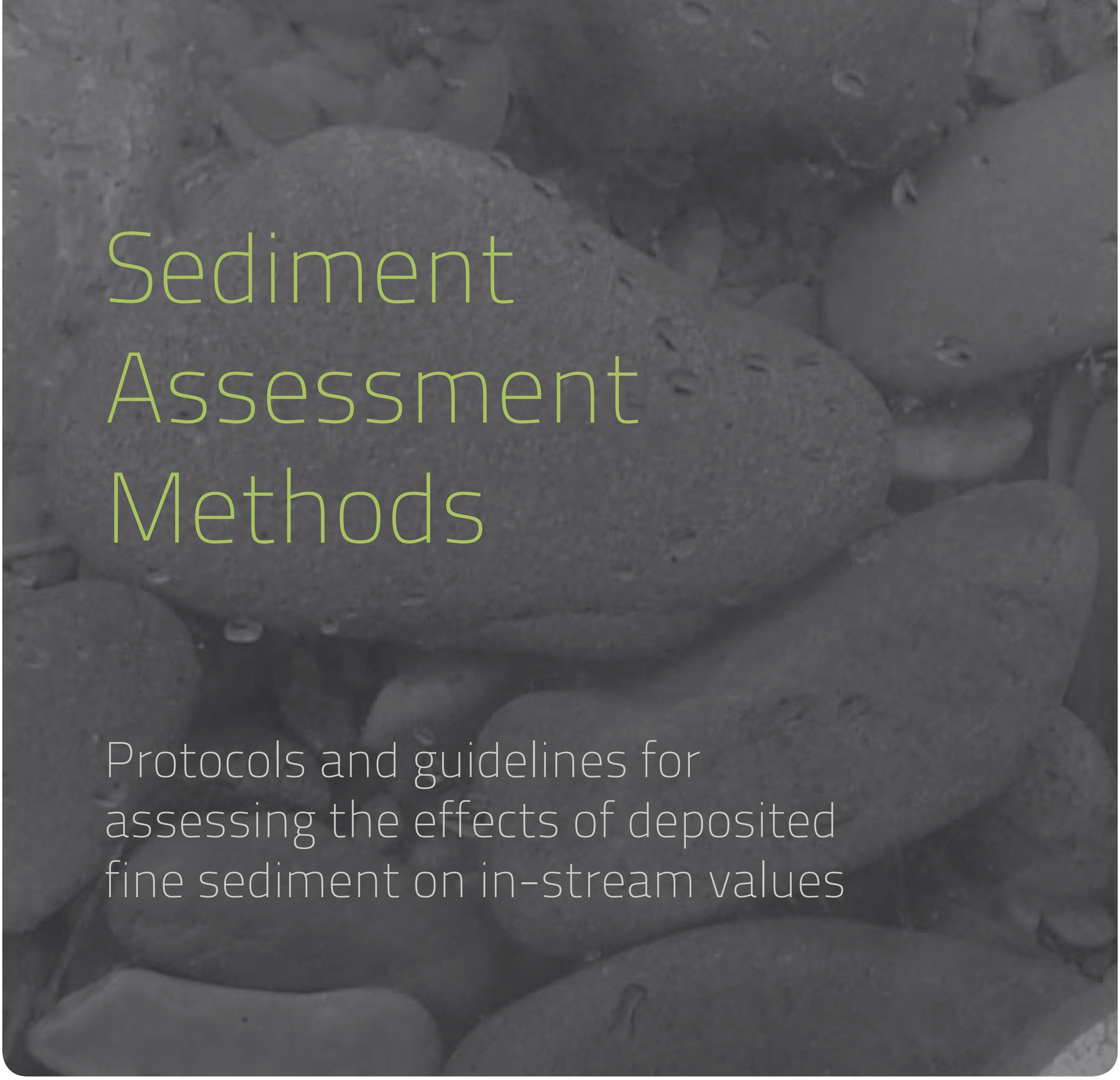
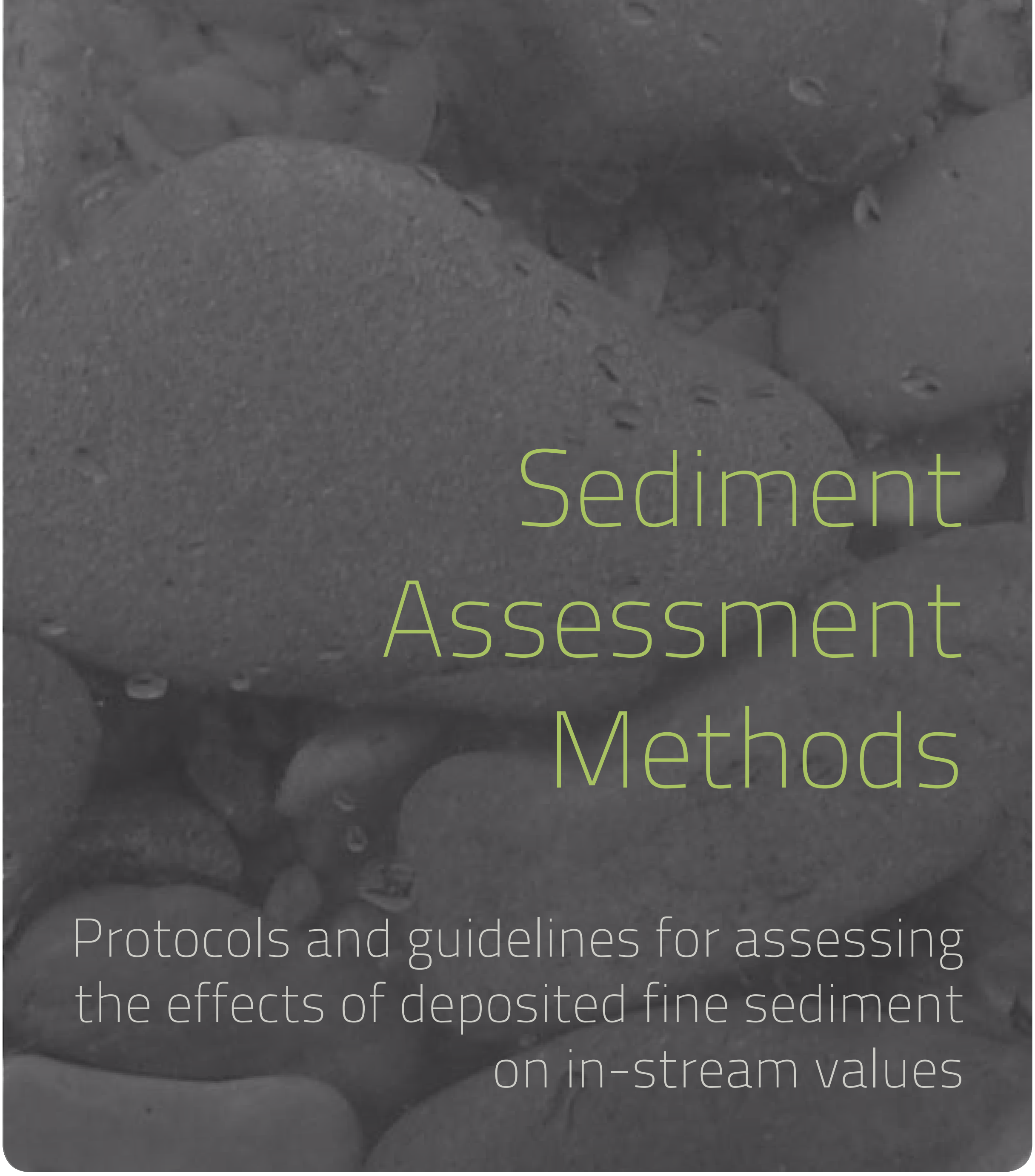


Sediment Assessment Methods

Protocols and guidelines for assessing the effects of deposited fine sediment on in-stream values

Joanne Clapcott
Roger Young
Jon Harding
Christoph Matthaei
John Quinn
Russell Death



Sediment Assessment Methods

Protocols and guidelines for assessing the effects of deposited fine sediment on in-stream values

Joanne Clapcott
Roger Young
Jon Harding
Christoph Matthaei
John Quinn
Russell Death

Sediment Assessment Methods

Protocols and guidelines for assessing the effects of deposited fine sediment on in-stream values

Published by

Cawthron Institute
Private Bag 2
Nelson 7042
New Zealand
www.cawthron.org.nz

Citation

Clapcott, J.E., Young, R.G., Harding, J.S., Matthaei, C.D., Quinn, J.M. and Death, R.G. (2011) Sediment Assessment Methods: Protocols and guidelines for assessing the effects of deposited fine sediment on in-stream values. Cawthron Institute, Nelson, New Zealand.

ISBN: 978-0-473-20105-0 (Print)
ISBN: 978-0-473-20106-7 (Online)

Cover images

Front cover - Wai-iti River (Kati Doehring); Okeover Stream (Jon Harding); Summer Warr trials the Shuffle method in the Porirua River (Juliet Milne); Kati Doehring trials the in-stream visual assessment method in the Wai-iti River (Joanne Clapcott); Ashley River (Mary Beech).
Back cover – St Albans stream showing the effects of liquefaction following the Christchurch earthquake, February 2011 (Jon Harding); Shuffle method in Heriot Burn (Justin Kitto); Ashley River (Mary Beech); St Albans stream (Jon Harding); Wairau River (Karen Shearer).

Graphic design

Downing Design, Nelson, New Zealand.

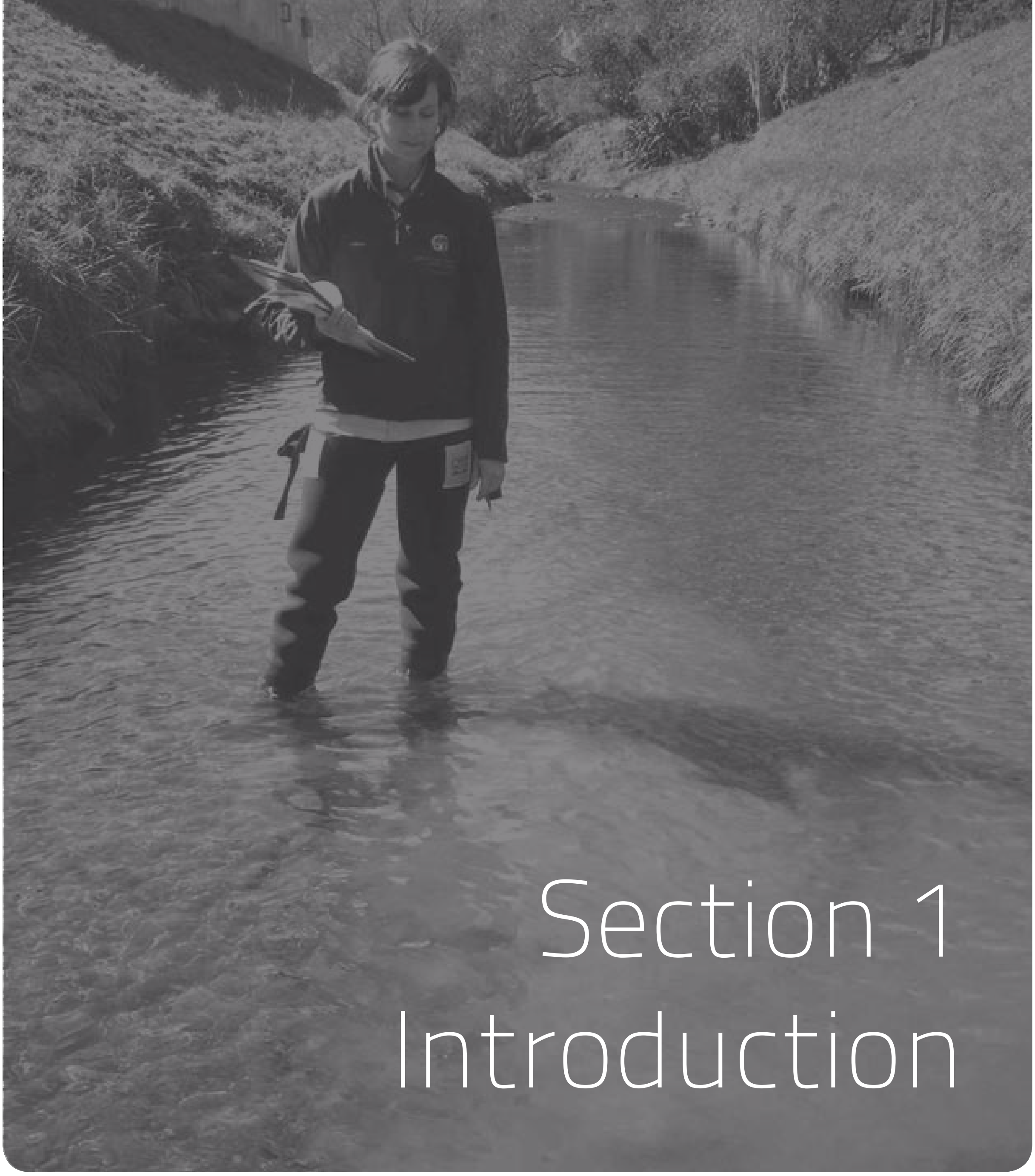
Acknowledgements

We are indebted to a large group of freshwater scientists and technicians who contributed to the development of protocols and guidelines presented in this document. First and foremost, 12 regional councils field tested protocols and provided valuable feedback and data, hence we are very grateful to the following and their field teams – Katrina Hansen (Northland Regional Council), Martin Neale (Auckland Regional Council), Kevin Collier and Mark Hamer (Environment Waikato), Kimberley Hope and Chris Fowles (Taranaki Regional Council), Sandy Haidekker (Hawkes Bay Regional Council), Kate McArthur and Carol Nicholson (Horizons Regional Council), Summer Warr and Alton Perrie (Greater Wellingtin Regional Council), Fleur Tiernan (Marlborough District Council), Trevor James (Tasman District Council), Mary Beech (Environment Canterbury), Justin Kitto and Rachel Ozanne (Otago Regional Council) and Kirsten Meijer (Environment Southland). Several of these people also provided photos contained within. We also thank participants at workshops held at the Ministry for the Environment in Wellington 2009 and at the New Zealand Freshwater Sciences Society Conference in Whangarei in 2009 and in Christchurch in 2010. Adrian Meredith, Kate McArthur, Graham-Sevicke Jones, Mary Beech, Juliet Milne, and Kirsten Meijer were members of the regional council steering committee that developed the brief for the project. We thank Les Basher and Olivier Ausseil for their advice throughout. We thank Eric Goodwin for contributing to the development of the boosted regression tree model and Kati Doehring for her assistance with spatial analysis. We thank David Reid, Kati Doehring , Duncan Gray and postgraduate students of the School of Biological Sciences (University of Canterbury) for their fieldwork contribution. We thank postgraduate students at the University of Otago, NIWA laboratory staff and Environment Canterbury for processing samples. We thank Annika Wagenhoff, Javad Ramezani and Logan Brown for providing additional data for guideline development and we thank Summer Warr, Kate McArthur, Mary Beech and Oliver Ausseil for providing editorial feedback on earlier versions of this document. The Sediment Assessment Methods were funded by the Envirolink Tools programme through the Ministry for Science and Innovation. We thank the Ministry for the Environment for helping publish this document and we thank Cherie Johansson for proofreading and arranging publication.

Ministry for the Environment
Manatū Mō Te Taiao

Contents

Contents



Section 1
Introduction

1 Introduction

This section contains an overview of the project which has been designed to develop protocols and guidelines to assess the effects of sediment on in-stream values.

Deposited fine sediment is defined as inorganic particles deposited on the streambed that are less than 2 mm in size. 'Sediment' henceforth refers to deposited fine sediment, unless stated otherwise.

1.1 Background

Sedimentation is a global issue where land-use change has resulted in excess sediment being delivered to and deposited on the beds of streams, rivers, estuaries and bays. Excess sediment directly affects the health of a waterway, decreasing its mauri or life-supporting capacity.

Deposited fine sediment occurs naturally in the beds of rivers and streams. It usually enters a stream either because of terrestrial weathering processes, or bank erosion and in-stream fluvial processes. Sediment particles are transported and deposited in streams and receiving waters, such as lakes, estuaries and coastal bays, as the result of flowing water. Because sediment is naturally transported longitudinally through a river network, its state at any given point will be influenced by climate, geology, topography and current velocity.

Human activities can impact on this natural sediment cycle by accelerating the delivery of sediment to streams and increasing the quantity of smaller particle sizes. The effect of excess in-stream sedimentation is recognised as a major impact of changing land use on river health. In particular, sediment alters the physical habitat by clogging interstitial spaces used as refugia by benthic invertebrates and fish, by altering food resources and by removing sites used for egg laying. As such, sediment can affect the diversity and composition of biotic communities. Excess sediment can also affect the aesthetic appeal of rivers and streams for human recreation.

Although there is a general recognition of the significance of sedimentation in New Zealand, there are currently no widely accepted protocols for the measurement of deposited sediments, or guidelines to interpret the results in relation to ecological or recreational values. A number of regional councils have recognised the need to collect sediment information and have started to include some measure of deposited sediment in their monitoring programmes (Appendix 6.1). However, in the absence of established national guidance, different methodologies are currently being used. This lack of consistency could compromise the validity of any inter-region comparisons, or national state of the environment reporting. Furthermore, the absence of robust and tested methods may also compromise use of the data in any regulatory context (policy development, resource consents, prosecutions).

The protocols and guidelines presented in this document were developed at the request of New Zealand Regional Councils to address a lack of national consistency. The aim of this document is to provide scientifically robust in-stream protocols and guidelines for the measurement of deposited sediment. The document also includes scientific justification and background information on the testing of these protocols.

1.2 Scope

The key to establishing standardised protocols is identifying methodology that can be applied across a broad range of conditions and yet be sensitive enough to distinguish change. Similarly, guidelines need to be applicable to various river types present in New Zealand.

This document provides information on the development of protocols and guidelines for assessing fine deposited sediment in wadeable rivers and streams in New Zealand. Recommended protocols and related guidelines focus on providing a measure of sediment quantity that relates to specific in-stream values.

In developing a series of protocols the following aspects are addressed:

- Protocols cover both qualitative and quantitative measurements of deposited sediment.
- Protocols are precise and directive enough to be undertaken by any reasonably experienced freshwater scientist/technician. Level of skill, site selection, field equipment, and field and laboratory procedures are described.
- Protocols are scientifically robust, repeatable, and relatively easy to use.
- The key advantages and limitations of each protocol are outlined to help identify the protocol best suited for the aim of the assessment.

Protocols do NOT address:

- Suspended sediment (*e.g.*, turbidity, clarity).
- Sediment quality (*e.g.*, associated contaminants, dissolved oxygen concentration, decomposition potential).
- Non-wadeable waterways.
- Standing water bodies (have not been tested, but some protocols may be suitable for these systems).

In developing a series of guidelines the following aspects are addressed:

- Numerical guideline values are proposed for a range of waterway uses and values (*e.g.*, biodiversity, fish habitat, and aesthetics). These have been based on current best estimates or knowledge, which are provided, along with key limitations and needs for further research and validation.
- Numerical guideline values are a single value defining the threshold between an acceptable or unacceptable state.
- The applicability of numerical guidelines across a range of river types is described.

1.3 Defining deposited fine sediment

Sediment is the collective term for particles that are transported by natural processes (wind, water, glaciers) and eventually deposited. In flowing water, sediment can be defined by its composition, locality and particle size. As such, sediment is organic or inorganic in nature and can be suspended in the water column (causing turbidity) or deposited on the streambed. Using the Wentworth (1922) classification system, sediment is characterised by particle size as mud and silt (<0.0625 mm) and sand (0.0625-2 mm).

During normal flow conditions, suspended sediment is dominated by particles less than 0.0625 mm and can include colloids, clay, mud and silt. These smallest particles also form part of the deposited sediment, and can be collectively referred to as 'suspendible sediments'. Larger particles deposited on the streambed are collectively referred to as 'bed load'. The movement of sediment is dependent on channel morphology and flow. For example, higher water velocities are able to transport larger particles.

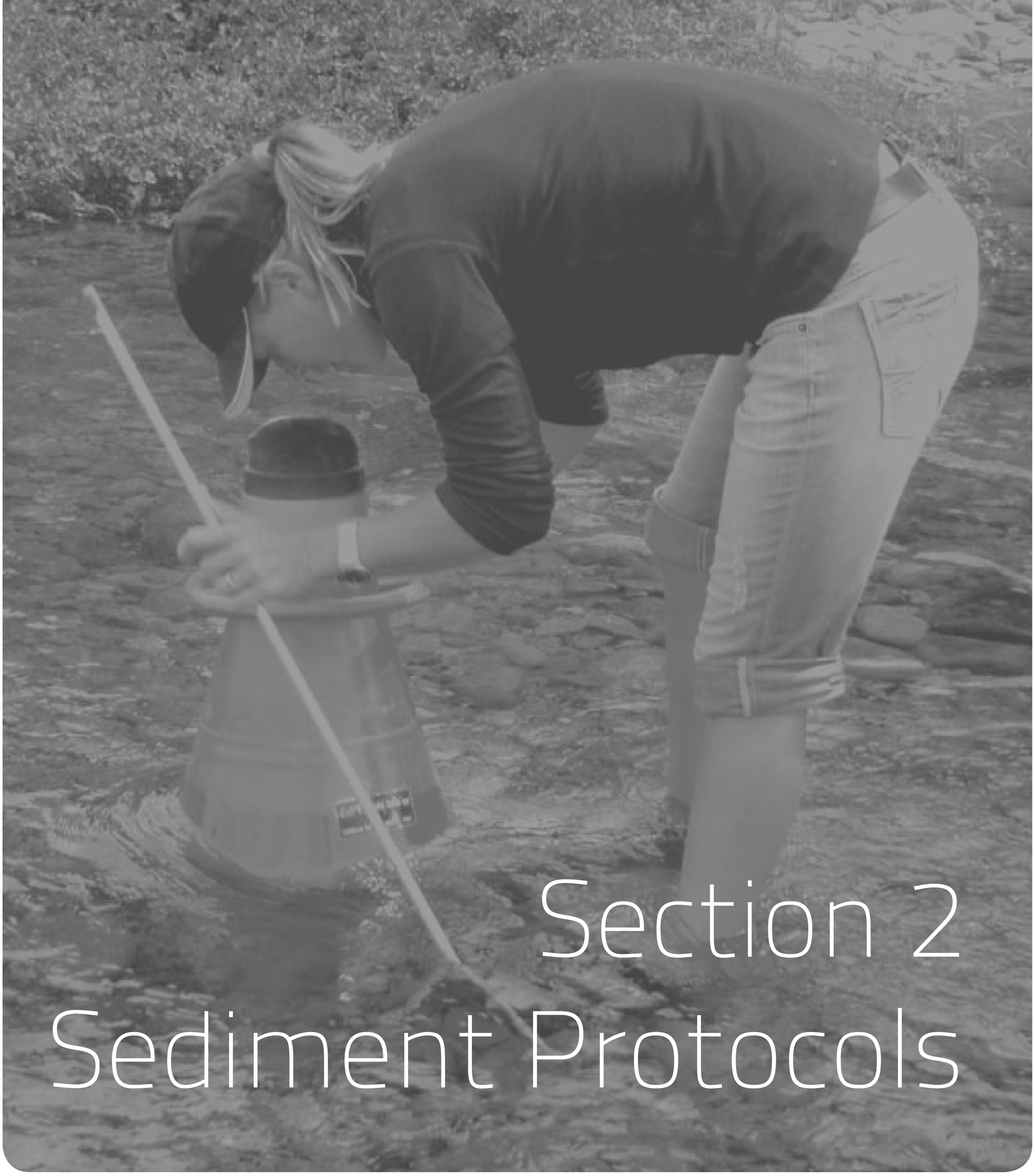
In this document, deposited fine sediment refers to inorganic particles deposited on the streambed that are less than 2 mm in size. 'Sediment' henceforth refers to deposited fine sediment, unless stated otherwise.

1.4 Sediment and in-stream values

Human activities, including urban development, agriculture and forestry, can accelerate the delivery of sediment to streams or disrupt their natural downstream progression. When this occurs, resource managers and stakeholders need to know to what degree this affects in-stream values and biota.

In 2009, a survey of regional councils in New Zealand (Appendix 6.1) identified what in-stream values were perceived as being affected by sediment. These in-stream values were ranked in declining importance from invertebrate community composition and abundance, native fish spawning/habitat, biodiversity, sports fish habitat (*i.e.*, trout and other salmonids), to aesthetics and swimming. Other values identified include mahinga kai (food-gathering places), interstitial space and groundwater connectivity, phosphorus levels, river function and habitat integrity, and *E. coli*.

The primary values identified by regional councils (invertebrates, fish and amenity) strongly correlate to qualities well recognised as being significantly affected by excess in-stream sediment (Owens *et al.* 2005). As such there is considerable literature on anecdotal and quantitative relationships between deposited sediment and in-stream values (Section 4.1). This information was used to assist in the selection of protocols and development of guidelines in this document.



Section 2
Sediment Protocols

2 Sediment Protocols

This section outlines the guiding principles to applying sediment protocols, such as where, when and how.

Overviews, field procedures and useful images for training purposes are provided for six recommended protocols.

A summary of findings from a literature review, protocol testing and data evaluation is provided to inform method selection – for a full description of methods, references and data summaries the reader is referred to Section 4.

2.1 Guiding principles

2.1.1 Site selection

The protocols provided in this document are measures of sediment quantity for a single site; developed to provide a representative measure of sediment at a reach scale, but focus specifically in runs (defined below). There will be error associated with extrapolating information collected from a single habitat to a larger spatial scale and practitioners are directed to other resources to determine the appropriateness of such extrapolation (see Downes *et al.* 2002; Harding *et al.* 2009).

Although the sediment protocols presented in this document were developed for specific stream habitats and in-stream values, this does not exclude their application to other in-stream habitats and this is noted when applicable.

Rationale to inform site selection:

- **Include single run habitat –** runs are intermediary between riffles and pools and therefore provide an average measure for a stream reach (see Section 4.3.1)
- **Assess the full run –** by walking the length of the habitat for bankside visual assessments (light refraction off surface water can impede assessments from a stationary point); by systematically sampling in an upstream direction for in-stream visual and other protocols
- **Restrict to the wetted stream width –** assessment of the wetted channel provides less error (see Section 4.2.2); most methods are also restricted to the wetted channel
- **Avoid runs with aquatic plants –** macrophytes entrap sediment and can have high seasonal variability; macrophytes and periphyton also make visual assessments difficult (see Section 4.3.9)
- **Replicate across several runs –** where time and resources allow a more accurate and robust measure of reach-scale sediment can be obtained by sampling three run habitats.

2.1.2 Sample collection

The mobility of sediments means that at any point in a river their quantity will vary naturally over time. Fine sediment movement is influenced by channel slope, channel roughness and flow (discharge and velocity). The relationship between these stream properties has been used to calculate bed load movement and sediment load budgets (Gordon *et al.* 2004). Given that channel slope and roughness are relatively stable, the stream property that will most affect short to medium term (months to years) variability in sediment is flow. Therefore sampling to measure changes in sediment should take into consideration the effects of discharge and velocity. Unless sampling is designed to specifically assess the effects of a discharge event, sampling should occur at a relatively stable point in the hydrograph.

Rationale to inform the timing of sampling:

- **Low to median discharge conditions** – fine sediment is suspended during high flow; visual assessments are difficult during high flow; it is unsafe to enter a waterway during high flow.
- **Low to median velocities** – in-stream assessments are impeded by high velocities.

2.2 Method selection and field validation[1]

An assessment of sediment quantity requires knowledge of areal cover, substrate size and interstitial space (Cantilli *et al.* 2006). These requirements were used to review and assess potential sediment protocols. Following a literature review (Section 4.2), protocols for six methods were developed and tested (Table 2-1).

Table 2-1. Description of sediment methods and metrics trialled as part of the protocol testing and validation stage.

Sediment Component	Method	Metric	Description
Sediment cover	Bankside visual	% sediment cover	A bankside semi-quantitative measure of the relative cover of fine sediment in comparison to other substrate classes
	In-stream visual	% sediment cover	An in-stream (using an underwater viewer) semi-quantitative measure of the relative cover of fine sediment in comparison to other substrate classes
Substrate size	Wolman pebble count	% sediment ("W2"), d16, d50, d86	A quantitative measure of the percent of fine sediment calculated from at least 100 random substrate measurements
Interstitial space	Quorer	SIS (mg/m^2), SOS(mg/m^2), %SIS	A quantitative measure of the amount of suspendible inorganic sediment (SIS) and suspendible organic sediment (SOS) on the streambed
	Shuffle index	Shuffle index score	A qualitative rank (1-5) measure of the degree of suspendible fine sediment on the streambed
	Sediment depth	Depth (mm)	A quantitative measure of the depth of fine sediment in runs

[1]This section provides a summary of findings from a literature review, protocol testing and data evaluation – a full description of methods, references and data summaries is provided in Section 4.

Protocol testing and validation involved a national-scale effort by 12 regional councils, Cawthron Institute (Cawthron), National Institute for Water and Atmospheric Research (NIWA), University of Canterbury and University of Otago over a period of six months and covering 264 river sites.

Results of the protocol testing and validation showed a high degree of consistency in the output provided by the different methods (Section 4.3.6). Sediment depth was the only metric not correlated with other measures of sediment. Results indicated that the bankside visual estimate of % sediment had the strongest and most consistent relationship with biological indicators of in-stream values (Section 4.3.8). The bankside visual estimate of % sediment was also strongly correlated with the more labour intensive in-stream visual estimate of % sediment (Section 4.3.6). The bankside method is likely to be a suitable measure for broad-scale state of the environment assessments. The bankside method provides a single numerical value, whereas the in-stream visual method includes multiple visual observations and therefore would be more suitable when a measure of error/variability is needed (Table 2-2).

Substrate size composition using a Wolman pebble count provides an assessment of % fine particles as well as other useful substrate composition data, for example, d50 (*i.e.*, the median particle size) (Table 2-2). The Quorer method provides a quantitative measure of sediment in the surface and subsurface layers and as such could also be used to indicate the 'embeddedness' of particles and interstitial space. The Quorer method has several alternative measures that can be applied to assess suspendible sediment (*i.e.*, SIS, SOS, suspendible benthic sediment volume (SBSV), Section 4.3.7). Whilst the Shuffle method was only weakly correlated with Quorer results, it does provide a rapid assessment of suspendible sediment in relation to amenity values (Section 4.3.6; see also Section 4.5.8).

Whilst the bankside visual estimate of % sediment was most consistently related to invertebrate metrics, all protocols trialled showed a significant correlation ($p < 0.01$) with the macroinvertebrate metrics of stream biotic health, the Macroinvertebrate Community Index (MCI) and/or the number of taxa belonging to the sensitive insect families Ephemeroptera, Plecoptera and Trichoptera (EPT) (Section 4.3.8).

Table 2-2. Recommended sediment protocols based on protocol testing and validation.

Type of assessment	**Sediment component**		
	Sediment cover	**Substrate composition**	**Interstitial space**
State of the Environment	Bankside visual estimate of % sediment	Wolman pebble count	Quorer SIS or Quorer SBSV or Shuffle
Assessment of effects	In-stream visual estimate of % sediment	Wolman pebble count	Quorer SIS Sediment depth (mm)

2.3 Recommended protocols

Sediment Assessment Method 1 - Bankside visual estimate of % sediment cover

Rationale	Rapid qualitative assessment of the surface area of the streambed covered by sediment.
Equipment required	• Field sheet • Camera
Application	All streams
Type of assessment	State of the environment (broad-scale survey)
Time to complete	5 minutes
Description of variables	
Habitat length (m)	Estimation of habitat length in metres.
% sediment	A visual estimation from the stream bank of the proportion of the habitat covered by sediment (<2 mm).
ratio of sand:finer	Provides a rough indication of the relative components of sand versus mud and silt.
Useful hints	Complete at start of site survey/sampling.
	Note that this measure is also part of the Stream Habitat Assessment Protocols P2c (*i.e.*, an estimate of all substrate size classes).

Field procedure

- Estimate habitat length (m) and the percentage of streambed within the wetted width covered by sediment <2 mm in size (0-100%) from the stream bank, for each riffle, run, pool present.
- Record percentages (%) in the table below.
- Take a representative photograph.

Habitat	Riffle	Run	Pool	(Comments)
Habitat length (m)				
% sediment				
Ratio sand:finer (silt, clay, mud)				
Photo (Yes/No)				

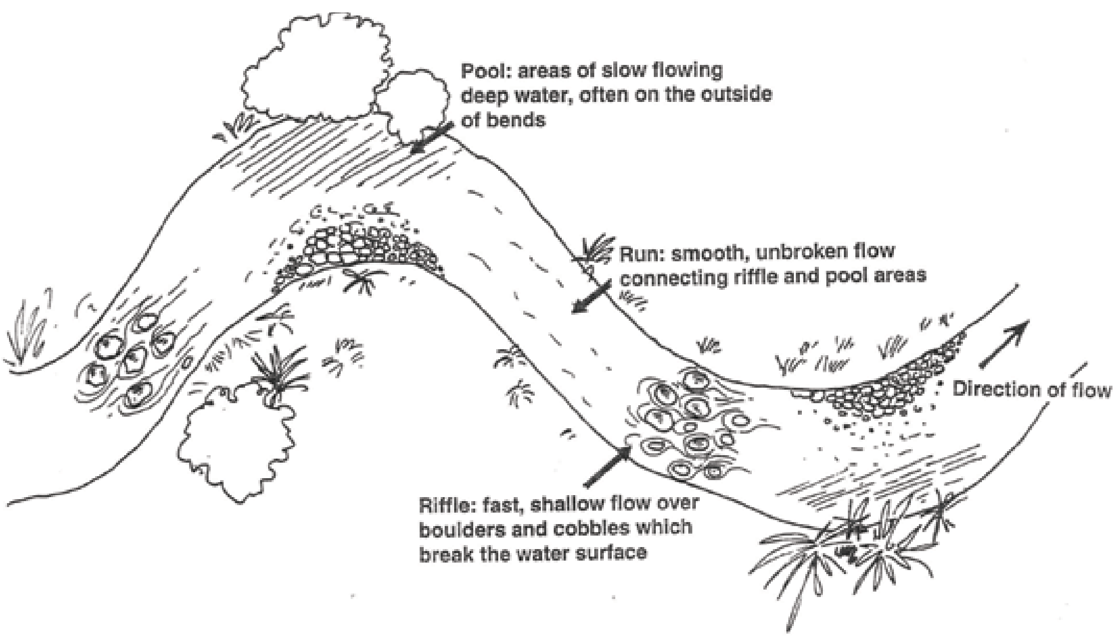
Notes:

- The average value for each habitat present weighted by length is used to calculate % sediment at the reach scale
- If all habitats are not present record % sediment for a run habitat only.
- The assessment of all substrate size classes can be obtained at the same time, but it is not necessary for the determination of % sediment cover.
  The table below can be used to assess all substrate size classes.

Habitat	**Riffle**	**Run**	**Pool**	**(Comments)**
Habitat length (m)				
% mud/silt (<0.06 mm)				
% sand (0.06-2 mm)				
% fine gravel (2-16 mm)				
% coarse gravel (16-64 mm)				
% cobbles (64-256 mm)				
% boulders (>256 mm)				
% bedrock (layer of solid rock)				

Useful images

Run, riffle and pool habitat locations (Image courtesy of Cathy Kilroy – from Biggs *et al.* 2002).



Sediment Assessment Method 2 – In-stream visual estimate of % sediment cover

Rationale	Semi-quantitative assessment of the surface area of the streambed covered by sediment. At least 20 readings are made within a single habitat
Equipment required	• Underwater viewer - *e.g.*, bathyscope (www.absolutemarine.co.nz) or bucket with a Perspex bottom marked with four quadrats • Field sheet
Application	Hard-bottomed streams
Type of assessment	Assessment of effects
Time to complete	30 minutes
Description of variables	
% sediment	A visual estimate of the proportion of the habitat covered by deposited sediment (<2 mm)
Useful hints	Work upstream to avoid disturbing the streambed being assessed. Mark a four-square grid on the viewer to help with estimates – determine the nearest 5% cover for each quadrat. Calculate the average of all quadrats as a continuous variable following data entry. More than five transects may be necessary for narrow streams, to ensure 20 locations are sampled.

Field procedure

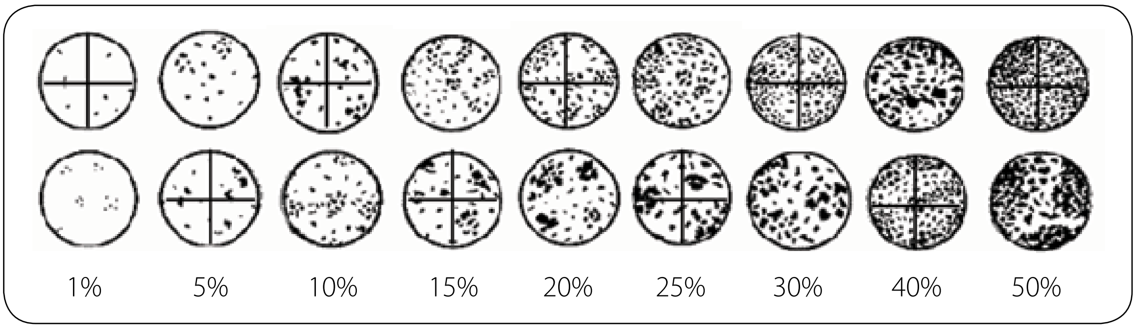
- Locate five random transects along the run.
- View the streambed at four randomly determined locations across each transect, starting at the downstream transect.
- Estimate the fine sediment cover in each quadrat of the underwater viewer in increments (1, 5, 10, 15, 20 …100%).
- Record results in the table below.
- Repeat for four more transects so that 20 locations are sampled in total.

Note: Estimation of cover in each quadrat is important during training but may not be necessary for experienced viewers – instead one measurement per location could be recorded.

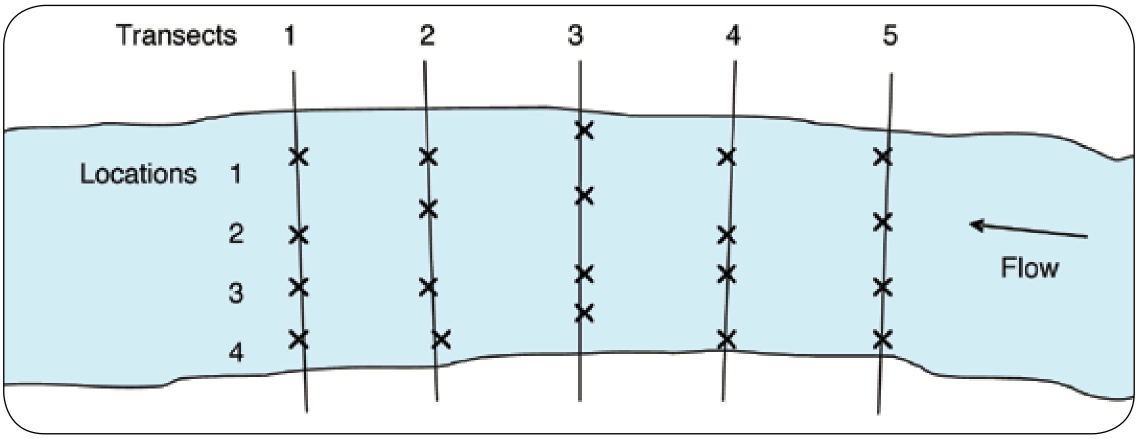
% sediment	Transect 1		Transect 2		Transect 3		Transect 4		Transect 5	
Location 1	Q1	Q2								
	Q3	Q4								
Location 2										
Location 3										
Location 4										

Useful images

Digital examples of percent cover of sediment on the streambed as seen through an underwater viewer.

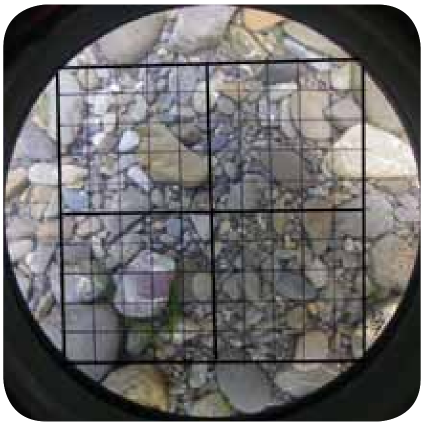


An example of viewer locations (x) for the in-stream visual assessment of sediment.

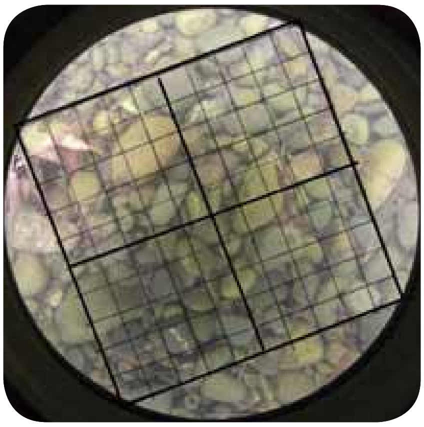


Real examples of percent cover of sediment on the streambed as seen through an underwater viewer.

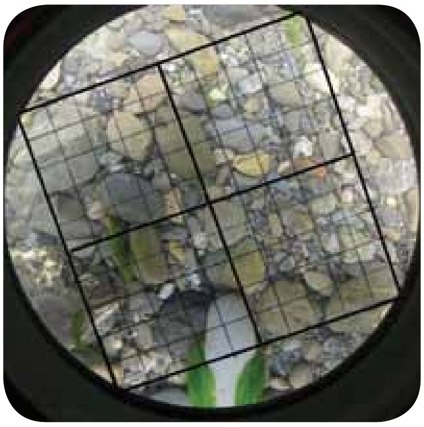
1%



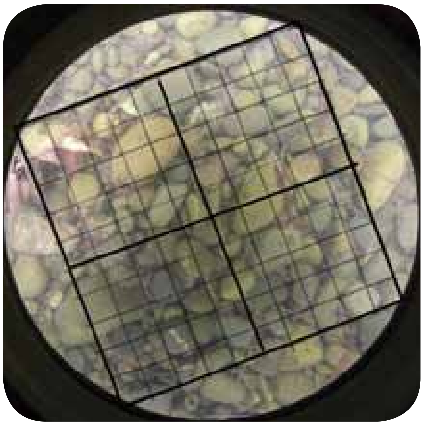
1%



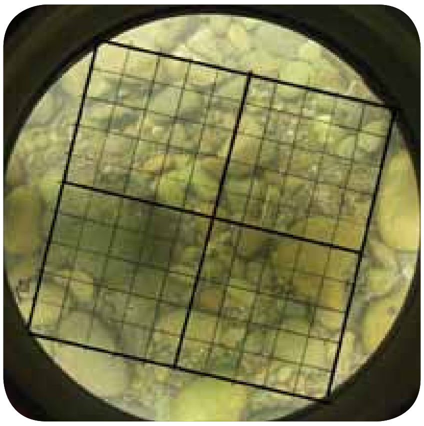
5%



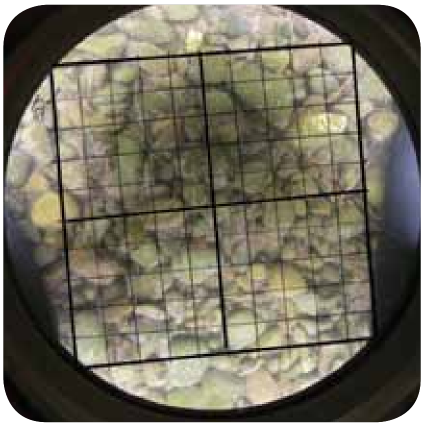
5%



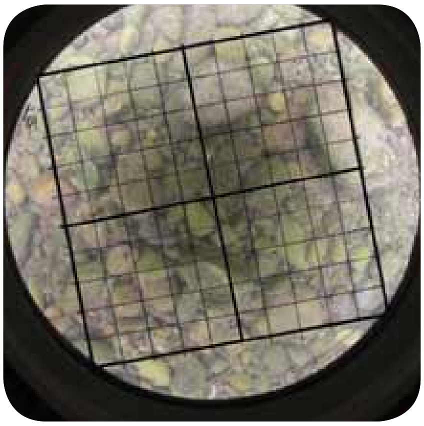
10%



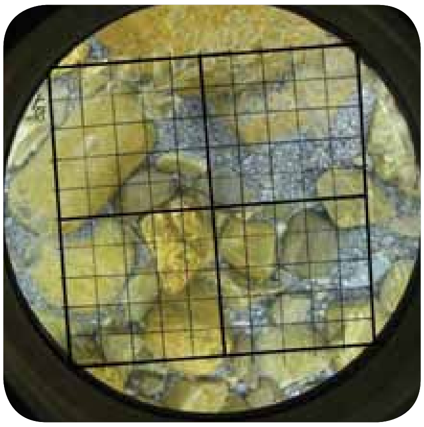
10%



15%



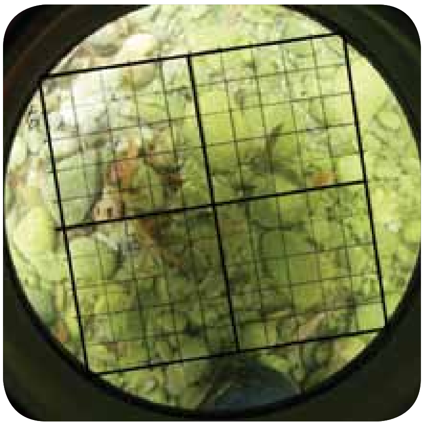
15%



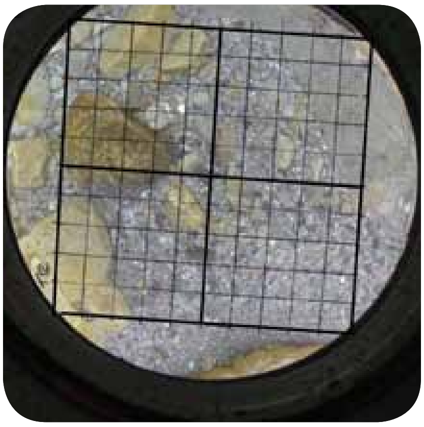
20%

20%

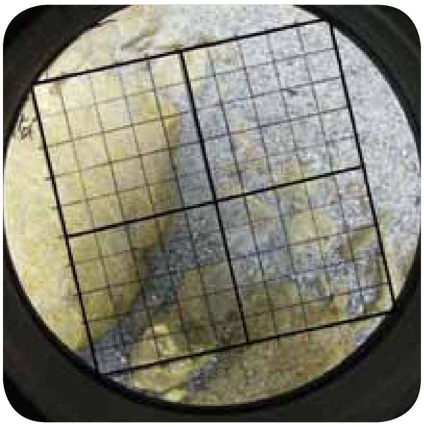
25%



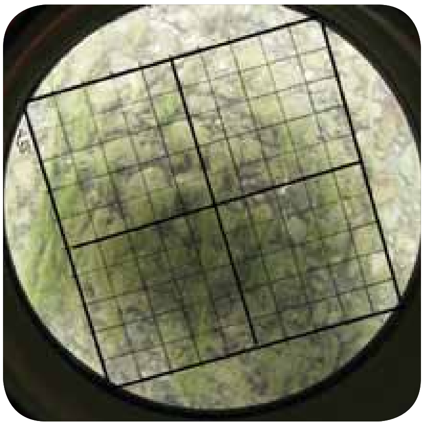
30%



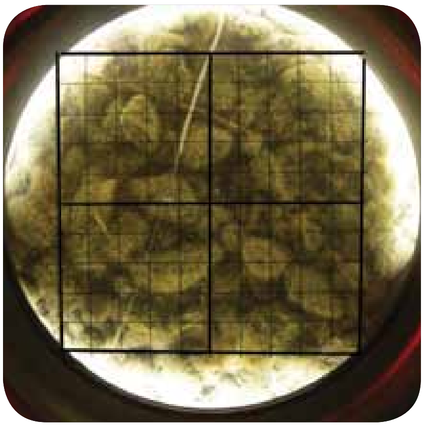
40%



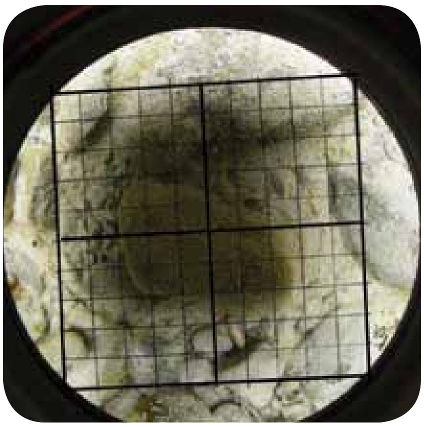
50%



90%



100%



Sediment Assessment Method 3 – Wolman pebble count

Rationale	Semi-quantitative assessment of the particle size distribution, including fine sediment, on the streambed. At least 100 particle measurements are made within a single habitat.
Equipment required	• Gravelometer (www.envco.co.nz) or a ruler marked with a modified Wentworth scale (*e.g.*, 2, 8, 16, 32, 64, 128, 256, >256 mm, bedrock) • Field sheet
Application	Hard-bottomed streams
Type of assessment	State of the environment (broad-scale survey) Assessment of effects
Time to complete	20 minutes
Description of variables	
Particle size class	The length of the particle B-axis in millimetres.
Useful hints	Avoid bias in foot placement or in particle selection, *i.e.*, be rigorous about selecting the particle in the middle of the front of the boot at regular paces across the stream. Assess any particles picked up – this should include silt/clay particles on top of larger particles. This measure is similar to that of the Stream Habitat Assessment Protocols P3c.

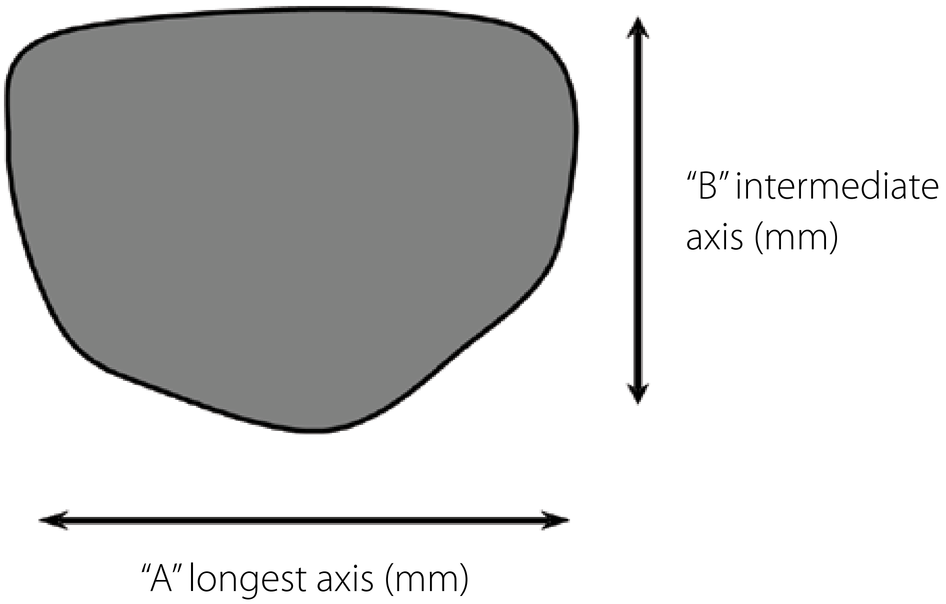
Field procedure

- Sample beginning at the downstream end of a run and proceed across and upstream.
- Select particles at the front of your foot.
- Select at least 100 particles within the wetted width of a run.
- Use a gravelometer or a ruled rod, to measure the B-axis size class. The B-axis would prevent a particle from passing through a gravelometer/sieve.
- Record particle size classes (on a modified Wentworth scale) as tally marks in the table below.
  Note: Measurement of particle size is important during training but may not be necessary for experienced field staff – instead the descriptive table may be a useful guide.

Particle size class	Count	Description
Clay/silt (<0.06 mm)		Not gritty between fingers and hard to pick up but visible as particles
Sand (>0.06-2 mm)		Gritty between fingers Smaller than a match head
Small gravel (>2-8 mm)		Match head to little finger nail size
Small-Med Gravel (>8-16 mm)		Little finger nail to thumb nail size
Med-Large Gravel (>16-32 mm)		Thumb nail to golf ball size (or circle when thumb and index finger meet)
Large Gravel (>32-64 mm)		Golf ball to tennis ball size (or fist)
Small Cobble (>64-128 mm)		Tennis ball to softball size (or circle when thumb and index fingers of two hands meet)
Large Cobble (>128-256 mm)		Softball to basketball size
Boulders (>256 mm)		Basketball or greater
Bedrock		Continuous layer of solid rock

Useful images

B-axis of a pebble



Sediment Assessment Method 4 – Resuspendible sediment (Quorer method)

Rationale	Quantitative measure of total suspendible solids deposited on the streambed. Six samples are collected from a single habitat. Samples are processed in the laboratory for Total Inorganic/Organic Sediment by area (SIS and SOS, respectively) or Suspendible Benthic Solids by Volume (SBSV).
Equipment required	• Cylindrical tube (*e.g.*, 45 cm length of 35 cm diameter plumbing tube for gravel bed streams, or 60 cm length of 50 cm diameter metal tube for cobble bed streams) • 7 x >120 ml screw topped sample bottles • Stirrer • Ruler (*e.g.*, broom handle marked with 1 cm graduations) • Field sheet
Application	Hard-bottomed streams
Type of assessment	State of the environment (broad-scale survey) Assessment of effects
Time to complete	30 minutes
Description of variables	
Sample	Sample number
Average water depth (m)	The average of five water depths inside the cylinder in metres.
Average stirred depth (m)	The average of five water depths inside the cylinder in metres to the depth that the sediments were stirred. Measured after water sample collection.
Useful hints	A split garden hose placed around the top of the tube aids with the insertion into coarse substrates. Welded handles at hand-height assist with use of large diameter corers used in cobble bed rivers. This method is not suitable for streambeds dominated by large boulders. Large cobbles can be removed from the corer prior to stirring. Do not over-fill sample bottles because they expand when frozen (samples should be frozen until analysis).

Field procedure

- Collect a background water sample (*i.e.*, control sample).
- Insert an open-ended cylinder into the streambed in a run and measure water depth at five random locations within the cylinder. Record average water depth. Stir the upper 5-10 cm of sediment for 15 seconds.
- Collect a sample of slurry (dirty water) and label.
- Estimate average stirred depth (sediment + water).
- Repeat Quorer method at five more locations.
- Freeze the six slurry samples and one background sample per site until laboratory analysis.

Sample	Average water depth (m)	Average stirred depth (m)
Control	na	na
1		
2		
3		
4		
5		
6		

Notes

- Suspendible inorganic sediment (SIS) and suspendible organic sediment (SOS) are determined using the standard protocol for Total Suspended Solids (TSS method 2540D in APHA 1998) and Volatile Suspended Solids (VSS method 2540E in APHA 1998).
    - o SIS (g/m^2) = ($TSS_{(sample – control)}$ – $VSS_{(sample – control)}$) x average depth (m) in cylinder
    - o SOS (g/m^2) = $VSS_{(sample – control)}$ x average depth (m) in cylinder
- Stirred depth (m) is used to calculate SIS or SOS in g/m^3.
- Suspendible benthic sediment volume (SBSV) is determined using a settling assay (See Appendix 6.4 for details).
- The average value is calculated for each site.

Sediment Assessment Method 5 - Resuspendible sediment (Shuffle index)

Rationale	Rapid qualitative assessment of the amount of total suspendible solids deposited on the streambed. A score from 1-5 is assigned, where 1 = little/no sediment and 5 = excessive sediment.
Equipment required	• Camera • 10 cm x 10 cm white tile • Field sheet
Application	All streams
Type of assessment	State of the environment (broad-scale survey) Assessment of effects (as support variable)
Time to complete	5 minutes
Description of variables	
Water depth (m)	Depth of water in metres at tile location
Water velocity (fast/medium/slow)	Water velocity at tile location
Score	A value of 1-5
Photo	Indication of whether a photo record was obtained (preferably 'Yes')
Useful hints	This method is best applied in an area where flow is between 0.2 0.6 m/sec and depth is between 20 and 50 cm. Depth and velocity may be estimated and are mainly recorded to ensure the method was applied in appropriate and comparable conditions. Photos could be taken by a second team member on the stream bank. Best completed at the end of sampling. The average score is calculated for each site.

Field procedure

- Place a white tile on the streambed in a run, and measure/estimate water depth and velocity at this point.
- Stand 3 m upstream of the tile and disturb the streambed by moving feet vigorously for five seconds.
- Allocate a score from 1-5 depending on the visibility and duration of the resulting plume in relation to the white tile downstream.
- Take a photo record of the plume where possible.
- Repeat this process twice upstream.

Sample	Water Depth (m)	Water velocity (fast/medium/slow)	Score	Photo (yes/no)
1				
2				
3				

Useful images

Resuspendible sediment index examples.

Score 1: No or small plume

Score 2: Plume briefly reduces visibility at tile

Score 3: Plume partially obscures tile but quickly clears

Score 4: Plume partially to fully obscures tile but slowly clears

Score 5: Plume fully obscures tile and persists even after shuffling ceases

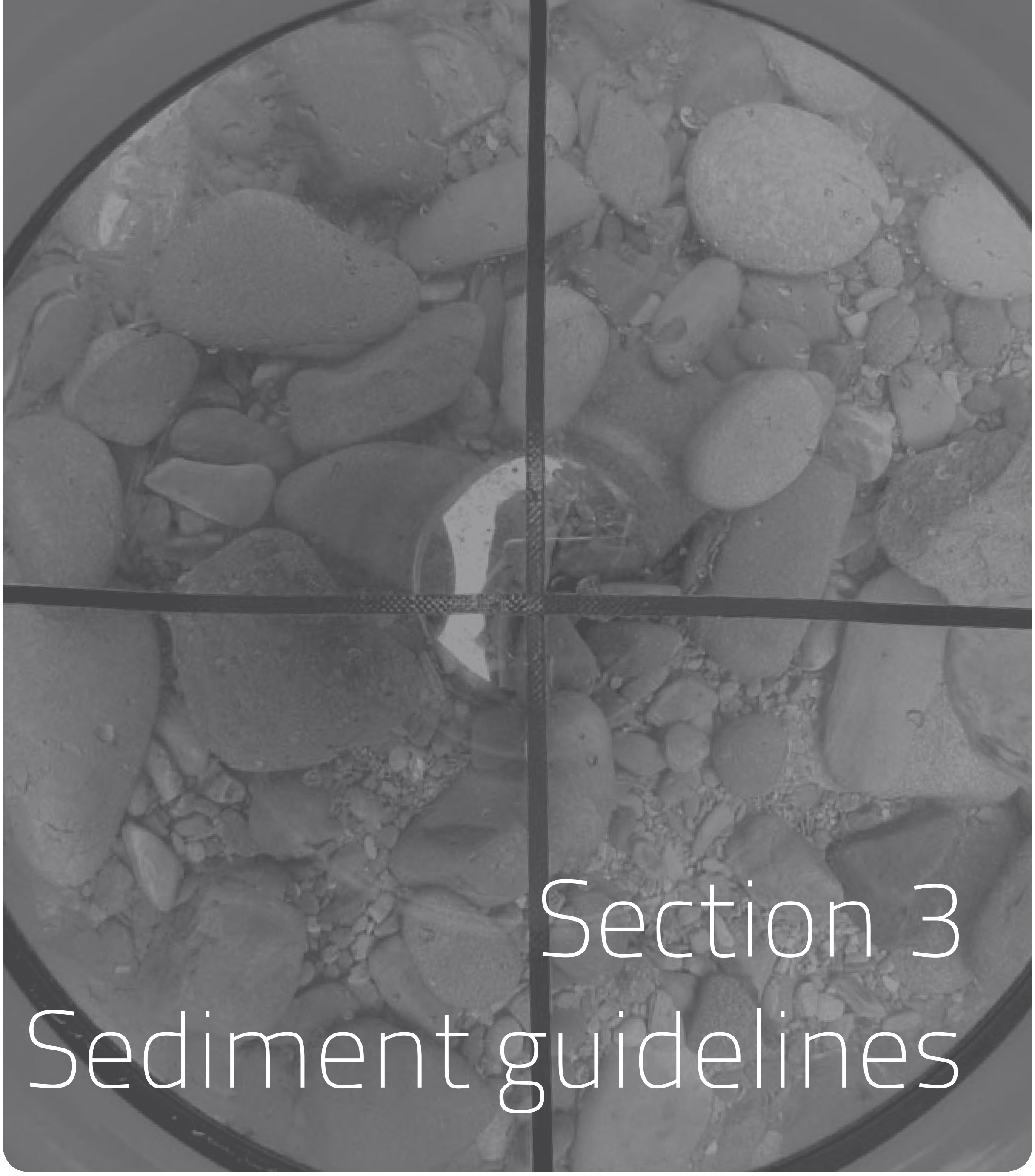
Sediment Assessment Method 6 –Sediment depth

Rationale	Quantitative assessment of the depth of sediment in a run habitat. At least 20 readings are made within a single habitat
Equipment required	• Ruler or ruled rod • Field sheet
Application	Hard-bottomed streams
Type of assessment	Assessment of effects
Time to complete	30 minutes
Description of variables	
Sediment depth (mm)	A measure of the depth of sediment (mm).
Useful hints	Determine the sampling grid first to ensure an even cover of edge and midstream locations. Move upstream to avoid disturbing the streambed being assessed. Calculate the average depth for each site. This method is usually only suitable when fine sediment is visible from the stream bank.

Field procedure

- Start downstream and randomly locate five transects along the run.
- Measure the sediment depth (mm) at four randomly determined locations across each transect and record depth in the table below.

Depth (mm)	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5
Section 1					
Section 2					
Section 3					
Section 4					



Section 3
Sediment guidelines

3 Sediment Guidelines

This section outlines the guiding principles to applying sediment guidelines, such as their foundation on values based assessments and their application in hard-bottomed streams during low flow.

Numerical guideline values are recommended for the protection of biodiversity, fish spawning habitat and in-stream amenity values.

A summary of findings from a literature review, a survey and data analysis to inform guideline development is provided. Reference to scientific literature has been omitted for ease of reading – for more detail readers are referred to Sections 4.1, 4.4 and 4.5.

3.1 Guiding principles

3.1.1 Values-based assessment

There is a common acceptance that excessive fine sediment deposited on stream and river beds can adversely affect a number of environmental and community values, including, but not restricted to, ecosystem health, amenity and recreational values. However, there is currently little guidance about what constitutes acceptable and unacceptable levels of sediment in relation to the different in-stream values.

The key question driving the development of these guidelines is:

What level of sedimentation corresponds to a significant adverse effect on the different in-stream values?

The aim of these guidelines is to use the best current scientific information and knowledge available nationally and internationally to answer this question in relation to three key in-stream values identified by the regional councils (Section 1.4; see also Appendix 6.1):

- macroinvertebrate communities health, as an indicator of overall aquatic ecosystem health
- trout spawning
- aesthetic, amenity and contact recreation values.

These guidelines are formulated as numerical thresholds, representing levels of in-stream sedimentation beyond which specific in-stream values become impaired.

Rationale informing guideline development:

- **Guidelines relate to values –** proposed guidelines provide a level of protection of the identified primary in-stream values (invertebrates, fish, and aesthetics).

3.1.2 Hard- versus soft-bottomed streams

Whether a stream is naturally dominated by fine sediment is dependent on a number of factors including stream size, slope, rainfall, catchment vegetation and geology. Streams naturally dominated by sediment are usually very small streams with low slopes and low rainfall on sandy soils. Such 'soft-bottomed' streams currently account for approximately 20% of the length of rivers in New Zealand, according to Freshwater Ecosystems of New Zealand (FENZ) classification (Leathwick *et al.* 2011). Whereas, predictions from GIS models suggest less than 2% of all NZ streams would have greater than 50% fine sediment cover in the absence of human land-use activities (Section 4.5.4). Together these analyses indicate that the majority of streams in New Zealand are, or should be 'hard-bottomed', dominated by relatively coarse (gravel or larger) substrate.

During the protocol development stage sediment depth was trialled as a potential metric to assess naturally soft-bottomed streams. However, sediment depth was poorly related to invertebrate biotic metrics, possibly because many of the indicators used to assess stream condition in New Zealand are developed primarily for application in hard-bottomed streams, for example %EPT. Sediment depth data was also not as abundant as other protocol data.

Thus these guidelines focus on hard-bottomed streams and assume that an increase in sediment is detrimental to fauna and flora naturally occurring in hard-bottomed streams. However, some protocols reviewed in Section 4.2 may be applicable for assessing sediment accumulation in soft-bottom streams (*e.g.*, volume of sediment in pools). Guideline values are not provided for these untested methods.

Rationale informing guideline development:

- **Hard-bottomed streams –** majority of waterways in New Zealand are or should be dominated by coarse substrate.

3.1.3 Accounting for temporal and spatial variability

New Zealand is a geologically young and tectonically active country subject to strong erosive elements (wind, rain) and land forming processes (tectonic uplift, volcanism and earthquakes). New Zealand streams can be subject to high sediment loads on a continual or episodic nature and some river systems have among the highest sediment bed loads recorded globally (Hicks *et al.* 2000). Furthermore, human land-use activities can accelerate in-stream sediment delivery and alter downstream transportation. For example, a storm event can lead to land slumping that delivers sediment to a stream; the degree of slumping can be amplified due to vegetation clearance for agriculture, while water abstraction can reduce the power of a stream to redistribute sediment.

The above example illustrates the need to consider temporal and spatial variability in sediment distribution and accumulation when applying sediment guidelines. Therefore, it is important to determine 'excess' sediment in relation to what would occur naturally, *i.e.*, in respect to a reference condition. It is also important to be wary of undertaking sediment assessments at times of active sediment movement, for example, immediately after periods of high flow.

Rationale informing guideline development:

- **Comparison to reference –** New Zealand streams vary a lot over space and time. While an upper limit may be applicable to protect certain values in all waterways, the degree of departure from a reference state will provide a more sensitive assessment of sediment impact.

3.2 Determining sediment guideline values[2]

An evidence-based approach was used to develop guidelines for sediment quantity, based on reported relationships and available data. This is sometimes referred to as 'weight-of-evidence' or 'consensus-based' approach and is widely used to define guideline values and inform decision-making processes in regards to sediment quality (*e.g.*, MacDonald *et al.* 2000; Burton *et al.* 2002).

The methods used to determine sediment guidelines included:

[2]This section provides a summary of findings from a literature review, survey and data analysis to inform guideline development. Reference to scientific literature has been omitted for ease of reading. For more detail readers should refer to sections 4.4 and 4.5.

- a review of existing guidelines (Section 4.4)
- a review of quantitative relationships between sediment and in-stream values (Sections 4.1 and 4.5.7)
- correlative analyses among sediment metrics (Section 4.5.2)
- linear regression analyses among sediment metrics and biotic variables (Section 4.3.8)
- data mining to inform reference state (Section 4.5.5)
- boosted regression tree model to inform reference state (Section 4.5.4)
- survey of amenity values (Section 4.5.6).

A **review of existing sediment guidelines** for waterways identified a wide range in sediment criteria and standards because of a wide range in definitions of deposited fine sediment (*i.e.*, anywhere from <0.85 mm to <6.4 mm in size) and methods used to measure sediment (*e.g.*, Wolman pebble counts, embeddedness). Also, sediment guidelines have been developed to protect a range of values. Generally, sediment guidelines include an absolute upper limit and a target deviation from reference. In North America, upper limits range from less than 3% to less than 30% sediment with less than 5% to less than 27% recommended deviation from reference.

Environment Canterbury Regional Council is the only New Zealand authority to currently include sediment guidelines in regional planning, recommending between 10% and 40% absolute sediment cover, depending on the management purposes defined in each water quality management unit .

A **review of quantitative relationships** between sediment and in-stream values in New Zealand showed that sediment directly affects invertebrate community composition, EPT taxa richness and abundance, specific taxa density and invertebrate drift. Anywhere between 10% and 10-fold increases in sediment resulted in noticeable invertebrate responses, with changes amplified over time. Few quantitative relationships have been observed between native fish and deposited sediment. International literature suggests ideal sport fish habitat (*i.e.*, salmonids) has less than 10% sediment, but greater than 20% sediment will result in fish egg mortality.

Correlative analyses among sediment metrics showed that all visual estimates of sediment cover were strongly correlated, *i.e.*, in-stream visual, and bankside visual at a reach or run scale. This suggests that guidelines developed for sediment cover can be assessed using any visual assessment method. Quorer metrics were related to visual estimates of sediment cover at a run scale, but not at a reach scale. All other sediment metrics were related to each other except % sediment calculated from Wolman pebble counts and sediment depth. Results demonstrated the interdependence of sediment components, *i.e.*, cover, substrate size and suspendible sediment.

Linear regression analyses among sediment metrics and biotic variables showed few predictive relationships and a wide range in biotic values at low values of sediment. A linear relationship between bankside visual % sediment and MCI suggested a negative value of sediment at 120 MCI (*i.e.*, MCI value indicative of good health). A negative linear relationship between bankside visual % sediment and %EPT richness suggested a value of 7% sediment at 50% EPT (*i.e.*, EPT value potentially indicative of good health). A negative linear relationship between SIS (log-transformed) and MCI suggested a value of 22 g/m^2 at 120 MCI. A negative linear relationship between sediment depth (log-transformed) and the total number of invertebrate taxa and EPT richness was also observed.

Data mining to inform reference state involved viewing the distribution of sediment data to determine the 75th percentile for sites with greater than 80% native vegetation in their catchments, and the 75th percentile for sites with greater than 120 MCI and greater than 50% EPT. These approaches resulted in a similar value for each of the sediment metrics (Table 3-1).

Table 3-1. Sediment reference values derived from two approaches to examine the distribution of sediment data collated to develop sediment guidelines.

Summary of 75th percentile values	>80% native vegetation	>120 MCI	>50% EPT
% sediment (bankside visual reach scale)	15	20	20
% sediment (bankside visual run scale)	20	20	20
% sediment (in-stream visual)	17	13	17
% sediment (Wolman pebble count)	17	8	20
SIS (g/m^2)	405	429	953
SOS (g/m^2)	28	43	69
%SIS	91	94	94
Shuffle index score	2	2	3
Sediment depth (mm)	9	4	63

SIS = Suspendible inorganic sediment, SOS – suspendible organic sediment, %SIS = percentage of suspendible sediment that is inorganic

A **boosted regression tree model to inform reference state** was used to make national predictions of sediment cover in the absence of land-use impacts. Percent sediment data from the New Zealand Freshwater Fish Database (NZFFD) was used along with land-use and environmental descriptors for each stream reach from FENZ. The model predicted a current national average of 29% sediment cover, but when the influence of land-use was factored out, the model predicted a national average of only 8% sediment cover. A range in predicted 'reference' sediment conditions was evident for different stream types as classified by FENZ 20-level stream types, for example, 29.4% sediment for Group B (*i.e.*, small warm coastal streams) down to 2.4% sediment for Group S (*i.e.*, cold steep mountainous streams).

Finally, a **survey of amenity values** was conducted to inform the level of sediment acceptable for swimming and recreation. Results suggested that amenity value changes from acceptable to unacceptable between 12% and 27.5% sediment cover and swimming value decreases from acceptable to unacceptable between a Shuffle index score of 2 and a Shuffle index score of 3.

Information from all of the above approaches was used to inform recommended guidelines. For biodiversity values, weight was given to the results of data mining to inform absolute limits because the results of the regression analyses were weak. The national sediment model provides guidance for assessing deviation from predicted reference. For salmonid values, weight was given to relationships reported in the literature. For amenity values, weight was given to results of the user survey.

3.3 Recommended Guidelines

The following are recommended guidelines for assessing the effects of deposited fine sediment on the in-stream values of hard-bottomed streams.

In-stream value = Biodiversity*

[* includes native fish on the assumption that benthic invertebrates are their primary food source]

Sediment measure	Sediment value	Core method	Supporting data	Application
Sediment cover (%)	< 20% OR within 10% cover of reference	Bankside visual estimate	Photo	State of the environment reporting
	< 20% OR within 10% cover of reference	In-stream visual estimate	Photo	Assessment of effects
Substrate size (%)	< 20% OR within 10% cover of reference	Wolman pebble count		State of the environment reporting OR Assessment of effects
Suspendible sediment	< 450 g/m^2	Quorer (SIS)		State of the environment reporting OR Assessment of effects

In-stream value = Salmonid spawning habitat

Sediment measure	Sediment value	Core method	Supporting data	Application
Sediment cover (%)	< 20% OR within 10% cover of reference	Bankside visual estimate	Photo	State of the environment reporting
	< 20% OR within 10% cover of reference	In-stream visual estimate	Photo	Assessment of effects
Substrate size (%)	< 20%	Wolman pebble count		State of the environment reporting OR Assessment of effects

In-stream value = Amenity

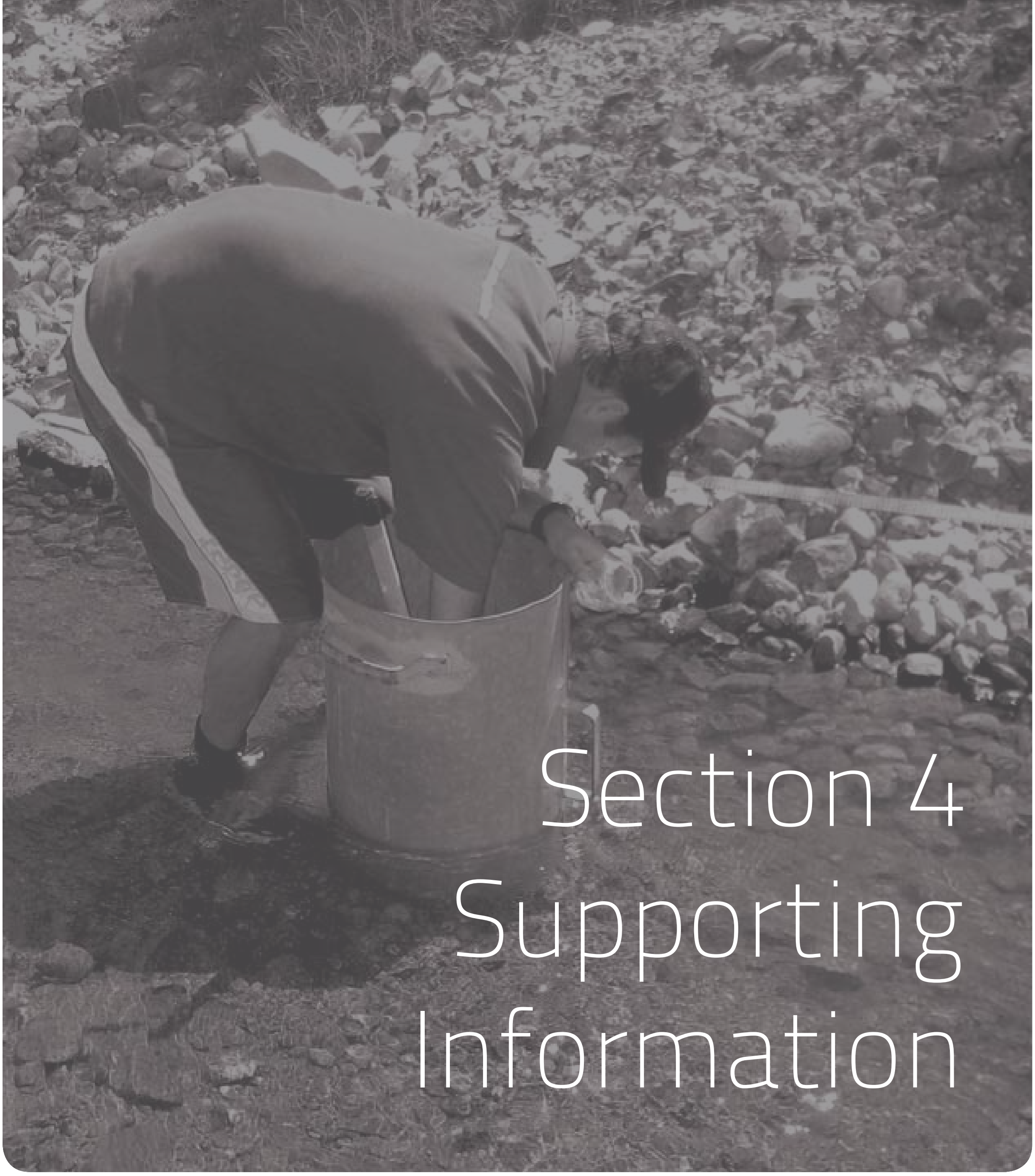
Sediment measure	Sediment value	Core method	Supporting data	Application
Sediment cover (%)	< 25%	Bankside visual estimate	Photo	State of the environment reporting
	< 25%	In-stream visual estimate	Photo	Assessment of effects
Suspendible sediment	< 3	Shuffle index	Photo	State of the environment reporting

The following guidelines are recommended; that sediment should not exceed either:

1) 20% cover or 450 g/m^2 (SIS) to protect stream biodiversity and fish (native and trout) habitat.

2) 25% cover or Shuffle index score of 3 to protect stream amenity.

We recommend that these numerical guidelines provide upper limits on the amount of fine sediment that will affect in-stream values, *i.e.*, any amount of sediment greater than 20% cover will detrimentally affect biodiversity and fish habitat. Note that there are likely to be lower limits at which in-stream value levels will be negatively affected by sediment. The available data makes it difficult to locate those limits, so for this reason it is recommended that a comparison of sediment values with a reference condition is applied.



Section 4 Supporting Information

4 Supporting Information

This section contains detailed information used to support the development of protocols and guidelines to assess the effects of sediment on in-stream values.

Included are literature reviews on sediment effects on biota and sediment assessment methods, and a review of existing sediment guidelines.

Comprehensive details on protocol testing and validation, guideline development including the prediction of reference values, and other useful things we learnt along the way are also included.

4.1 Review of sediment effects on biota and in-stream values

4.1.1 Benthic invertebrates

The most commonly inferred causal pathway for invertebrate response to sediment is a change in habitat. By definition, benthic invertebrates live on or in the streambed and hence any change to this habitat will directly affect the invertebrate community. However, there is a wide range of responses of benthic invertebrates to increased sediment including changes in invertebrate feeding and growth, behaviour, community composition, diversity and abundance (Ryan 1991; Waters 1995; Wood & Armitage 1997; Crowe & Hay 2004).

Invertebrate feeding can be directly affected by clogging of feeding apparatus (*i.e.*, impeded filter-feeding) and by loss of suitable habitat for attachment or feeding (Ryan 1991). Indirect effects on invertebrate feeding may also occur, via changes in food source and nutritional content as well as the adherence of toxicants to sediment (Ryder 1989; Collier 2002).

Sediment deposition can alter invertebrate behaviour. Interstitial spaces between substrata are used by invertebrates to avoid predators and the scouring effects of high flow (Sedell *et al.* 1990). Increased sediment deposition can lead to the short-term increase in invertebrate drift (Larsen & Omerod 2009; Molinos & Donohue 2009), and in the long term, invertebrate recolonisation through upstream movement may also be disrupted by large-scale fine sediment accumulation (Luedtke & Brusven 1976).

Ultimately the clogging of both surface and subsurface habitats by sediment leads to changes in invertebrate density and community composition (Waters 1995; Matthaei *et al.* 2006). As the level of sediment increases, taxa that favour stony habitat such as EPT taxa (Ephemeroptera, Plecoptera and Trichoptera) are replaced by burrowing taxa such as chironomids and worms (Wood & Armitage 1997; Rabeni *et al.* 2005; Townsend *et al.* 2008).

In New Zealand, there is more information available on the quantitative relationships between sediment and benthic invertebrates than for other in-stream values (Table 4-1).

Table 4-1 Quantitative relationships that have been documented between proportions of sediment and invertebrate populations in New Zealand (adapted from Crowe & Hay 2004).

Taxon / Community descriptor	Experimental method	Sediment size	Quantitative relationship established	Source
Deleatidium	Introduced substrates in relatively 'sediment-free' stream	0.5-2 mm	12-17% increase in interstitial fine sediments resulted in a 27-55% decrease in abundance	Ryder (1989)
Deleatidium, hydrobiosid caddisflies	Sediment additions into stream section	0.125-1 mm	Abundances decreased as amount of fine sediment increased	Ryder (1989)
Elmidae, Oligochaeta, *Potamopyrgus antipodarum*	Sediment additions into stream section	0.125-1 mm	No significant change in abundance	Ryder (1989)
Trichoptera, Chironomidae	Introduced substrates in relatively 'sediment-free' stream	0.5-2 mm	Generally more common on substrates without interstitial fine sediments	Ryder (1989)
Pycnocentrodes, Austrosimulium, P. antipodarum	Introduced substrates in relatively 'sediment-free' stream	0.5-2 mm	Abundance not affected by increased interstitial fine sediments	Ryder (1989)
Elmidae	Introduced substrates in relatively 'sediment-free' stream	0.5-2 mm	Abundance increased as amount of interstitial fine sediments increased	Ryder (1989)
Total invertebrate abundance	Introduced substrates in relatively 'sediment-free' stream	0.5-2 mm	12-17% increase in interstitial fine sediments resulted in a 16-40% decrease in abundance	Ryder (1989)

Taxon / Community descriptor	Experimental method	Sediment size	Quantitative relationship established	Source
Total invertebrate density, biomass, taxa richness	Survey of 88 NZ rivers	Silt <0.063 mm, sand 0.063-2 mm.	Decreased invertebrate density, biomass and taxa richness in rivers with high proportions of silt and sand in surface sediments, *c.f.* communities in rivers with coarser substrate compositions	Quinn & Hickey (1990)
Total invertebrate abundance, taxa richness	Sediment additions into stream sections	<4 mm	Following 21 days exposure, total invertebrate abundance and taxa richness had decreased significantly (*c.f.* controls). Mean total number of individuals decreased by 40-55%, and mean taxa richness decreased by 15-30%	Dunning (1998)
Helicopsyche, Zephlebia	Sediment additions into stream sections	<4 mm	Following 21 days exposure, abundance of *Zephlebia* and *Helicopsyche* had decreased significantly (*c.f.* controls)	Dunning (1998)

Taxon / Community descriptor	Experimental method	Sediment size	Quantitative relationship established	Source
Diptera	Sediment additions into stream sections	<4 mm	Following 21 days exposure, abundances had increased (*c.f.* controls), but not statistically significant	Dunning (1998)
Potamopyrgus antipodarum, Elmidae	Sediment additions into stream sections	<4 mm	Following 21 days exposure, abundances had not changed significantly (*c.f.* controls) for either	Dunning (1998)
% EPT taxa, QMCI, MCI	Sediment additions into stream sections	<4 mm	Following 21 days exposure, %EPT taxa and QMCI had decreased significantly (*c.f.* controls), whereas MCI showed no significant change	Dunning (1998)
Deleatidium drift	Sediment additions to artificial channels containing cobble substrate and established algae and invertebrate communities. *Deleatidium* added to channels after sediment additions.	<2 mm	16% increase in interstitial fine sediment resulted in a 80% mean increase in numbers of drifting *Deleatidium*	Suren & Jowett (2001)

Taxon / Community descriptor	Experimental method	Sediment size	Quantitative relationship established	Source
Paracalliope fluviatilis, Oxyethira albiceps, Hydrobiosis sp. and chironomid larvae drift	Sediment additions to artificial channels containing cobble substrate and established algae and invertebrate communities	<2 mm	16% increase in interstitial fine sediment resulted in a doubling of drift rates After 3 days, abundances of chironomid, *Oxyethira* and *Hydrobiosis* larvae were significantly lower in sedimented channels	Suren & Jowett (2001)
Chironomid emergence, diurnal drift patterns	Sediment additions to artificial channels containing cobble substrate and established algae and invertebrate communities	<2 mm	16% increase in interstitial fine sediment had no significant effect on chironomid emergence or diurnal drift patterns	Suren & Jowett (2001)
Ephemeroptera, Trichoptera	Longitudinal and temporal sampling of anthropogenic point-source inputs of fine sediment to a river	'Sand'	A *c.* 10-fold increase in percentage cover by sand (*c.* 5% cover at upstream control vs. 50-54% at downstream sites), resulted in a 30-75% reduction in Ephemeroptera and a 70-80% reduction in Trichoptera	Cottam & James (2003)

Taxon / Community descriptor	Experimental method	Sediment size	Quantitative relationship established	Source
Diptera, Oligochaeta	Longitudinal and temporal sampling of anthropogenic point-source inputs of fine sediment to a river	'Sand'	A *c.* 10-fold increase in percentage cover by sand resulted in a 0.5 to 2.4-fold increase in Diptera and a 1 to 8-fold increase Oligochaeta	Cottam & James (2003)
Taxa richness, EPT richness	Longitudinal and temporal sampling of anthropogenic point-source inputs of fine sediment to a river	'Sand'	A *c.* 10-fold increase in percentage cover by sand resulted in a 40-50% reduction in median taxa richness, and a 25-50% reduction in median EPT richness	Cottam & James (2003)
Potamopyrgus antipodarum & *Deleatidium*	Laboratory preference trials using cobbles subject to differing sediment and algae treatments	<0.5 mm	Both species preferred a sediment contaminated version of their respective food source over alternative alga	Suren (2005)
Invertebrate density, taxa richness, EPT richness, specific taxa density	Sediment addition to natural stream channels	<2 mm	Decrease in taxa richness, EPT richness and specific taxa density. Effects most significant in pasture streams where pre-treatment richness and diversity were highest. 10/20 taxa unaffected	Matthaei *et al.* (2006)

Taxon / Community descriptor	Experimental method	Sediment size	Quantitative relationship established	Source
Taxa richness, EPT richness	Sediment addition to natural stream channels	<2 mm (mean = 0.2 mm)	Increase from 35% to 83% fine cover correlated with increased taxa and EPT richness	Townsend *et al.* (2008)
Invertebrate density, EPT richness	Spatial survey of 32 streams	<1 mm	With an increase in fine sediment cover there was an increase in invertebrate density, and a decrease in EPT taxa richness	Townsend *et al.* (2008)

4.1.2 Fish

Sediment influences fish directly through physical effects and indirectly through impacts on habitat and food supply. Most physical effects are attributed to the gill damaging properties of suspended sediment, which can limit fish growth and make fish susceptible to disease (Waters 1995). Suspended sediment can also reduce the visual foraging efficiency of fish including the avoidance of highly turbid rivers by migratory species (Boubée *et al.* 1997; Rowe & Dean 1998). In comparison, deposited sediment limits the amount of habitat available for spawning and can reduce the viability of egg survival (Wood & Armitage 1997; Harvey *et al.* 2009). Salmonids are particularly susceptible to excess sediments that suffocate eggs in redds (Hay 2005).

Deposited fine sediment also reduces the amount of habitat and cover available to juvenile and adult fish. Native fish species favour habitats with large interstices (*e.g.*, gaps between cobbles) which are important for refuge (Jowett & Boustead 2001; McEwan 2009). In terms of food availability, sediment can alter the macroinvertebrate community in favour of less preferred food items for some fish species, *i.e.*, a reduction in drifting species. As such, sediment can affect the small-scale distribution of fishes and hence fish density and richness.

Information on the effects of deposited sediment on native New Zealand fish is limited to studies of habitat and food preferences. For many species information is anecdotal at best. Few quantitative relationships have been reported, although there are some established relationships between suspended sediment and fish populations (Table 4-2).

Table 4-2. Quantitative and observational relationships that have been documented between proportions of deposited sediment, suspended sediment and fish populations in New Zealand.

Taxon / Community descriptor	Experimental method	Fine sediment metric	Relationship established	Source
Upland bullies (adult)	Sediment addition (12.4 kg/ m^2) in artificial stream	96% <2 mm and 4% >2 mm	50% decline in numbers after six days	Jowett & Boustead (2001)
Redfin bully, Shortjaw kokopu	Survey of a natural stream	0.5 mm as part of substrate index	Presence associated with gravel and larger substrates in day and gravel and smaller substrates at night	McEwan (2009)
Koaro	Survey of a natural stream	0.5 mm as part of substrate index	Presence associated with larger substrates day and night	McEwan (2009)
Banded kokopu	Spotlight survey of a natural stream	2 mm and as part of a substrate index	Size-based microhabitat selection observed with smaller fish associated with smaller substrate sizes	Akbaripasand *et al.* (2011)
Banded kokopu	Laboratory preference trials	17 NTU 25 NTU	50% avoidance response	Boubée *et al.* (1997)
Redfin bully	Laboratory preference trials	1110 NTU	No avoidance behaviour	Boubée *et al.* (1997)
Koaro	Laboratory preference trials	70 NTU	50% avoidance response	Boubée *et al.* (1997)
Inanga	Laboratory preference trials	420 NTU	50% avoidance response	Boubée *et al.* (1997)
Large eels	Laboratory preference trials	1110 NTU	No avoidance behaviour	Boubée *et al.* (1997)

Taxon / Community descriptor	Experimental method	Fine sediment metric	Relationship established	Source
Smelt	Laboratory tank experiment	640 NTU	59% reduction in feeding rate	Rowe & Dean (1998)
Banded kokopu	Laboratory tank experiment	20 NTU	45% reduction in feeding rate	Rowe & Dean (1998)
Redfin Bully	Laboratory tank experiment	Between 40 and 640 NTU	50% reduction in feeding rate	Rowe & Dean (1998)
Banded kokopu	Laboratory tank experiment	120 mg/l suspended solids	60% avoidance response	Rowe *et al.* (2000)
Banded kokopu	Suspended sediment addition to natural stream channel	25 NTU	40% moved upstream when NTU was below 25 NTU, after which there was 0% movement	Richardson *et al.* (2001)
Longfin eel, shortfin eel, Common bully, Redfin bully, Bluegill bully, Torrentfish, Inanga, Smelt, Koaro	Survey of natural stream channel	Clarity	Range in clarity values explained 40% variation in species richness	Richardson & Jowett (2002)
Smelt	Laboratory tank experiment	1700 to 3000 NTU	50% mortality after 24 hours	Rowe *et al.* (2004)
Inanga	Laboratory tank experiment	1750 to 2100 NTU	50% mortality after 24 hours	Rowe *et al.* (2004)
Banded kokopu	Laboratory tank experiment	43000 NTU	10% mortality after 24 hours	Rowe *et al.* (2009)
Redfin Bully	Laboratory tank experiment	43000 NTU	15% mortality after 24 hours	Rowe *et al.* (2009)

4.1.3 Recreational and aesthetic values

Excess fine sediment can detrimentally affect the amenity value of rivers and streams including recreational use for swimming and other water sports, fishing and general aesthetics. Poor water clarity associated with suspended sediments, or bed sediments that are suspended on contact, usually results in a negative experience for swimmers, as does the 'feel' of fine sediment under the toes.

Aesthetic value can be a very personal experience and difficult to measure. However, studies have demonstrated how people prefer streams with good visual clarity for bathing (Smith *et al*. 1995) and low turbidity for aesthetic value (Pflüger *et al*. 2010). This is reflected in surface water quality guidelines that set minimum clarity levels for recreational water use (*e.g.*, >1.6 m black disc visibility, MfE 1994). However, currently there are no quantitative relationships between deposited fine sediment and recreational value.

4.2 Review of sediment assessment methods

A wide range of methods have been applied in New Zealand and elsewhere to quantify sediment in rivers and streams (Bunte & Abt 2001; Meredith *et al*. 2003; Sutherland *et al*. 2008). Although it is recognized that there is not necessarily one universal method to assess fine sediment in streams, some standardisation appeared necessary and was a key reason for initiating this project. Different properties of sediment may relate more informatively to some in-stream values compared to others. A conceptual model of the proximate stressors and causal pathways that lead to a response in benthic biota due to increased deposited sediments can help identify the required focus of sediment metrics (Figure 4-1). This conceptual model suggests that at minimum sediment metrics should assess substrate size, interstitial space and the coverage of fine sediment if all components of the issue are being evaluated. However, the model does not take into account the interdependence of these components.

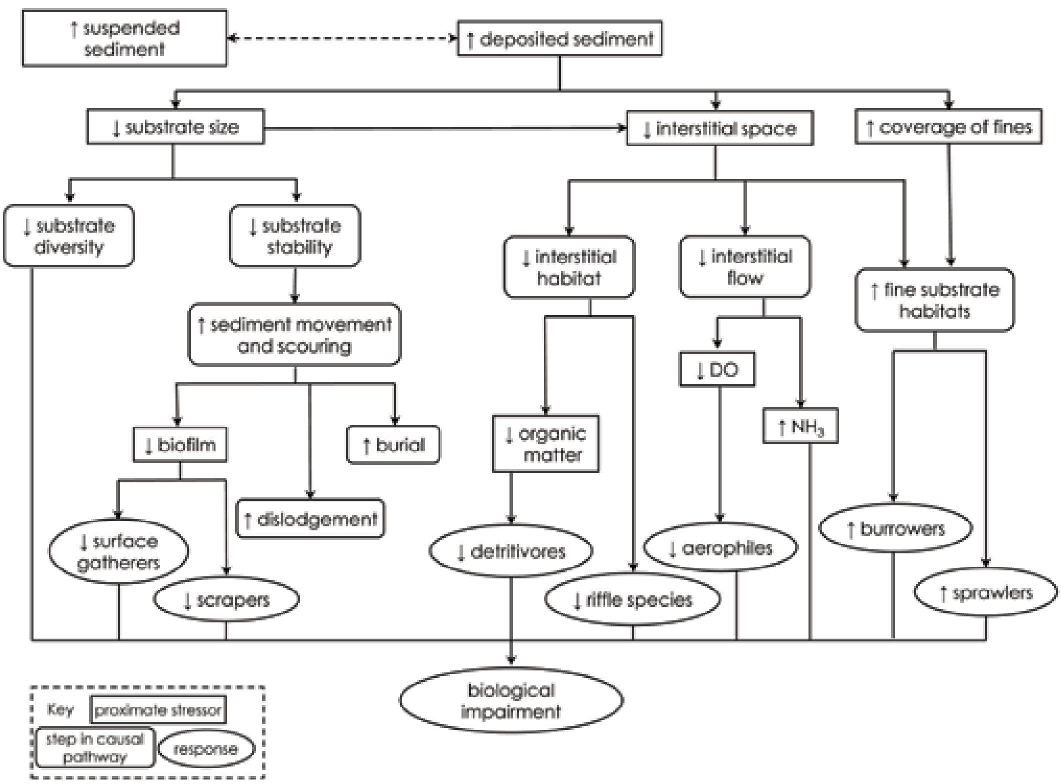


Figure 4-1. Conceptual model depicting the relationship between increased deposited sediment and the effects on in-stream biota (adapted from Cantilli *et al.* 2006).

A review of the most common protocols used globally was used to determine the most robust and appropriate protocols for application in New Zealand (Table 4-3).

Table 4-3. Measures of in-stream sediment reviewed in this document (Section 4.2) Trialled protocols and associated metrics tested in this study are in bold.

Sediment component	Sediment measure	Protocols and metrics
Substrate size	Particle size distribution	**Wolman pebble count: % sediment**, d16, d50, d86, central tendency
		Volumetric sample sorting: % sediment , d16, d50, d86, central tendency
	Relative bed stability	Calculation using particle size distribution, channel slope, roughness, and flow
Surface cover	Percent cover of sediment	**Bankside visual: % sediment**
		In-stream visual: % sediment
Interstitial space	Suspendible sediment	**Quorer[#]: SIS, SOS, %SIS**
		Shuffle method: index score
	Embeddedness	In-stream visual: % embedded
	Sediment depth	**Depth: mm**
	Volume of sediment in pools	In-stream measure: V*

[#]SIS = suspendible inorganic sediment, SOS = suspendible organic sediment

Below is a description of sediment methodologies that are currently used to assess cover, substrate size (diversity and stability) and interstitial space or suspendible sediment. For each method, a boxed summary of their likely relevance for quantifying deposited fine sediment in New Zealand is included.

4.2.1 Percent cover of sediment

Bankside estimates

The areal cover of sediment is a visual assessment of the relative surface area of the streambed covered with deposited sediment. A visual assessment can be applied either at the habitat scale (*e.g.*, run or riffle) or the reach scale (which might include multiple habitats). It may involve a single estimate to provide a qualitative measure for the reach, or multiple assessments for individual habitats which are combined to provide a value for the reach.

There is a long history of rapid bankside assessments of sediment cover in New Zealand. The New Zealand Freshwater Fish Database (NZFFD) includes bankside assessment data from as early as 1909. Similarly, almost all regional council SOE data are accompanied by a rapid habitat assessment, *e.g.*, the length of the habitat sampled, stream width, water depth and the relative proportion of substrate size cover are all metrics readily recorded. Since the development of Stream Habitat Assessment Protocols (Harding *et al*. 2009) a number of councils are routinely recording this information. Bankside visual assessments result in a single measure for a habitat or reach.

Metric	Percent cover of fines
Method	Bankside visual assessment
Nature of data	Semi-quantitative
Recommended measure	SOE monitoring

In-stream estimates

An underwater viewer is used to systematically sample multiple patches of the streambed in an in-stream visual assessment (Figure 4-2). Multiple estimates of fine sediment cover are averaged to provide a measure for a given habitat or reach. Protocols for this technique have been developed independently in New Zealand; in the Motueka River (Phillips & Basher 2005) and in Otago (Matthaei *et al*. 2006). Matthaei *et al*. (2006) detected a significant biological response to sedimentation assessed using this technique. Best results would seem to be obtained when the resolution of measurements is small enough to detect changes but large enough to minimise user bias (*i.e.*, choosing measurements which are multiples of 5%). As with other patch-scale assessments, replication needs to be sufficient to incorporate substrate variability (*i.e.*, more samples are required in heterogeneous substrates). These visual classification techniques generally require a high level of training to minimise user error (Latulippe *et al*. 2001). Dividing the viewer into smaller fields (Figure 4-2) helps to decrease user bias and are useful during user training, but do not necessarily improve the accuracy of visual assessment (Buffington & Montgomery 1999a).

Figure 4-2. Photos of an underwater viewer used to assess fine sediment cover.

Metric	Percent cover of fines
Method	In-stream visual assessment with an underwater viewer
Nature of data	Semi-quantitative
Recommended measure	SOE monitoring Effects-based assessments

4.2.2 Particle size distribution

Pebble count

Surface particle size distribution, or central tendency, is assessed by a systematic grid method or a pebble count method. Pebble counts are usually based on the Wolman technique (1954), where a predetermined number of particles are measured in a reach or habitat. The B-axis (width) of each particle is measured with a ruled rod or gravelometer (Figure 4-3). Particles are chosen from the front of the boot or using a rod or stick placed on the streambed along designated transects. Alternatively, particles are chosen by the random placement of a hoop. The B-axis size classes of between 60 (Harding *et al*. 2009) and 400 (Bunte & Abt 2001) particles are measured depending on the goals of the study.

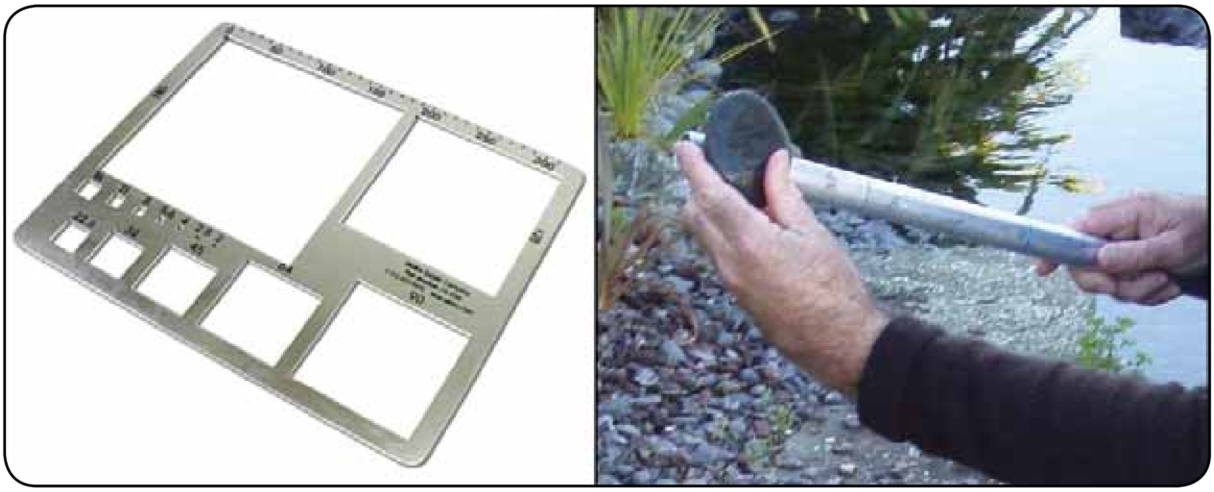


Figure 4-3. Photos of common tools used to measure particle grain size: a gravelometer (left) and a rod graduated with Wentworth scale size classes (right).

Pebble counts are a simple and effective technique for assessing size distributions, but results can be misrepresentative when the method is not conducted rigorously. For example, particle selection can bias towards larger particles because these are easily seen and there is a tendency to avoid areas of unstable footing (*e.g*., bedrock or large cobbles) (Bunte *et al*. 2009).

Due to operator bias, sampling error and the high replication required to detect a change in % fines from pebble count data (Bevenger & King 1995; Bunte & Abt 2001), a pebble count is often not recommended for the robust analysis of deposited sediment. However, with proper application, this technique can be confidently used to quantify percent sediment as well as other substrate attributes, for example, mean particle size and particle size variability. Proper application requires user training, appropriate equipment (*e.g*., gravelometer) and rigorous and careful application (*i.e*., the counting of particles from representative habitats). This method is likely to be useful for sediment assessment as well as general habitat assessment and the characterisation of sites (see Stream Habitat Assessment Protocols for further information, Harding *et al*. 2009).

Metric	Particle size distribution
Method	Wolman pebble count
Nature of data	Semi-quantitative
Recommended measure	SOE monitoring Useful for site establishment data and/or general habitat assessment

Volumetric sampling

Collecting a grab sample of sediment is one way to overcome operator bias in calculating particle size distributions. Systematic sampling of the streambed using a shovel or corer collects sediments for quantitative sorting in the laboratory (Bunte & Abt 2001; Sutherland *et al*. 2010), however, this method is very labour intensive. Furthermore, depending on the nature of substrate (fine or coarse) and uniformity of the bed material, large quantities of substrate may need to be sampled. For example, sites with heterogeneous substrate may require over 200 samples to determine d50 within $\pm$ 10% (Mosley & Tindale 1985). However, the sorting of sediments in the laboratory also allows for the determination of finer grain sizes, *i.e*., the relative proportion of silt and clay (<0.063 mm), fine sand (0.063 – 125 mm), medium sand (0.125 – 0.5 mm) and coarse sand (0.5 – 2 mm). Resulting data accurately reflect the particle size distribution of the sampled habitat.

Metric	Particle size distribution
Method	Volumetric sample sorting (systematic sample collection and laboratory analysis)
Nature of data	Quantitative
Recommended measure	Effects-based assessments Site specific values and/or research

4.2.3 Relative bed stability

Relative bed stability (RBS) is not a direct measure of sediment abundance; rather it is a measure of how resistant a streambed is to substrate movement at a prescribed flow, usually bank-full flow. For example, in a stream where the majority of sediment is finer than the substrate size moved during bank-full flows then the RBS metric will indicate that the stream is relatively unstable. Generally the more fine sediment that is present, the lower the RBS. There are several methods to calculate RBS, but they all involve an assessment of median particle size, channel slope and bank-full channel dimensions (Jowett 1989; Buffington & Montgomery 1999b; Gordon *et al*. 2004; Kaufman *et al*. 2009). In a recent study, K aufmann *et al*. (2009) showed how a derivative of RBS decreased in relation to the level of human disturbance in the catchment, although streams in soft sedimentary geologies appeared more susceptible than others.

In New Zealand, studies suggest that RBS may not provide a good estimate of bed stability and seldom correlates to bed load movement in river types other than homogenous gravel streams (Death & Winterbourn 1994; Schwendel *et al*. 2009). Given the time involved in measuring data for RBS calculation and the potentially system-limited application of this metric it is not recommended for regular assessment of deposited fine sediment.

Metric	Relative bed stability
Method	Calculation using particle size distribution, channel slope, roughness, and flow
Nature of data	Quantitative
Recommended measure	Useful for site establishment data Site specific values and/or research

4.2.4 Embeddedness

Embeddedness refers to the degree to which coarse particles are surrounded by fine particles and can provide an indication of the availability or clogging of interstitial spaces. Common methods range from subjective description of the proportion of streambed covered by fine sediment (an erroneous use of the term embeddedness) (Platts *et al*. 1983) through to the measurement of the depth or width of a particle surrounded by fine sediment (Burns & Edwards 1985). A comparison of methods suggested that the United State Environmental Protection Agency (USEPA) method was most likely to provide results that conformed with the expectation of embeddedness as an effect of altered sediment regimes below a dam (Sennatt *et al*. 2006). The USEPA method involves estimating the fraction of the surface area of at least 55 particles (>10 cm in diameter) which are surrounded by sediment (<2 mm). For particles less than 2 mm, embeddedness is recorded as 100% (Peck *et al*. 2000).

Metric	Embeddedness
Method	In-stream visual assessment
Nature of data	Qualitative
Recommended measure	SOE assessments Effects-based assessments

4.2.5 Suspendible fines

Quorer method

A volumetric measure of sediment deposition on and within the stream bed can be gained by re-suspending sediment in the water column and then collecting and weighing the suspendible proportion of sediment deposited. The Quorer method was developed to measure the suspendible surface and subsurface sediments in gravel-bed rivers (Lambert & Walling 1988; Quinn *et al*. 1997). This method involves using an open-ended container or tube to isolate a patch of the streambed (Figure 4-4). Surface and subsurface sediments are collected after stirring the streambed within the corer. Samples are processed in the laboratory to provide relative measures of suspendible inorganic sediment (SIS) and suspendible organic sediment (SOS), which need to be standardised to background stream concentrations. Interstitial sediment is inferred from the amount of fine sediment recorded. The percent of SIS in relation to total suspendible solids (*i.e.*, SIS + SOS) provides a measure of sediment composition and quality.

Collins and Walling (2007) showed that measures of suspendible fines can vary a lot within sites and over time. The sensitivity of these measures was illustrated in Waikato hill-country streams where suspendible sediment was shown to be significantly greater in streams draining pasture and pine catchments compared to streams draining native forest catchments (Quinn *et al*. 1997). Like all patch-scale measures, the replication required to accurately characterise a site and to detect differences over space and time is dependent on substrate variability within each site.

Figure 4-4. Photos of sample collection using the Quorer method.

Metric	Suspendible fine sediment
Method	Quorer (in-stream corer to collect sediment and laboratory analysis)
Nature of data	Quantitative
Recommended measure	SOE assessments Effects-based assessments

Shuffle method

A rapid qualitative assessment of suspendible sediment may be gained by a subjective rating of the sediment plume resulting from disturbing the streambed. Used by Environment Canterbury and Tasman District Council, the 'Shuffle' index can provide useful effects-based assessments. The method involves standing in the stream and disturbing the streambed by shuffling for a set time and subjectively ranking (1-5) the size and duration of the resulting sediment plume (Figure 4-5). This method can be improved by taking photographs of the plume (for training and illustration purposes). The Shuffle index also has the potential to directly assess the effects of sediment deposition on the aesthetic or swimming value of streams, *i.e.*, a river or stream that becomes highly turbid is less attractive to many recreational users (see Section 4.5.6).

Figure 4-5. Suspendible fines index (Shuffle index).

Metric	Suspendible fine sediment index
Method	Shuffle method
Nature of data	Qualitative
Recommended measure	SOE assessments Effects-based assessments

4.2.6 Sediment depth

A quantitative measure of sediment depth can be made by inserting a ruler into the streambed. This technique is most appropriate in naturally occurring soft-bottom streams or in specific habitats where sediment accumulates, for example, the tail of pools. Replicate measurements can be averaged to provide a mean depth for any given habitat (see also, Section 4.2.7 Volume of fines in pools)

Difficulties in measuring fine sediment associated with macrophyte dominated streams can be overcome by measuring sediment depth. Average sediment depth is multiplied by an areal estimate of macrophyte cover to obtain volumetric estimates of sediment deposition (Heppell *et al*. 2009). In their study, Heppell *et al*. (2009) demonstrated how sediment deposition was strongly correlated to the seasonal growth and subsequent cover of macrophytes in lowland river reaches.

Metric	Sediment depth
Method	Ruler measurement of sediment depth
Nature of data	Quantitative
Recommended measure	SOE assessments Effects-based assessments

4.2.7 Volume of fines in pools

The relative amount of sediment in pools (V*) has been shown to correlate to in-stream sediment supply (Lisle & Hilton 1992; Hilton & Lisle 1993; Lisle & Hilton 1999). Fine sediment in pools can account for 5-20% of fine sediment in the active channel (Lisle & Hilton 1999). However, fines in pools are usually much finer and more readily suspended than deposited sediments in other parts of a river, and V* can vary a lot over time (Lisle & Hilton 1999). Another aspect that limits the application of V* is that sampling error can be high and requires between four and eight transects of four to 26 pools per reach (Lisle & Hilton 1999). Lisle & Hilton (1999) recommend that the metric is most suitable for assessing streams subject to high sediment loads (where V* is greater than 20%) and for long-term monitoring in relation to a flow record, rather than broad-scale spatial monitoring.

Metric	Volume of fines in pools
Method	In-stream measurement
Nature of data	Quantitative
Recommended measure	Effects-based assessments Site specific values and/or research

4.3 Protocol testing and validation

Six protocols were trialled as part of the protocol testing and validation stage of the project (Table 4-4). Protocols were chosen following a literature review and an expert assessment (by the authors) of their potential applicability in wadeable rivers and streams in New Zealand. Protocols included bankside visual estimate (% sediment), an in-stream visual estimate (% sediment), Wolman pebble count (% sediment), Quorer suspendible sediment (g/m^2), Shuffle method (index score), and sediment depth (m).

Draft protocols for applying each of these metrics were trialled at a total of 174 sites by councils during their sampling programmes in 2009/2010 (Table 4-4). Not all protocols were applied at all sites. Councils were provided with a document outlining project goals, field protocol applications and field sheets.

Specific aspects of the protocols (*e.g.*, user variability, interhabitat variability) were further tested at an additional 63 sites in 2010 (Table 4-4). Data from previous studies, where the selected protocols had been used, were also collated to be used in analyses; n = 90 sites.

Table 4-4. Number of sites where sediment protocols were trialled by regional councils in 2009/2010 and data from additional and previous studies (totals in parentheses).

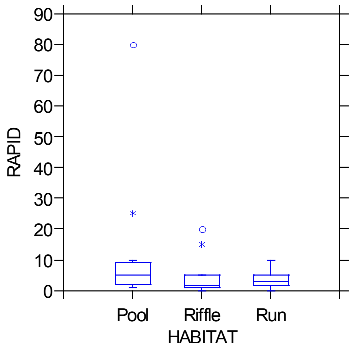
	Protocol					
Region	**Bankside visual**	**In-stream visual**	**Wolman pebble**	**Quorer**	**Shuffle index**	**Sediment depth**
Northland	10	6	7	7	10	10
Auckland	32		32			
Waikato	10	10	10	10	10	
Horizons	37	37		40		
Hawkes Bay	8	8	8			
Taranaki	6	6	6	6	4	6
Wellington	10		10	10	10	
Marlborough	4	5	5	5	5	4
Tasman	4	4	4	4	4	3
Canterbury	29	29	29	29	29	29
Otago	16	16	16	8	16	
Southland		3				
Additional studies	*64*	*106*	*111*	*162*	*64*	*106*
Total	166 (*230*)	124 (*230*)	127 (*228*)	119 (*281*)	88 (*152*)	52 (*158*)

4.3.1 Do results vary for different habitats?

Variability in sediment levels between habitats was tested by applying draft protocols in runs, riffles and pools at twelve streams in the Tasman region. Streams were all located on 'Moutere gravels' sedimentary geology where stream form (*i.e.*, substrate composition and flow) is relatively similar among habitats compared to other geologies. This means any observed difference in sediment metrics among habitats is likely to be greater in other geological settings. Stream catchments ranged in native vegetation cover from 2% to 99%; any significant habitat effects should reflect a consistent response across streams subject to varying land uses.

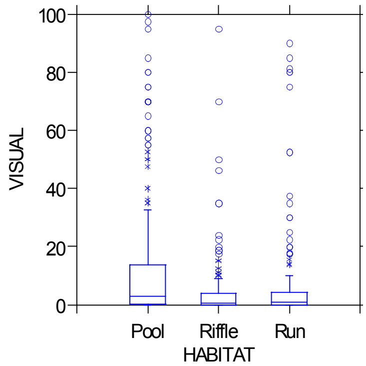
Run and riffle habitats had significantly less sediment than pool habitats according to the in-stream visual protocol, Quorer and sediment depth metrics (Figure 4-6). This result was repeated for sediment cover based on the bankside visual, Wolman pebble count and for the Shuffle index score, however, the values were not statistically significant among habitats. Because runs are usually intermediary in flow and form to riffle and pools, results from this survey suggest that the application of protocols in run habitats should provide a representative assessment of fine sediment at a reach scale.

Furthermore, the close similarity between data collected from runs and riffles also implies that it is reasonable to compare sediment data collected from runs with biotic data collected from riffles (Section 4.3.8).



Bankside visual (% sediment)

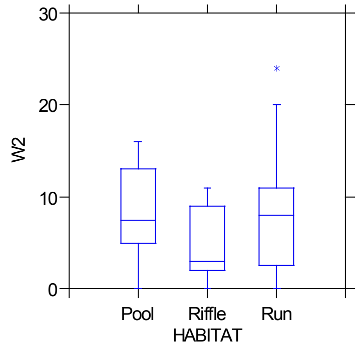
Habitat: $F_{(2, 33)} = 1.51$, $p = 0.231$



In-stream visual (% sediment)

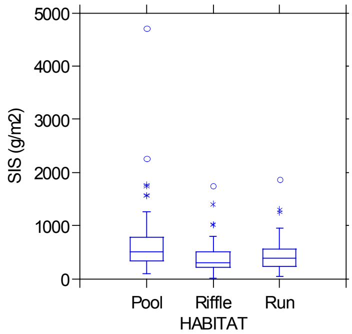
Habitat: $F_{(2, 684)} = 28.53$, $p < 0.001$

Post hoc: Pool > Run ≥ Riffle



Wolman (% sediment)

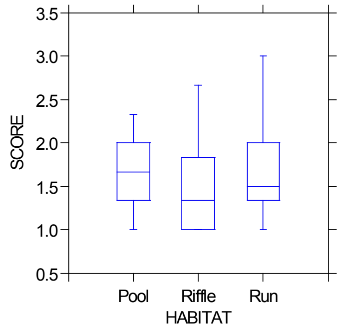
Habitat: $F_{(2, 33)} = 1.56$, $p = 0.225$



Quorer SIS (g/m^2)

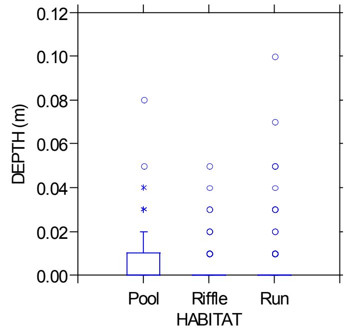
Habitat: $F_{(2, 144)} = 7.42$, $p = 0.001$

Post hoc: Pool > Run ≥ Riffle



Shuffle index score

Habitat: $F_{(2, 72)} = 1.75$, $p = 0.181$



Sediment depth (m)

Habitat: $F_{(2, 684)} = 8.99$, $p < 0.001$

Post hoc: Pool > Riffle = Run

Figure 4-6. Variation in sediment metrics among run, riffles and pools illustrated with box plots of the mean, upper and lower quartiles and outliers, and results of analysis of variance of metrics among habitats.

4.3.2 Do results vary among different users?

In order to test the amount of variation which might occur between observers in the field, ten freshwater researchers were asked to make bankside visual estimates of % sediment in the same reach. Findings indicated that having only one to two staff making observations can lead to poor accuracy in bankside visual estimates. However, in this trial observers were not given any training or allowed to discuss their estimates with each other. Therefore, to maximize consistency of results, it is recommended that observers are trained (*e.g.*, by showing a series of photographs with the level of sediment cover shown or doing training assessments at sites covering a range of measured % cover values) and, if possible, either using a consistent single observer or two observers in consultation.

Observed trials were conducted in a total of three reaches where the percentages of fine sediment cover (based on Wolman pebble counts) were 10%, 40% and 80%, respectively.

In general, low sediment sites were correctly assessed as having low levels of bed sediment, moderate sediment sites were assessed as moderate and high sediment sites assessed as having high sediment using bankside visual estimates (Figure 4-7).

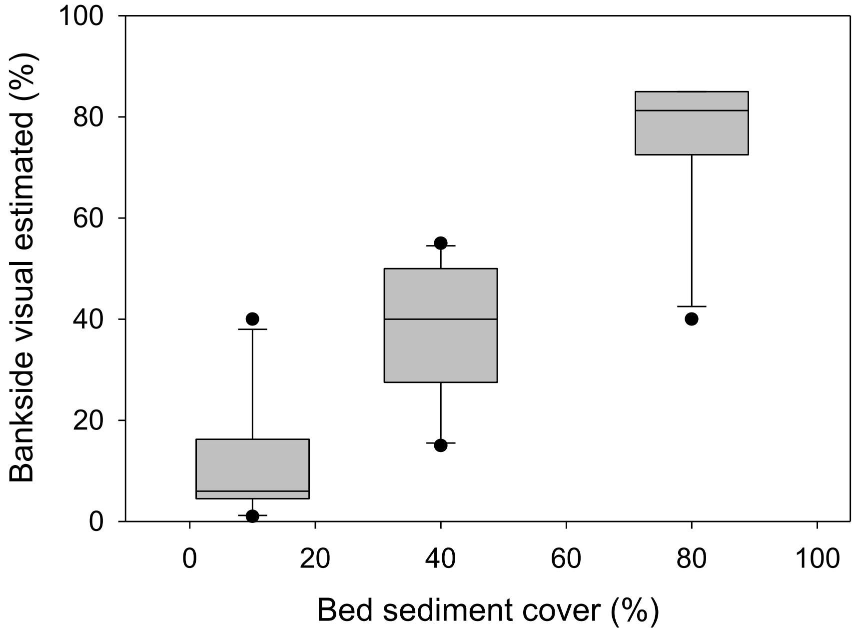


Figure 4-7. Median values and 25th and 75th quartiles and range of bankside visual estimates of sediment cover by 10 observers at three reaches with varying sediment levels measured using the Wolman pebble count (10, 40, and 80%).

In-stream visual assessments using an underwater viewer were also made with 10 observers in the three reaches with differing levels of bed sediment (Figure 4-8). These results indicate that observers were able to accurately determine sites with low sediment levels; however the variation in observations increased markedly as sediment levels increased. In the high sediment reach, some observers had difficulty agreeing that % sediment cover was greater than 50%, despite being supplied with diagrams to help estimates. If in-stream visual estimates are used, then training of field staff is essential to reduce variability and improve accuracy. If possible, taking photos will allow quality control of observations. User-variability of the Shuffle method or the Wolman pebble count method was not tested.

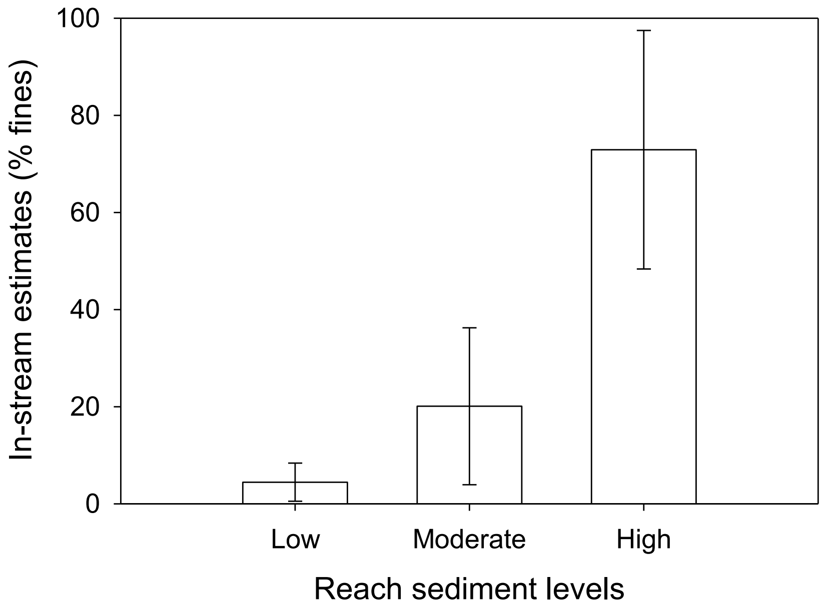


Figure 4-8. Mean values for in-stream visual estimates of sediment cover in three stream reaches with varying sediment levels: low = 10%, moderate = 40%, high = 80% (n = 10, ± SE) as assessed using Wolman pebble counts.

4.3.3 Do results vary in different land uses?

Whether metric values differ between different land uses may reflect their sensitivity to anthropogenic pressure and/or natural environmental variation. For instance, small Waikato hill-country streams draining native forest had 2-3-fold lower SIS Quorer values than those draining pasture and pine forests (Quinn *et al*. 1997). SIS also tended to be higher in small Coromandel streams draining clear-cut pine plantations than non-harvested pine and native forest catchments and logged sites with continuous riparian buffers (Quinn *et al*. 2004).

To examine broad-scale spatial variability draft protocols were applied at 50 sites in the Canterbury region; predominantly first to third order streams on low gradient alluvial floodplains. Sites were grouped into five land-use and waterway categories: agricultural, urban, forest, spring-fed or mountain streams with 10 streams in each category. This was done in order to test potential variability in the protocols across both a gradient of sediment stress but also variable physical habitats.

Using the bankside visual protocols, some land uses and stream types had markedly higher levels of sediment than others (Figure 4-9). The agricultural and urban streams averaged 35-40% sediment. The forested streams of Banks Peninsula also had relatively high levels of sediment presumably due to ultrafine windblown loess soils that dominate these catchments, whereas spring-fed and mountain streams averaged about 20% sediment. The variation in % sediment (error bars) within each grouping of streams was similar among land uses, indicating that the protocols worked equally well under differing stream conditions.

Using Wolman pebble counts of % sediment, agricultural, urban and forested streams also showed relatively high % sediment, whereas spring-fed and mountain streams had lower % sediment consistent with the bankside visual estimates.

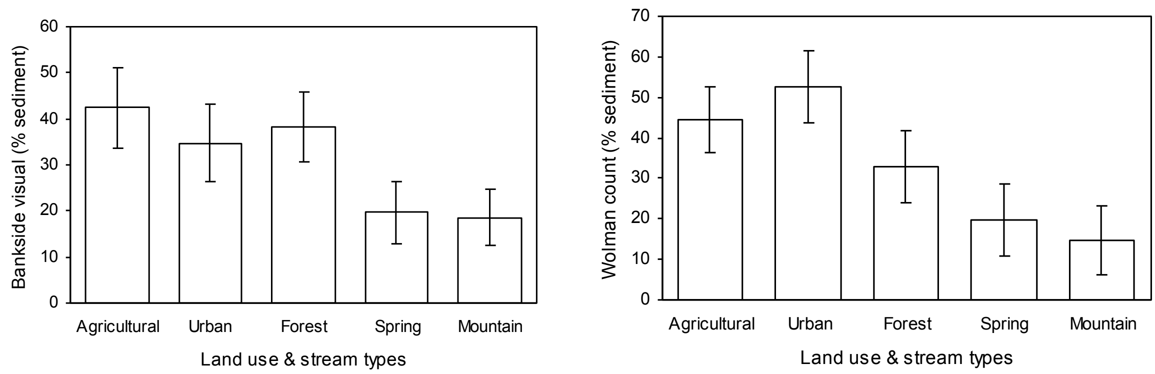


Figure 4-9. Mean % sediment for bankside visual and Wolman pebble counts in differing land uses and stream types in the Canterbury Plains (± 1SE, n = 10).

Comparisons of data from the Quorer and Shuffle methods showed slightly different results (Figure 4-10). The Quorer (using SIS values) showed urban streams had higher quantities of suspendible inorganic matter than the other four types of streams. The Quorer method differs from the bankside visual and Wolman method in that it measures the quantity of fine sediment on and within the upper layer of the streambed, rather than cover. The Shuffle method indicated that agricultural, urban and forested streams had higher amounts of bed sediment than spring-fed and mountain streams. The Shuffle method does not distinguish between organic and inorganic components of suspendible sediment, which may contribute to the different trend among land uses. The Shuffle results ranked stream types in a similar order as the bankside visual assessment – this suggests that protocols that do not distinguish between organic and inorganic components of sediment may result in similar spatial trends.

In general, results from all methods detected differences in sediment values associated with different land uses. The similarity in variability among land uses suggests that the methods work similarly well in a range of stream settings.

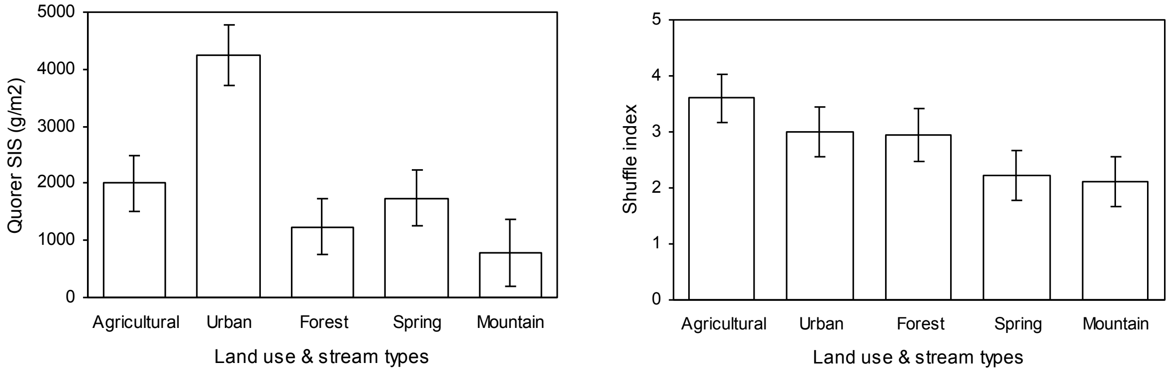


Figure 4-10. Mean values for Quorer SIS (g/m^2) and Shuffle index scores in differing land uses and stream types in the Canterbury Plains (±1SE, n = 10).

4.3.4 How do results vary over time?

The draft protocols were tested in one season (summer 2009/2010). However, historic datasets show that in-stream visual methods, Quorer SIS and Wolman pebble counts can be used to detect significant trends in sediment over time. Temporal trends in sediment may be caused by seasonal flow influences on the distribution of sediment, or pulses in sediment as a result of land use or natural disturbance events.

Datasets exist for Quorer and Wolman pebble counts from 11 years in the Whatawhata streams where SIS and % sediment, averaged across all sites, were 28% and 29% higher, respectively, in early autumn (March) than in spring (September) (Quinn *et al*. 2009). Both SIS and % sediment increased at a native forest stream after a tree fell into the reach and accumulated sediment upstream, demonstrating that these methods are able to detect changes due to natural influences even at relatively small scales. Percent sediment also showed a significant decrease in a small pasture stream following native forest riparian planting (Quinn *et al*. 2009).

Quorer derived SIS showed significant temporal patterns along the Tongariro River, a gravel-cobble bed river, in a one-year study of hydro-electricity generation related impacts on stream habitat and biota (Quinn & Vickers 1992) (Figure 4-11). SIS varied markedly with season and tended to be higher in winter and lower in spring, however this trend was strongly influenced by larger scale processes influencing the reach. This study indicates that SIS values at any site might fluctuate by 100% or more within a year.

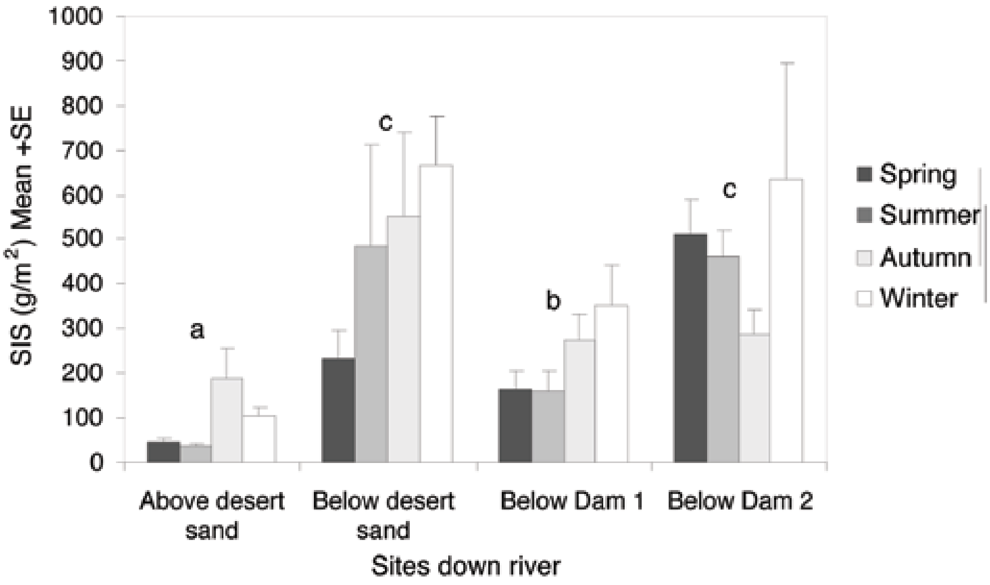


Figure 4-11. Seasonal patterns of Quorer suspendible inorganic sediment (g/m[2]) in run habitat at sites down the Tongariro River in relation to the influences of sand input (from Rangipo Desert) and dams. Letters (above the bars) and lines (in seasons legend) indicate significant differences ($p < 0.05$) using two-way ANOVA with Bonferroni post-hoc multiple comparisons (adapted from Quinn & Vickers 1992).

Temporal variability has been observed over several years at sites throughout the Motueka River catchment using a method comparable to the in-stream visual assessment (L. Basher, pers. com.). A large flood in March 2005 mobilised sediment along the river resulting in greater than 20% of the bed having more than 50% sediment cover (Figure 4-12). Within six months, much of this sediment had been flushed from the site.

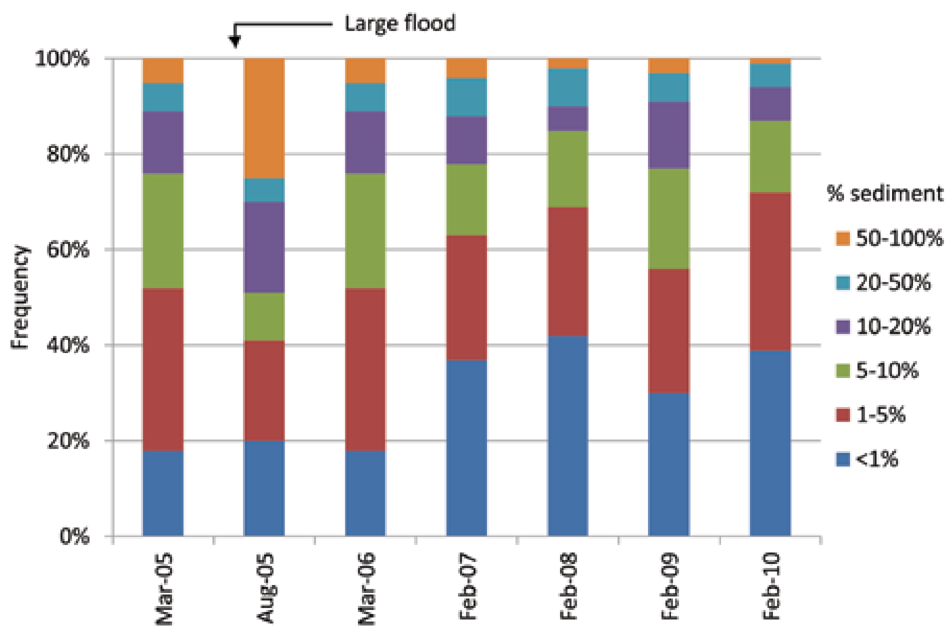


Figure 4-12. Temporal changes in % sediment cover in a run site on the Motueka River. A significant temporal trend was observed over a 5-yr period ($p = 0.003$). Data courtesy of Les Basher, Landcare Research.

4.3.5 How many replicates are required?

The number of replicates required for a sampling programme depends on the expected variability among replicate measurements, the size of the effect, and the statistical power required to detect an effect of this size. Statistical power is maximised when there are a large number of replicate measurements, low variability among replicate measurements, and there is a large effect. Typically a statistical power of 0.8 is considered satisfactory – *i.e.*, there is an 80% chance of detecting an effect of a certain size given the number of replicates and the variability among those replicates.

By examining the observed variability among replicate measurements for each of the protocols it is possible to give some guidance on the number of replicate samples required to detect an effect of a particular size. For example, using the average variability observed within sites for the protocol trials only three to four replicate measurements of suspendible sediment are required to have satisfactory statistical power to detect a 500 g/m^2 change in suspendible sediment. However, six replicate measurements are required to have the same statistical power to detect a change of 400 g/m^2 (Figure 4-13). The proposed protocol for suspendible sediment assessment which involves six replicate measurements (Section 2.3) will enable satisfactory power to detect a change in SIS of 400 g/m^2.

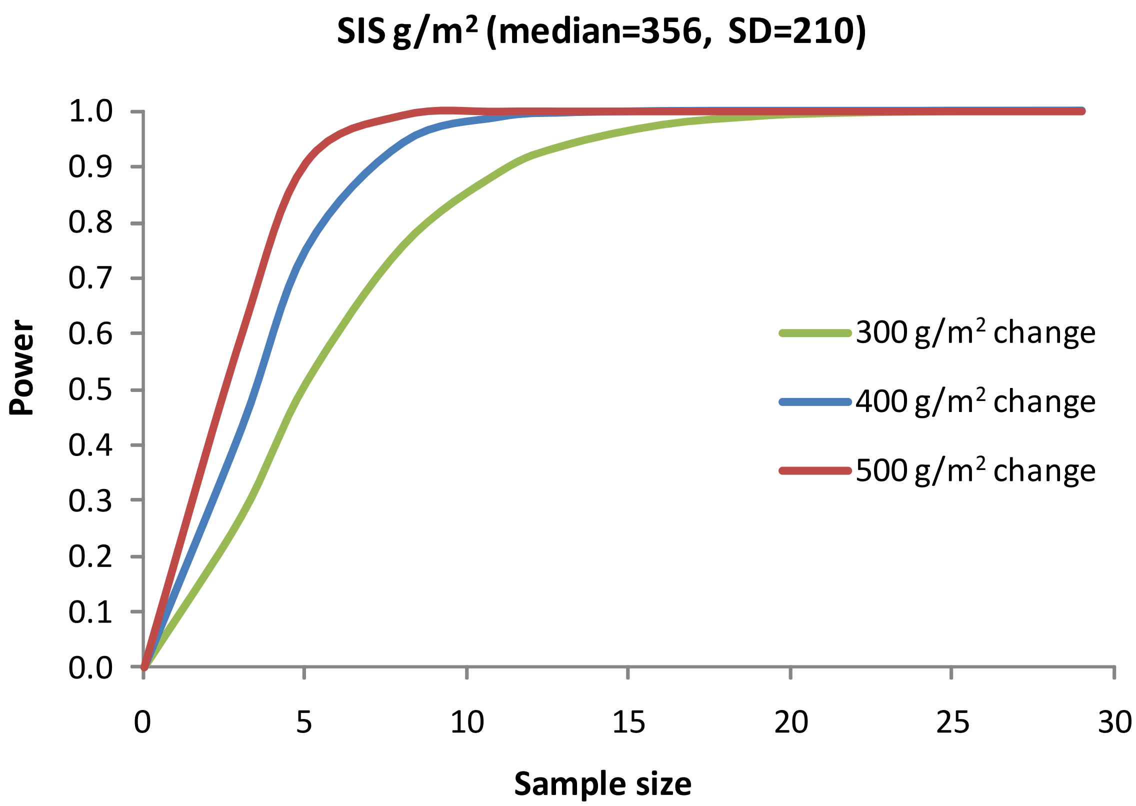


Figure 4-13. The effect of sample size and the desired effect size on statistical power of comparisons of suspendible inorganic sediment (SIS) measurements.

A similar analysis can be conducted for the other protocols which involve replicate measures at a site. With 20 replicate measurements the proposed in-stream visual protocol should enable satisfactory statistical power to detect a change of 15% fine sediment cover at a site (Table 4-5). Similarly, the proposed Shuffle method involving three replicate measurements should enable satisfactory power to detect a change of one unit in the Shuffle index score.

Table 4-5. Summary of the number of replicates required for sediment protocols to confidently (power = 0.8) detect a range of effect sizes.

Protocol	Size of effect to be detected	Number of replicates required to have satisfactory statistical power (0.8)
Suspendible sediment	300 g/m^2	9
	400 g/m^2	6
	500 g/m^2	4
In-stream visual	10% change in cover	36
	15% change in cover	18
	25% change in cover	10
Shuffle	0.3 units	26
	0.5 units	10
	1 unit	3
Sediment depth	10 mm	50+
	20 mm	16
	30 mm	8

4.3.6 How do results from different protocols compare?

Data from regional council trials were used to examine the correlations between data from different protocols, including bankside visual (Bankside), in-stream visual (In-stream), % sediment from Wolman pebble counts (Wolman), suspendible inorganic sediment (SIS), suspendible organic sediment (SOS), Shuffle index score (Shuffle) and sediment depth (Depth). Data were transformed to improve normality where necessary. The only protocol which did not compare well was sediment depth. Pearson correlation coefficients showed strong relationships between visual estimates of fine sediment cover, for example, bankside and in-stream visual $r = 0.89$, $p < 0.01$ (Figure 4-14). The Quorer metrics were also highly correlated, for example, log-SIS and log-SOS, $r = 0.85$, $p < 0.001$. The Shuffle index was significantly correlated with all other sediment measures, except sediment depth (Figure 4-14).

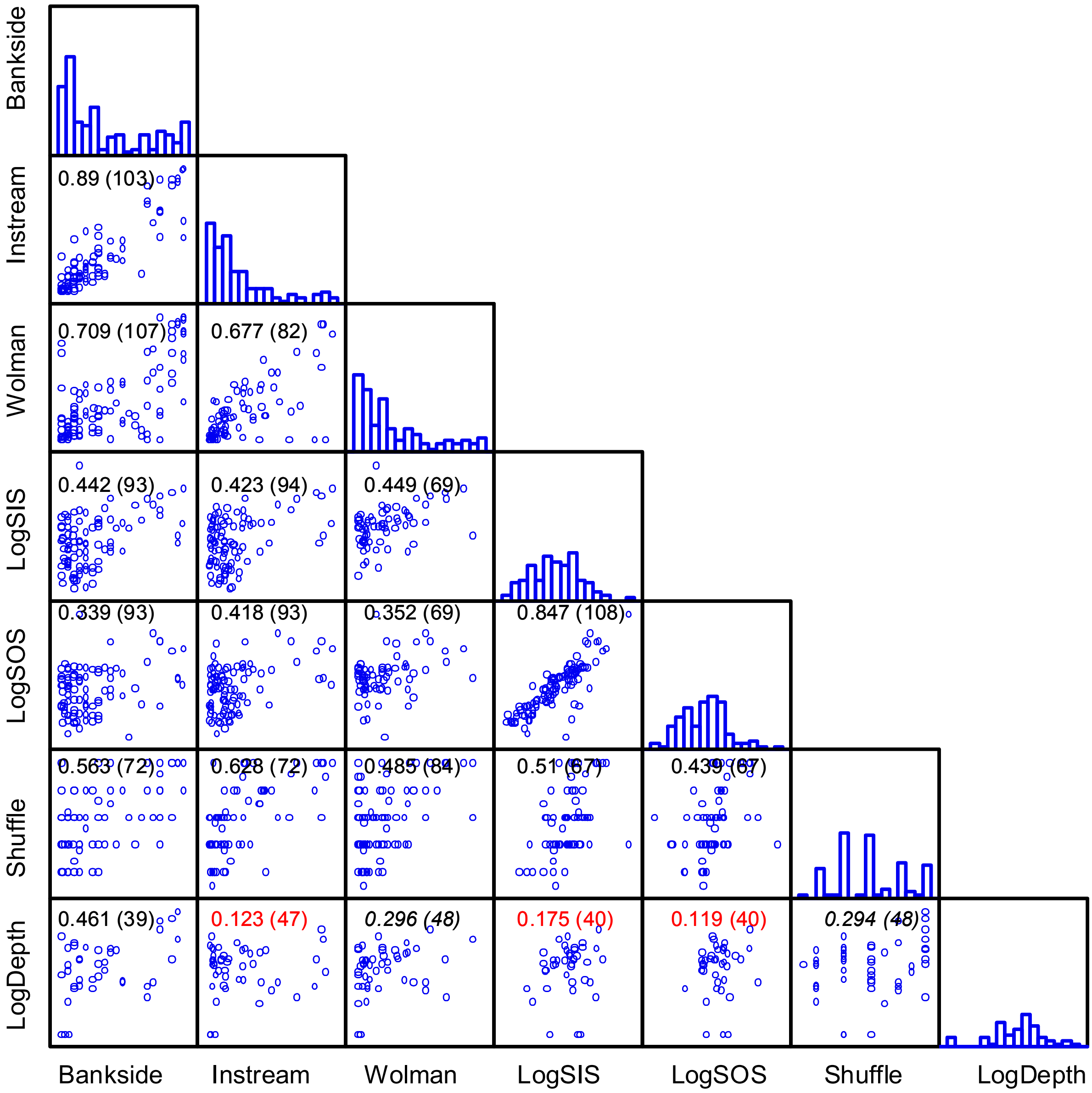


Figure 4-14. Correlations among sediment protocols. Values are the Pearson correlation coefficients (r) with the number of sites in parentheses, $p < 0.01$. Italicised values are where $p < 0.05$ and red values are where $p > 0.1$.

4.3.7 Are there cheaper, quicker methods?

The Quorer method provides a quantitative assessment of surface and interstitial sediment. The sample collection in the field is relatively quick – however, the method has a financial cost associated with laboratory analysis for total and volatile suspended solids. Therefore alternatives were investigated to reduce this processing cost. These included measuring turbidity in the Quorer method sample in the laboratory, and measuring the volume of suspendible sediment in the Quorer method sample using a settling assay.

Turbidity of a Quorer method sample was measured in the laboratory prior to settling the sample to calculate suspendible benthic sediment volume (SBSV). Turbidity (NTU values) was significantly related to Quorer SIS (g/m^2) values and a stronger positive relationship was noted with Quorer SBSV values (Figure 4-15). Comparisons of turbidity of the Quorer method sample with other sediment data collected from the same 50 sites showed no relationships. It appears that more research is required to determine the conditions in which turbidity within the Quorer method sample might provide a useful measure of suspendible sediment, if at all.

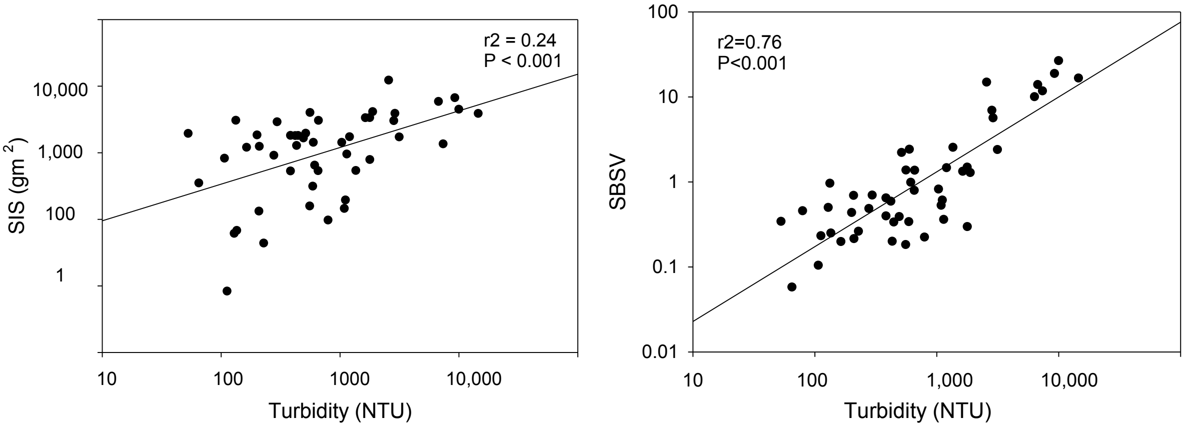


Figure 4-15. Comparison of metrics generated from Quorer method samples collected from 50 sites on the Canterbury Plains, including turbidity (NTU), suspendible inorganic sediment (g/m^2) and suspendible benthic sediment volume (ml/m^2). Note the log-scale of both axes.

Ninety-three Quorer method samples were processed to measure suspendible inorganic sediment (SIS) and suspendible benthic sediment volume (SBSV) using a settling assay. This assay involved letting the samples settle in a cylinder and measuring the volume of settled sediment. The values from these two methods were generally closely correlated for any given sample (Figure 4-16). A linear regression showed a significant positive relationship ($r^2 = 0.43$, $F (1, 48) = 35.79$, $p < 0.001$) and results suggested that SBSV could provide a surrogate for SIS. An SIS value of 400 g/m^2 is in the region of a SBSV value of 3000 ml/m^2. However, the same method should be used for all samples which are going to be compared; this trial indicated that not all data points fall directly along the trend line and converting from one measure to the other will introduce some error.

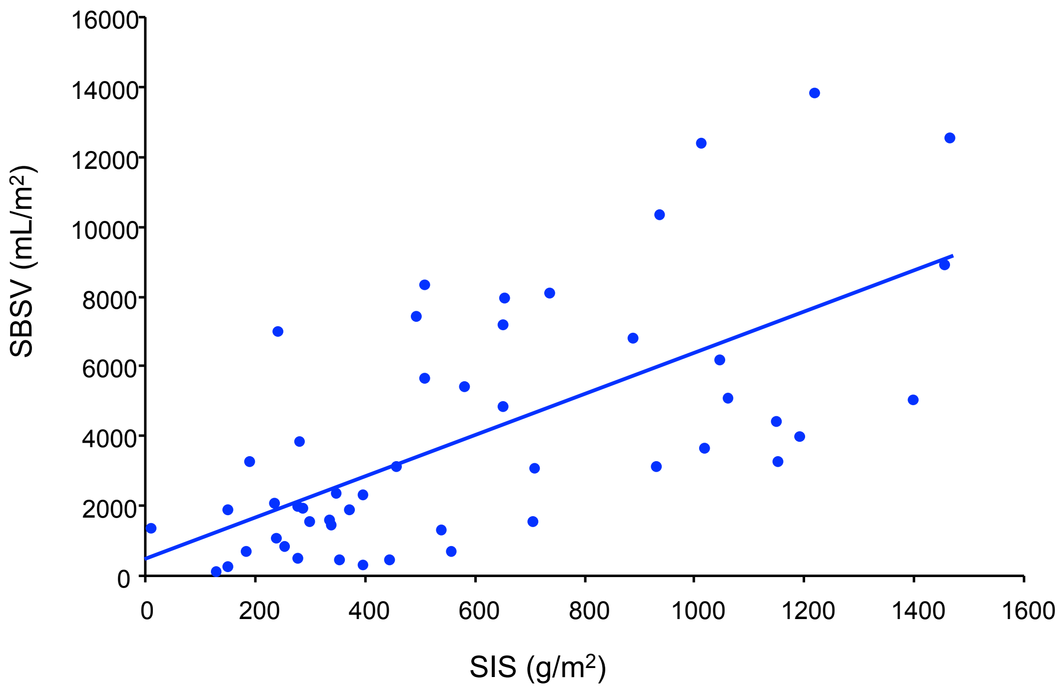


Figure 4-16. Comparison of measurements of amounts of suspendible inorganic sediment (SIS) based on dry weights with areal suspendible benthic sediment volume from settled volumes for 93 samples (five outliers, with SIS >2000 g/m^2, are not shown).

4.3.8 How well are sediment metrics related to in-stream biota?

Data from regional council trials was used to calculate all possible sediment metrics (Table 2-1). For the bankside visual assessment, % sediment cover data was available at both a reach and run-scale, so both metrics were examined. Sediment metrics were then compared to eight macroinvertebrate variables as representative measures of in-stream biota (Table 4-6). A series of correlations, regressions and analysis of covariances (ANCOVAs) were used to examine the relationship between sediment metrics and biological variables.

Table 4-6. Description of macroinvertebrate variables.

Biotic variable	Description
No. of taxa	Number of taxa
No. of individuals	Number of individuals
EPT abundance	Number of individuals belonging to the sensitive Ephemeroptera, Plecoptera or Trichoptera taxa
%EPT richness	Percentage of taxa belonging to the sensitive Ephemeroptera, Plecoptera or Trichoptera taxa
%EPT abundance	Percentage of individuals belonging to the sensitive Ephemeroptera, Plecoptera or Trichoptera taxa
MCI	Macroinvertebrate Community Index (calculated from presence/ absence data)
QMCI	Quantitative Macroinvertebrate Community Index (calculated from abundance data)
SQMCI	Semi-quantitative Macroinvertebrate Community Index (calculated from rank abundance data)

First Pearson and Spearman's rank correlations were used to identify potential relationships. Of the 12 sediment variables suitable for this analysis[3], the three visual assessments (Bankside reach, Bankside run and In-stream visual) performed best because they were significantly related to the largest number of invertebrate response variables. These metrics were significantly correlated with seven (In-stream) or six (Bankside reach, Bankside run) of the eight invertebrate variables. Percent sediment from the Wolman pebble count and Shuffle index score were related to three invertebrate variables each, and %SIS (Quorer) to two variables.

Non-linear relationships in addition to the linear ones were identified using scatter plots and non-linear regressions. In some cases, log-transformations were used to help fulfil the assumptions of the analysis. This analysis was computed for the seven better-performing sediment variables identified in the correlation analyses (the three visual % sediment metrics, log-SIS, log-SOS, % sediment from Wolman pebble counts and median particle size from Wolman pebble counts [d50]). Seven invertebrate measures (No. of taxa, No. of individuals, EPT abundance, %EPT richness, %EPT abundance, MCI, QMCI) had sample sizes that were large enough across all seven sediment predictors to allow running this

[3]The database for sediment depth was too small to be included. A separate analysis showed a negative correlative relationship with No. of taxa, but no other invertebrate variables were significantly related to sediment depth.

analysis. Once again, the three visual % sediment metrics performed best, and 'Bankside reach' was the top performer overall. It was significantly related to all key invertebrate metrics (r^2 values ranged from 0.13-0.32); all five invertebrate metrics showing either linear or quadratic declines with increasing sediment. Log-SOS (Quorer) had the strongest relationship with MCI and QMCI ($r^2 = 0.24$ in both cases) but was relevant for fewer invertebrate metrics than the % sediment measures. The relationship between Bankside reach and MCI had similar strength ($r^2 = 0.16$). Percent sediment in Wolman counts and Shuffle index were both less relevant (in terms of the number of invertebrate metrics affected and also the r^2 values of these relationships). The generally fairly low r^2-values for these relationships indicate that several other factors influenced the investigated invertebrate response variables besides the amount of deposited fine sediment at the study sites. The potential roles of two of these additional factors were examined in our next analysis.

Finally, the influence of region and stream size in the relationships between six sediment metrics (three % sediment metrics, log-SIS, log SOS and % sediment in Wolman pebble counts) and MCI and %EPT richness was investigated. Adding 'region' as a predictor had a significant effect for all six sediment variables and increased the r^2-values of the linear models to a precision (26-54% of the variation in the data explained) that is fairly high for ecological survey data. In every single case, the effect size for region (range 0.17-0.38; effect sizes can theoretically range from 0.0 to 1.0) was greater than the effect size of the sediment predictor in question (range 0.05-0.18). Nevertheless, all three visual % sediment metrics (and also Wolman % sediment, but neither SIS nor SOS) were still significantly and negatively correlated with MCI and %EPT. Based on their effect sizes, In-stream visual and Bankside reach were the best sediment predictors for MCI, and Wolman % sediment and In-stream were the best predictors for %EPT richness. In conclusion, regional variation and/or variation between different operators played an important role in this study as expected, but this variation had relative little effect on the main conclusions drawn from the previous analyses.

In practise, differences between geographical regions should not be a major problem for determining sediment-invertebrate relationships during future biomonitoring in New Zealand because regional councils usually collect all their data within a single geographical region. However, because the factor 'region' also included potential differences between different operators, training all operators using standardised criteria to minimise between-operator variation in all assessments of sediment is recommended.

Adding 'stream size' (using stream width and depth data) as a covariate had no significant effect: $p = 0.11$ for Wolman % sediment and MCI, and $p > 0.29$ in all other cases. The results indicated that the observed relationships between the six sediment predictors and MCI or %EPT were independent of stream size.

4.3.9 Other useful things discovered along the way

Bankside visual estimate

Can I stand in one place to make an assessment (e.g., on a bridge)?

The bankside visual assessment should take into account the full sample reach. Usually, it is necessary to walk along the river bank (sometimes both sides in larger rivers) to estimate sediment cover for the full sample habitat. Bankside reach-scale and run-scale assessments of % cover are highly correlated, but analyses show a stronger relationship between run-scale assessments and in-stream values.

In-stream visual estimate

Do I need to record a measurement for every quadrant on the viewer?

Quadrants are very useful for training purposes and quality control among users. Once a user 'has their eye in' it is not necessary to record data for every quadrant.

Limitations with the bathyscope

The scope can be difficult to use in shaded areas where the stream bed is hard to see. It is difficult to use in faster water and if you have shallow, fast water the scope can cause turbulence which will entrain sediment, altering your readings.

Wolman pebble count

To work well this needs the observer to take care in randomly selecting particles and ensuring that they record fine sediment among larger particles.

Quorer method

How long do I stir the sediment before collecting a sample?

A small experiment was conducted where samples were collected after 15, 30, 45 and 60 seconds of stirring. Results (Figure 4-17) suggested that 15 seconds was ample to provide an accurate measure of SIS.

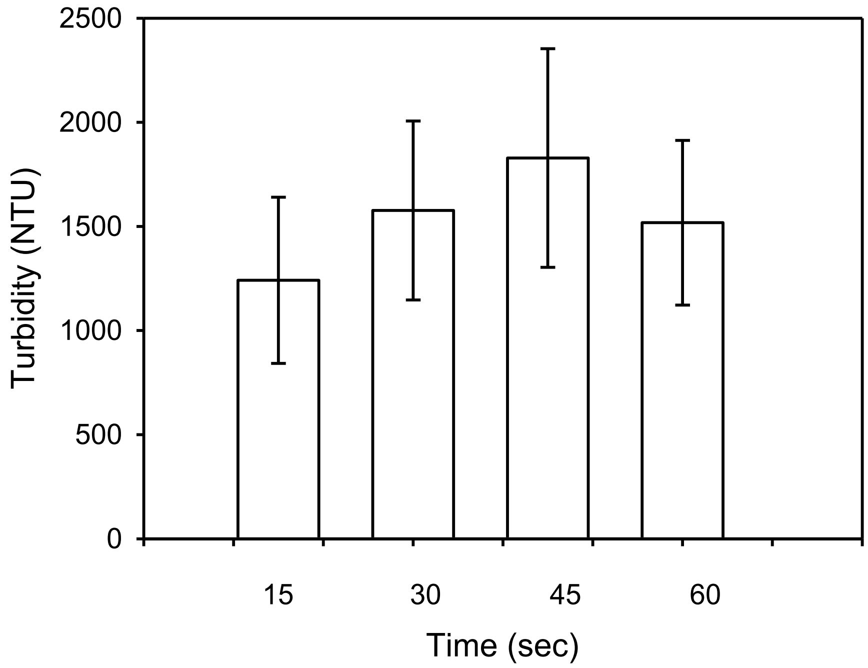


Figure 4-17. Relationship between turbidity and time of stirring in a Quorer sampler. N = 18.

Are there any physical limitations to applying the Quorer method?

The Quorer method is limited to locations where a corer can be deployed to form a tight seal on the streambed (influenced by streambed roughness, substrate size and current velocity) without the stream water over-topping into the cylinder (influenced by depth). In general, the method is limited to depths and velocities below approximately 0.5 m and 0.5 m/s, respectively, and substrate sizes up to gravel/cobble (not boulders). These limitations can be met to some extent by increasing the Quorer diameter (to deal with cobble/gravel beds) and depth. Large Quorers have been used with success by NIWA and Tasman District Council scientists (Figure 4-18). A metal Quorer method sampler with handles can be useful.

Figure 4-18. Large corers successfully applied to extend the physical limitations of the Quorer method.

Shuffle method

Both water depth and flow appear to bias this protocol when assigning scores based on views of a white tile. Possible refinements include using a pilot measure to inform the assessor as to which way the flow is going and where to place the tile, attaching the white tile to a pole and ensuring readings are made at 200 mm depth. The categorical nature of the index could be refined in future to a continuous variable which takes into account both flow and depth; by measuring the depth of the plume in relation to a white pole and the time it takes for the sediment plume to reach and subsequently clear the tile. However, it would be difficult to take into account the horizontal dispersion of the plume in the water column. Another possible approach involves reading the effect of standard bed disturbance in horizontal clarity with a water sample from the Quorer method measured in a mini Stream Health Monitoring and Assessment Kit (SHMAK) clarity tube. There are currently no data to validate this approach, but see Section 4.3.7 for discussion on surrogate measures.

Sediment depth

Limited data and weak relationships observed during protocols development suggested sediment depth is not a very sensitive indicator of sediment effects on biota (however, guideline development analyses indicated a relationship with taxa richness – see Section 4.5.3). Sediment depth might be a valuable measure for effects-based assessments. Measuring sediment depth in pools may also provide a more sensitive measure, but this was not tested in these trials.

4.4 Review of existing guidelines

4.4.1 New Zealand

Environment Canterbury is the only Regional Council to currently provide numerical guidelines and include numerical objectives for the areal coverage of fine sediments within a spatial framework for the region (Environment Canterbury 2011, see Hayward *et al*. 2009 for rationale). Objectives range from 10% to 40% cover depending on the surface water 'management unit' of interest. These objectives have been calculated from data collected at 144 sites measured since 1999.

There are currently no national standards or guidelines to assess the effects of sediment on in-stream values in New Zealand.

4.4.2 International

Many river-type specific guidelines have been developed for areas of the United States and Canada (Table 4-7). To summarise, the most common sediment criteria in northern America are for the percent of sediment calculated from pebble counts or by mass and substrate embeddedness assessed using the USEPA qualitative method. Unfortunately recommended values for each state and province are difficult to interpret because of inconsistencies in the definition of fine sediment, *i.e.*, anything from 0.64 mm to 6.4 mm.

4.5 Guideline development

An essential criterion for any guideline is that it must relate to a demonstrable effect that can be quantified (Jones *et al*. 2011). Thus manipulative experiments (laboratory and field-scale experiments) are often used to identify chronic and acute concentrations of contaminants (Table 4-8). There are examples of manipulative experiments in New Zealand that have identified biotic responses to sediment additions, although none specifically tested sediment thresholds (*e.g.*, Ryder 1989; Dunning 1998; Suren & Jowett 2001; Matthaei *et al*. 2006; but see also Wagenhoff 2011). Decreases in mayfly, stonefly and caddisfly richness have been associated with increases in sediment cover (Table 4-1). Notably, Townsend *et al*. (2008) observed a decrease in EPT richness associated with higher sediment levels in a survey of 32 streams, whereas the response of EPT to experimental sediment and nutrient addition in nine agricultural streams was more complex.

More commonly, correlations with field survey data are used to develop sediment guidelines (Sutherland *et al*. 2008). While surveys do not provide proof of cause and effect and can be confounded by multiple stressor effects, they do identify sediment levels associated with changes in in-stream values.

Table 4-7. Sediment criteria and standards for the United States and Canada (from Sutherland *et al.* 2008 and Culp *et al.* 2009)

Location	Performance criteria	Standard (target)
Alaska	% fine sediment (0.1 mm – 4.0 mm by mass)	≤ 5% above reference or ≤ 30% absolute
Arizona	% sediment in riffles (Wolman)	≤ 35%
British Columbia	% fine sediment in redds (by mass) Geometric mean diameter	≤ 10% (<2 mm) or ≤ 25% (<6.35 mm) ≥ 12 mm
California	Geometric mean diameter % embeddedness in riffles % fine sediment in redds (by wet mass)	> 69 mm ≤ 25% ≤ 14% (<0.85 mm) or ≤ 30% (<6.4 mm)
Colorado	% sediment (Wolman)	90-100% of expected condition = fully supporting 73-89% of expected condition = partially supporting
	% embeddedness	90-100% of expected condition = fully supporting 73-89% of expected condition = partially supporting
Hawaii	Fine sediment depth in hard-bottom streams	≤ 5 mm
Idaho	% fine sediment in riffles (by mass) Riffle stability index (RSI)	≤ 10% (<0.85 mm) ≤ 70 RSI
Montana	% fine sediment in riffles (by mass)	≤ 30% (<6.35 mm)
New Brunswick	% sediment (Wolman + visual estimate) Median particle size % sediment in riffles (by mass)	≤ 7.2% (<2 mm) ≤ 9.3% (<6.35 mm) > 56.9 mm ≤ 3% (<2 mm)
New Mexico	% embeddedness	≤ 33% = fully supporting > 33% is compared to reference
	% sediment in riffles (Wolman)	< 20% = fully supporting > 20% compared to reference
Oregon	% fine sediment in riffles (by mass)	< 20%
Prince Edward Island	% sediment (Wolman + visual estimate) Median particle size Relative bed stability (RBS)	≤ 12.9% (<2 mm) ≤ 12.7% (<6.35 mm) > 47.4 mm ≤ 3.8 RBS

Table 4-8. Summary of approaches used to define sediment criteria summarised from Jones *et al*. (2011).

Guideline approach	Advantages	Disadvantages
Laboratory assessments	Controlled Definition of mortality limits Individual response observable	Limited to target organisms/ populations Limited treatment options Difficult to scale to stream
Field-scale experimental manipulations (experimental channels and simulated events)	Similar to natural conditions Population and community level response observable	Limited treatment options High logistical requirements
Case studies of pollution events	Population through to ecosystem response observable	Logistically difficult Requires opportunistic sampling often results in lack of 'before' data Difficult to discern sediment effect versus other/background effect
Correlation with field survey data	Natural conditions and results relevant at management scale Effects in the presence of multiple pressures observable Population through to ecosystem response observable	Does not provide proof of cause and effect Separating effects of co-variables (natural variability) is difficult

4.5.1 Sources of data

An historic dataset was combined with data collected from our research to provide sediment information for 454 sites. Sites ranged from first to seventh order streams and had a wide spatial coverage – from Northland to Southland and all regions in between, except the West Coast. Classifying sites by stream type showed that five of the 20 FENZ 20-level groups were represented by the data (Groups A, C, D, G, H; for a description of stream types see Leathwick *et al*. 2011), but these five groups account for 83% of the national river network (Leathwick *et al*. 2011).

4.5.2 Correlation among sediment and biota

Initially, sediment measures were compared with each other. Variables were transformed where necessary to improve the normality of data distributions.

Correlation analyses identified similarity among all sediment measures (Figure 4-19). All three visual assessments of % cover (Bankside reach, Bankside run, In-stream visual) were strongly related ($r > 0.85$). Quorer measures (log-SIS, log-SOS) were significantly related to each other ($r = 0.86$, $p < 0.01$) and to bankside and in-stream visual assessments of % sediment cover at the run-scale ($r = 0.42$, $p < 0.01$), but not the reach-scale measure. The Shuffle index and Wolman measure of % sediment were significantly related to all metric measures ($r > 0.40$), except log-sediment depth. Sediment depth was only significantly related to five other metrics and the strongest of these relationships was with log-SOS ($r = 0.48$).

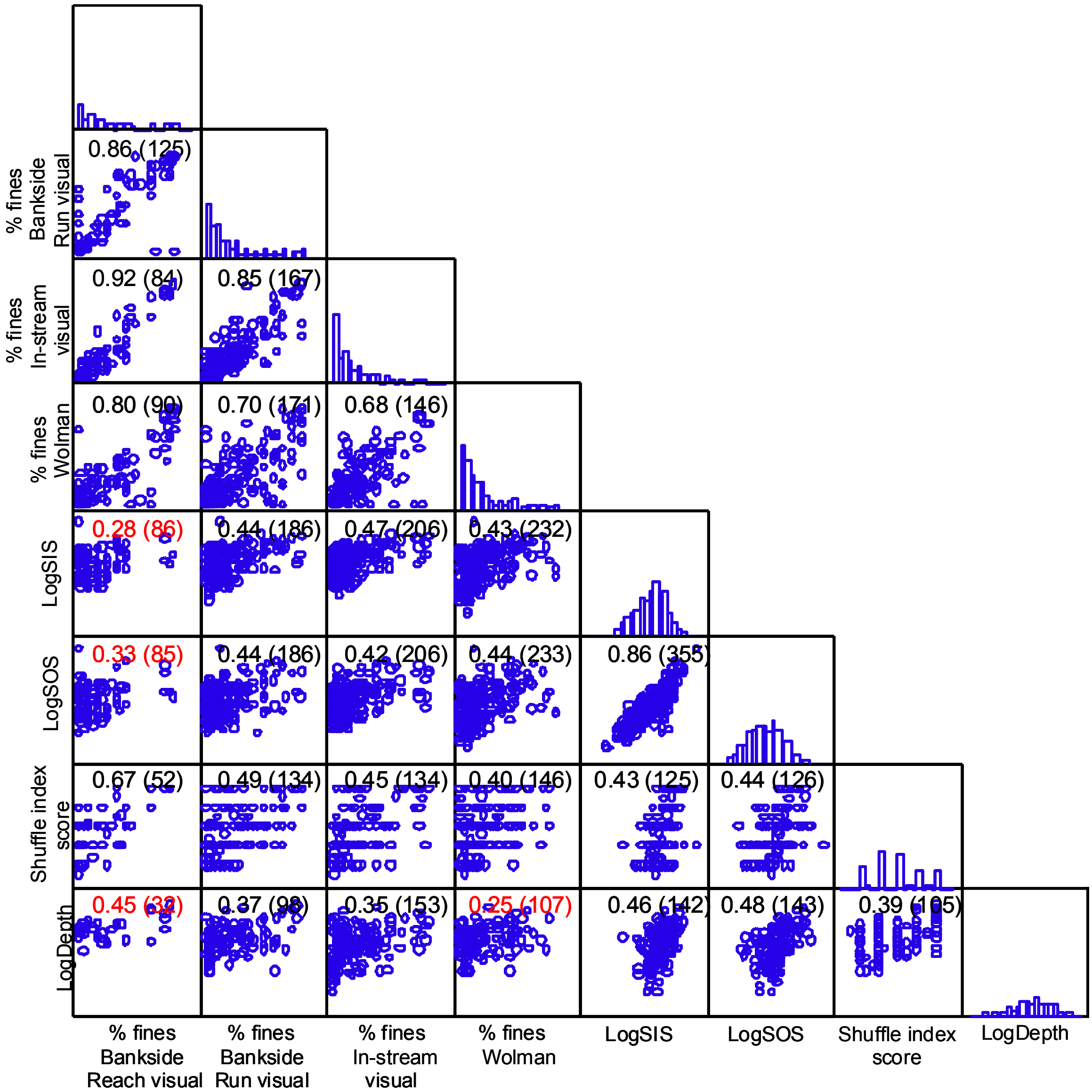


Figure 4-19. Correlations among metrics from data collated for guideline development. Values are the Pearson correlation coefficient (r) with number of sites in parentheses, $p < 0.01$. Red values are where $p > 0.1$. Note log_{10} transformations of SIS, SOS and sediment depth data.

Sediment data was then compared in relation to biotic metrics representing in-stream values: MCI, %EPT richness, taxonomic richness, EPT taxa richness, % trout, % native fish, koura abundance, and eel abundance. There were no significant relationships between the Shuffle index score and any of the values metrics. There were also no significant correlations between any of the sediment measures and fish metrics; however, both MCI and %EPT richness were related to sediment metrics. Log-sediment depth had a significant relationship with the number of invertebrate taxa and the number of EPT taxa (Figure 4-20).

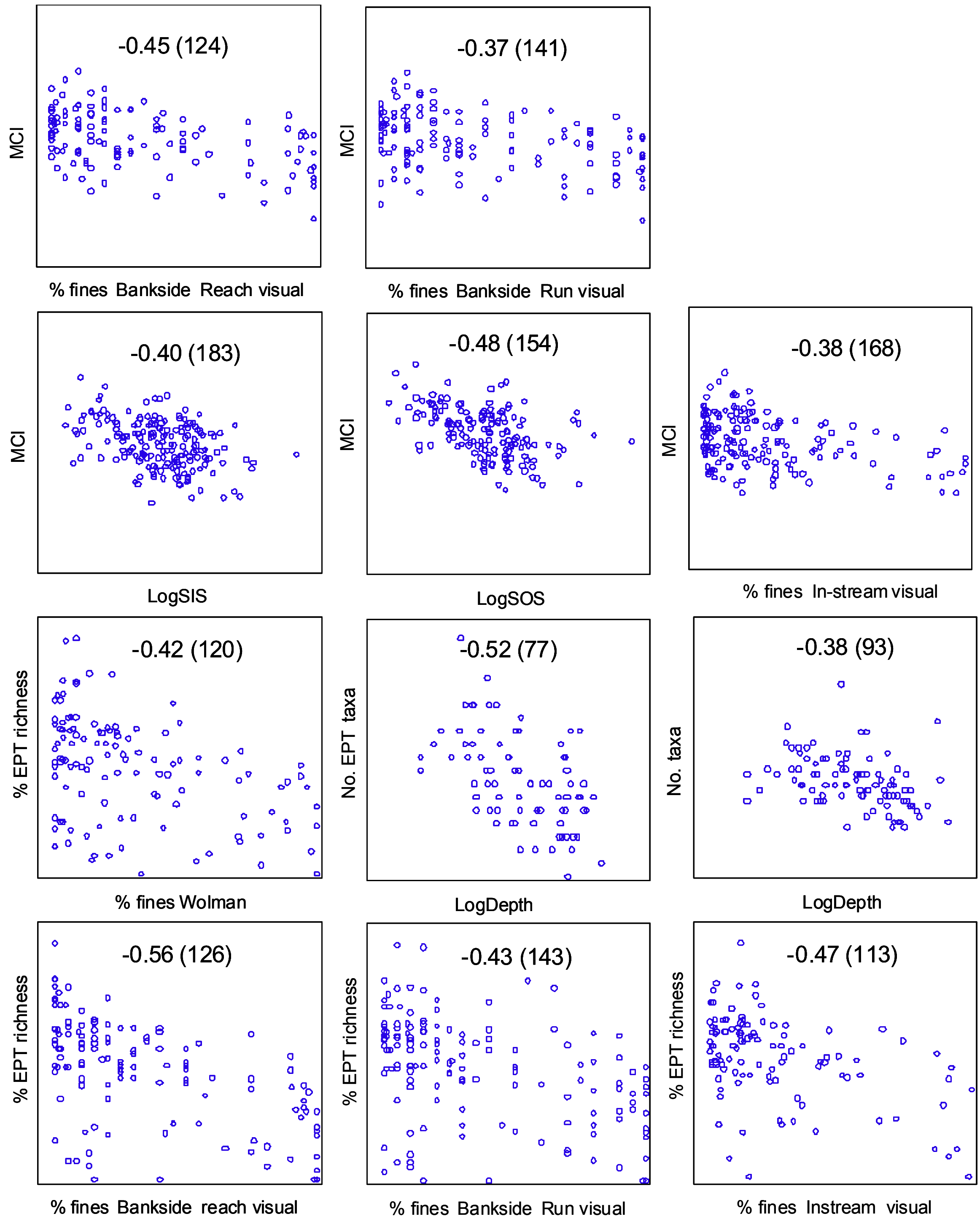


Figure 4-20. Correlations among sediment measures and metrics of in-stream values. Values are the Pearson correlation coefficient (r) with number of sites in parentheses. Only significant relationships ($p < 0.01$) are shown.

4.5.3 Predictive relationships between sediment and biota

Based on the results of correlation analyses, the strength of relationships between biotic indices and sediment metrics was investigated using linear regression of the combined data set.

1. Percent sediment and MCI and %EPT richness

The strongest relationship observed between MCI and % sediment was for the reach scale bankside measure: $r^2 = 0.20$, $p < 0.001$ (Figure 4-21). Using the linear relationship (y=113.19-0.29x) to predict the sediment value at 120 MCI (*i.e.*, the value separating clean waters from possible pollution) leads to a theoretical value of -23% sediment cover, *i.e.*, an absence of sediment. Also, it is apparent from Figure 4-21 that there is a large spread of MCI values at 0% sediment cover, anywhere between 90 and 142 MCI, probably reflecting the effects of factors other than % sediment on MCI. Clearly a regression approach is not a meaningful or sensitive way to assign guideline values.

The bankside reach scale estimate of % sediment had the strongest relationship with %EPT richness: $r^2 = 0.32$, $p < 0.001$ (Figure 4-21). Using the linear relationship (y=52.49-0.33x) to predict sediment cover at a %EPT value indicative of clean water (50% EPT) results in sediment cover value of 7%. However, there was a wide range of %EPT values at less than 7% sediment; 7% EPT – 90% EPT.

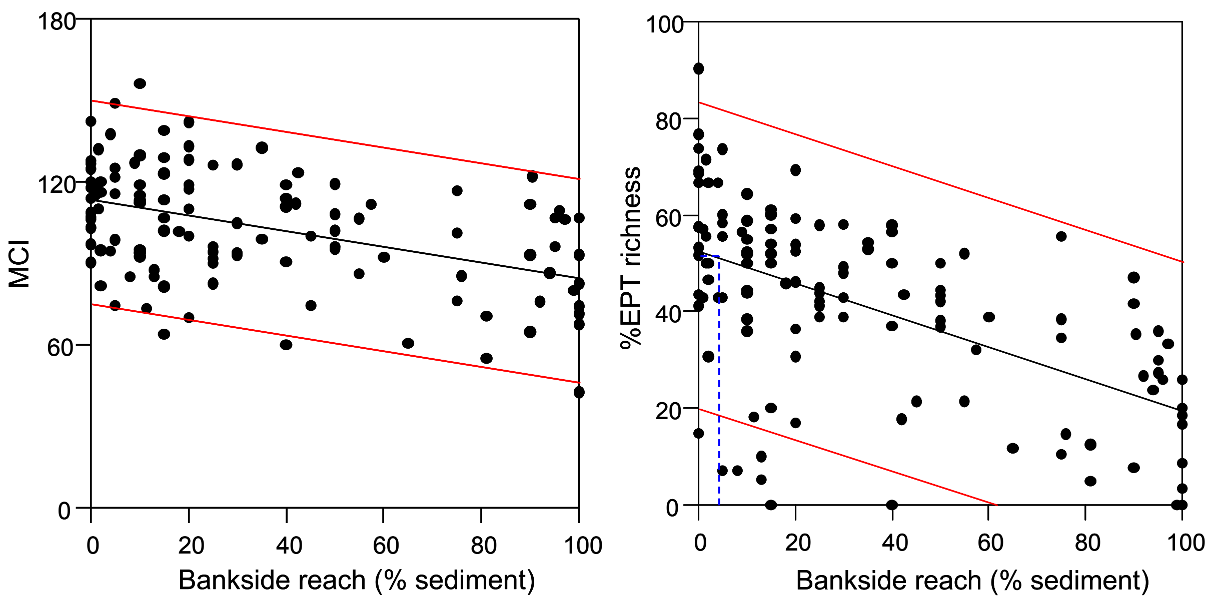


Figure 4-21. Linear relationship (with 95% prediction confidence intervals) between a reach scale bankside estimate of % fine sediment cover and the MCI metric (n = 124), and %EPT richness (n = 126). The blue line indicates the % fine sediment value where %EPT exceeds 50%.

2. Suspendible sediment and MCI

The relationship between measures of organic and inorganic suspendible sediment and MCI was examined. There were relatively weak yet significant linear relationships with MCI for log-transformed SOS: $r^2 = 0.26$, $p < 0.001$ and log-transformed SIS: $r^2 = 0.18$, $p < 0.001$ (Figure 4-22). Using the linear relationship (y=125.90-13.93x) to predict the log-SOS value at 120 MCI (*i.e.*, clean water) results in a value of 0.42, equivalent to a back-transformed value of 2.65 g/m^2. Similarly, for log-SIS the predicted value at 120 MCI based on the linear relationship (y=135.62-11.67x) was 1.34, equivalent to a back-transformed value of 21.8 g/m^2.

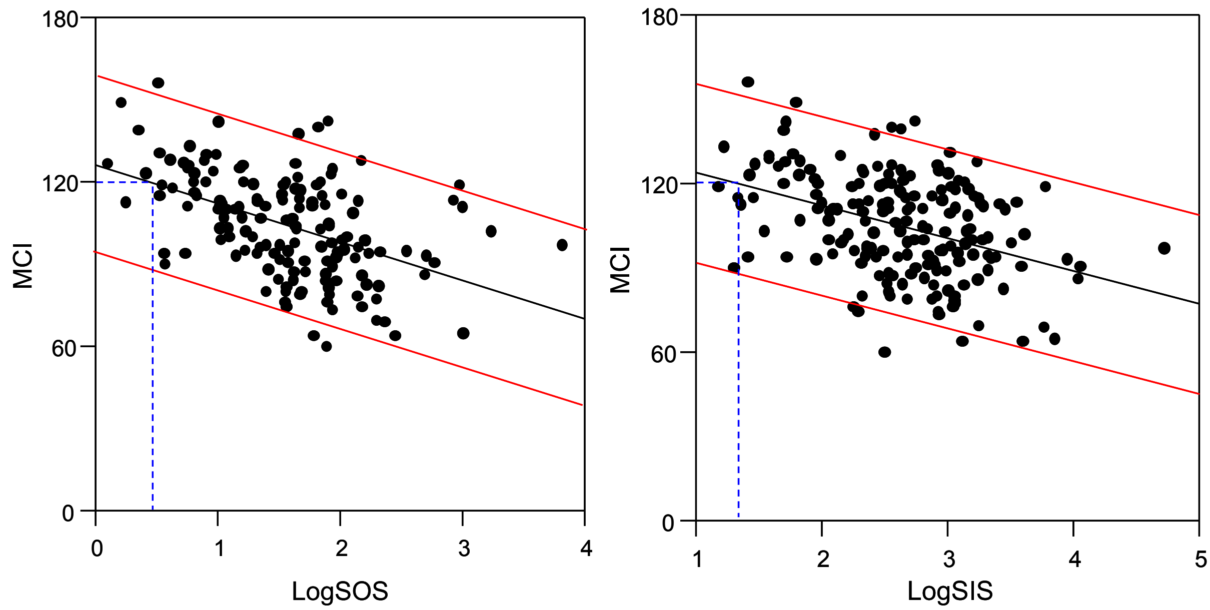


Figure 4-22. Linear relationships (with 95% prediction confidence intervals) between MCI and suspended organic sediment (n = 154), and suspended inorganic sediment (n = 183). Note that suspended sediment metrics are log-transformed. The blue line indicates the suspended sediment value where MCI exceeds 120.

3. Sediment depth and taxa and EPT taxa richness

Notably the only sediment metric significantly related to total numbers of invertebrate taxa and total numbers of EPT taxa was sediment depth (Figure 4-23), although the relationships were weak: No. taxa $r^2 = 0.20$, $p < 0.001$; No. EPT taxa $r^2 = 0.27$, $p < 0.001$ [Linear relationships: No. taxa ($y = 19.339 - 2.448x$). No EPT taxa ($y = 8.962 - 2.074x$)]. There are no guideline values for each of these invertebrate metrics; however, these relationships suggest sediment depth may be an indicator of the effects of fine sediment accumulation on invertebrate diversity.

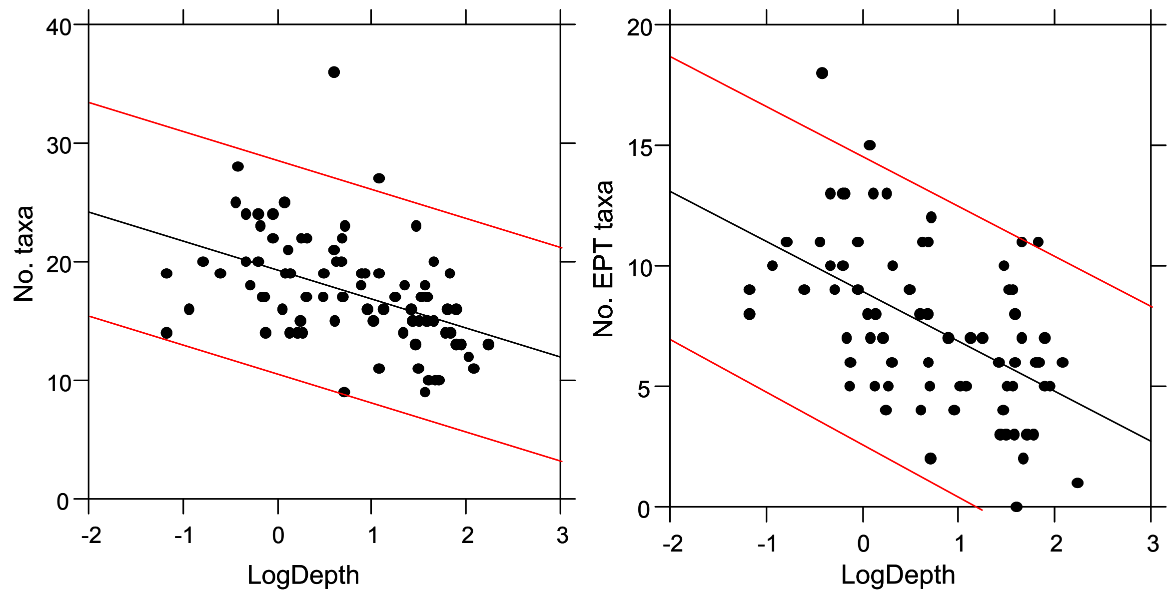


Figure 4-23. Linear relationships (with 95% prediction confidence intervals) between the number of taxa and the number of invertebrate taxa and log-transformed sediment depth (mm).

4.5.4 Boosted regression tree model to inform reference state

An output of a parallel research project (MSI contract C01X1005) was the development of a regression model that determines the relationship between fine sediment cover and environmental predictors. This model was then used to predict the relative proportion of fine sediment cover in every stream reach in New Zealand (see Appendix 6.3 for model details). Sediment data used in model development was sourced from the Freshwater Fisheries database. The % fine sediment cover was calculated from a bankside estimate of the relative proportion of substrate size classes. Environmental variables were sourced from the FENZ database and included measures of land use, climate, geology, morphology and topography as described in Leathwick *et al*. (2011). The resulting boosted regression tree model had a cross-validation error of 0.67 and explained 45% of the variance in % fine sediment cover (n = 10,026), which indicate good model performance. The fitted functions of explanatory variables were as expected with fine sediment cover increasing in response to decreasing upstream average slope and segment slope, decreasing native vegetation cover in the catchment, segment flow and flow stability. Sediment cover increased in response to increasing mean air summer and temperature annual variability and land-use intensification. Fitted functions from the model were used to predict fine sediment cover in each NZREACH stream segment in New Zealand (Figure 4-24). Predicted fine sediment cover values ranged from 0% to 100% and the national average value was 29.4%.

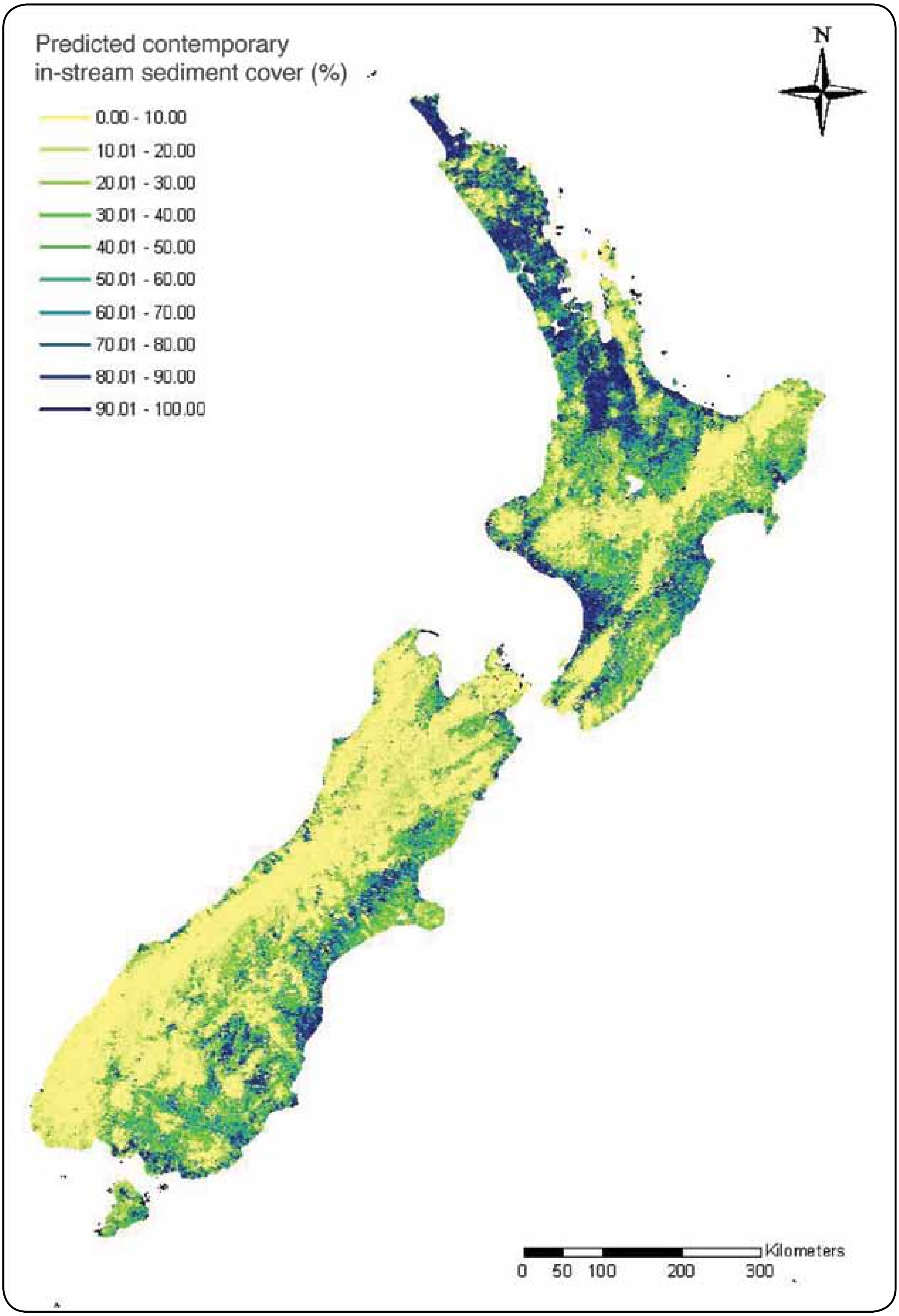


Figure 4-24. Predicted contemporary sediment cover for stream segments in the New Zealand river network. For more information on the source model see Appendix 6.3.

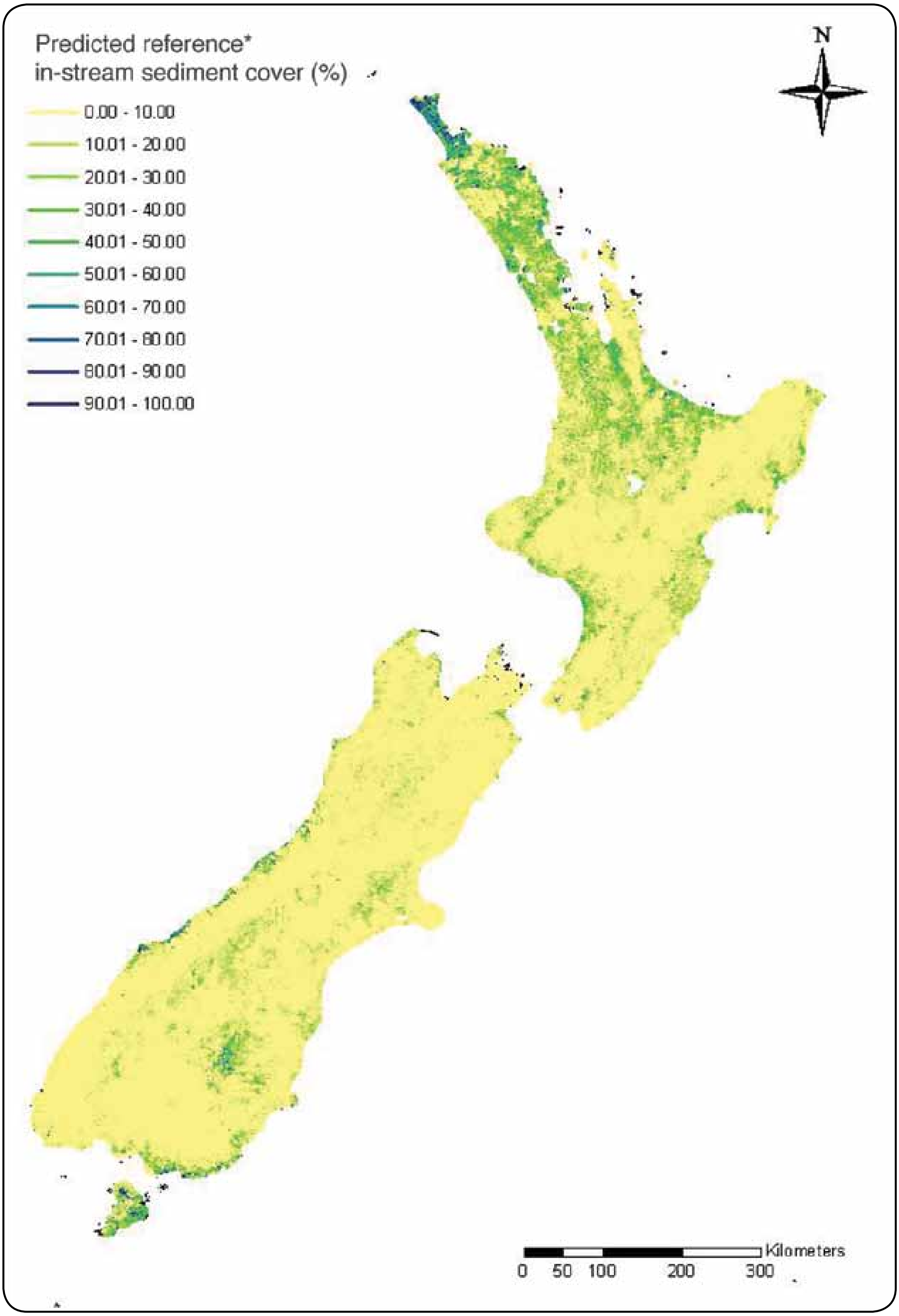


Figure 4-25. Predicted reference* values for fine sediment cover in the New Zealand river network. *Reference is defined by the absence of human land-use impacts. For more information on the source model see Appendix 6.3.

Next, the effect of land-use variables (native vegetation cover, impervious surface cover and predicted nitrogen concentrations as an indicator of land-use intensity) were fixed and used as an offset in a model to predict fine sediment cover in the absence of land use. The resulting boosted regression tree model had a cross-validation error of 0.63 and explained 42% of the variance in the sediment data. The small decrease in model performance compared to the former inclusive model provides confidence in the fixed model output. The fitted functions from this second model were used to predict sediment cover for each NZREACH based solely on environmental variability, *i.e.*, expected 'reference' values in the absence of land use (Figure 4-25). As expected, from the fitted functions of the former model, high levels of fine sediment cover were predicted for areas of relatively low slope, high temperature and low rainfall, low flow and soft geology, for example, Northland, coastal Bay of Plenty, coastal Manawatu and Hawkes Bay, and plateau areas of upland Otago.

Predicted reference values for fine sediment cover in New Zealand streams ranged from 0% to 100% with an average value of 7.7%. A summary of modelled contemporary and modelled reference values for sediment cover in each stream segment based on FENZ 20-level groupings further illustrates the logical output of the model predictions (Table 4-9). As expected, small coastal to inland streams with low gradient and low rain days had the highest predicted sediment cover (Groups A-D, F & G); but these streams have also been subject to the highest land-use pressure and hence have the largest divergence between predicted contemporary and predicted reference values.

Independent values from the protocol development phase were used to validate the model predictions. The strongest correlation was between the bankside reach scale estimate of sediment cover and the modelled observed measure: $r = 0.58$, $p < 0.001$ (Figure 4-26). The relationship with all other estimates of % sediment were significant ($p < 0.001$), but not as strong: Bankside run, $r = 0.40$, $n = 244$; In-stream visual, $r = 0.29$, $n = 236$; Wolman $r = 0.42$, $n = 291$).

The validation is good and the correlation is almost as strong as the predictive error of the model (CV = 0.63). However, it is clear from Figure 4-26 that the model has the potential to both over- and under-estimate sediment cover at both the high and low ends of the range in values. The linear relationship suggests the predictive model is likely to overestimate low sediment cover and underestimate high sediment cover.

Table 4-9. Fine sediment spatial model predictions of contemporary values (O), reference values (E) and the 75th percentile value at sites with greater than 80% vegetation (O80) summarised by FENZ 20-level grouping. Mean values are shown for each FENZ group.

FENZ Group	O	E	O80
A	67.52	16.14	57.84
B	74.90	29.45	77.62
C	23.90	5.85	9.66
D	33.41	5.70	8.48
E	23.56	16.43	29.41
F	45.72	23.21	44.40
G	25.21	6.71	15.29
H	8.73	4.19	8.42
I	9.64	7.59	12.65
J	4.42	2.55	5.56
K	3.19	2.79	4.87
L	2.31	1.96	3.03
M	7.07	5.98	11.10
N	7.48	5.75	10.10
O	4.57	3.46	5.94
P	5.45	4.72	7.20
Q	4.88	4.06	6.27
R	8.16	8.14	5.64
S	2.59	2.44	3.25
T	3.37	3.34	4.10

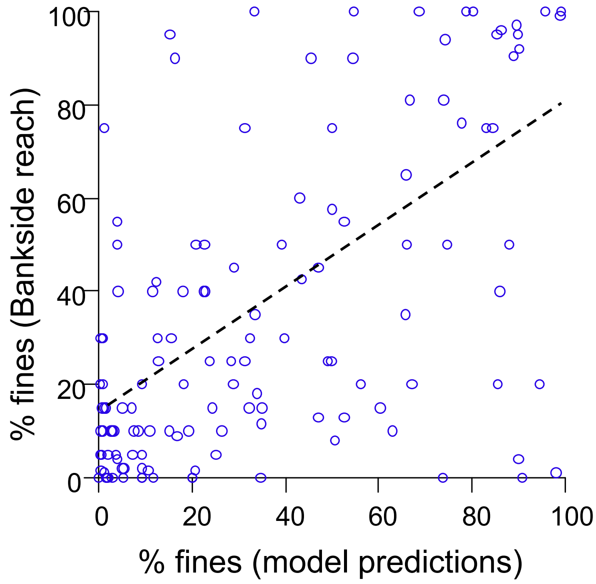


Figure 4-26. Correlation between % fine sediment estimated from the bankside reach measure and predictions from the spatial model (n = 130).

4.5.5 Data mining to inform reference state

Expected sediment values for minimally impacted sites ('reference') were defined by examining the distribution of data collated to develop guidelines by using sites:

1. characterised by greater than 80% native vegetation cover in the catchment,
2. where MCI values were >120 (*i.e.*, clean water, Boothroyd & Stark 2000), and
3. where %EPT values were >50.

For example, using this approach the % fine sediment cover measured using the bankside visual method (at a run scale) suggests two alternative reference values, the 75th percentile at greater than 80% native vegetation cover is 15% and the 75th percentile at greater than 120 MCI and 50 %EPT is 20% (Figure 4-27). The reference values were very similar for determinations based on greater than 80% native vegetation cover (Table 4-10) and >120 MCI (Table 4-11) and >50 %EPT (Table 4-12) for most metrics.

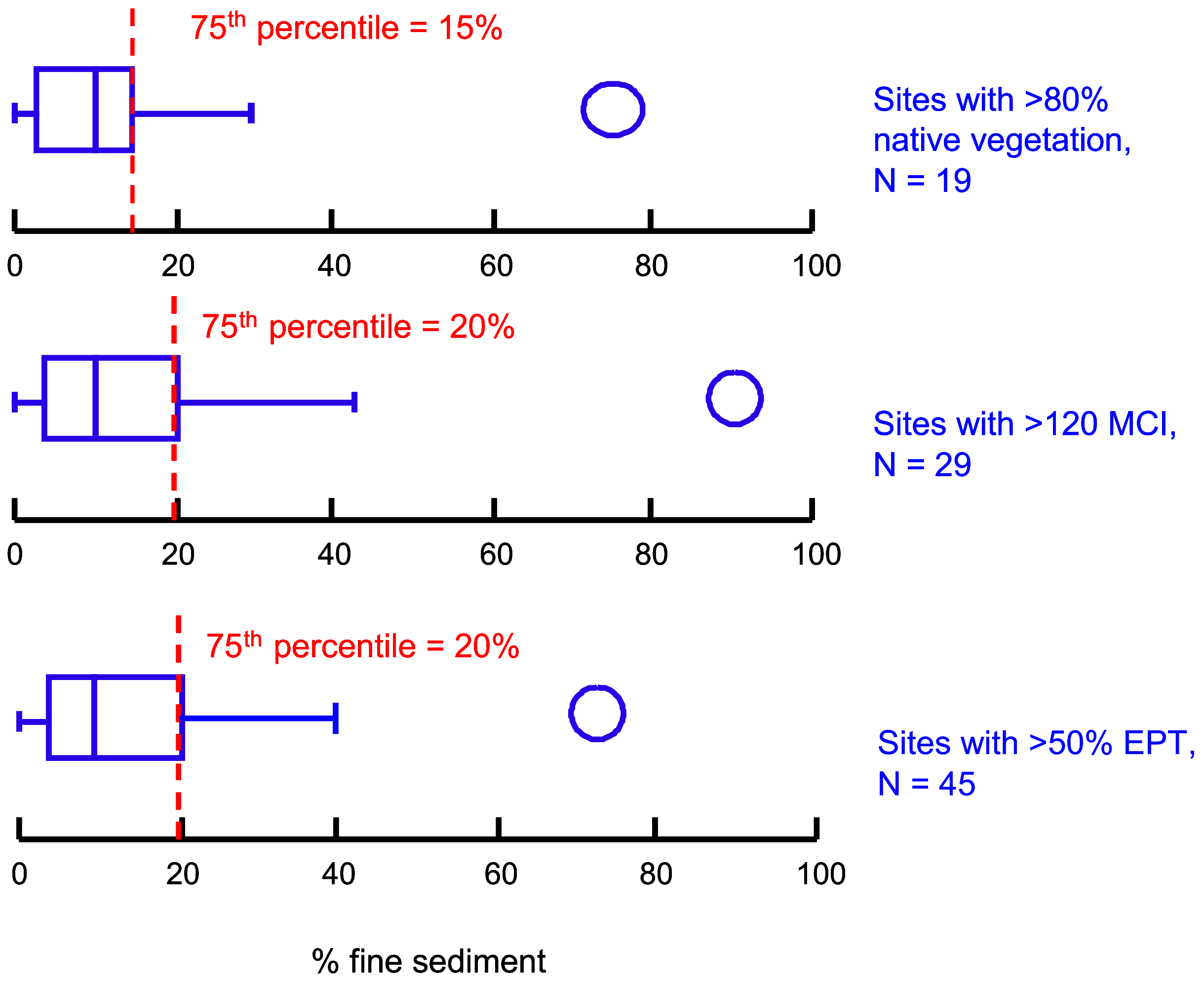


Figure 4-27. Example of using data distributions to calculate guideline values for % fine sediment cover estimated using the bankside reach protocol.

Table 4-10. The 75th percentile for sediment metrics at sites with greater than 80% native vegetation cover in their catchments.

Site with greater than 80% native vegetation	N	75th percentile
% sediment (Bankside reach)	19	15.00
% sediment (Bankside run)	37	20.00
% sediment (In-stream visual)	36	17.02
% sediment (Wolman)	58	17.50
SIS (g/m^2)	74	404.53
SOS (g/m^2)	69	28.20
%SIS	69	91
Shuffle index score	24	2.15
Sediment depth (mm)	23	8.87

Table 4-11. The 75th percentile for sediment metrics at sites with >120 MCI.

Sites with greater than 120 MCI	N	75th percentile
% sediment (Bankside reach)	29	20.00
% sediment (Bankside run)	35	20.00
% sediment (In-stream visual)	36	13.02
% sediment (Wolman)	20	8.00
SIS (g/m^2)	41	429.28
SOS (g/m^2)	33	43.47
%SIS	33	94
Shuffle index score	14	2.00
Sediment depth (mm)	15	4.10

Table 4-12. The 75th percentile for sediment metrics at sites with >50 %EPT.

Sites with greater than 50 %EPT	N	75th percentile
% sediment (Bankside reach)	45	20.00
% sediment (Bankside run)	56	20.00
% sediment (In-stream visual)	48	16.60
% sediment (Wolman)	39	20.50
SIS (g/m^2)	48	952.72
SOS (g/m^2)	48	69.39
%SIS	48	94
Shuffle index score	35	3.00
Sediment depth (mm)	12	62.69

4.5.6 Amenity values

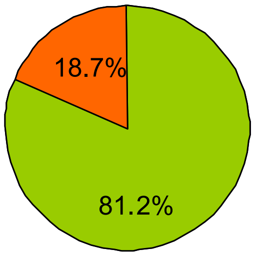
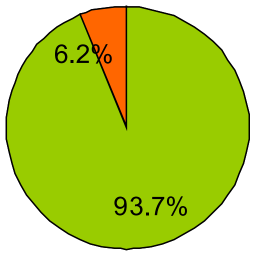
A functional approach to defining benchmarks is often used when values other than aquatic life are of interest. For example, visual clarity guidelines are an example of a 'functional benchmark' to protect recreational use: 'The visual clarity guidelines are based on the objective that to protect visual clarity of waters used for swimming, the horizontal sighting of a 200 mm diameter black disc should exceed 1.6 m (ANZECC 2000). Functional benchmarks can be determined by results from the literature, field data or social data, for example, surveys.

A survey was conducted to determine what levels of sediment are socially acceptable for swimming and to determine the levels of sediment that affect the aesthetic values of streams. Participants of a sediment workshop at the New Zealand Freshwater Science Society annual conference (Christchurch, November 2010) were asked to complete a survey (Appendix 6.2). The survey contained a series of photos and participants[4] were asked to provide good/bad or yes/no responses to the following questions:

1. Focussing on the level of fine sediment, how do you feel (gut feeling) about this stream?
2. In your opinion, is this level of fine sediment acceptable for swimming?

Results were used to determine a range in sediment values that were indicative of a change in aesthetic and swimming values of streams. Based on 48 responses to the first question, amenity value changes from acceptable to unacceptable between 12% and 27.5% sediment cover (Table 4-13). Based on 48 responses to the second question, swimming value decreases from acceptable to unacceptable between a Shuffle index score of 2 and a Shuffle index score of 3 (Table 4-14).

Table 4-13. Summary of responses to Question one from the Amenity Values Survey, "Focussing on the level of fine sediment, how do you feel (gut feeling) about this stream?" Survey results are the percentage of responses where green indicates an answer of "Good" and orange "Bad".

% sediment	Survey photo	Survey results	Overall rating
2.5%			Good
5%			Good

[4]A recognised biased sample of people who are likely to make informed decisions based on their professional experience in freshwater. Of the 48 respondents, 62% were male; the average age was 39 years (range 24-65 yrs) with an average number of 13 years (range 1-40 yrs) of professional experience in freshwater.

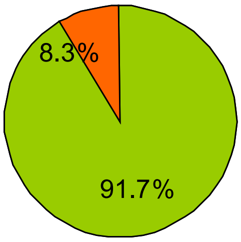
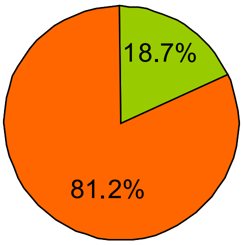
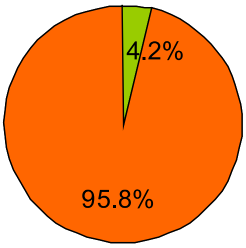
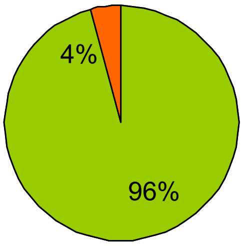
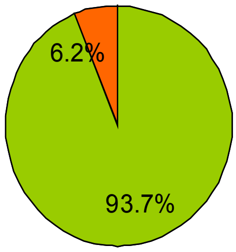
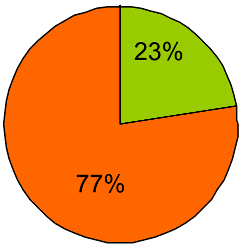
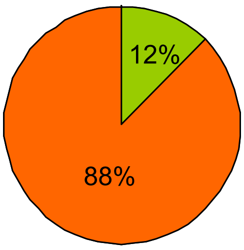
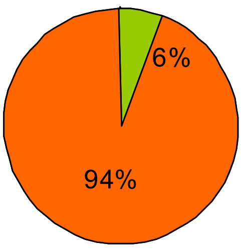
% sediment	Survey photo	Survey results	Overall rating
12%			Good
27.5%			Bad
50%			Bad

Table 4-14. Summary of responses to Question two from the Amenity Values Survey, "In your opinion, is this level of fine sediment acceptable for swimming?" Survey results are the percentage of responses where green indicates an answer of "Yes" and orange "No".

Shuffle	Survey photo	Survey results	Overall rating
1			Yes
2			Yes
3			No
4			No
5			No

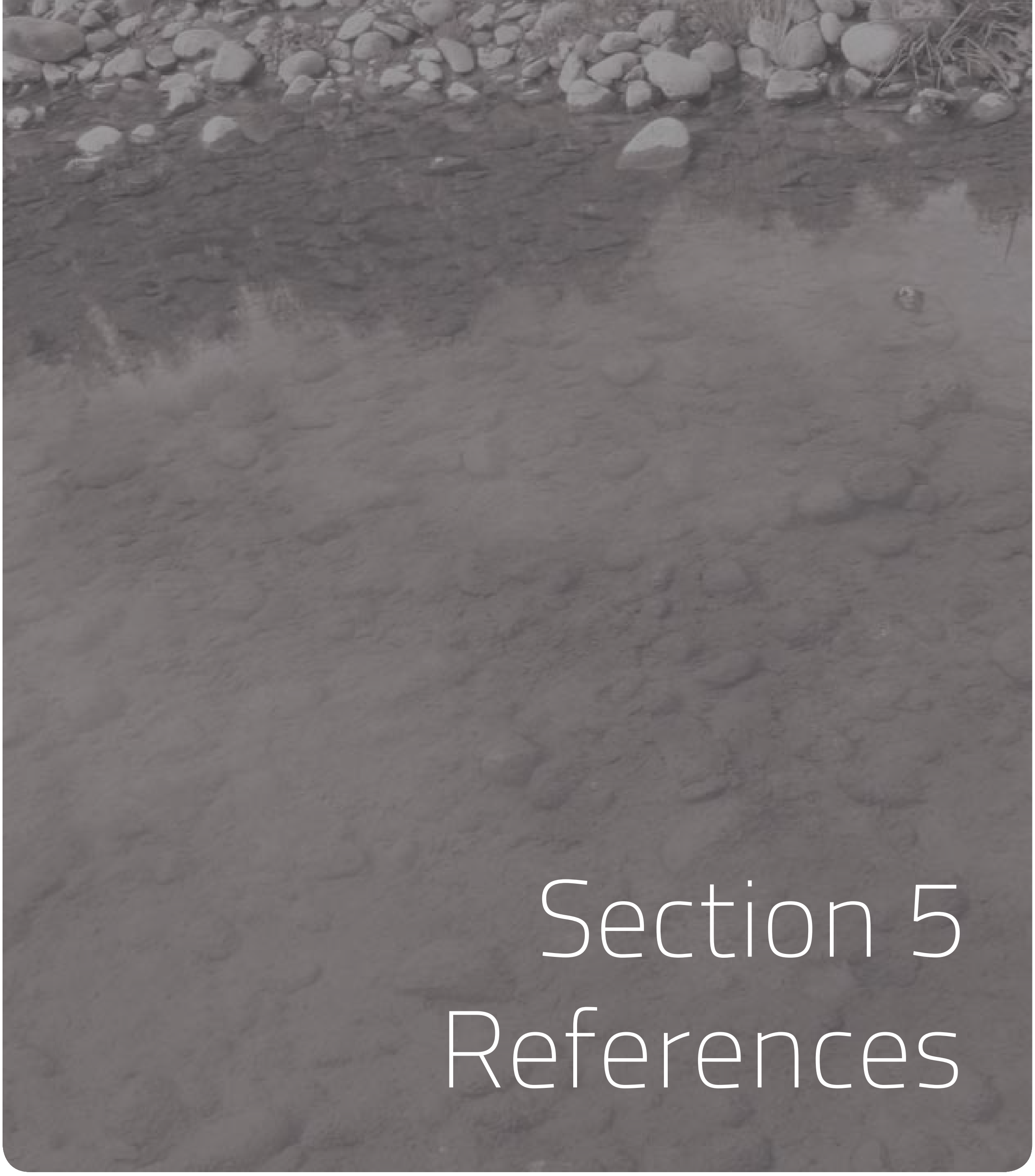
4.5.7 Fish values

A literature review was conducted to determine what levels of sediment were detrimental to fish. As noted earlier (Section 4.1.2), there is evidence to suggest that upland bullies avoid sediment (Jowett & Boustead 2001) and koaro, shortjaw kokopu and redfin bullies prefer substrate with large interstitial spaces (McEwan 2009). There have been no studies that have directly tested the mortality of native fishes in response to deposited sediments. Results of recent studies on the spawning habitat of inanga (*Galaxias maculatus*) have illustrated that fine sediment clogs the interstitial spaces in riparian grasses, dramatically reducing the habitat critical for egg deposition and development (Mike Hickford, University of Canterbury, unpublished data).

Several studies have identified the lethal levels of suspended sediment on native fish species (Rowe *et al*. 2000) and determined levels of sediment that lead to fish avoidance behaviours (Rowe *et al*. 2004). These findings form the basis of maximum turbidity levels for riverine fish[5]. In the absence of established quantitative relationships between suspended and deposited sediments, guidelines for the protection of native fish should probably be based on the effect of sediment on fish food. Decreases in EPT taxa richness and abundance due to increased sediment will affect native fish because these are the preferred foods of many native fish (McDowall 2000).

International studies have investigated the impact of sediment on salmonid breeding success and survival. For example, the emergence success of cutthroat trout was reduced from 76 to 55, 39, 34, 26 and 4%, respectively, when the proportion of fine sediment was increased from 0 to 10, 20, 30 , 40 and 50% (Weaver & Fraley 1993). Similarly, Olsson & Persson (1988) found that greater than 20% deposited sediment cover resulted in dramatic declines in embryo survival and reduced fitness in surviving brown trout alevins. Greater than 20% sediment is generally seen as a threshold for suitable spawning habitat, 10-20% sediment provides adequate to poor spawning habitat (embryo survival will be affected), less than 10% is good and no sediment is optimal (Crisp & Carling 1989). It is feasible that international guidelines to protect salmonid habitat are applicable in New Zealand streams.

[5]http://www.niwa.co.nz/our-science/freshwater/tools/turbidity Accessed 14 July 2011



Section 5
References

Akbaripasand A, Nichol EC, Lokman PM, Closs GP 2011. Microhabitat use of a native New Zealand galaxiid fish, *Galaxias fasciatus*. *New Zealand Journal of Marine and Freshwater Research 45 (1)*: 135-144.

ANZECC 2000. Australian and New Zealand guidelines for fresh and marine water quality. Volume 1, The guidelines. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand.

Bevenger GS, King RM 1995. A pebble count procedure for assessing watershed cumulative effects. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colarado. 17 pp.

Biggs BJF, Kilroy C, Mulcock CM, Scarsbrook MR 2002. New Zealand Stream Health Monitoring and Assessment Kit. Stream Monitoring Manual. Version 2. NIWA Technical Report 111. 190 pp.

Boothroyd I, Stark J 2000. Use of invertebrates in monitoring. Pp 344-373. *In*: Collier KJ, Winterbourn MJ ed. *New Zealand stream invertebrates: ecology and implications for management*. Caxton Press, Christchurch.

Boubée J, Dean TL, West DW, Barrier RFG 1997. Avoidance of suspended sediment by the juvenile migratory stage of six New Zealand freshwater fish species. *New Zealand Journal of Marine and Freshwater Research 31 (1)*: 61-69.

Buffington JM, Montgomery DR 1999a. A procedure for classifying and mapping textural facies in gravel-bed rivers. *Water Resources Research 35 (6)*: 1903-1914.

Buffington JM, Montgomery DR 1999b. Effects of sediment supply on surface textures of gravel-bed rivers. *Water Resources Research 35 (11)*: 3523-3530.

Bunte K, Abt SR 2001. Sampling surface and subsurface particle-size distributions in wadable gravel-and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. 428 pp.

Bunte K, Abt SR, Potyondy JP, Swingle KW 2009. Comparison of three pebble count protocols (EAMP, PIBO, and SFT) in two mountain gravel-bed streams. *Journal of the American Water Resources Association 45 (5)*: 1209-1227.

Burns DC, Edwards RE 1985. Embeddedness of salmonid habitat of selected streams on the Payette National Forest. USDA Forest Service, Payette National Forest, McCall, Idaho.

Burton GAJ, Batley GE, Chapman PM, Forbes VE, Smith EP, Reynoldson T, Schlekat CE, den Besten PJ, Bailer AJ, Green AS, Dwyer RL 2002. A weight-of-evidence framework for assessing sediment (or other) contamination: Improving certainty in the decision-making process. *Human and Ecological Risk Assessment 8 (7)*: 1675-1696.

Cantilli R, Stevens R, Sweitlik W, Berry W, Kaufman P, Paul J, Spehar R, Cormier S, Norton D 2006. Framework for developing suspended and bedded-sediments (SABS) water quality criteria. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

Collier KJ 2002. Effects of flow regulation and sediment flushing on instream habitat and benthic invertebrates in a New Zealand river influenced by a volcanic eruption. *River Research and Applications 18*: 213-226.

Collins AL, Walling DE 2007. Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. *Hydrological Processes 21*: 1448-1459.

Cottam DP, James TI 2003. Effects of fine sediment discharges on Card Creek and New River. West Coast Regional Council, Greymouth, New Zealand.

Crisp DT, Carling PA 1989. Observations on siting, dimensions and structure of salmonid redds. *Journal of Fish Biology 34 (1)*: 119-134.

Crowe A, Hay J 2004. Effects of fine sediment on river biota. Prepared for Motueka Integrated Catchment Management Programme. Cawthron Report No. 951. 35 pp.

Culp JM, Benoy GA, Brua RB, Sutherland AB, Chambers PA 2009. Total suspended sediment, turbidity and deposited sediment standards to prevent excessive sediment effects in Canadian streams. National Agri-Environmental Standards Initiative Synthesis Report No. 13. Environment Canada, Gatineau, Quebec. 84 pp.

Death RG, Winterbourn MJ 1994. Environmental stability and community persistance: a multivariate response. *Journal of the North American Benthological Society 13 (2)*: 125-139.

Downes BJ, Barmuta LA, Fairweather PG, Faith DP, Keough MJ, Lake PS, Mapstone BD, Quinn GP 2002. Monitoring ecological impacts: concepts and practice in flowing waters. Cambridge University Press, New York. 446 pp.

Dunning KJ 1998. Effects of exotic forestry on stream macroinvertebrates: the influence of scale in North Island, New Zealand streams. MSc thesis. Massey University. Palmerston North, New Zealand.

Environment Canterbury 2011. Canterbury Natural Resources Plan. Report no. R11/2. Environment Canterbury Regional Council, Christchurch.

Gordon ND, McMahon TA, Finlayson BL, Gippel CJ, Nathan RJ 2004. Stream Hydrology: An Introduction for Ecologists. Wiley, Chichester, England.

Harding JS, Clapcott JE, Quinn JM, Hayes JW, Joy MK, Storey RG, Greig HS, Hay J, James T, Beech MA, Ozane R, Meredith AS, Boothroyd IKD 2009. Stream habitat assessment protocols for wadeable rivers and streams of New Zealand. University of Canterbury Press.

Harvey BC, White JL, Nakamoto RJ 2009. The effect of deposited fine sediment on summer survival and growth of rainbow trout in riffles of a small stream. *North American Journal of Fisheries Management 29*: 434-440.

Hay J 2005. Survival of trout eggs in relation to sediment composition of redds in Waikakahi Stream. Prepared for Fish & Game New Zealand. Cawthron Report No. 965.

Hayward S, Meredith A, Stevenson M 2009. Review of proposed NRRP water quality objectives and standards for rivers and lakes in the Canterbury region. Environment Canterbury Report R09/16.

Heppell CM, Wharton G, Cotton AC, Bass JAB, Roberts SE 2009. Sediment storage in the shallow hyporheic of lowland vegetated river reaches. *Hydrological Processes 23*: 2239-2251.

Hicks DM, Gomez B, Trustrum NA 2000. Erosion thresholds and suspended sediment yields, Waipaoa River Basin, New Zealand. *Water Resources Research 36 (4)*: 1129-1142.

Hilton S, Lisle TE 1993. Measuring the fraction of pool volume filled with fine sediment. Pacific Northwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, CA. 11 pp.

Jones JI, Murphy JF, Collins AL, Sear DA, Naden PS, Armitage PD 2011. The impact of fine sediment on macro-invertebrates. *River Research and Applications* doi:10/1002/rra.1516.

Jowett IG 1989. River Hydraulic and Habitat Simulation, RHYHABSIM Computer manual. New Zealand Fisheries Miscellaneous Report 49, Ministry of Agriculture and Fisheries, Christchurch. 39 pp.

Jowett IG, Boustead NC 2001. Effects of substrate and sedimentation on the abundance of upland bullies (*Gobiomorphus breviceps*). *New Zealand Journal of Marine and Freshwater Research 35*: 605-613.

Kaufman PR, Larsen DP, Faustini JM 2009. Bed stability and sedimentation associated with human disturbances in Pacific Northwest streams. *Journal of the American Water Resources Association 45 (2)*: 434-459.

Lambert CP, Walling DE 1988. Measurement of channel storage of suspended sediment in a gravel-bed river. *Catena 15*: 65-80.

Larsen S, Omerod SJ 2009. Low-level effects of inert sediments on temperate stream invertebrates. *Freshwater Biology 55(2)*: 476-486.

Latulippe C, La Point MF, Talbot T 2001. Visual characterization technique for gravel-cobble river bed surface sediments; variation and environmental applications contribution to the programme for CIRSA (Centre Interuniversitaire de Rescherche sur le Saumon Atlantique). *Earth Surface Processes and Landforms 26*: 307-318.

Leathwick JR, Snelder T, Chadderton WL, Elith J, Julian K, Ferrier S 2011. Use of generalised dissimilarity modelling to improve the biological discrimination of river and stream classifications. *Freshwater Biology 56*: 21-38.

Lisle TE, Hilton S 1992. The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams. *Journal of the American Water Resources Association 28 (2)*: 371-383.

Lisle TE, Hilton S 1999. Fine bed material in pools of natural gravel bed channels. *Water Resources Research 35 (4)*: 1291-1304.

Luedtke RJ, Brusven MA 1976. Effects of sand sedimentation on colonization of stream insects. *Journal of the Fisheries Research Board of Canada 33*: 1881-1886.

MacDonald DD, Ingersoll CG, Berger TA 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Archives of Environmental Contamination and Toxicology 39 (1)*: 20-31.

Matthaei CD, Weller F, Kelly DW, Townsend CR 2006. Impacts of fine sediment addition to tussock, pasture, dairy and deer farming streams in New Zealand. *Freshwater Biology 51*: 2154-2172.

McDowall RM 2000. The Reed Field Guide to New Zealand Freshwater Fishes. Reed Books, Auckland.

McEwan AJ 2009. Fine scale spatial behaviour of indigenous riverine fish in a small New Zealand stream. MSc thesis. Massey University. Palmerston North, New Zealand. 95 pp.

Meredith AS, Cottam D, Anthony M, Lavendar R 2003. Ecosystem health of Canterbury rivers: development and implementation of biotic and habitat assessment methods 1999/2000. Environment Canterbury technical report R03/3.

MfE 1994. Water Quality Guidelines No. 2: Guidelines for the management of water colour and clarity. Ministry for the Environment, Wellington, New Zealand.

Molinos JG, Donohue I 2009. Differential contribution of concentration and exposure time to sediment dose effects on stream biota. *Journal of the North American Benthological Society 28 (1)*: 110-121.

Mosley MP, Tindale DS 1985. Sediment variability and bed material sampling in gravel-bed rivers. *Earth Surface Processes and Landforms 10 (5)*: 465-482.

Olsson TI, Persson B-G 1988. Effects of deposited sand on ova survival and alevin emergence in brown trout (*Salmo trutta* L.). *Archiv für Hydrobiologie 113*: 621-627.

Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA 2005. Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications 21*: 693-717.

Peck DV, Lazorchak JM, Klemm DJ 2000. Environmental monitoring and assessment program - surface waters: Western pilot study field operations manual for wadeable streams. U.S. Environmental Protection Agency, Washington, D.C.

Pflüger Y, Rackham A, Larned ST 2010. The aesthetic value of river flows: An assessment of flow preferences for large and small rivers. *Landscape and Urban Planning 95*: 68-78.

Phillips C, Basher L 2005. Catchment channel characteristics and riverbed substrate assessment - a review and trial of a method of fine sediment assessment in the Motueka River. Report prepared for Stakeholders of the Motueka Integrated Catchment Management Programme. Landcare Research. 55 pp.

Platts WS, Megahan WF, Minshall WG 1983. Methods for evaluating stream, riparian, and biotic conditions. USDA Forest Service, Rocky Mountain Research Station, Ogden, Utah.

Quinn JM, Hickey CW 1990. Characterisation and classification of benthic invertebrate communities in 88 New Zealand rivers in relation to environmental factors. *New Zealand Journal of Marine and Freshwater Research 24*: 387-409.

Quinn JM, Vickers ML 1992. Benthic invertebrates and related habitat factors in the Tongariro River. Water Quality Centre Consultancy Report No. 6025/2. 50 pp.

Quinn JM, Cooper AB, Davies-Colley RJ, Rutherford JC, Williamson RB 1997. Land use effects on habitat, water quality, periphyton, and benthic invertebrates in Waikato, New Zealand, hill-country streams. *New Zealand Journal of Marine and Freshwater Research 31*: 579-597.

Quinn JM, Boothroyd IKG, Smith BJ 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams: 2. Invertebrate communities. *Forest Ecology and Management 191*: 129-146.

Quinn JM, Croker GF, Smith BJ, Bellingham MA 2009. Integrated catchment management effects on runoff, habitat, instream vegetation and macroinvertebrates in Waikato, New Zealand, hill-country streams. *New Zealand Journal of Marine and Freshwater Research 43*: 775-802.

Rabeni CF, Doisy KE, Zweig LD 2005. Stream invertebrate community functional responses to deposited sediment. *Aquatic Sciences 67*: 395-402.

Richardson J, Rowe DK, Smith JP 2001. Effects of turbidity on the migration of juvenile banded kokopu (*Galaxias fasciatus*) in a natural stream. *New Zealand Journal of Marine and Freshwater Research 35*: 191-196.

Richardson J, Jowett IG 2002. Effects of sediment on fish communities in East Cape streams, North Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research 36*: 431-442.

Rowe D, HIcks M, Richardson J 2000. Reduced abundance of banded kokopu (*Galaxias fasciatus*) and other native fish in turbid rivers of the North Island of New Zealand. *New Zealand Journal of Marine and Freshwater Research 34*: 547-558.

Rowe DK, Dean TL 1998. Effects of turbidity on the feeding ability of the juvenile migrant stage of six New Zealand freshwater fish species. *New Zealand Journal of Marine and Freshwater Research 32*: 21-29.

Rowe DK, Smith J, Williams E 2004. Lethal turbidities and native fish. *Water and Atmosphere 12 (2)*: 26-27.

Rowe DK, Hicks M, Smith JP, Williams E 2009. Lethal concentrations of suspended solids for common native fish species that are rare in New Zealand rivers with high suspended solids loads. *New Zealand Journal of Marine and Freshwater Research 43 (5)*: 1029-1038.

Ryan PA 1991. Environmental effects of sediment on New Zealand streams: a review. *New Zealand Journal of Marine and Freshwater Research 25*: 207-221.

Ryder GI 1989. Experimental Studies on the Effects of Fine Sediments on Lotic Invertebrates. PhD thesis. University of Otago. Dunedin, New Zealand.

Schwendel AC, Death RG, Fuller IC 2009. The assessment of shear stress and bed stability in stream ecology. *Freshwater Biology 55(2)*: 261-281.

Sedell JR, Reeves GH, Hauer FR, Stanford JA, Hawkins CP 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. *Environmental Management 14*: 711-724.

Sennatt KM, Salant NL, Renshaw CE, Magilligan FJ 2006. Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated streams. *Journal of the American Water Resources Association 42 (6)*: 1671-1682.

Smith DG, Croker GF, McFarlane K 1995. Human perception of water appearance 1. Clarity and colour for bathing and aesthetics. *New Zealand Journal of Marine and Freshwater Research 29 (1)*: 29-43.

Suren AM, Jowett IG 2001. Effects of deposited sediment on invertebrate drift: an experimental study. *New Zealand Journal of Marine and Freshwater Research 35*: 725-737.

Suren AM 2005. Effects of deposited sediment on patch selection by two grazing stream invertebrates. *Hydrobiologia 549*: 205-218.

Sutherland AB, Culp JM, Benoy GA 2008. Development of physical and biological performance standards for deposited sediments in agricultural watersheds. National Agri-Environmental Standards Initiative Technical Series Report No. 4-58. Environment Canada, Gatineau, QC. 107 pp.

Sutherland AB, Culp JM, Benoy GA 2010. Characterizing deposited sediment for stream habitat assessment. *Limnology and Oceanography: Methods 8*: 30-44.

Townsend CR, Uhlmann SS, Matthaei CD 2008. Individual and combined responses of stream ecosystems to multiple stressors. *Journal of Applied Ecology 45*: 1810-1819.

Wagenhoff A 2011. Multiple-stressor effects along gradients of deposited fine sediment and dissolved nutrients in streams. PhD thesis. University of Otago. Dunedin. 164 pp.

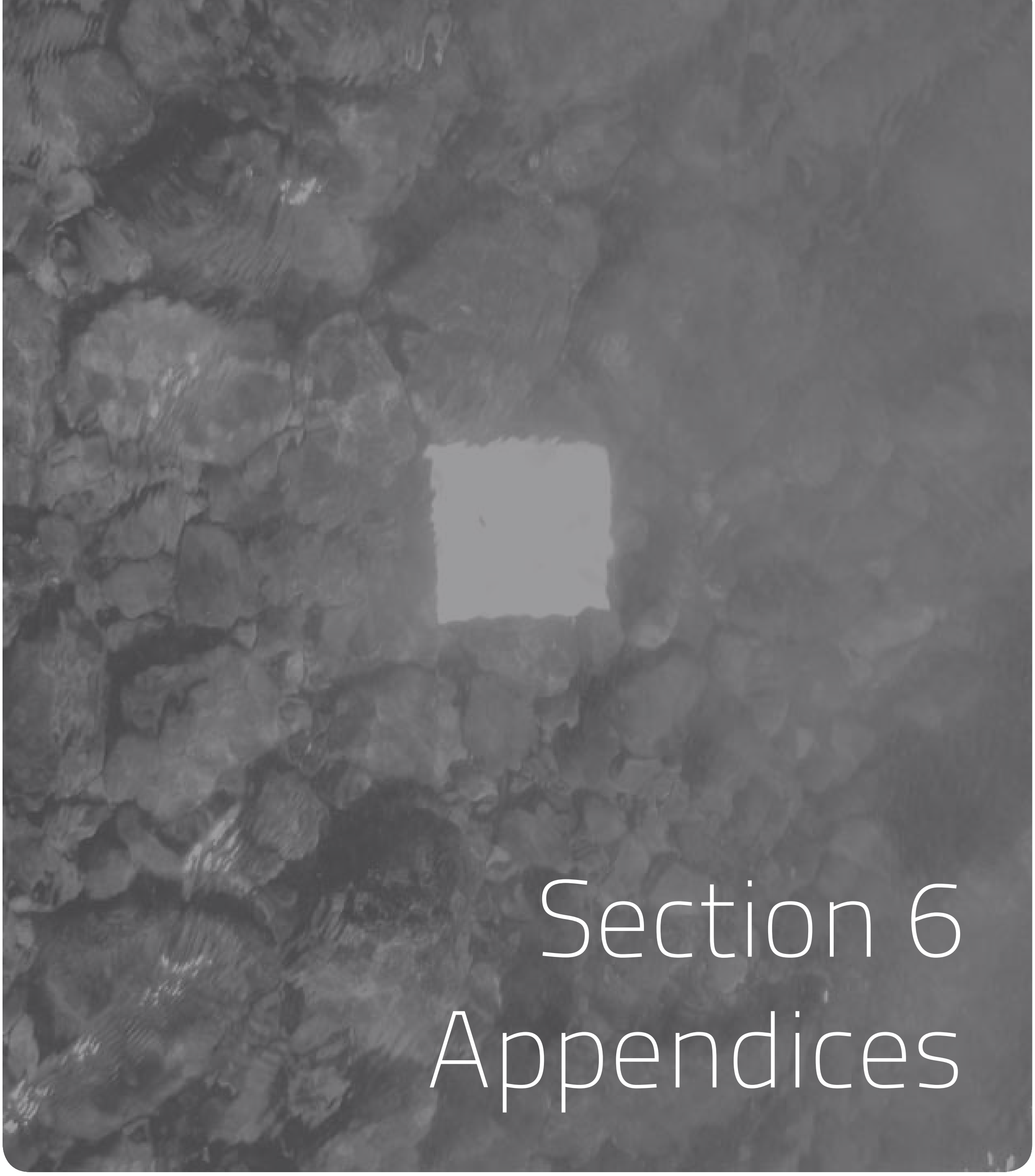
Waters TF 1995. Sediment in streams: sources, biological effects, and control. American Fisheries Society, Bethesda, MA. 251 pp.

Weaver TM, Fraley JJ 1993. A method to measure emergence success of Westslope cutthroat trout fry from varying substrate compositions in a natural stream channel. *North American Journal of Fisheries Management 13 (4)*: 817-822.

Wentworth CK 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology 30*: 377-392.

Wolman MG 1954. A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union 35 (6)*: 951-956.

Wood PJ, Armitage PD 1997. Biological effects of fine sediment in the lotic environment. *Environmental Management 21 (2)*: 203-217.



Section 6 Appendices

6.1 Survey of regional council objectives for sediment monitoring

A survey of regional councils was conducted in October 2009 to review the current state of sediment monitoring in New Zealand and to determine the key in-stream values recognised as being affected by in-stream fine sediment. This process provided an opportunity to identify the range of data that may be available to assist in guideline development as well as identify the resource capacity of regional councils to trial a range of sediment assessment methods during summer sampling in 2010.

A summary of responses from the telephone-based survey involving sixteen regional council and unitary authority representatives is presented here.

Question one: Does your Council currently use any tools/protocols to assess in-stream sedimentation? If so, what?

For example: Wolman pebble count, visual assessment of particle size, fine sediment cover, Quorer, sediment traps.

Method	Data	When	Number of councils
Wolman pebble count	Quantitative	SOE [Consent]	2 [1]
Resuspendable solids	Qualitative	SOE	2
Substrate stability	Qualitative	SOE	2
Embeddedness	Qualitative	SOE	5
% substrate size	Qualitative	SOE	8
% substrate size	Quantitative	SOE	1
% sediment cover	Qualitative	SOE	4
Quorer	Quantitative	SOE [Consent]	1 [2]

Question two: Does your Council currently use any tools/protocols to assess in-stream sedimentation potential? If so, what?

For example: turbidity, total suspended solids, water clarity.

Method	Data	When	Number of councils
Turbidity	Quantitative	Monthly-Quarterly	14
Continuous turbidity	Quantitative	Continuous	3
Total suspended solids	Quantitative	Monthly-Quarterly	13
Black disc clarity	Quantitative	Monthly-Quarterly	12
Clarity tube	Quantitative	Monthly-Quarterly	1

Question three: What do you consider to be the in-stream values that are most significantly affected by sedimentation in your region?

For example: biodiversity, invertebrate community composition, fish spawning, mahinga kai, swimming appeal, loss of interstitial space and/or groundwater connectivity, river function, fish habitat, aesthetic values.

Value	Number of councils
Invertebrate community	15
Native fish spawning	14
Biodiversity	13
Trout spawning	13
Swimming/Aesthetic	10
Fish habitat	9
Mahinga kai	5
Interstitial space	4
Groundwater connectivity	4
Phosphorus levels	2
Endemic species	2
River function	2
Habitat integrity	2
E.coli	2

Question four: Does your Council have any data available for the comparison of sedimentation metrics to measures of in-stream values? If so, what?

For example: State of the Environment data that includes both biological data, such as periphyton, invertebrates, or fish data, as well as sediment data.

For example: habitat surveys that include sediment data, such as percent fine sediment cover, that could be examined in relation to spatial land-use data.

For example: survey data that includes cultural or social measures, such as trout or koura information, as well as sediment data.

Sediment data	Biota	Number of sites
Wolman pebble count	Invertebrates	12+66
Quorer	Invertebrates	12
Qualitative resuspendable solids	Invertebrates	56
Qualitative resuspendable solids	Periphyton	56+40
Qualitative visual assessment	Invertebrates	70+28+56+35+100+120+100
Qualitative visual assessment	Periphyton	28+56+35
Qualitative visual assessment	Fish	56+200
Quantitative visual assessment	Invertebrates	8+43
Qualitative embeddedness	Invertebrates	70+56+35+40+50+120
Wolman/Quorer	Koura	70
Wolman/Quorer	Fish	70

Question five: Does your Council have the time and resources available to include a limited number of sedimentation protocols in 2010 SOE monitoring to provide data to aid in the development of guidelines for in-stream sediment values?

This may involve as little as 15 minutes per site or up to 3 hours per site depending on resource availability. Summer students or volunteers could potentially fill this role!

Approach	Number of councils
SHAPS P2	4
Rapid/a few sites	6
Wolman	2
Quorer, % sediment, rapid	2
Nothing	2

6.2 Survey of opinion on acceptable levels of sediment for amenity values

Two versions of a tri-fold survey were handed to participants of a sediment workshop at the New Zealand Freshwater Sciences Society annual conference (Christchurch, November 2011). The versions differed in the order in which photos were shown in subsequent questions; one from low to high levels of sediment, and the other in reverse. The survey contained two questions that required respondents to consider photos of in-stream sediment and respond with good/bad or yes/no:

1. Focussing on the level of fine sediment, how do you feel (gut feeling) about this stream? (Figure 1)
2. In your opinion, is this level of fine sediment acceptable for swimming? (Figure 2)

Of the 48 respondents, 62% were male; the average age was 39 years (range 24-65 yrs) with an average number of 13 years (range 1-40 yrs) of professional experience in freshwater.

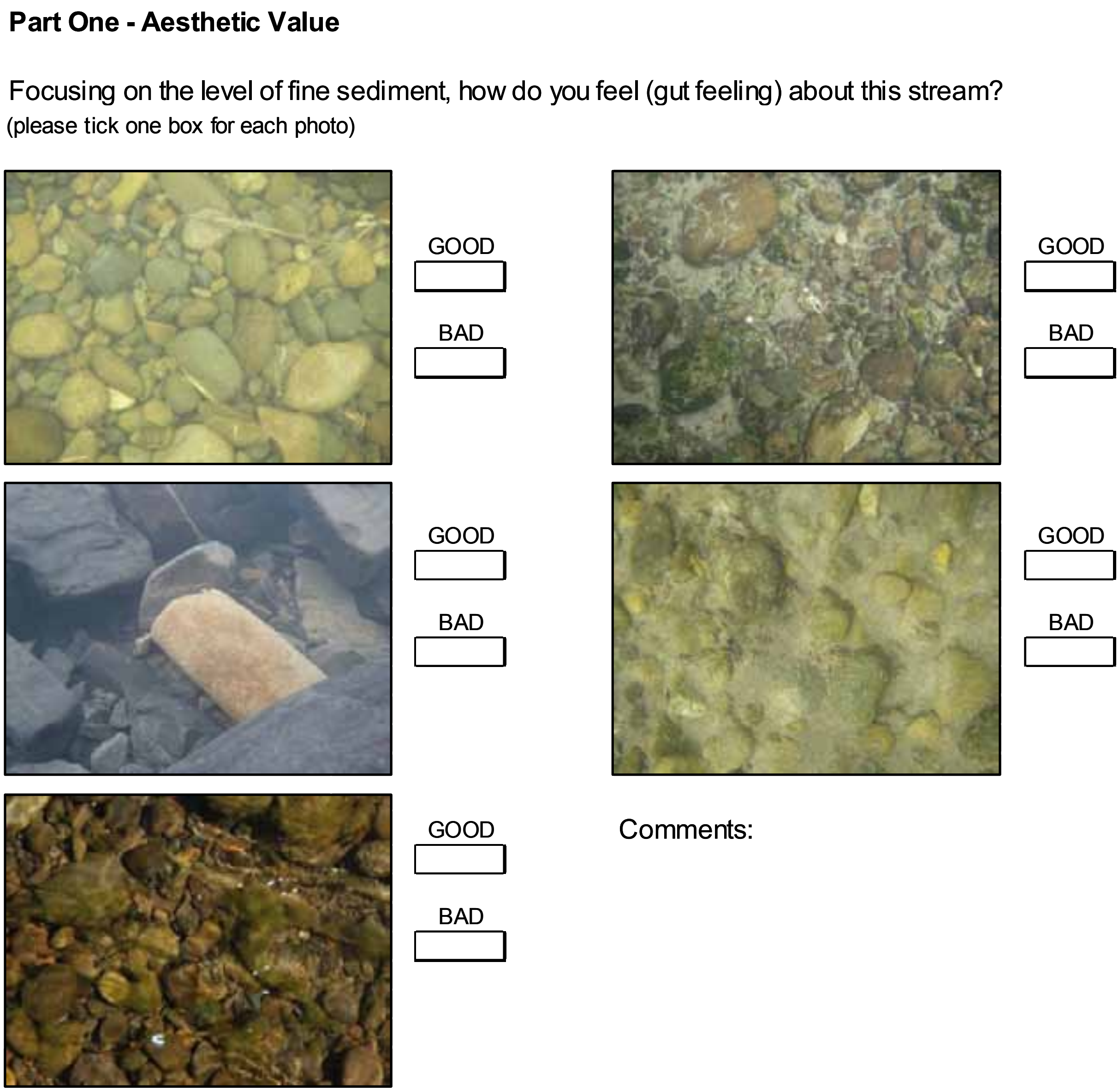


Figure 1. Question one in the survey of amenity value.

Part Two - Swimming Value

In your opinion, is this level of suspended sediment acceptable for swimming?
(please tick one box for each photo)

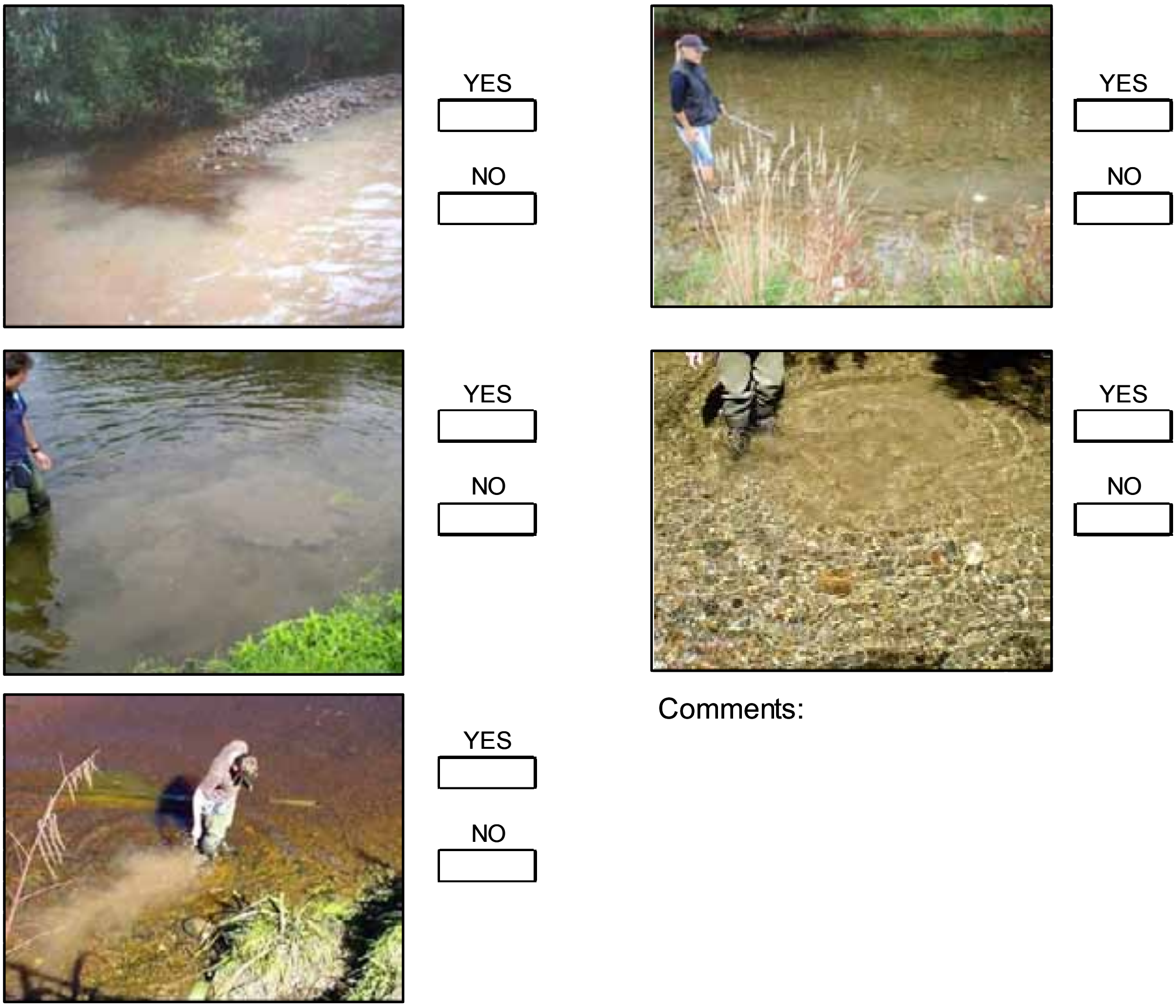


Figure 2. Question two in the survey of amenity value.

6.3 Details of the boosted regression tree model used to predict variation in fine sediment cover[6]

Source data

Sediment data used in model development was sourced from the Freshwater Fisheries database (http://www.niwa.co.nz/our-services/databases/freshwater-fish-database). The sediment response variable was calculated from a bankside estimate of the relative proportion of substrate size classes. Environmental variables were sourced from the FENZ database and included segment and catchment

[6] This research was conducted by Joanne Clapcott and Eric Goodwin (Cawthron Institute) as part of a Ministry of Science and Innovation funded project on Cumulative Effects (C01X1005)

scale descriptors of land use, climate, geology, morphology and topography as described in Leathwick *et al*. (2011). Variables were chosen for their likely linkage with sediment delivery and retention in stream (Table 1).

Table 1 Environmental variables used in the development of a predictive model of fine sediment cover.

Environmental variable	Description
Vegetation cover *(A_WT_Natco)*	Percentage of native vegetation cover in the catchment 65 (0, 100)
LogN	Stream nitrogen concentration, mg L^{-1}, log-transformed
Impervious cover *(A_WT_Imper)*	Percentage of impervious cover in the catchment
SegFlow	Mean annual flow (m^3 s^{-1})
SegLowFlow	Mean annual 7-day low flow (m^3 s^{-1})), fourth-root transformed
SegFlowStability	Annual low flow/annual mean flow (ratio)
SegJanAirT	Mean summer air temperature (°C)
SegMinTNorm	Mean winter air temperature (°C), normalised with respect to SegSumT
SegShade	Riparian shade (proportional)
SegSlopeSQ	Segment slope (°) square-root transformed
USRainDays	Days/year with rainfall in the catchment >25 mm
USAvgTNorm	Average air temperature (°C) in the catchment, normalised with respect to SegSumT
USAvgSlope	Average slope in the catchment (°)
USCalcium	Average calcium concentration of rocks in the catchment, 1 = very low to 4 = very high
USHardness	Average hardness of rocks in the catchment, 1 = very low to 5 = very high
USPhosphorus	Average phosphorus concentration of rocks in the catchment, 1 = very low to 5 = very high
USPeat	Area of peat in upstream catchment (proportional)
USLake	Area of lake in upstream catchment (proportional)
USGlacier	Area of glacier in upstream catchment (proportional)

Data preparation

1. From the Freshwater Fisheries database Mud and Silt were summed in a new metric, FINES, ranging from 0-100%.
2. Data entries from lakes, ponds, lagoons, swamps, tarns, estuaries, reservoirs, dams, deltas, wetlands and oxbows were systematically deleted. The rationale for deleting non-flowing habitats was that the fine sediment distribution would be driven by a relationship between hydrodynamics and slope different to that in flowing waters. Many deleted entries had 100% FINES.
3. All data collected from and post 1990 was collated. The rationale was twofold; data prior to this time may not reflect the contemporary cover of in-stream sediment, and environmental data available for predictive modelling is compiled from 1996-2000 satellite data.
4. An investigation of the spatial distribution of resulting entries showed an obvious gap in representation of the Fiordland region. A further spatial analyses revealed only 64/100 FENZ classes were represented by post1990 data opposed to 68/100 FENZ classes in the complete dataset. Three of the four additional FENZ classes were present in pre1990 Fiordland data. It was determined unlikely that land-use had changed in that region pre and post 1990 and therefore all data entries from flowing waters with Easting less than 2080000 (*i.e.*, Fiordland) were re-added to the dataset.
5. Finally, data entries with missing predictors (*e.g.*, A_WT_NATCO = NA) were removed and the FINES variable was arc-sine transformed to improve normality. Final dataset N = 10026.

Modelling contemporary sediment cover

Several boosted regression tree models were explored including:

1. The use of all 19 predictor variables.
2. The substitution of geological variables (USPeat and USGlacier) with River Environment Classification (REC) variables Geology and Source of Flow.
3. A reduced set of the top 12 explanatory variables following a back step model selection procedure (simplify script).

There was no significant reduction in predictive power between a 19-predictor model and a 12-predictor model. Furthermore, the back step procedure suggested at least another three variables could be left out, but a preference was for increased explanatory power rather than the most parsimonious model (*i.e.*, the 12-predictor model). None of the geological descriptors (FENZ or REC) were significant contributors to the models.

After deciding on model parameters, a boosted regression tree model was then fitted with a learning rate of 0.05 and a tree complexity of five and using Gaussian model error. The final model had a cross-validation error of 0.67 (se = 0.005) and explained 45% of the variance in % fine sediment cover (n = 10,026), which suggest good model performance. Fitted functions for the 12 most important explanatory variables are shown in Figure 1. These fitted functions were used to predict fine sediment cover in each NZREACH stream segment in New Zealand.

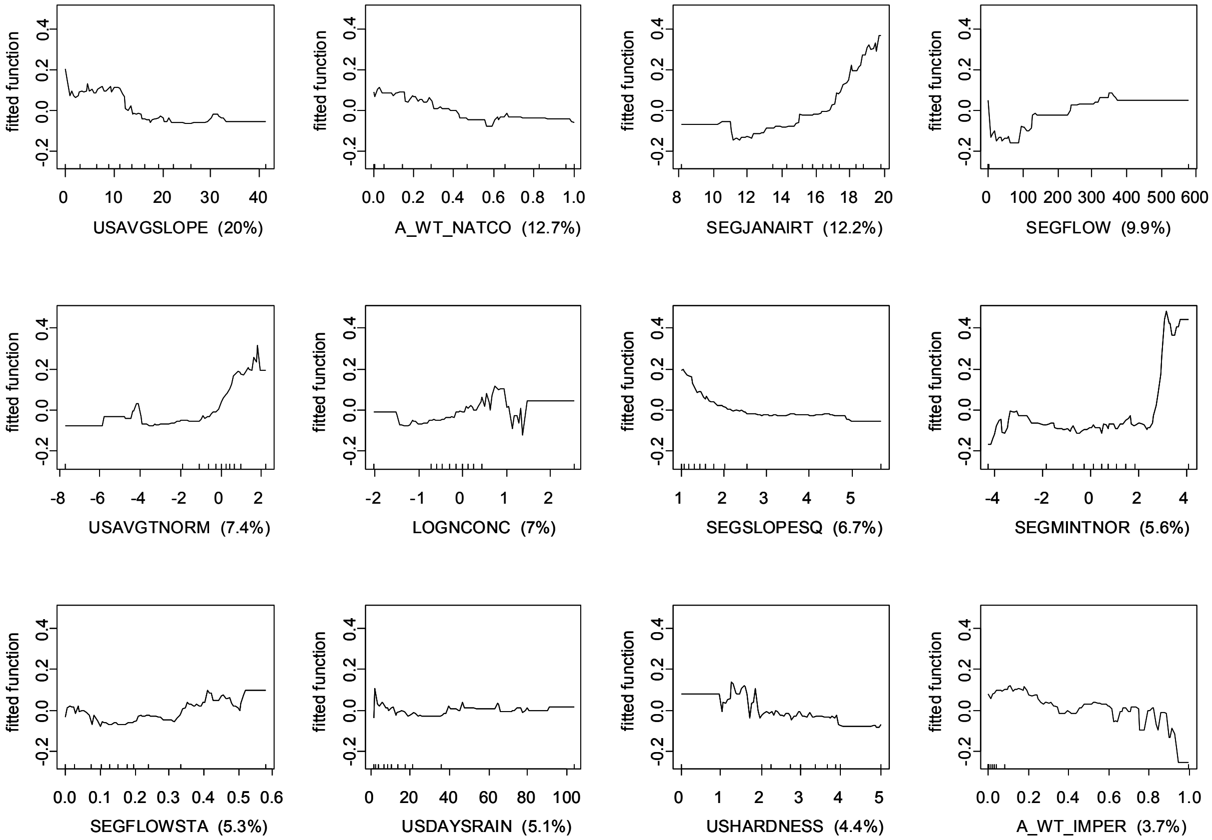


Figure 1 Fitted functions for the 12 most explanatory variables explaining deviance in percent sediment cover at the reach scale.

Modelling 'reference' sediment cover

Land-use predictors were the 2nd, 6th and 12th most explanatory variables in the sediment cover model (Figure 1). The fitted functions for the relationship between sediment cover and land-use predictors were as expected, with increasing fine sediment in response to decreasing native vegetation cover and impervious cover, and increasing sediment in response to increasing land-use intensity, *i.e.*, increasing predicted nitrogen levels (within 95% of the data distribution). As such a 3-predictor model was developed where the responses were directionally constrained and the output from this 3-predictor model was used as a fixed offset in a model to predict sediment cover in the absence of land use.

The 3-predictor model was fitted using a learning rate of 0.05 and a tree complexity of five. The fitted model used 750 trees and had a cross-validation error of 0.51 and explained 26% (se = 0.008) of the variance in % fine sediment cover. The constrained fitted functions are shown in Figure 2.

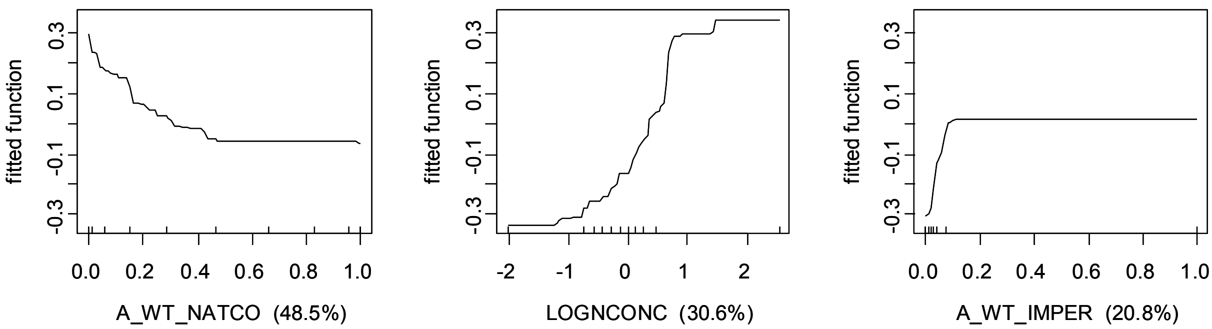


Figure 2. Fitted functions for percent sediment cover at the reach scale in response to three land-use variables (relative explanatory deviances are in parentheses).

The 3-predictor model output was used as a fixed offset in a new model with the remaining nine environmental variables used to explore variation in sediment cover in the absence of land use, *i.e.*, in reference condition. This offset model was fitted using a learning rate of 0.05 and a tree complexity of five. The fitted model used 1550 trees and had a cross-validation error of 0.64 (se = 0.004) and explained 42% of the variance in % fine sediment cover. The low decrease in model performance compared to the former inclusive 12-predictor model provides confidence in fixed model output. Fitted functions from the offset model were used to predict fine sediment cover in each NZREACH stream segment in New Zealand based solely on environmental variability, *i.e.*, expected 'reference' values in the absence of land use.

6.4 Volumetric Quorer method

This method is termed Suspendible Benthic Sediment Volume (SBSV). This method is the same as the standard Quorer method (http://www.niwa.co.nz/our-science/freshwater/tools/estimating-deposited-fine-sediment) except that the level of fine suspendible sediment is measured by settling overnight in a conical glass rather than gravimetrically (as SIS = dry mass minus ash-free dry mass) per unit area of streambed. Adapted champagne flutes (as in this example) can be used if standardised Imhoff cones are unavailable.

Collected Quorer samples are transferred into Imhoff cones or champagne flutes (c. 170 ml volume) and left to settle overnight. Volumes of acrylic flutes can be marked by scoring the outside of each flute to graduate the levels at appropriate volumes (*e.g.*, 1, 2.5, 5, 7.5, 10, 15, 20, 25, 30, 40, 60, 80, 100, 120, 140 ml) using a craft knife and label using a water-proof pen (Figure 1).

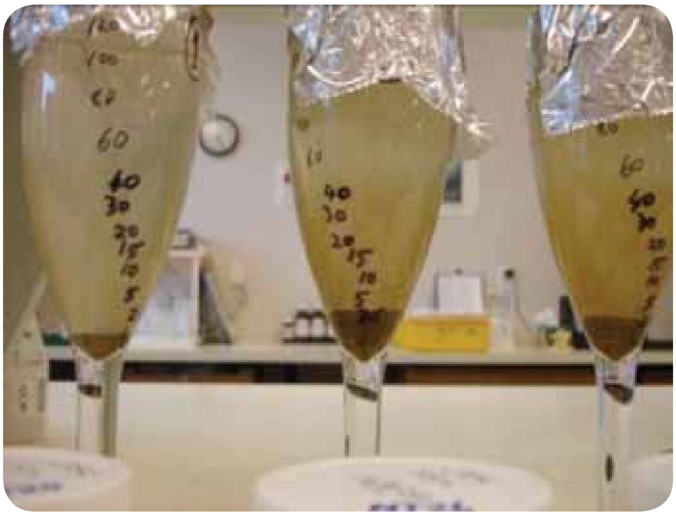


Figure 1. Graduated acrylic champagne flutes used to measure settled volume of Quorer method samples.

In initial trials using this method it was possible to distinguish between the volumes of coarse particles that settled in a layer below fine material (Figure 1) and between organic sediment that settled above the inorganic sediment. It will be useful to evaluate whether this is a practicable and meaningful measure in future trials.

Initial trials indicate that acrylic flutes are preferable to glass ones because they are physically robust and are easily etched allowing for individual calibration. Use of these relatively inexpensive settling vessels enables lots of replication and many samples to be processed simultaneously (Figure 2).

Figure 2. Reading settled volumes on multiple samples from contrasting sites from Whatawhata Research Centre streams.

The settled volume of fine sediment after overnight settling and the total sample volume are recorded and both used to calculate SBSV:

Areal SBSV (litres/m^2 of streambed)

= 1000 x (settled sediment volume (ml) / total sample volume (ml)) x average water depth in the Quorer sampler (m).

Volumetric SBSV (litres/m^3 of streambed)

= Areal SBSV / (average stirred depth – average water depth).

Example calculations for SBSV:

Attribute	Data or calculated value
Settled sediment volume (ml)	8
Total sample volume (ml)	140
Average water depth (m)	0.1
Average stirred depth (m)	0.15
Areal SBSV (litres /m^2 streambed)	5.7
Volumetric SBSV (litres /m^3 bed sediment)	114.3

Deposited fine sediment occurs naturally in the beds of rivers and streams, but human activities can accelerate sedimentation. Excess sediment directly affects the health of a waterway, decreasing its mauri or life-supporting properties. The protocols and guidelines presented in this document provide robust and nationally consistent tools to assess the effects of deposited sediment on the in-stream values of New Zealand's waterways.

ISBN: 978-0-473-20105-0 (Print)
ISBN: 978-0-473-20106-7 (Online)