table 1 in Chapter 5 and Table 1 in Chapter 6.

Site	Periphyton biomass (µg cm^{-1})	Native forest (%)	Pasture (%)	Willows (%)	Exposed bed (%)	Embeddedness	D_{50}	D_{70}	D_{90}
Tararua Range									
Mangatainoka	0.19	70	30	0	0	3	f	g	h
Rawnsley	0.21	100	0	0	0	2.5	g	g	h
Kiriwhakapapa	0.06	50	0	0	0	2.5	e	g	h
Kahuterawa	0.38	0	20	0	30	2.5	e	f	g
Tokomaru	0.59	20	50	0	20	3	e	f	g
Makahika	-	50	50	0	5	3	e	g	h
Ohau	0.27	100	0	0	50	2.5	e	g	h
Panatewaewae	-	100	0	0	35	3	f	g	h
Waikawa	-	70	0	0	20	2.5	f	g	h
Waitohu	-	70	30	0	10	2.5	e	g	h
Pukeatua	1.24	100	0	0	0	3	f	g	h
Waiotauru	1.13	60	0	0	70	3	f	g	h
Ruahine Range									
Waipawa	0.10	100	0	0	90	3	e	f	g
Manawatu	1.60	5	95	0	0	2.5	e	g	h
Tamaki	0.07	20	0	75	85	3	c	d	f
Rokaiwhana	0.43	0	0	50	70	3.5	d	e	f
Mangapuaka	0.37	25	0	75	90	3	c	d	f
Raparapawai	0.61	20	0	80	50	2.5	e	f	g
Coppermine	1.49	0	100	0	0	2.5	d	f	h
Cone	0.11	100	0	0	0	3	f	g	h
Makiekie	0.46	60	40	0	0	3	f	g	h
Konewa	0.78	50	0	0	0	2	e	f	g
Makawakawa	0.14	50	50	0	50	2	e	g	g
Central Volcanic Plateau									
Poutu	*0.96	80	0	20	10	-	*e	*f	*g
Oturere	*1.11	80	0	0	10	-	*g	*h	*h
Mangatoetoenui	0.42	100	0	0	30	1.5	f	g	h
Te Piripiri	1.85	30	0	0	70	1.5	c	e	g
Waikato	-	0	0	0	80	4	a	b	c
Wahianoa	*0.11	10	0	0	80	-	*g	*g	*h

Appendix 2 (continued). Periphyton biomass, composition of riparian environment, substrate embeddedness (tight – 1, good – 2, moderate – 3, loose – 4) and size classes (a – 16-22.6 mm, b – 22.6-32 mm, c – 32-45.3 mm, d – 45.3-64 mm, e – 64-90.5 mm, f – 90.5-128 mm, g – 128-300 mm, h – >300 mm) containing the 50th, 70th and 90th percentile of the substrate size distribution assessed between October 2007 and March 2010 at the sampling sites in the southern North Island of New Zealand. * denotes measurements taken by J. Tonkin. This table complements Table 1 in Chapter 5 and Table 1 in Chapter 6.

Site	Periphyton biomass (μg cm^{-1})	Native forest (%)	Pasture (%)	Willows (%)	Exposed bed (%)	Embedded -ness	D_{50}	D_{70}	D_{90}
Central Volcanic Plateau (continued)									
Waiharakeke	*1.06	10	0	0	30	-	*f	*g	*g
Pukeonake	0.93	100	0	0	0	1	h	h	h
Whakapapaiti	*1.12	100	0	0	30	-	*f	*g	*h
Mangahuia	-	100	0	0	10	2	g	g	h
Makomiko	-	95	0	5	5	3.5	f	g	h
Orautoha	*0.40	80	20	0	0	-	*g	*h	*h
Makotuku	-	100	0	0	10	1.5	f	g	h
Mt. Egmont/ Taranaki									
Mangorei	2.58	70	0	0	50	3	h	h	h
Kaiauahi	1.81	50	50	0	20	2.5	g	h	h
Waiwhakaiho	1.38	0	100	0	30	2	f	g	h
Waiongana	2.61	0	100	0	20	2.5	g	g	h
Manganui	0.14	50	0	0	0	3.5	g	h	h
Patea	1.25	100	0	0	0	3.5	g	h	h
Kapuni	0.67	10	90	0	70	3.5	e	f	g
Kaupokonui	0.66	80	20	0	40	3	g	g	h
Kiri	0.14	100	0	0	80	3.5	g	h	h
Oakura	0.53	100	0	0	50	2.5	g	h	h
Timaru	0.03	100	0	0	100	3.5	g	h	h
Katikara	0.02	100	0	0	90	3.5	g	h	h
Oaonui	0.53	0	100	0	0	3.5	e	f	g
Waiaua	0.21	0	30	0	20	3	d	e	h
Waiaua Forks	1.52	40	60	0	0	3	g	g	h
Waiaua trib.	3.12	100	0	0	0	3.5	g	g	h
Cold	2.21	0	100	0	0	3	e	f	g
Punehu	1.94	0	100	0	0	2.5	e	g	g

Appendix 3. Mean invertebrate taxa abundance per site from Surber samples collected in riffles between October 2007 and March 2010 at 48 streams in the southern North Island of New Zealand. Sites in italics were sampled in Austral spring, late summer and winter (total n = 15) while the remaining sites were sampled once in late Austral spring/ summer (n = 5). See Appendix 1 for site codes.

#	Taxon	oao	wau	waf	wat	col	pun	kau
	Insecta							
	Ephemeroptera							
1	*Ameletopsis perscitus*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	*Austroclima sepia*	0.0	0.0	0.0	0.0	0.0	1.0	0.2
3	*Coloburiscus humeralis*	0.0	0.0	10.2	8.2	9.2	1.2	0.8
4	*Deleatidium* spp.	73.6	24.2	178.6	114.8	150.8	139.4	135.2
5	*Ichthybotus hudsoni*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	*Mauiulus luma*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	*Neozephelbia scita*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	*Zephlebia* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	*Zephlebia dentata*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	*Zephlebia spectabilis*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	*Zephlebia versicolor*	0.0	0.0	0.0	0.0	0.0	0.0	0.2
	Plecoptera							
12	*Austroperla cyrene*	0.4	0.0	0.0	0.6	0.2	0.0	0.2
13	*Megaleptoperla grandis*	1.4	0.0	9.6	18.4	4.4	0.8	8.0
14	*Nesameletus ornatus*	0.0	0.0	1.0	0.0	0.0	1.4	0.4
15	*Nesoperla fulvescens*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	*Stenoperla prasina*	0.4	0.0	0.0	2.6	2.2	0.4	0.2
17	*Zealandobius confusus*	0.0	0.0	5.4	1.4	6.4	1.2	0.8
18	*Zelandoperla* spp.	11.6	0.6	22.2	15.0	5.6	1.0	7.0
	Trichoptera							
19	*Aoteapsyche* sp.	0.2	0.0	1.0	2.6	1.8	3.8	1.2
20	*Beraeoptera roria*	0.4	0.0	5.4	38.4	112.8	20.8	14.6
21	*Confluens hamiltoni*	0.0	0.0	0.0	0.6	0.0	0.0	0.0
22	*Costachorema callistum*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	*Costachorema psaropterum*	0.8	0.0	0.4	1.2	0.0	0.0	0.8
24	*Costachorema xanthopterum*	0.0	0.0	0.0	0.6	0.0	0.2	0.0
25	*Cryptobiosella* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	*Ecnomina zealandica*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	*Helicopsyche albescens*	0.0	0.0	0.6	1.0	1.2	2.2	43.6
28	*Hudsonema* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	*Hydrobiosella mixta*	0.0	0.0	0.6	0.6	0.2	0.2	0.8
30	Hydrobiosidae early instar A	0.0	0.2	0.8	0.8	0.4	1.8	0.4
31	Hydrobiosidae early instar B	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	*Hydrobiosis* early instar	1.4	0.0	0.0	0.0	0.0	0.0	0.0

#	Taxon	oao	wau	waf	wat	col	pun	kau
33	*Hydrobiosis charadrea*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	*Hydrobiosis clavigera*	0.0	0.0	0.0	0.0	0.0	0.0	0.4
35	*Hydrobiosis frater*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	*Hydrobiosis parumbripennis*	1.2	0.0	0.2	1.4	0.4	0.6	1.4
37	*Hydrobiosis silvicola*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	*Hydrobiosis spatulata*	0.0	0.0	0.0	0.0	0.4	0.0	0.0
39	*Hydrobiosis umbripennis*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	*Hydrochorema crassicaudatum*	0.0	0.0	0.0	0.0	0.4	0.0	0.0
41	*Hydrochorema tenuicaudatum*	0.0	0.0	0.2	0.0	0.0	0.0	0.0
42	*Neurochorema confusum*	0.0	0.0	0.0	0.2	0.0	0.0	0.0
43	*Neurochorema fosteri*	0.0	0.0	0.0	0.6	0.0	0.0	0.0
44	*Olinga feredayi*	0.0	0.0	0.0	0.0	1.6	1.8	5.2
45	*Orthopsyche thomasi*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	*Oxyethira albiceps*	0.2	0.0	0.0	0.0	0.0	0.0	0.0
47	*Paroxyethira hendersoni*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
48	*Plectronemia maclachlani*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	*Psilochorema* early instar	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	*Psilochorema* spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51	*Psilochorema bidens*	0.0	0.0	0.6	0.0	0.0	0.2	0.0
52	*Psilochorema leptoharpax*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53	*Psilochorema macroharpax*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	*Psilochorema nemorale*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55	*Pycnocentria evecta*	0.0	0.0	0.2	0.6	5.8	0.0	0.0
56	*Pycnocentria gunni*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57	*Pycnocentrodes* spp.	1.2	0.0	1.4	3.0	0.2	12.6	25.4
58	*Tiphobiosis* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
59	*Triplectides* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Hemiptera							
60	*Sigara* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Coleoptera							
61	*Hydora* sp. adult	8.2	1.0	15.8	9.8	2.0	26.4	6.6
62	*Hydora* sp. larvae A	6.6	0.2	4.4	10.2	23.2	27.6	37.6
63	*Hydora* sp. larvae B	0.0	0.0	0.0	0.2	0.6	0.0	0.0
64	Hydraenidae adult	1.2	0.0	2.6	2.2	1.8	1.4	1.6
65	Hydraenidae larvae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	Hydrophilidae adult	0.0	0.0	0.0	0.0	0.0	0.0	0.0
67	Hydrophilidae larvae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
68	*Liodessus plicatus*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
69	Ptilodactylidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
70	Scirtidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
71	Staphylinidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	Taxon	oao	wau	waf	wat	col	pun	kau
	Diptera							
72	*Aphrophila neozelandica*	1.4	0.0	8.4	15.4	3.4	0.8	5.4
73	*Austrosimulium* spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
74	*Austrosimulium* spp. pupae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75	Chironomidae pupae	0.4	0.0	0.2	0.6	2.6	0.2	0.6
76	*Chironomus zealandicus*	0.0	0.0	0.2	0.0	0.0	0.0	0.0
77	Empididae A	0.0	0.0	0.0	0.0	0.0	0.0	0.0
78	Empididae B	0.0	0.0	0.0	0.0	0.0	0.0	0.0
79	Empididae C	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	Eriopterini	1.0	0.4	1.4	2.8	1.2	0.6	1.4
81	Hexatomini	0.0	0.0	0.0	0.0	0.0	0.0	0.0
82	*Limonia* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
83	*Maoridiamesa* spp.	0.0	0.4	0.0	7.2	7.8	0.0	0.2
84	*Mischoderus* spp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
85	*Molophilus* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.2
86	Muscidae	0.2	0.0	0.0	1.0	1.6	0.0	0.2
87	*Neocuripira* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88	*Nothodixa* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
89	Orthocladiinae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90	Orthocladiinae A	0.0	0.0	0.0	0.0	1.2	0.0	0.2
91	Orthocladiinae B	1.6	0.0	0.0	0.4	15.6	0.0	0.4
92	*Paradixa* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
93	*Paralimnophila skusei*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94	Podonominae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95	*Polypedilum* spp.	0.0	0.0	0.4	0.2	0.6	0.0	0.0
96	Stratiomyidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
97	Tanypodinae	0.0	0.0	0.0	0.0	0.0	0.0	0.0
98	Tanytarsini	0.0	0.0	0.0	0.0	0.0	0.0	0.0
99	*Zelandotipula* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Megaloptera							
100	*Archichauliodes diversus*	0.4	0.0	0.0	0.4	0.2	0.6	1.0
	Crustacea							
101	Amphipoda A	0.0	0.0	0.0	0.0	0.0	0.0	0.0
102	Amphipoda B	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103	*Paranephrops planifrons*	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Gastropoda							
104	*Gyraulus* sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
105	*Potamopyrgus antipodarum*	0.0	0.0	0.0	0.2	1.0	0.0	0.2
106	**Acari**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
107	**Nematoda**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
108	**Oligochaeta**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
109	**Platyhelminthes**	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	kap	pat	man	wog	wwi	kai	mag	kir	oak	tim	kat
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.2	10.8	0.0	2.6	0.0	0.2	0.2	0.0	0.2	0.0	0.0
3	0.4	3.6	0.0	7.4	0.0	2.4	3.8	0.4	2.2	0.2	0.0
4	157.8	76.6	7.4	252.8	68.0	206.6	126.2	52.8	48.2	14.6	0.4
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	1.0	0.0	0.0	0.0	0.2	0.0	0.2	0.4	0.2	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
12	0.0	1.6	0.0	0.4	0.0	0.2	0.6	0.2	2.2	0.0	0.0
13	1.2	1.2	0.0	2.8	1.0	0.0	1.0	1.4	0.8	0.0	0.0
14	0.0	0.0	0.0	8.2	0.8	1.2	0.4	0.4	0.8	0.6	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.8	0.0	0.0	0.0	0.0	1.0	0.6	0.2	0.0	0.0
17	2.4	3.4	0.2	0.4	0.0	2.2	0.6	1.0	2.8	0.4	0.0
18	19.0	10.0	11.0	7.8	4.8	34.2	64.4	71.0	4.2	1.4	0.0
19	0.0	2.4	0.0	20.2	1.0	8.2	2.2	4.4	0.6	0.2	0.0
20	1.0	40.4	0.0	27.8	0.2	19.4	8.4	1.0	0.0	0.0	0.0
21	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.2	0.8	0.8	0.6	0.4	0.0
23	1.6	0.4	0.8	0.6	2.4	0.0	0.0	0.4	2.0	0.0	0.0
24	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	109.8	0.0	0.4	0.0	2.6	2.8	0.0	0.2	0.2	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	2.0	0.2	0.2	0.0	0.0	1.2	0.2	0.0	0.2	0.0	0.2
30	0.8	0.2	0.0	0.8	0.8	1.0	0.6	0.2	0.2	1.2	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	0.2	0.4	0.0	0.8	0.0	1.0	1.8	0.4	0.6	0.4	0.0
35	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	1.6	0.0	0.2	1.2	0.6	0.8	0.4	0.0	0.0	0.0	0.0
37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0

#	kap	pat	man	wog	wwi	kai	mag	kir	oak	tim	kat
39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44	0.2	5.2	0.2	0.2	0.0	0.4	2.2	1.0	0.0	0.0	0.0
45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0	0.4	0.2	0.2	0.4	0.0	0.0	0.0
47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0
51	0.0	0.2	0.0	0.2	0.4	0.4	0.0	0.0	0.0	0.0	0.0
52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0
56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57	0.0	1.2	0.0	5.2	0.0	14.2	0.4	0.0	0.0	0.0	0.0
58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
59	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
61	0.6	3.0	0.2	0.6	0.2	0.4	1.6	0.2	0.0	0.0	0.0
62	32.2	20.0	0.4	16.6	14.2	12.6	3.6	8.6	0.8	0.2	0.0
63	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
64	0.2	2.8	0.0	2.6	0.0	1.4	1.0	0.8	0.4	22.0	0.2
65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
67	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
71	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
72	8.2	2.6	0.0	21.4	0.8	4.4	2.0	1.8	0.6	0.0	0.0
73	0.0	0.0	0.2	1.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0
74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75	0.0	0.8	0.2	1.6	0.2	1.2	0.8	0.0	0.0	0.0	0.2
76	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0
77	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	kap	pat	man	wog	wwi	kai	mag	kir	oak	tim	kat
78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
79	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	2.4	0.2	0.2	2.0	4.2	1.0	0.0	0.6	0.4	0.0	0.0
81	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
82	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
83	0.2	0.0	0.2	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0
84	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90	0.2	1.0	0.0	0.8	0.4	0.4	0.4	0.4	0.8	0.0	0.0
91	0.4	0.4	0.0	3.6	0.4	0.6	0.4	0.0	0.4	0.2	0.6
92	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95	0.0	0.2	0.0	0.4	0.2	0.0	0.4	0.2	0.8	0.0	0.0
96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
97	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0
99	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.4	0.0	7.6	1.0	6.2	0.8	2.8	0.2	13.2	1.0
101	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0
102	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
104	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
105	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
106	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
107	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
108	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
109	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0

#	con	mki	kon	mkw	rok	rap	kah	tok	raw	tui	*wpw*
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	8.2	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
3	1.8	0.0	14.8	0.4	0.0	0.0	50.6	16.2	29.6	2.8	0.0
4	46.4	102.8	93.0	59.8	31.0	67.2	67.4	87.0	56.6	105.2	15.4
5	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.2	0.2	0.0	0.0	0.0	0.0	0.8	0.0	1.0	1.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	3.6	0.0	0.0	0.0	0.0
12	10.0	3.6	0.0	1.2	1.4	1.6	2.0	0.4	3.2	0.6	0.1
13	0.6	0.2	0.0	0.0	0.2	0.0	0.0	0.0	0.8	0.2	0.0
14	0.4	2.6	0.0	0.8	0.0	0.6	10.2	3.4	7.4	7.0	0.1
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	2.4	2.4	0.4	0.4	0.2	0.4	0.0	0.2	1.0	0.8	0.0
17	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.2	0.1
18	14.2	18.6	8.4	5.4	2.6	6.8	85.6	14.2	22.4	29.0	3.4
19	6.0	1.8	36.4	3.8	0.0	0.0	8.4	4.6	8.6	3.4	0.2
20	50.2	41.2	15.4	0.2	0.0	0.2	4.0	0.2	5.6	1.4	1.3
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.1
23	0.0	0.4	0.0	0.4	0.2	0.0	0.0	1.4	1.2	0.2	0.0
24	0.0	0.0	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	2.0	1.4	0.0	0.4	0.0	0.0	0.6	1.4	42.0	2.6	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.4	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0
30	0.4	0.2	0.4	0.0	0.0	0.0	0.6	0.6	0.0	0.8	0.1
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
34	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.8	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	0.0	0.4	1.8	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0

#	con	mki	kon	mkw	rok	rap	kah	tok	raw	tui	*wpw*
39	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.1
40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44	16.2	5.4	1.6	2.0	2.0	0.0	0.4	1.2	16.2	7.0	0.3
45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.0
47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	0.0	0.8	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51	0.4	0.0	0.0	0.4	0.2	1.2	0.2	0.0	0.6	0.0	0.1
52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55	0.2	0.0	8.0	0.2	0.0	0.0	0.0	0.4	0.0	0.0	0.7
56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57	0.2	0.6	2.8	0.0	0.6	0.6	0.2	0.6	0.0	0.0	0.0
58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
59	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
61	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0
62	4.4	27.8	29.6	7.2	64.4	16.2	2.8	26.8	1.2	2.0	0.6
63	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
64	2.6	1.6	2.0	0.0	0.4	0.2	2.0	2.6	1.8	0.2	0.0
65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
67	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
69	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
71	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
72	1.4	0.4	11.2	0.2	0.0	0.0	1.0	0.2	0.4	0.4	0.2
73	0.2	0.2	54.4	0.6	0.6	1.2	0.6	1.0	0.2	0.0	0.0
74	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75	0.4	0.6	5.0	3.0	0.2	0.6	0.4	1.2	0.2	0.0	0.1
76	0.0	0.0	8.4	0.0	0.0	0.2	1.2	1.4	0.0	0.0	0.0
77	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	con	mki	kon	mkw	rok	rap	kah	tok	raw	tui	*wpw*
78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
79	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.0	1.2	1.4	0.6	0.0	0.2	0.0	0.8	0.2	0.0	0.1
81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
82	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
83	0.0	0.0	0.0	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.1
84	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
87	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
90	1.0	0.4	1.6	7.8	1.0	0.8	0.0	2.8	1.0	0.4	0.0
91	2.8	0.2	0.2	1.4	0.4	0.8	3.0	4.8	1.4	0.6	0.0
92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95	0.0	0.6	2.6	4.2	0.2	0.0	2.0	2.2	0.8	0.0	0.0
96	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	4.8	3.8	6.2	0.6	0.2	0.0	7.2	4.2	1.6	0.0	0.0
101	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.7
102	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0
103	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
104	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
105	0.2	0.0	0.4	0.0	0.0	0.0	0.2	0.2	0.6	0.0	0.0
106	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.4	0.0	0.0	0.0
107	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
108	0.4	0.0	0.0	0.2	0.0	0.4	0.0	0.2	0.0	0.0	0.0
109	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	*mwt*	*tam*	*mpk*	*cop*	*kiw*	*wtr*	*pkt*	*oha*	*pkn*	*mtn*	*pir*
1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.1	0.0	0.0	0.1	0.0	0.0	3.7	0.0	0.0	0.1	3.7
3	6.7	0.0	0.0	1.5	23.9	0.6	1.1	0.1	0.3	0.0	0.0
4	147.1	42.6	81.0	137.4	167.3	120.4	46.3	75.4	18.9	1.5	5.3
5	1.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.3
7	2.2	0.1	0.0	0.6	0.7	0.0	0.1	0.1	0.1	0.0	0.0
8	0.1	0.0	0.0	0.0	0.3	0.0	1.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	2.9	1.6	0.7	3.0	16.1	0.2	0.1	1.4	0.0	0.0	0.1
13	1.2	0.1	2.8	1.7	0.0	0.2	0.0	0.6	0.0	0.1	0.0
14	1.0	1.0	0.1	9.2	0.6	3.6	0.2	2.9	0.2	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7
16	2.6	0.0	0.0	1.5	2.5	0.2	0.1	0.2	0.0	0.0	0.0
17	2.9	0.1	0.8	0.7	1.1	0.2	0.4	0.2	0.1	0.1	1.2
18	16.1	4.6	3.1	18.3	4.3	9.0	16.7	27.1	0.7	5.0	2.2
19	17.1	0.3	0.3	4.1	12.7	2.6	2.3	0.7	0.1	3.7	0.1
20	127.2	1.4	3.9	28.2	23.2	14.3	0.5	3.5	0.5	0.1	0.1
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.5	0.0	0.0	0.1	1.2	0.3	0.5	0.1	0.0	0.1	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
27	134.3	0.0	0.0	0.0	15.6	0.4	0.1	0.0	0.0	0.0	0.0
28	0.1	0.1	0.0	0.7	2.3	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0
30	0.2	0.0	0.1	0.5	0.6	0.1	0.0	0.1	0.1	0.3	0.8
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.2	0.4	0.0	1.6	0.0	0.7	1.1	0.1	0.2	0.1	0.2
33	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.3	0.0
34	0.0	0.1	0.0	0.5	0.1	0.2	0.0	0.1	0.0	0.0	0.0
35	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	0.1	0.0	0.3	0.1	0.3	0.2	0.7	0.0	0.3	0.2	1.8
37	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
38	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	*mwt*	*tam*	*mpk*	*cop*	*kiw*	*wtr*	*pkt*	*oha*	*pkn*	*mtn*	*pir*
39	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41	0.3	0.0	0.5	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1
44	105.3	2.7	0.1	8.0	28.2	1.2	2.1	0.3	0.1	0.0	0.6
45	0.2	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0
46	0.0	0.1	0.0	0.4	0.2	0.1	2.3	0.1	0.7	0.0	0.1
47	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
48	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0
49	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
51	0.9	2.3	0.5	0.9	0.3	0.5	0.7	0.1	0.0	0.0	0.0
52	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
54	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55	0.5	0.1	0.0	1.9	0.0	0.0	0.5	0.0	0.1	0.0	0.1
56	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	4.1
57	1.7	5.7	0.5	8.3	0.6	0.1	0.1	0.1	0.0	0.0	0.8
58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
59	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
61	0.0	0.1	0.0	0.1	0.2	0.2	0.0	0.1	0.5	0.1	0.0
62	12.7	1.9	0.5	10.3	6.9	12.6	6.5	11.7	2.3	0.0	0.2
63	2.7	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
64	13.1	0.3	0.3	0.8	4.3	0.1	0.7	0.1	0.1	0.1	0.1
65	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
67	0.0	0.0	0.2	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0
68	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
69	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
70	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
71	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
72	2.6	0.1	0.9	3.9	1.2	0.9	0.7	0.3	0.2	1.7	0.4
73	0.2	1.0	0.1	0.5	0.0	0.1	0.2	0.0	1.1	0.0	25.2
74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
75	0.3	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.0	1.2
76	0.0	0.1	0.0	2.3	0.4	0.1	0.5	0.1	0.1	0.4	3.0
77	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6

#	*mwt*	*tam*	*mpk*	*cop*	*kiw*	*wtr*	*pkt*	*oha*	*pkn*	*mtn*	*pir*
78	0.1	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
79	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.8	0.8	1.1	1.0	0.1	0.7	0.8	0.2	0.2	0.8	2.0
81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
82	0.5	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
83	1.6	0.9	0.3	0.3	0.7	0.5	0.7	0.0	0.5	3.1	48.6
84	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
85	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9
87	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0
88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.1	0.5	1.7
90	0.4	0.1	0.1	0.1	0.5	0.1	2.6	0.1	1.7	1.3	16.2
91	0.5	0.5	0.4	4.9	0.0	0.0	0.0	0.0	0.8	0.1	4.5
92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
94	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95	0.7	0.0	0.1	0.7	1.0	0.0	0.0	0.2	0.0	0.8	1.5
96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
97	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
98	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	6.3	0.0	0.1	5.7	2.6	0.2	0.3	0.3	0.0	0.0	0.0
101	0.5	0.2	0.3	0.1	0.0	1.1	0.7	0.1	0.2	0.1	0.3
102	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
104	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
105	3.1	0.0	0.0	2.7	0.0	0.0	0.1	0.0	0.0	0.0	0.0
106	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
107	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
108	1.7	0.0	2.3	0.3	0.7	0.1	0.1	0.0	0.0	0.0	1.0
109	2.7	0.0	0.0	0.1	1.1	0.0	0.0	0.0	0.0	0.0	0.1

#	wth	wkw	ptw	mhk	wkt	mha	mkm	mkt
1	0.0	0.2	0.0	0.8	0.0	0.2	1.2	0.0
2	0.6	0.0	0.0	0.0	0.0	2.6	6.0	0.0
3	15.6	2.8	8.8	29.4	0.0	9.8	48.8	2.0
4	180.4	45.0	42.0	116.2	0.0	75.2	75.4	48.2
5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.6	0.4	0.0	2.0	0.0	0.8	7.2	0.2
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	2.6	1.8	0.4	0.8	0.0	10.4	5.6	4.4
13	0.2	0.0	0.4	0.0	0.0	0.4	1.2	3.2
14	0.4	0.2	0.2	0.0	0.0	1.4	3.8	7.6
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.6	0.0	1.4	0.4	0.0	2.4	1.8	0.6
17	1.4	1.0	1.6	0.0	0.0	2.2	3.6	7.6
18	11.2	2.2	1.4	2.4	4.6	11.6	16.4	21.0
19	2.2	0.2	1.0	6.8	0.0	0.6	1.8	0.0
20	21.6	6.8	4.4	1.4	0.0	19.0	24.4	4.4
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
23	1.8	0.0	0.6	0.0	0.0	0.8	0.4	1.0
24	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.2
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	1.4	1.6	8.6	9.4	0.0	133.4	24.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.2	0.0	0.6	0.4	0.0	0.2	0.2	0.6
30	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.2
34	0.0	0.0	0.0	0.4	0.0	0.0	1.2	0.4
35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	0.0	0.0	0.0	1.0	0.8	0.2	1.0	0.0
37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	wth	wkw	ptw	mhk	wkt	mha	mkm	mkt
39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
44	23.2	1.0	4.0	12.8	0.0	9.0	41.6	2.6
45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0	9.2	0.0	0.0	0.0
47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51	0.8	0.0	0.4	0.2	0.0	1.0	0.0	0.0
52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	0.0	0.0	0.0	7.2	0.0
56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57	2.4	0.0	0.2	11.2	0.0	4.8	0.0	0.0
58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
59	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
61	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62	14.2	2.0	4.6	27.0	0.0	5.2	10.0	6.6
63	0.0	0.0	0.0	0.0	0.0	0.4	2.0	0.0
64	9.8	1.0	1.6	6.4	0.0	3.4	7.6	1.2
65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	0.2	1.2	0.2	0.6	0.2	1.4	0.2	0.0
67	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
68	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
69	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
71	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
72	0.8	0.0	0.4	0.0	0.0	0.4	2.6	0.4
73	0.0	0.0	0.0	0.2	6.8	0.0	0.2	0.2
74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75	0.0	0.0	0.2	0.2	0.6	1.8	3.6	0.0
76	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
77	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

#	wth	wkw	ptw	mhk	wkt	mha	mkm	mkt
78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
79	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.2	0.0	0.6	0.0	0.4	0.2	0.0	3.0
81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
82	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
83	0.0	0.0	0.0	0.2	7.6	0.0	1.0	0.0
84	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
87	0.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0
88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90	0.0	0.0	0.0	0.2	1.2	1.0	5.0	0.2
91	0.4	0.0	0.0	0.0	0.6	0.0	4.4	0.0
92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95	0.2	0.2	0.0	0.0	0.0	0.8	1.6	0.0
96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
97	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	3.2	0.0	0.6	2.0	0.0	2.6	13.6	0.0
101	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
102	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
104	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
105	0.2	0.0	0.0	2.4	0.0	0.0	25.4	0.0
106	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
107	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
108	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0
109	0.0	0.0	0.2	0.0	0.0	0.0	0.4	0.0

Appendix 4. Stream bed stability measured between October 2007 and March 2010 at stream reaches in the southern North Island of New Zealand. ITM denotes an index derived from the transport of *in situ* marked tracer stones over an initial period of three months, BCP is the bottom component of the Pfankuch Stability Index, FCB is the predicted percentage of stream bed area affected by entrainment at bankfull discharge and SBSI is a new approach described in Chapter 5.

Site	**ITM (m)**	**FCB (%)**	**BCP**	**SBSI**
Tararua Range				
Mangatainoka	-	-	52.0	75.9
Rawnsley	-	-	52.0	72.0
Kiriwhakapapa	12.7	57.9	35.0	69.1
Kahuterawa	-	-	38.0	64.3
Tokomaru	-	-	40.0	75.6
Makahika	-	-	40.0	53.0
Ohau	14.6	82.9	42.5	76.9
Panatewaewae	-	-	50.0	58.5
Waikawa	-	-	50.0	68.8
Waitohu	-	-	43.0	63.8
Pukeatua	24.4	100.0	49.0	78.1
Waiotauru	66.0	76.2	39.0	72.7
Ruahine Range				
Waipawa	135.8	100.0	52.0	87.3
Manawatu	0.0	72.6	34.0	69.7
Tamaki	125.2	80.8	43.5	77.2
Rokaiwhana	-	-	51.0	80.7
Mangapuaka	39.1	60.1	56.5	78.1
Raparapawai	-	-	51.0	73.5
Coppermine	2.8	98.8	37.5	70.6
Cone	-	-	37.0	70.5
Makiekie	-	-	43.0	73.0
Konewa	-	-	28.0	68.0
Makawakawa	-	-	32.0	72.6
Central Volcanic Plateau				
Poutu	-	-	37.0	70.1
Oturere	-	-	39.0	69.3
Mangatoetoenui	34.8	60.3	27.5	76.2
Te Piripiri	8.6	47.3	26.0	64.5
Waikato	-	-	49.0	72.0
Wahianoa	-	-	46.0	73.6
Waiharakeke	-	-	29.0	66.0
Pukeonake	0.0	35.4	25.0	79.2
Whakapapaiti	-	-	31.0	70.9
Mangahuia	-	-	31.0	54.4

Appendix 4 (continued). Stream bed stability measured between October 2007 and March 2010 at 54 stream reaches in the southern North Island of New Zealand. ITM denotes an index derived from the transport of *in situ* marked tracer stones over an initial period of three months, BCP is the bottom component of the Pfankuch Stability Index, FCB is the predicted percentage of stream bed area affected by entrainment at bankfull discharge and SBSI is a new approach described in Chapter 5.

Site	ITM	FCB (%)	BCP	SBSI
Central Volcanic Plateau (continued)				
Makomiko	-	-	32.0	53.6
Orautoha	-	-	18.0	62.1
Makotuku	-	-	43.0	54.7
Mt. Egmont/ Taranaki				
Mangorei	-	-	39.0	74.2
Kaiauahi	-	-	39.0	69.1
Waiwhakaiho	-	-	44.0	76.6
Waiongana	-	-	39.0	74.0
Manganui	-	-	56.0	79.8
Patea	-	-	32.0	65.9
Kapuni	-	-	45.0	71.9
Kaupokonui	-	-	37.0	69.3
Kiri	-	-	45.0	75.5
Oakura	-	-	37.0	77.0
Timaru	-	-	44.0	86.5
Katikara	-	-	43.0	87.9
Oaonui	-	-	45.0	78.2
Waiaua	-	-	51.0	87.3
Waiaua Forks	-	-	41.0	75.0
Waiaua trib.	-	-	33.0	68.3
Cold	-	-	34.0	66.9
Punehu	-	-	33.0	69.0