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Taihoro Nukurangi

Monitoring fine sediment loads in Northland rivers and streams

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Authors/Contributors:
Lucy McKergow
Andrew Hughes

For any information regarding this report please contact:

Andrew Hughes
Land and Water Scientist
Aquatic Pollution
+64-7-856 1794
a.hughes@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 7026
Fax +64-7-856 0151

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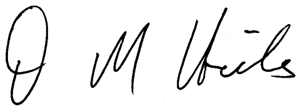

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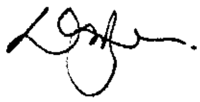

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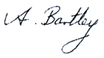

Executive summary

Sediment is a major contaminant of Northland rivers and at present the Northland Regional Council undertakes ad hoc sediment sampling. The Council would like to develop and implement a robust programme for monitoring sediment in rivers and streams and sought advice on monitoring programme requirements and best practice methods. The monitoring programme's key objectives, as identified by the Council, include (1) quantification of the sediment load and (2) identification of the sediment sources in rivers and streams.

For Objective (1) emphasis must be on collecting storm suspended sediment concentration (SSC) samples (manually, autosamples &/or siphon samplers). We have identified three possible levels of monitoring that could be adopted across sites. The most basic level (Level 1) involves sediment gaugings and/or grab sampling during flood and low flow conditions at existing flow sites. These data would then be used to construct discharge sediment rating curves. Level 2 uses automated storm suspended sediment sampling at flow sites to develop discharge-sediment rating curves. Level 3 monitoring adds turbidity as a sediment surrogate to provide an extended and detailed time series of SSC and suspended sediment loads (SSL).

Our recommendations are:

1. Level 1 monitoring (flood sediment gaugings) should be adopted at both pristine and impacted sites for trend analysis purposes and load estimation. This storm focused, labour intensive approach must target medium-high flows and include rising and falling limb samples and cover a range of seasons. Continuous flow measurement is a co-requisite at all sites.

2. Level 2 monitoring (autosamplers) should be adopted at: (1) smaller catchments where SSC changes rapidly, (2) sites where event loads are required in a short time frame (1-2 years), (3) remote sites and (4) small catchment studies requiring detailed results in a short time period (e.g., evaluating SS best management practices). Telemetry should be used to ensure that samples are retrieved shortly after collection.

3. Level 3 monitoring (turbidity) should be adopted when a high frequency time series of SSC and SSL is required. Laboratory turbidity should be determined on all SSC samples and telemetry should be used to assist with maintaining a high quality turbidity record by highlighting maintenance requirements promptly.

4. Samples should be analysed for SSC using the wet sieve and filtration methods (ASTM 2002b) rather than total suspended solids (TSS; APHA 1995) to provide basic particle size data (proportions of sand and silt/clay).

5. Suitable software for data processing and analysis should be identified before monitoring commences.

For Objective (2), sediment source identification, we have focused on two basic approaches: sediment fingerprinting and sediment hysteresis. While, alternative methods, such as mapping or aerial photograph analysis, can assist with identifying sediment sources, they do

not address the delivery of sediment into and through the river system to the catchment outlet. Both sediment fingerprinting and sediment hysteresis analysis incorporate the mobilisation of sediment sources and delivery to catchment outlet. Sediment hysteresis analysis requires Level 2 or preferably Level 3 monitoring over a range of event sizes and seasons. Sediment fingerprinting, in contrast, can be achieved without the need for discharge or long-term sediment monitoring, however specialist skills are required for this approach. Sediment fingerprinting involves determining the relative importance of sediment, in terms of source location and/or erosion process, by comparing the properties of suspended sediment samples to samples taken from identified source areas for catchments without existing records. It may be the most valuable and cost-effective approach, particularly in un-monitored catchments.

1 Introduction

Sediment is a major contaminant of Northland rivers. At present the Northland Regional Council (NRC) undertakes ad hoc sediment sampling in rivers and streams around the region. Suspended solids are currently monitored at five Regional Water Quality Monitoring Network (RWQMN) rivers on a monthly basis and at two catchment project sites. The Council would like to develop and implement a robust programme for monitoring sediment in rivers and streams.

The Council has requested advice on best-practice for sediment sampling in rivers and streams and options on how to apply this in Northland. The advice needs to cover, but is not limited to:

- monitoring programme requirements to determine trends, loads and sources of sediment in rivers and streams (includes both quantity and texture), and
- best-practice methods for monitoring fine sediment in rivers and streams in Northland (including parameters, equipment, procedures, frequency, duration, benefits, limitations etc.).

Hicks and Gomez (2002) stress the importance of three steps when developing a sediment transport monitoring program: 1) define the purpose of the measurements; 2) determine the measurement approach; and 3) determine the appropriate tools to use in measuring sediment transport. The monitoring programme objectives identified by the Council include:

1. identification of the sources of sediment in rivers/streams
2. estimate/calculate the sediment load in rivers and streams, and
3. have robust and defensible data to support management and decision making such as:
   - prioritising catchments for monitoring/management
   - land management (fencing, re-vegetation, soil/erosion control, best-practice land-use/management, etc.)
   - consent conditions (sediment control mechanisms, discharge rules, best-practice, etc.)
   - water quality (WQ) targets for specific rivers/catchments
   - determine trends in sediment concentration and loads in rivers over time
   - evaluate effectiveness of any/all actions on sediment load in rivers
   - differentiate between “background” or natural sediment loads and those resulting from different land management practices.

Suspended sediment (SS) consists of both mineral and organic particles. Suspended sediment transported from land to water may include clay (<4 µm), silt (4-62 µm), and sand (63 µm-2 mm)[1]. Suspended sediment may also include aggregated particles, including aggregates (dominated by mineral particles) and flocs (organic and inorganic particles and pore water, (Droppo 2001). The conventional operational definition of SS is that it only includes particles that are > 0.7 µm and retained on a filter. Particles may exist below this 0.7 µm boundary and particles in this range are frequently referred to as colloids (1 nm-1 µm; (Gimbert et al. 2007).

1.1 Monitoring programme design

In order to meet the objectives a range of experimental designs are required, but the range of recommended techniques is limited. The information requirements for each management decision have been identified in Table 1. For example, to differentiate between natural sediment loads and those resulting from different land uses, several approaches could be used. One approach might be sediment fingerprinting to assess the contributions from various land uses combined with analysis of sediment cores to provide data on natural erosion rates. A longer term and possibly more costly approach, includes quantification of sediment loads. This would require monitoring sites with un-impacted (e.g., native forest catchment) and impacted (e.g., pastoral farming or forestry) catchments.

Table 1: Suitable approaches meeting monitoring programme objectives.

Objective/Purpose	Approaches
Objective 1: Sediment source identification.	- Sediment source mapping (field, aerial, satellite imagery) of actual sediment sources. - Erosion measurements (e.g., plot, surveying). - Load monitoring. - Sediment hysteresis analysis. - Sediment fingerprinting.
Objective 2: Load quantification.	- Monitoring of storm SSC, discharge and possibly turbidity.
Objective 3: Robust data to support management decisions such as:	
Prioritising catchments for monitoring/management.	- Basic monitoring of concentration.
Determining consent conditions (sediment control mechanisms, discharge rules, best-practice etc.).	- Real time monitoring.
Determine trends in sediment concentrations and loads in rivers over time.	- Monitoring concentration. - Monitoring load. - For historical records consider assessing floodplain/estuary accumulation rates.
Differentiate between “background” or natural sediment loads and those resulting from different land management practices.	- Monitoring “pristine” catchments and developed catchments (e.g., pastoral farming or forestry land use). - Sediment fingerprinting including historical (e.g., floodplain cores) and current SS.

[1] Note that soil scientists and some geomorphologists define the clay-silt boundary at 2 µm.

Objective/Purpose	Approaches
Land management (fencing, re-vegetation, soil/erosion control, best-practice land-use/management etc.).	- Monitoring using either a before and after approach or paired catchments. Preferably smaller catchments in order to detect a signal.
WQ targets for specific rivers/catchments.	- Concentration and/or load data from monitoring.
Evaluate effectiveness of any/all actions on sediment load in rivers.	- Monitoring at a scale suitable to detect changes as a result of actions (typically smaller catchments).

2. Monitoring for load quantification and trend detection analysis

The majority of sediment transport occurs during storm runoff events, therefore storm sampling must be the focus of any monitoring programme that aims to quantify sediment loads. The NRC sediment monitoring programme must be able to provide data suitable for both load quantification and trend analysis. Any monitoring programme also requires a quality assurance/quality control programme, but this is beyond the scope of this report.

Changes in sediment trends can be detected by examining changes in suspended sediment concentration (SSC) or suspended sediment load (SSL) over time. Concentrations and loads may alter by (1) changes in the mean concentration or load, (2) changing variability in concentration or load, (3) decreasing the concentration or load maxima or minima, and (4) changes in the frequency of high concentrations or loads (Viaud et al. 2004). For SSC trend analysis paired (one without change and one with change) sites are recommended. To optimise the accuracy of results it may require some compromise in the sampling and analytical techniques which enables an extension of the length of the monitoring to produce a more representative data set (Olive & Reiger 1992). A change in SSL could be detected by a change in a discharge sediment rating curve, or through detailed analysis of an SSL time series For trend analysis it is important that there are no gaps in the data set, that analysis methods not change, that the hydrological control is stable, and a causal link between the sediment concentration and catchment activities can be made (ASTM 2002a).

Estimation of sediment loads transported from catchments by rivers fundamentally involves quantifying the total load of sediment transported by rivers past a point, usually at the bottom of the catchment, over a fixed time period. The common approach to estimating total SSL, however, involves infrequent estimates of SSC and frequent estimates of discharge. Numerous techniques have been developed to estimate mass loads (see Cohn 1995) and the most commonly adopted technique is regression of a continuous variable (traditionally flow; more recently turbidity) with SSC. Additional explanatory variables, such as season or rising/falling stage hysteresis can also be added (Cohn 1995). To develop a discharge-sediment rating curve a power model is frequently used, with coefficients fitted using least squares linear regression on logarithmic transformed variables. While biases arise when the model results computed in log space are transformed to real units, techniques exist to overcome this limitation (see Cohn 1995). In contrast a simple linear regression model relating turbidity to SSC is often sufficient for reliable computations (Anderson et al. 2010). In March 2009, the USGS endorsed turbidity for use in suspended sediment monitoring programmes. This is the first sediment-surrogate technology to receive USGS endorsement (Anderson et al. 2010). When a turbidity-SSC model is adequate, the regression computed SSC is more reliable and reproducible than discharge-sediment rating curves (Rasmussen et al. 2009).

An adequate regression dataset must cover the observed range of SSC and discharge/ turbidity values for the site. For example, a regression model developed from 15 samples more or less evenly distributed across the seasons and range of discharge/turbidity at a site might be more representative than a 50-sample dataset which covers a limited range or seasons (Rasmussen et al. 2009). Monitoring efforts should therefore be focused on medium-high flows. It is therefore likely that it will take a period of two to five years to capture a good dataset for developing a sediment rating curve.

An alternative method for predicting a continuous SSC time series is the event-load rating method (Hicks & Gomez 2002). This approach is useful when there is greater interest in SS loads during individual runoff events than in the long-term average. A relationship is developed between event sediment load and some index of event magnitude, such as peak flow. Care is required in modelling the event-yield versus peak flow relationship and in extrapolating it beyond the range of the data. One advantage of this approach is that it can be compiled over 1-2 years, with intensive autosampling of individual events (Hicks & Gomez 2002).

Many different methods can be used to collect SSC samples from streams and rivers. Each technique has strict guidelines for its use and benefits and limitations. These are summarised in Table 2.

Table 2: Common sample types.

Term	Definition	Benefits	Limitations	Best practice guides
Isokinetic samplers	Sampling at a rate such that the velocity and direction of a liquid entering the sampling nozzle is the same as that of the liquid in the sample stream.			
Depth integrated sample.	Designed to collect samples continuously while the sampler travels at a uniform rate from surface to the bed and back again (e.g., DH49 for cable and reel, DH48 for wading).	- Can account for velocity or stratification induced differences in water quality.		Hicks & Fenwick 1994; U.S. Geological Survey 2006.
Non-isokinetic samplers				
Grab sample.	Discrete sample, usually taken by hand by (1) dipping a narrow-mouthed bottle into a water body, or (2) using either the DH-81 or D-95.	- When low flow conditions render use of a depth integrated sampler impractical.		U.S. Geological Survey 2006.
Auto samples.	Sample collected from a point by an automatic sampler.	- Useful at remote sites. - Sampling of floods when discharge is rapidly changing. - Large number of samples are needed from several locations within a relatively short time.	- Collects a sample at a fixed horizontal and vertical point. - Intakes can become buried or overgrown with algae. - Limited to 24 bottles. - Limited pumping head, typically <7 m.	Edwards and Glysson, 1998; U.S. Geological Survey 2006.
Stage height or siphon sample.	Collect a sample representative of near-surface water quality during rising stages.	- Simple, inexpensive to make and operate. - Useful backup to autosamplers.	- Samples are collected near the water surface at one point in the stream, usually near the bank, so adjustments may be needed to describe the vertical and horizontal distributions in water quality, especially if the stream transports large sand-size particles. - Uncertainty in sample timing (could be solved by addition of a Tinytag temperature logger or similar) - Cannot sample on falling limb of hydrograph unless US U77 design. - Sometimes the sediment content of the sample changes during subsequent submergence.	Edwards and Glysson, 1998.

Several levels of monitoring could be adopted within the monitoring programme to maximise the number of sites while containing costs:

1. flood and monthly sampling
2. automatic sampling of storm events
3. turbidity as a surrogate.

Level 1 monitoring could be adopted as the basic platform for trend analysis and load estimation at any existing or new hydrometric site. Levels 2 and 3 could be adopted at selected sites, possibly on a rotational basis.

2.1 Level 1: Flood and monthly sampling

Level 1, the most basic monitoring strategy, would focus on sampling during floods, particularly sediment gaugings. The purpose of a SS gauging is to measure the discharge-weighted cross-sectionally averaged SSC, and this is typically done by using depth-integrated samplers to sample sub-sections. Sediment gaugings would be required for both rising and falling limbs of hydrographs, over a wide range of flows, and in sufficient numbers to develop quality rating curves. The rapid development of a discharge-SS rating curve would require repeated and targeted storm sampling to provide an adequate dataset. Grab samples could also be collected during storm events. However these would not provide the mean SSC and therefore could be of limited use in rivers where mixing is incomplete and there are variations in the SSC through the cross-section. Monthly grab sampling would provide sufficient data to determine trends in low flow conditions (which may be useful for determining instream ecosystem effects). Such sampling, however is insufficient for load estimation due to the under-representation of storm events.

The NIWA Suspended Sediment Manual (Hicks & Fenwick 1994) and the revised USGS Field Manual (U.S. Geological Survey 2006) outline the field procedures in detail.

Table 3: Basic sediment gauging sampling equipment and associated on-going costs. .

Equipment required	Indicative cost[†]
Depth integrated samplers + bottles	
e.g., DH48 wading	~$300 US
DH59 hand reel	~$800 US
Bottles	~$50 US per crate of 24 glass bottles
Ongoing costs	
Field work, sample analysis, data processing	

[†] Priced from Rickly Hydrological, Columbus, Ohio. More economical samplers may be available.

2.2 Level 2: Automated event sampling

In small streams, flow and sediment concentrations often change quickly in response to rainfall, and field staff may not be able to reach streams quickly enough to manually sample. To overcome this, Level 2 or automated sampling of storms should be adopted at selected sites. Autosamplers are most commonly triggered using stage thresholds (float switch or logger) and then time, stage or flow paced. Time pacing is simple, with no consideration of flow (and therefore no requirement to directly link the sampler and flow instrumentation) but may fail to capture the variability in concentration, particularly in small catchments which respond quickly to rainfall. Flow proportional samples are collected at given predetermined flow volume intervals (e.g., when each 200 m^3 has passed the site), and sampling frequency varies with flow rate and ensures that more samples are collected about event peaks, when SSCs tend to vary rapidly. This requires that the sampler is controlled by a logger recording and processing flow data and is strongly dependent on the reliability and stability of stage-discharge rating curves.

Composite sampling (multiple samples into one bottle) can be used to increase the number of samples collected over an event, reducing the analytical costs and providing a reliable event sediment load. This approach is best matched with event discharge-SSL rating curves rather than instantaneous discharge-SSC rating curves. The event discharge-SSL rating method allows a relationship between peak event discharge and event sediment load to be determined. This relationship can then be used to estimate loads of future events and possibly previous events if there is an adequate flow record for a site and there has been no significant change in catchment characteristics (e.g., major landuse change). The instantaneous discharge-SSC rating curve method is the "traditional" (and widely accepted) technique whereby a relationship is determined between instantaneous measurements of SSC and discharge. This requires obtaining many individual samples over a range of flow conditions. Although more time consuming and analytically more expensive, the instantaneous discharge-SSC rating curve method has the advantage of being based on actual raw data. In contrast the peak discharge-SSL rating curve method relies on transformed data (loads calculated from composited samples). Accordingly, if the stage-discharge rating (programmed into the logger and used to trigger the sampler with flow proportional sampling) was later found to be incorrect for a site the compositing would also be incorrect and the event concentration may be incorrect. The event concentration could, however, be recalculated using the corrected flow values. Although timing of samples may not be optimal, reasonable estimates of load would be provided.

Correct installation, strict maintenance and correct operation of the autosamplers is crucial to ensure collection of reliable sediment load information. Collection of useful data requires intensive planning and quality assurance, including careful site selection, selection of the type and construction material of the sampler, a review of historical hydrologic information, and collection of an adequate number and types of quality-control samples (U.S. Geological Survey 2006). Best practices for autosampler use are briefly summarised in Table 4 (for more details refer to Edwards & Glysson 1998).

Automatic samplers may have either peristaltic or vacuum pumps. Different brands have varying reliabilities. Our current recommendation is to use ISCO (3700 or 6712 with on-board logger) peristaltic pump samplers as they are robust, reliable, simple to programme and interrogate, and are less likely to get blocked. However, the latest generation of vacuum or peristaltic Manning sampler may be an improvement on previous models. Previous Manning vacuum sampler models (e.g., GLi and older models) had unreliable and non-waterproof electronics, and were more difficult to programme and interrogate than the ISCO 3700. Autosamplers cost in the order of $7000 depending on the model, exchange rates and number of samplers ordered at the same time. We recommend that at least four bottle sets are purchased for each sampler.

We recommend that any site with autosamplers is telemetered to reduce operational costs and to ensure that samples are collected from the field promptly.

Table 4: Autosampler operation best practice. (Edwards & Glysson 1998).

	Best practice
Training	Staff training in installing, maintaining and programming autosamplers.
Intake placement	Ideally the intake should be at a point where SSC approximates the mean SSC across the range of flows. Some guidelines (Edwards and Glysson, 1999) include: (1) normal and horizontal to flow (avoid intake facing upstream, up or down). If sand is an important component then downstream facing should be adopted so the intake does not become blocked (2) the cross section should be stable (3) in a zone of high velocity and turbulence (and therefore well mixed) (4) at a depth that avoids burial by bed load or dune migration but sufficient to ensure submergence at all times.
Bottles	Reusable bottles are suitable for SSC determination. They must be cleaned prior to use to remove any residue that remains after the analytical process. Sample bottles are cleaned by soaking in a water bath with a laboratory detergent, followed by a hot, tap-water rinse in an automatic dishwasher. Washed bottles are turned upside down in a wire carrying case to air dry. After drying, the bottles are turned upright and capped, and are then ready for field use. Before capping, the bottles must be inspected for excessive residue or damage. Bottles with visible residue or staining that requires additional cleaning are rinsed with a 10-percent hydrochloric acid solution. After acid rinsing, the bottles are rewashed and rinsed with tap water. Disposable bags (e.g., ISCO ProPak) are not recommended as it can be difficult to remove all sediment from the bag.
Sample volumes	Sample volumes should be at least 350 ml. Larger volumes reduce variability but may add to the laboratory costs.
Sample storage & preservation	For basic SSC determination there are no rules for sample turnaround. AS/NZS 5667 recommends 24 hours. Hicks and Fenwick (1994) suggest < 6 weeks for flood samples if there is no risk of algal growth. Samples should be stored in the dark and kept cool and sent to the laboratory at the earliest opportunity, particularly if there is a risk of algal growth.
Sample frequency	If flow records exist then sample intervals can be estimated to ensure that the sampler does not run out of bottles (autosamplers typically have 24-28 bottles) during a single event (unless it can be serviced mid-event). Without historical flow information an adaptive approach is required.
Manual sediment gaugings	Concurrent manual depth integrated and autosample collection should be used to check on representativeness of autosamples. Lewis and Eads (2009) suggest that with well-mixed streams, there is normally little or no bias in the point sample concentrations; but a bias model should be developed, the point samples should be corrected if a difference exists, and the correction should be stated in reports or publications. Lewis and Eads (2009) suggest that the autosampler and manual sample pairs should be distributed over the measured range of turbidities and twenty or more pairs may be needed to detect small biases in pumped samples.

Because of the high capital and maintenance costs associated with autosamplers, simpler alternatives have been developed to collect event samples (FISP 1961). Simple siphon samplers are inexpensive to build, operate, and maintain, so they are cost effective to use at a large number of sites. The USGS has two basic designs, a simple sampler that costs around ~$US 30 (which collects from the rising hydrograph limb only) and a more sophisticated design (US U73) that costs ~$US800 and can collect a sample on either the rising or falling limb of a hydrograph (plans are available from FISP). Both of these samplers would be simple to mass manufacture locally. Gracsyk et al. (2000) could not detect a statistical difference between SS samples collected by autosamplers and siphon samplers on three small catchments (< 25 km^2). We recommend that any autosampler monitoring site also has siphon samplers as a backup and to enable ongoing monitoring without autosamplers at sites where there is no statistical difference between the two methods of sample collection. Before single-stage samplers can be installed, some knowledge of the seasonal stage characteristics of the stream is needed so that an appropriate sequence of samples can be obtained for a given storm season and so that support structures are adequately designed for flood flows (U.S. Geological Survey 2006).

Table 5: Equipment requirements per site and ongoing costs. (Assuming site is an existing flow site and stage data can be fed to logger/computer in real time; indicative costs excl. GST).

Site equipment required	Indicative cost ($NZ unless otherwise indicated)
Autosampler (e.g., ISCO 3700 + 5 bottle sets + logger cable + strainer + intake tubing).	~$7000
Logger (if flow proportional sampling) with modem (e.g., Neon Metering Module).	~$2000
Set up/programming support.	~$1000
Secure sheds.	
Power supply (e.g., solar panel + connections).	~$500
Stage height samplers (US SS59A)†	~$US 30 each (could be produced locally for less).
Stage height sampler (US SS77) †	~$US 800 each (could be produced locally for less).
Ongoing costs	
Monthly site visits to maintain equipment.	1 hr + travel.
Daily auto downloads from sites via cellular modem.	(~$40/month) more for satellite telemetry.
Clearance of samplers following storms.	1 hr + travel.
Sample analysis.	$4000 (~$40/sample ASTM 3977 wet sieving & filtration), 100 samples per year).
Data collection, checking, recording.	
Data analysis.	Depends on software choices.

† Priced from Rickly Hydrological, Columbus, Ohio.

2.3 Level 3: Turbidity as a surrogate

If an extended and detailed time series of SSC and SSL are required then optical sensors are a practical and economical option. Turbidity is the most frequently used optical property and is a measure of the scattering of light within water. When a good turbidity-SSC relationship can be developed the computed SSC time series will have lower uncertainty than one derived from an SSC-discharge relationship (Rasmussen et al. 2009). A turbidity-SSC rating is only valid for a particular instrument type and range of suspended particle composition. A continuous electronic record of turbidity provides details about sediment transport that cannot be obtained manually and can greatly enhance our understanding of sediment dynamics (Kirchner et al. 2004). Short-duration, high-amplitude sediment pulses would not be reliably identified by fixed-interval or discharge-driven sampling schemes (even with automatic sampling) unless deployed at very high sampling frequencies (Lewis & Eads 2009). An additional advantage is that it may also be possible to identify the sources and timing of sediment more accurately. Turbidity time series may also be used to estimate time series of total nitrogen (Rasmussen et al. 2009), total phosphorus (Grayson et al. 1996) or *E. coli* (McKergow & Davies-Colley 2010; Davies-Colley et al. 2008). A disadvantage is that

SSC calculated from turbidity measured at a point may not be representative of the mean cross sectional SSC. However, with careful sampling this can be assessed. Just as discharge-based ratings can change with time, so can turbidity ratings, because suspended particle composition (e.g., the proportion of fine organic material or clay content) can change with time (Lewis & Eads 2009). The sensor's internal calibration may also drift.

An adequate model calibration dataset consists of an appropriate number of instantaneous SSC samples and concurrent turbidity and streamflow measurements, made over most of the observed range of hydrologic conditions for the period of record. The larger the variability in the relationship between turbidity and SSC at a site, the greater the need to collect more calibration data (Anderson et al. 2010).

Maintaining a high quality turbidity record can be challenging. Biofouling of the lens requires a mechanical wiper, water pumps or manual cleaning. For this reason a mechanical wiper or micro-jet water pump is mandatory to reduce operational costs associated with site visits. In addition, telemetry (radio, cell phone or satellite) allows frequent assessment of the data quality and is recommended to help maintain a high quality record. At high flows there is a risk that the instrument may over-range so careful selection of the turbidity range is required. We recommend an instrument that can measure over a range from 0 to at least 2000 nephelometric turbidity units (NTU). A guide to selecting an appropriate instrument is available in Anderson (2005). We typically use Greenspan TS100 (near infra-red, 880 nm, 90° detection angle) or D&A Instruments OBS3/3A (ne ar infra-red, 30±15° detection angle), calibrated to the range 0-2000 NTU.

Correct installation of a turbidity sensor must ensure: (1) the sensor is anchored or held in position or located so it is not subject to any movement during normal operations, (2) the sensor is protected from direct sunlight to avoid high temperature fluctuations, (3) the sensor is protected against high turbulence and possible debris loading during flow events and (4) ensure the minimum clearance around the optical head (sensor dependent) is met.

Once an adequate turbidity-SSC relationship has been developed for a site the sampling triggers may be modified to reduce analysis costs. For example, by controlling sampling using turbidity very accurate load estimation is possible with a moderate number of physical samples (Lewis 2003). The Turbidity Threshold Sampling method distributes sample collection over the range of rising and falling turbidity values and attempts to sample all significant turbidity episodes (Lewis 2003). Full procedures for this methodology are outlined in Lewis and Eads (2009) and many resources are available at http://www.fs.fed.us/psw/topics/water/tts/.

Laboratory turbidity should also be measured on all samples sent for SSC determination. All laboratory turbidity samples should be analysed on the same model instrument, as turbidity is instrument-dependent (Davies-Colley & Smith 2001). Laboratory turbidity can be useful for validating or reconstructing field turbidity measurements (e.g., when turbidity exceeded the field sensor's range). A relationship between laboratory turbidity and SSC can be established from a subset of samples collected at fixed time intervals, then used to estimate SSC for the remaining samples (Lewis & Eads 2009). To measure laboratory turbidity, a small volume of the sample must generally be extracted from field samples for placement in the turbidity meter. This is best done before analyzing samples for SSC, but the turbidity subsample must be rinsed back into the original container before SSC is determined. Therefore, it is important to determine the original sample volume before subsampling (Lewis & Eads 2009).

If contracted externally, on-going costs for Levels 2 & 3 might be in the order of $30K per year per site.

Table 6: Equipment requirements. (Assuming site is an existing flow site with autosampler; indicative costs excl. GST).

Equipment required	Indicative cost ($NZ)
Turbidity sensor with wiper/pump (e.g., Greenspan TS1200 0-2000 NTU) & calibration	~$4000
Programming support	~$500
Ongoing costs	
Data processing	

2.4 Analytical methods

Several techniques may be used to measure SSC in a natural water sample. Consistency is required in any monitoring programme. A change of analytical method should ideally include a period of overlap between the two methods. A review of US Geological Survey data by Gray et al. (2000) highlighted the difference between analysis of a subsample (TSS APHA 2450-D) and the entire sample (SSC ASTM 3977) and notes that they are not comparable and should not be used interchangeably. Gray et al. (2000) compared the SSC-ASTM 3977 and TSS APHA 2450-D analytical methods and derivative data, and concluded that the SSC-ASTM 3977 method was more accurate and reliable.

A total suspended solids (TSS) analysis (TSS APHA 2450-D) normally entails withdrawal of an aliquot of the original sample for analysis. In contrast, the SSC analytical method (ASTM 3977-97) measures all sediment and the mass of the entire water-sediment mixture by evaporation, filtration or wet sieving (Table 7). If a sample contains a substantial proportion of sand-sized material, then stirring, shaking, or otherwise agitating the sample before obtaining a subsample (TSS APHA 2450-D), will rarely produce a representative sample for SSC or particle-size distribution analysis. Additionally, the percentage of sand-size and finer material can be determined as part of the SSC ASTM 3977-filtration method, but not as part of the TSS APHA 2450-D method (Gray et al. 2000).

Table 7: Suspended sediment analytical methods.

Term	Description	Benefits	Limitations
Suspended sediment concentration by wet sieving (ASTM 3977-97, ASTM 2002b).	The sample is poured onto a sieve with 63 µm openings. Analysis includes the entire coarse and if possible, the entire fine fraction is analysed by the filtration method, but if the sample volume is unwieldy, it may be reduced by splitting.	- Yields a concentration for the total sample, a concentration of the sand-size particles, and a concentration for the silt- and clay-size particles.	
Suspended sediment concentration by filtration (ASTM 3977-97, ASTM 2002b).	The sample consisting of river water, sediment, and dissolved solids is weighed and then filtered through a glass fibre disk. The disk and sediment are dried and weighed, then the sediment concentration is calculated.	- Fast for low concentration samples. - Correction factors for dissolved solids are not required.	- Clogging of filters for high concentration samples. Suitable for samples with concentrations of sand-size material (diameters greater than 0.062 mm) less than about 10,000 mg/L and concentrations of clay-size material of about 200 mg/L.
Suspended sediment concentration by evaporation (ASTM 3977-97, ASTM 2002b).	Samples weighed then allowed to settle. After the sediment has settled, most of the supernatant water is poured or siphoned away. The volume of water-sediment mixture remaining is measured so that a dissolved solids correction can be applied later. The sediment is then dried and weighed.	- Equipment and technique are simple.	- Can be used only on sediments that settle within the allotted storage time of the samples which usually ranges from a few days to a few weeks, so less useful if there is a significant amount of clay. - A correction factor must be applied if dissolved-solids concentration exceeds about 10 % of the sediment concentration. - May be less precise weighing if the ratio of sample mass to tare mass is small.
Total suspended solids Method 2540 D, "Total Suspended Solids Dried at 103°-105°C" (APHA 1995).	Uses a predetermined volume from the original water sample obtained while the sample is being mixed with a magnetic stirrer. An aliquot of the sample — usually 0.1 L, but a smaller volume if more than 200 mg of residue may collect on the filter — is withdrawn by pipette. The disk and sediment are dried and weighed, then the sediment concentration is calculated.	- As for SSC-filtration.	- As for SSC-filtration. - Subsampling technique developed for wastewater and is not applicable to natural waters. - Has large bias and variance compared to SSC (ASTM 3977-97) (Gray et al. 2000). - Subsampling by pipette or by pouring from an open container will generally result in production of a sediment-deficient subsample (Gray et al. 2000).

2.5 Textural analysis

The type of particle size data required governs the type of analysis. For example, physical data on particle dimensions is required for ecological, turbidity or contaminant transport applications, while settling (fall-speed) data is required for hydraulic studies. An additional consideration is whether effective (*in situ*) particle size (including flocs and aggregates) is required or whether the absolute particle size[2] is required. Sample stability during storage must be considered if effective particle size is required. If the sand fraction is of interest samples must be collected using depth-integrated manual sampling as the sand fraction is typically poorly mixed and concentrated near the bed.

A simple approach to including some textural analysis is to adopt SSC (ASTM 3977-97) wet sieving (ASTM 2002b) as the measure of sediment concentration. The method yields a concentration for the total sample, a concentration of the sand-size particles, and a concentration for the silt- and clay-size particles.

If further differentiation between silt-and clay-size particles is required, particle size distributions must be measured. Three techniques are summarised in Table 8. Laser diffraction analysis can be conducted at the University of Waikato and time of transition measurements are available from NIWA-Hamilton for about $75/sample (depending on sample numbers and urgency).

Table 8: Particle size distribution analysis techniques.

Technique	Principle	Instrument	Benefits	Limitations
Sedimentation	Calculate grain size from settling velocity of particles.	e.g., pipette.	- Traditional approach.	- Requires a specialist laboratory for analysis.
Laser diffraction	Particles in a laser beam scatter light at angles inversely proportional to particle size.	e.g., Malvern Mastersizer (0.05-900 µm, up to 64 classes).	- Excellent reproducibility - Fast analysis (seconds). - Small sample.	
Time of transition	Based on detection of particles by a rotating laser beam, direct measurements of particles.	e.g., Ankersmid “EyeTech” (0-2000 µm).	- High resolution. - Fast analysis (seconds/minutes). - Small sample volume.	- Poor reproducibility as individual particles are measured.

2.6 Data management and analysis

Consideration must be given to data management, analytical methods and additional software requirements. Table 9 summarises the suitability of some freely available software for sediment concentration, load and trend analysis. Regression analysis may also be conducted using any statistical software package by trained personnel.

[2] chemically dispersed mineral fraction (Phillips, J.M.; Walling, D.E. (1995). An assessment of the effects of sample collection, storage and resuspension on the representativeness of measurements of the effective particle-size distribution of fluvial suspended sediment. *Water Research 29(11)*: 2498-2508).

Table 9: Sediment analysis software.

Software	Supplier/availability	Capability
SedRate	NIWA/free from Murray Hicks (NIWA Christchurch).	- Designed for SSC-discharge based load predictions. - Uses multiple regression methods (parametric and non-parametric) to estimate loads including least squares, minimum variance, load weighted and LOWESS. - Reports loads, errors and specific loads.
LOADEST	USGS/ free at http://water.usgs.gov/software/loadest/	- Designed for SSC-discharge based load predictions (can be tricked into producing SSC concentration time series by setting discharge to 1): - Can be used with ancillary measurements (e.g., turbidity). - Flow input is in imperial units. - Explanatory variables within the regression model include various functions of streamflow, decimal time, and additional user-specified data variables. The formulated regression model then is used to estimate loads over a user-specified time interval (estimation). Mean load estimates, standard errors, and 95 percent confidence intervals are developed on a monthly and/or seasonal basis. - Uses Adjusted Maximum Likelihood Estimation (AMLE) and Maximum Likelihood Estimation (MLE) when the calibration model errors (residuals) are normally distributed. Uses Least Absolute Deviation (LAD), is an alternative to maximum likelihood estimation when the residuals are not normally distributed.
Turbidity Threshold/ R	http://www.fs.fed.us/psw/topics/water/tts/loads/Rprocedures.pdf	- Scripts for R statistical software (free). - SI units.
TimeTrends	NIWA/free at http://www.niwa.co.nz/our-science/freshwater/tools/time-trends.	- Provides a series of linked procedures to import data, explore time series patterns and analyse for trends using recognised statistical methods.

3 Sediment sources

Several approaches are available to assess sediment sources and Collins and Walling (2004) group them into indirect and direct approaches. The indirect approach uses a range of techniques (e.g., mapping, aerial photograph/satellite image analysis, erosion surveying, erosion plots and load monitoring) to measure or evaluate sediment mobilisation. However, these indirect techniques take no account of source-river connectivity and the uncertainties associated with sediment routing, and therefore only allow one to infer sources. In contrast, the direct approach, which takes into account both sediment mobilisation and delivery to the catchment outlet, includes sediment hysteresis and sediment fingerprinting. The benefits and limitations of the commonly used approaches are summarised in Table 10.

In catchments where load monitoring is occurring, sediment or turbidity hysteresis could be a cost-effective technique to help identify sediment sources. Sediment fingerprinting offers a useful approach in both monitored and un-monitored catchments.

Table 10: Sediment source identification techniques. (Collins & Walling 2004).

Approach	Technique	Benefits	Limitations
Indirect (mobilisation only).	Mapping.	- Spatial distribution of erosion sources.	- Identify sediment origins. -Subjectivity. - Difficult to assess age of erosion surfaces.
	Aerial photograph/ satellite imagery analysis.	- Detect morphological change. - No fieldwork expenses. - Useful for assessing bank, gully and landslide erosion rates. -Catchment scale assessment.	- Gross erosion features (no hillslope erosion).
	Erosion surveys (e.g., erosion pins, cross section surveys).	- Erosion rates measured.	- At a site analysis.
	Erosion plots.		- Long duration event monitoring. -Typically overestimate erosion rates.
	Load monitoring.	-Suitable for larger catchments.	- Cost of running multiple monitoring sites. -Interpretation difficult unless erosion sources/land management practices are tributary specific.
Direct (mobilisation and delivery).	Sediment fingerprinting.	- Can be used at a range of scales. -Links sources and transported sediment. -Cost effective.	-Selecting fingerprint properties can be difficult. - Mass movement has not been assessed using this technique.
	Sediment hysteresis.	- Cost effective at existing monitoring sites.	- Interpretation can be difficult.

3.1 Sediment source identification from load monitoring data

Sediment (and/or turbidity hysteresis) has been used to infer different processes and therefore sediment sources. Patterns of SSC versus discharge through individual events may be symmetrical, or contain clockwise or anti-clockwise hysteresis. Clockwise hysteresis is classically interpreted as mobilisation of sediment of limited availability (e.g., channel sediment). In contrast, anti-clockwise hysteresis (SS peak arrives after peak discharge) is classically interpreted as the arrival of more distant particles derived from processes, such as hillslope soil erosion or bank collapse, which occurs in the latter stages of events. Interpretation can be difficult, but this approach can yield some insights into possible sediment sources.

An alternative, (but indirect) approach to quantifying sediment sources is to monitor sub-catchment and catchment outlet loads. However, this approach still may not readily lend itself to interpreting the processes occurring, except where these factors are tributary specific (Collins & Walling 2004). However, each Level 2/3 SS monitoring site may cost about $30K/year to operate, so running several sites within the same catchment may be prohibitively expensive.

3.2 Sediment fingerprinting

Sediment fingerprinting involves determining the relative importance of sediment, in terms of source location and/or erosion process, by comparing the properties of suspended sediment samples to samples taken from identified source areas (Collins & Walling 2004). The source concentrations are compared with the concentrations of samples from downstream sediment deposits (e.g., river bed) or flood samples using a numerical mixing model to determine the relative contribution of each of the sources. The fingerprinting approach has been applied to a wide range of sediment properties, including geochemistry (Collins et al. 1997; Hughes et al. 2009), mineral-magnetism (Foster et al. 1998), radionuclides (Olley et al. 1993), (Hughes et al. 2009), compound-specific isotopes (Gibbs 2008) and sediment colour (Martínez-Carreras et al. 2010). Collins and Walling (2004) suggest that a combination of properties, or ‘composite fingerprint’ will most reliably distinguish sediment sources.

Two approaches exist: (1) determining where in a catchment sediment is coming from (e.g., land use type for hillslope erosion; lithology type) and (2) which erosion processes dominate. Using both approaches provides the most powerful application as it provides both information on key erosion processes and the locations that contribute the most sediment. Differentiation of spatial sources is usually determined on the basis of the geochemistry of different rock/soil types (e.g., Collins et al. 1997); Table 11), so its feasibility would depend on the catchment size and lithological range. Fallout radionuclide tracing has been used to determine the relative contribution of different erosion processes (e.g., hillslope erosion on cultivated land or uncultivated pasture, and channels) on the basis of their radionuclide (e.g., caesium- 137 (^{137}Cs), radium-226 (^{226}Ra), and excess lead-210 ($^{210}Pb_{ex}$) concentrations. Within New Zealand catchments there are generally three primary sources of sediment: river channel erosion, hillslope erosion (sheetwash and rill erosion), and mass movement (mainly in the form of landslides). In catchments where mass movement (i.e., landslides) contributes significant sediment these techniques have not been tested for their ability to differentiate between mass movement and other subsurface sources. The Compound-Specific Isotopic

(CSI) analysis of naturally occurring biomarkers (fatty acids) derived from plants can be used to differentiate hillslope erosion according to land use types (Gibbs 2008).

Following identification of the key sources, the source areas must be sampled. The number of samples required depends on catchment size and number of potential sources. For example, to identify the relative contributions from hillslope (by land use type) and bank erosion, five source fingerprints would be required (hillslope versus bank erosion by fallout radionuclides and hillslope erosion by source by CSI – exotic forest, native forest and pasture). To ensure sample representativeness each sample should comprise a number of sub-samples. For example, at a pasture hillslope site, sub-samples (~20) could be collected within a 50 x 50 m grid. While there are no rules about the number of source samples required (Collins & Walling 2004), approximately 10 bulked samples for each source type should provide sufficient data to adequately differentiate sources. A small proportion of the samples should be processed and analysed initially to ensure the feasibility of the approach and to test the adequacy of the sampling regime.

Sediment samples are also required for the catchment outlet, either from storms or from historical sediment deposits. Storm SS samples are required to determine the relative contribution of current sediment sources. Sampling a range of flow event sizes might be necessary so that the conditions required to activate certain sediment sources can be assessed. Sampling could be achieved by bulk sampling water (e.g., Motha et al. 2004) with on site centrifugation, using a time-integrated sampler (e.g., Phillips et al. 2000); a simple in-situ PVC tube that provides conditions for particle setting) or sampling recent flood deposits. Historical sediment sources can be assessed by collecting material from catchment sediment sinks (e.g., floodplain or estuary cores) and combining fingerprinting with core dating using fallout radionuclides (^{137}Cs, ^{210}Pb, <100 yrs), pollen analysis (change in abundance with known landcover changes) or radiocarbon dating (> 500 yrs).

Sample analysis costs may be considerable, depending on the number of sediment sources to be differentiated (~10 samples per source; Table 11), and the number of suspended sediment/core samples required. Sample preparation may also be required. An experienced analyst is also required to process and interpret the results.

A sediment fingerprinting study to assess the relative contributions from different erosion processes (hillslope vs bank erosion) using fallout radionuclides and CSI fingerprints to differentiate between hillslope erosion from different land uses might cost in the order of $40K. Sample numbers would be about 20 fallout radionuclide source samples, 30 CSI source samples plus five SS samples. This cost includes sample collection, sample analysis, data analysis and reporting.

Table 11: Sediment fingerprint properties, limitations and approximate cost per sample. Indicative costs excl. GST.

Property	Fingerprint	Limitations	Indicative cost ($NZ)
Fallout radionuclides (^{137}Cs, ^{210}Pb, ^{7}Be).	Erosion process – can differentiate between hillslope erosion, cultivated land and sub-surface erosion (e.g., bank or gully erosion).	- Untested in New Zealand environments. - Mass movement differentiation untested.	~$180 per sample (excluding processing cost of sample preparation).
Compound specific isotopes (fatty acids).	Can differentiate between hillslope sediment sources – exotic forestry, native forest and pasture.	- Assumes hillslope erosion is a major sediment source.	~$200 per sample (excluding processing cost of sample preparation).
Geochemistry (major and minor minerals by X-ray fluorescence).	Which parts of the catchment are contributing sediment.	- Limited use for homogeneous geology.	~ $25 per sample for analysis (plus sample preparation costs ~$25 per sample).

4 Summary and recommendations

This report provides advice on sediment monitoring programme design, best practices, guidance on instrumentation and indicative costs. The council has two key objectives: (1) quantification of the sediment load and (2) identification of the sediment sources in rivers and streams.

For Objective (1), sediment load quantification, emphasis must be on collecting storm suspended sediment concentration (SSC) samples (manually, autosamples &/or siphon samplers). We have identified three possible levels of monitoring that could be adopted across sites. The most basic level (Level 1) involves sediment gaugings and/or grab sampling during flood and low flow conditions at existing flow sites. This option is restricted to sites with a continuous flow record (e.g., the Council's hydrometric network or new sites).These data would then be used to construct discharge sediment rating curves. Level 2 uses automated storm suspended sediment sampling at flow sites to develop discharge-sediment regression curves to apply to either event or instantaneous discharge. Level 3 monitoring adds turbidity as a sediment surrogate to provide an extended and detailed time series of suspended sediment loads (SSL).

Our recommendations are:

1. Level 1 monitoring (flood sediment gaugings) should be adopted at both pristine and impacted sites for trend analysis purposes and load estimation. This storm focused, labour intensive approach must target medium-high flows and include rising and falling limb samples and cover a range of seasons. Continuous flow measurement is a co-requisite at all sites.

2. Level 2 monitoring (autosamplers) should be adopted at: (1) smaller catchments where SSC changes rapidly, (2) sites where event loads are required in a short time frame (1-2 years), (3) remote sites and (4) small catchment studies requiring detailed results in a short time period (e.g., evaluating SS best management practices). Telemetry should be used to ensure that samples are retrieved shortly after collection.

3. Level 3 monitoring (turbidity) should be adopted when a high frequency time series of SSC and SSL is required. Care should be taken selecting a turbidity probe to ensure that the full turbidity range is captured during storms (minimum 0-2000 NTU), and either a micro-jet pump or wiper should be used to reduce biofouling on the lens. Laboratory turbidity should be determined on all SSC samples, and telemetry should be used to assist with maintaining a high quality turbidity record by highlighting maintenance requirements promptly.

4. Samples should be analysed for SSC using the wet sieve and filtration methods (ASTM 2002b) rather than total suspended solids (TSS; APHA 1995) to provide basic particle size data.

5. Suitable software for data processing and analysis should be identified before monitoring commences. Specialist programmes available include NIWA's

SedRate, USGS's Loadest or any good statistical software package (depending on staff expertise).

For Objective (2), sediment source identification, we have focused on two basic approaches: sediment fingerprinting and sediment hysteresis. Alternative methods, such as mapping or aerial photograph analysis, can assist with identifying sediment sources, however they do not address the delivery of sediment into and through the river system to the catchment outlet. Both sediment fingerprinting and sediment hysteresis analysis incorporate the mobilisation of sediment sources and delivery to catchment outlet. Sediment hysteresis analysis requires Level 2 or preferably Level 3 monitoring over a range of event sizes and seasons. This approach requires a continuous time series of SSC or turbidity and discharge or closely spaced SSC-discharge pairs. Interpretation of hysteresis can be difficult but this approach can yield some insights into possible sediment sources. It is recommended for sites with sediment load monitoring. Sediment fingerprinting, in contrast, can be achieved without the need for discharge or long-term sediment monitoring, however specialist skills are required for this approach. Sediment fingerprinting involves determining the relative importance of sediment, in terms of source location and/or erosion process, by comparing the properties of suspended sediment samples to samples taken from identified sources areas. For catchments without existing records it may be the most valuable and cost-effective approach.

Designing and undertaking a sediment monitoring programme is a complex task and we are happy to provide additional advice in the future.

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