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Northland Sediment Study:

Evaluation of Freshwater Sediment Attributes

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Executive summary

The aim of the Northland Sediment Study (NSS) is to develop a model that will integrate science and economics to assess the potential economic costs of meeting a range of attribute states for sediment and *E. coli* in Whangarei Harbour and freshwater environments that drain into Whangarei Harbour.

The NSS comprises two objectives:

1. To develop model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads and the expression of the environmental outcomes of these loads as attributes.
2. To incorporate the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment.

The selection of freshwater sediment attributes for the study is described in Green et al. (2015) (Workstream B). This report describes the way freshwater sediment attributes are to be evaluated.

We provide details of how to translate reduction in river sediment load into change in the five freshwater sediment attributes of turbidity, water clarity, euphotic depth, suspended sediment concentration and embeddedness. Reductions in river sediment load as a result of mitigation are predicted using the SedNetNZ catchment sediment model (Workstream C).

1 Introduction

1.1 The Northland Sediment Study

Northland Regional Council (NRC) has identified that sediment and *E. coli* are key water quality challenges in the Northland region (e.g., Ballinger et al. 2014).

As a result, the Ministry for Primary Industries (MPI) commissioned the Northland Sediment Study (NSS).

The aim of the NSS is to develop a model that will integrate science and economics to assess the potential economic costs of meeting a range of attribute states[1] for sediment and *E. coli* in Whangarei Harbour and freshwater environments that drain into Whangarei Harbour.

The Northland Sediment Study comprises two objectives:

1. Develop model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads and the expression of the environmental outcomes of these loads as attributes. MPI has contracted NIWA to deliver this objective.
2. Incorporate the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment. MPI is contracting another provider to deliver this objective.

Objective 1 of the NSS comprises 6 workstreams.

- **Workstream A** – Preparation. The tasks in Workstream A are: identify catchment locations for attribute evaluation; identify harbour habitats for attribute evaluation; digest feedback from November 19 (2014) workshop convened by the Ministry for the Environment on possible sediment attributes; develop thinking on possible *E. coli* attributes for freshwater and the estuary receiving waters, including a methodology for evaluating possible *E. coli* attributes from the products of the catchment and estuary modelling.
- **Workstream B** – Attributes. The tasks in Workstream B are: make final choice of estuary sediment attributes; make final choice of freshwater sediment attributes; make final choice of freshwater and estuary *E. coli* attributes.
- **Workstream C** – Whangarei catchment modelling. The tasks in Workstream C are: SedNetNZ sediment modelling; CLUES *E. coli* modelling.
- **Workstream D** – Mitigation costs and efficiencies. The task in Workstream D is to agree on and specify mitigation (sediment and *E. coli*) costs and efficiencies to be included in the economic model.
- **Workstream E** – Whangarei Harbour sediment budget. The task in Workstream E is to establish an annual-average sediment budget for Whangarei Harbour.
- **Workstream F** – external review.

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[1] The words "attribute" and "state" herein have the meanings ascribed by the National Policy Statement for Freshwater Management (NPSFM) (2014). An "attribute" is a measurable characteristic of freshwater, including physical, chemical and biological properties that support particular values. An "attribute state" is the level to which an attribute is to be managed to provide for a particular value.

The products from each workstream are to be provided to Objective 2 for incorporation in the catchment economic model.

1.2 The National Policy Statement for Freshwater Management

The National Policy Statement for Freshwater Management (NPSFM) (amended in 2014) establishes a legal and policy framework for building a national limits-based scheme for freshwater management. The Policy requires maintaining or improving overall water quality in a region and safeguarding of the life-supporting capacity, ecosystem processes and indigenous species (including their associated ecosystems) of freshwater. It also requires protection of (secondary) contact recreation.

Regional councils are required to have set freshwater objectives by 2030 that reflect national and local values; set flow, allocation and water quality limits to ensure freshwater objectives are achieved; address over-allocation; manage landuse and water in an integrated way; and involve iwi and hapū in freshwater decision-making. Councils and communities can choose the timeframes to meet freshwater objectives and limits.

The management process prescribed by the NPSFM centres on limiting resource use in “freshwater management units” in order to achieve specific, agreed values. The steps involved are:

- Agree on desired values, which are the intrinsic qualities that people appreciate or benefit from, or the uses to which people put freshwater. Examples are mahinga kai (Maori traditional food and other natural resources, including the places they are obtained and the practices around their acquisition) and swimming.
- For each value, identify the aspects to be managed. For example, for the value of ecosystem health, the aspects to be managed might include trophic state, toxicants and light.
- For each aspect to be managed, identify attributes. Attributes are the characteristics or properties of freshwater associated with each aspect to be managed. Examples are *E. coli* contamination, which is reflective of a health risk, or the DIN burden, which has a bearing on aesthetics (e.g., by stimulating periphyton blooms).
- Decide on the state of each attribute that is necessary to provide for the value at the desired level. This might be a particular DIN concentration during low flow.
- Convert attribute states into “SMART” (specific, measurable, achievable, realistic and time-bound) management objectives.
- Formulate limits to resource use that will result in the achievement of the objectives. There are two types of limit: limits to extraction (e.g., the amount of water taken for irrigation) and limits to disposal of contaminants (e.g., dairy-shed effluent).
- Develop a suite of management actions that, when implemented, will limit resource use accordingly.

The relationships between values, attributes and states in a range of freshwater environments are codified in the National Objectives Framework (NOF).

Estuaries and coastal systems are specifically excluded from consideration in the NPSFM, but they must be “given regard to” when setting limits for freshwater.

The Northland Sediment Study is designed to answer the question: what might it cost to manage, under the NPSFM, sediment and *E. coli* across a whole catchment that includes an estuary at the base of the freshwater drainage network?

The question is to be answered by developing a catchment economic model that links together sources and sinks of sediment and *E. coli* and overlays mitigation costs and efficiencies. Put simply, the model will allow different types and levels of mitigation to be applied to the catchment and will show, firstly, how sediment and *E. coli* in the waterways and in the estuary change as a result and, secondly, the costs incurred in applying the mitigation.

1.3 This report

The selection of freshwater sediment attributes for the study is described in Green et al. (2015) (Workstream B).

This report describes the way freshwater sediment attributes are to be evaluated.

We provide details of how to translate reduction in river sediment load into change in five freshwater sediment attributes:

- turbidity
- water clarity
- euphotic depth
- suspended sediment concentration
- embeddedness.

Reductions in river sediment load as a result of mitigation are predicted using the SedNetNZ catchment sediment model (Workstream C).

2 Data

There are three water-level recorders in the Whangarei Harbour catchment which are rated for flow. From these recorders, hourly water flow (m^3/s) may be derived from the beginning to the end of the record (see Table 2-1). From these hourly records it is possible to derive the time distribution of flow, that is, the fraction of time the river is below a given flow (Figure 2-1, Figure 2-2, Figure 2-3).

At sites near the water-level recorders, samples of turbidity and water clarity have been taken regularly (approximately monthly) since 2005 on the Hatea and Waiarohia Rivers, and since 2011 on the Otaika River, as part of state-of-environment monitoring performed by Northland Regional Council.

Samples of sediment concentration have been taken occasionally at the same time as the turbidity and water clarity samples.

Table 2-1: Number of turbidity, water clarity and sediment concentration samples collected from the Hatea, Waiarohia and Otaika Rivers near water-level recorders. Sample sites were Hatea River at Mair Park Foot Bridge, Waiarohia River at Lovers Lane and Otaika River at Otaika Valley Rd Culvert.

Water-level recorder	Length of flow record	No of turbidity samples	No of water clarity samples co-current with turbidity samples	No of sediment concentration samples co-current with turbidity samples
Hatea at Whareora Rd	1986-2014	71	62	6
Waiarohia at Lovers Lane	1979-2014	82	73	8
Otaika at Kay	2011-2015	30	30	11

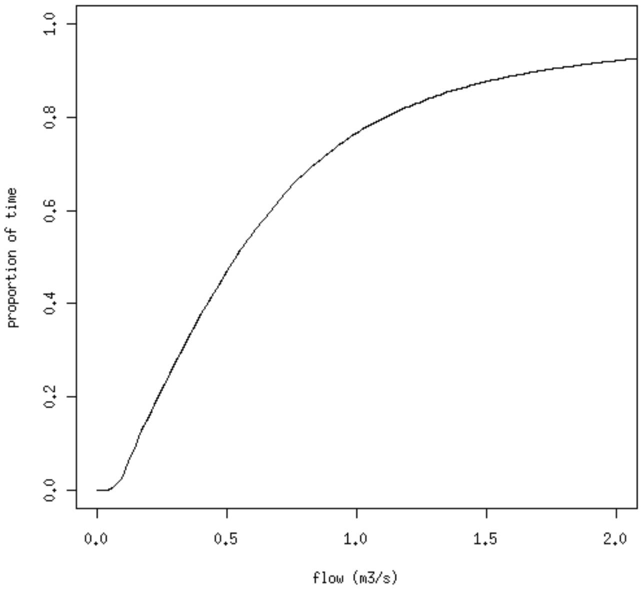

Figure 2-1: Time distribution of water discharge in the Hatea River at Whareora Rd (1986-2014). *y*-axis shows fraction of time that river is below water discharge on *x*-axis.

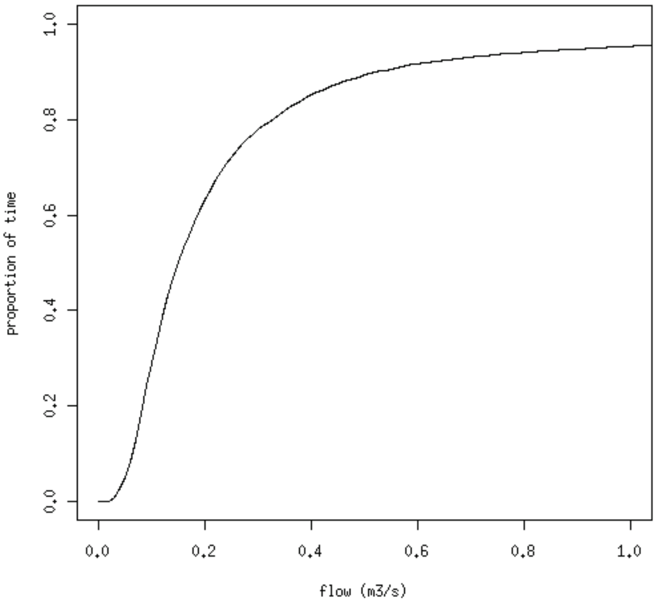

Figure 2-2: Time distribution of water discharge in the Waiarohia River at Lovers Lane (1979-2014). *y*-axis shows fraction of time that river is below water discharge on *x*-axis.

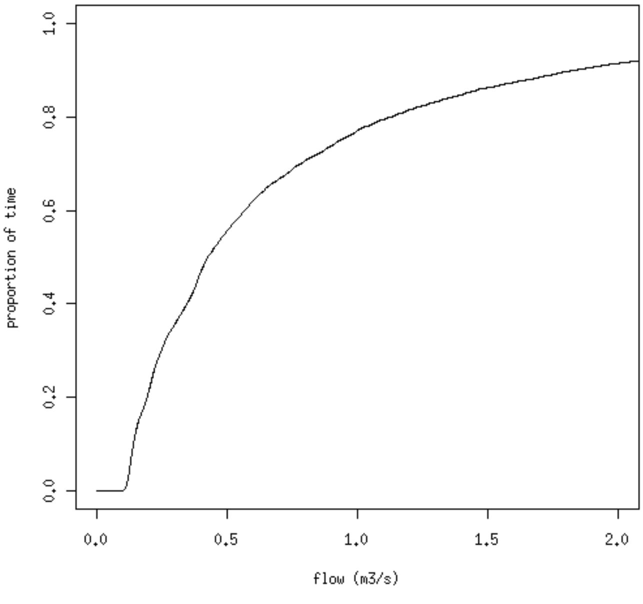

Figure 2-3: Time distribution of water discharge in the Otaika River at Kay (2011-2015). *y*-axis shows fraction of time that river is below water discharge on *x*-axis.

2.1 Flow

Flow percentiles are simply read off the derived time distribution of flow. We desire to characterise low, medium, high, and very high flows, so we have chosen 10, 50, 80, and 95 percentiles to represent these. Table 2-2 shows the flow percentiles.

Table 2-2: Flow percentiles in m^3/s of the Hatea, Waiarohia and Otaika Rivers. River flow is below the flow percentile for the percentile of time. For example, Hatea River flow is below 0.15 m^3/s for 10% of the time.

	10%	50%	80%	95%
Hatea at Whareora Rd	0.15	0.53	1.11	2.71
Waiarohia at Lovers Lane	0.06	0.15	0.33	0.92
Otaika at Kay	0.14	0.43	1.13	2.64

2.2 Turbidity

The 71 turbidity samples are not sufficient to derive an accurate time distribution. However, it is possible to derive a relationship between flow and turbidity and to use that relationship to associate turbidity percentiles with the accurate flow percentiles. It can be shown (Appendix 1) that if the flow percentiles are given by x_i (i = 1, 4) and turbidity y relates to flow x by $y = g(x)$ then the turbidity percentiles are simply $g(x_i)$ (i = 1, 4).

Figure 2-4, Figure 2-5 and Figure 2-6 show the relationships of turbidity with flow for the Hatea, Waiarohia, and Otaika Rivers, respectively.

Table 2-3 shows the turbidity percentiles inferred from the relationships and the flow percentiles in Table 2-2.

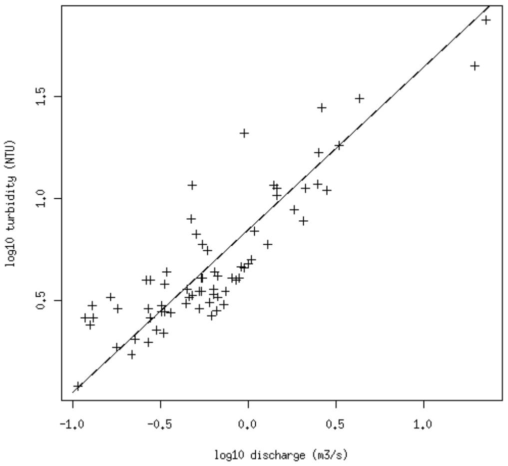

Figure 2-4: Log-log plot of turbidity versus flow for the Hatea River at Whareora Rd. Fitted line is given by $\log_{10}(\mathit{turbidity})= 0.8 \log_{10}(\mathit{flow})+ 0.85$.

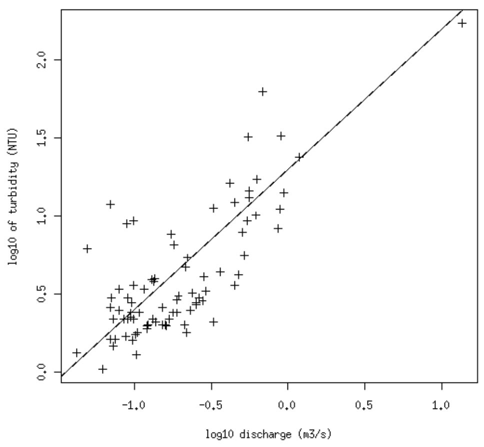

Figure 2-5: Log-log plot of turbidity versus flow for the Waiarohia River at Lovers Lane. Fitted line is given by $\log_{10}(turbidity) = 0.9 \log_{10}(flow) + 1.3$.

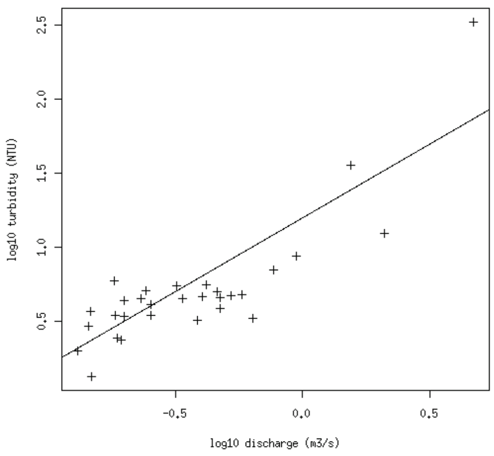

Figure 2-6: Log-log plot of turbidity versus flow for the Otaika River at Kay. Fitted line is given by $\log_{10}(turbidity) = 1.0 \log_{10}(flow) + 1.2$.

Table 2-3: Turbidity percentiles (NTU) of the Hatea, Waiarohia and Otaika Rivers. Turbidity is below the turbidity percentile for the percentile of time. For example, turbidity in the Hatea River is below 1.5 NTU for 10% of the time.

Percentile	Hatea River	Waiarohia River	Otaika River
10%	1.5	1.6	2.2
50%	4.3	3.6	6.8
80%	7.7	7.4	17.9
95%	15.7	18.5	41.8

2.3 Water clarity

The number of water clarity samples is not sufficient from which to derive an accurate time distribution. It is possible to derive a relationship between flow and water clarity, however, a much stronger relationship exists between turbidity and water clarity (as turbidity and water clarity are both functions of light attenuation).

Therefore, we derive the relationship between turbidity and water clarity and infer water clarity percentiles from the turbidity percentiles. Figure 2-7, Figure 2-8 and Figure 2-9 show the relationships of turbidity with water clarity for the Hatea, Waiarohia and Otaika Rivers, respectively.

Table 2-4 shows the water clarity percentiles inferred from the relationships and the turbidity percentiles in Table 2-3.

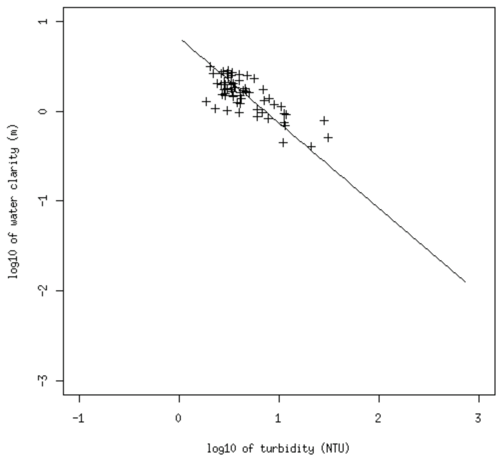

Figure 2-7: Log-log plot of water clarity versus turbidity for the Hatea River at Whareora Rd. Fitted line is given by log10(*water clarity*) = -0.95 log10(*turbidity*) + 0.82.

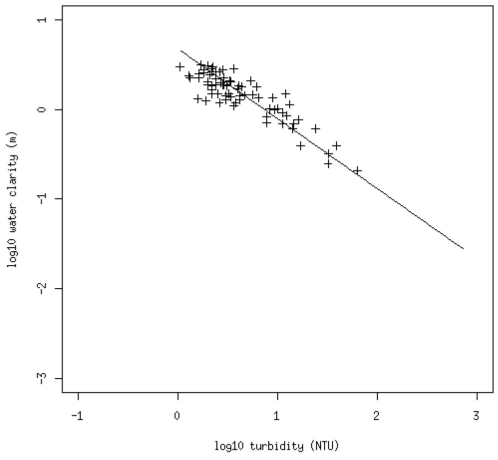

Figure 2-8: Log-log plot of water clarity versus turbidity for the Waiarohia River at Lovers Lane. Fitted line is given by log10(*water clarity*) = -0.78 log10(*turbidity*) + 0.6.

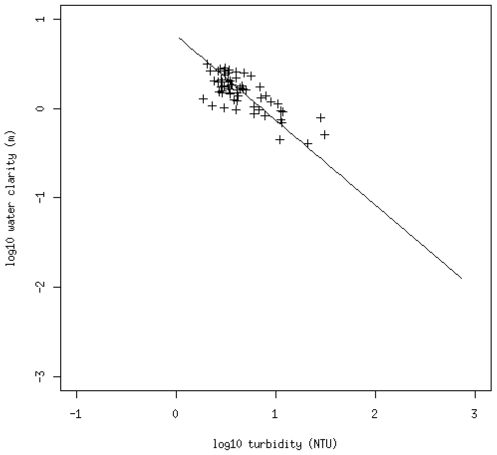

Figure 2-9: Log-log plot of water clarity versus turbidity for the Otaika River at Kay. Fitted line is given by $\log_{10}(\textit{water clarity}) = -0.95 \log_{10}(\textit{turbidity}) + 0.82$.

Table 2-4: Water clarity percentiles (m) of the Hatea, Waiarohia and Otaika Rivers. Water clarity is greater than the water clarity percentile for the percentile of time. For example, water clarity in the Hatea River is greater than 4.5 m for 10% of the time.

Percentile	Hatea River	Waiarohia River	Otaika River
10%	4.5	3.3	3.12
50%	1.7	1.8	1.1
80%	0.95	1.0	0.42
95%	0.48	0.49	0.19

2.4 Euphotic depth

There are no samples of euphotic depth from which to estimate percentiles. However, Davies-Colley and Nagels (2008) found that attenuation coefficients were approximately the square root of turbidity (*turb*) for New Zealand rivers.

Euphotic depth is defined as the depth at which light irradiance is attenuated to 1/100 of that at the surface. This equates to an exponential attenuation of 4.6 (i.e., exp(-4.6) = 0.01), which equates to the euphotic depth times the square root of turbidity. Euphotic depth *ED* may then be approximated by

$$ED = 4.6/sqrt(turb) \tag{1}$$

The percentiles of euphotic depth may then be estimated directly by applying equation (1) to the turbidity percentiles in Table 2-3. The results are shown in Table 2-5.

Table 2-5: Euphotic depth percentiles (m) of the Hatea, Waiarohia and Otaika Rivers. Euphotic depth is above the euphotic depth percentile for the percentile of time. For example, euphotic depth in the Hatea River is above 3.8 m for 10% of the time.

Percentile	Hatea River	Waiarohia River	Otaika River
10%	3.8	3.6	3.1
50%	2.2	2.4	1.8
80%	1.7	1.7	1.1
95%	1.2	1.1	0.7

2.5 Sediment concentration

The number of sediment concentration samples is small so it is difficult to estimate percentiles of these. However, there are usually strong relationships between sediment concentration and turbidity, so the sediment concentration percentiles may be inferred from the turbidity percentiles. Figure 2-10, Figure 2-11 and Figure 2-12 show the relationships of turbidity with sediment concentration.

Table 2-6 shows the inferred sediment concentration percentiles.

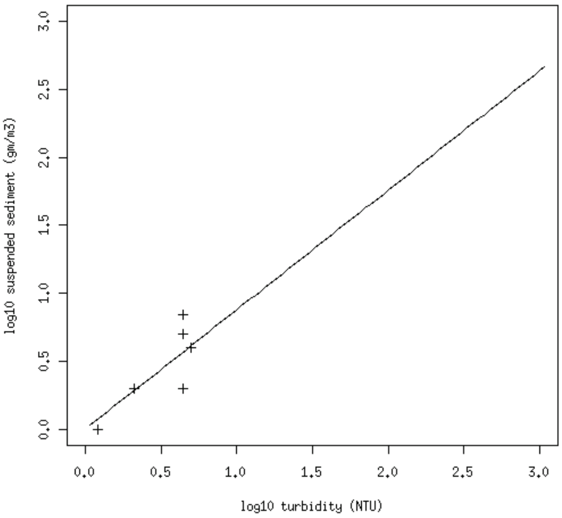

Figure 2-10: Log-log plot of suspended sediment concentration versus turbidity for the Hatea River at Whareora Rd. Fitted line is given by $\log_{10}(suspended\ sediment) = 0.88 \log_{10}(turbidity)$.

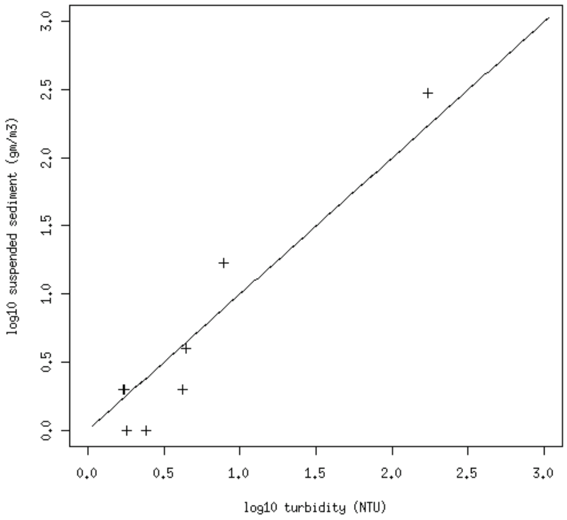

Figure 2-11: Log-log plot of suspended sediment concentration versus turbidity for the Waiarohia River at Lovers Lane. Fitted line is given by $\log_{10}$(*suspended sediment*) = $\log_{10}$(*turbidity*).

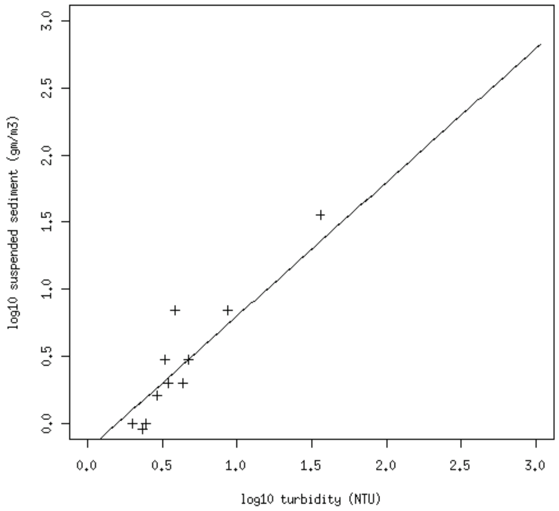

Figure 2-12: Log-log plot of suspended sediment concentration versus turbidity for the Otaika River at Kay. Fitted line is given by $\log_{10}$(*suspended sediment*) = $\log_{10}$(*turbidity*) - 0.2.

Table 2-6: Suspended sediment concentration percentiles (g/m^3) of the Hatea, Waiarohia and Otaika Rivers. Sediment concentration is below the sediment concentration percentile for the percentile of time. For example, sediment concentration in the Hatea river is below 1.4 g/m^3 for 10% of the time.

Percentile	Hatea River	Waiarohia River	Otaika River
10%	1.4	1.6	1.4
50%	3.6	3.6	4.3
80%	6.0	7.4	11.3
95%	11.3	18.5	26.3

2.6 Embeddedness

Embeddedness is a measure of the fine sediment trapped in channel gravel. Green et al. (2015) characterised embeddedness as the concentration of fine sediment in channel gravel expressed as a mass per unit volume of water in channel gravel (g/m^3). We hypothesise that embeddedness is equal to the sediment concentration of water at the time that bed movement of gravel ceases on the falling limb of a hydrograph.

Clausen and Plew (2004) showed that for New Zealand rivers the discharge at which channel gravel stops moving is approximately equal to one quarter of the mean annual flow. Therefore it follows that:

$$EB = S(\,T\left(\frac{MAF}{4}\right)) \tag{2}$$

where *EB* is embeddedness, *MAF* is the mean annual flood in m^3/s, *S* is the function that gives sediment concentration (g/m^3) from turbidity (NTU) and *T* is the function that gives turbidity from discharge (m^3/s).

The Waiarohia River has a gravel-based bed and so embeddedness may be estimated for it (the Otaika and Hatea Rivers do not have gravel-based beds).

The mean annual flood of the Waiarohia river at Lovers Lane is 30 m^3/s, hence the discharge at which gravel stops moving on the falling limb of a flood hydrograph is 7.5 m^3/s. The turbidity at 7.5 m^3/s is given by Figure 2-5 as 122 NTU. Then, Figure 2-11 gives a sediment concentration of 122 g/m^3 at an NTU of 122. Therefore, the embeddedness of the Waiarohia River at Lovers Lane is given by 122 g of sediment per m^3 of water.

3 Change in attributes as a result of change in river sediment load

The SedNetNZ model shows that catchment-wide soil conservation works can reduce sediment loads in rivers by up to 50% (Dymond et al. 2014).

We provide in the following details of how to translate reduction in river sediment load into change in the freshwater sediment attributes of sediment concentration, turbidity, water clarity, euphotic depth and embeddedness.

3.1 Sediment concentration

Sediment load is actually the summation of sediment discharge over time; hence, load is strongly related to concentration:

$$L = 10^6(\textstyle\sum_j q_j . s_j)/N \tag{3}$$

where *L* is the sediment load in t/yr, q_j is the river discharge in m^3/s at time interval *j*, s_j is the suspended sediment concentration in g/m^3 at time interval *j*, ∑ is the summation over *N* years of record, and 10^6 is a conversion factor for converting grams to tonnes.

In many rivers, there is a strong relationship between discharge *q* and the suspended sediment concentration *s*:

$$s = R(q) \tag{4}$$

This is called the sediment concentration rating curve, and is often used for estimating sediment loads in rivers.

Substitution of (4) into (3) gives:

$$L = 10^6 \sum_j q_j . R(q_j) \, / N \tag{5}$$

Equation (5) may be rewritten in distribution form as:

$$L = 10^6 \sum_i \; q_i R(q_i) H(q_i) / N \tag{6}$$

where $H(q_i)$ is the number of times discharge records fall in the bin q_i to $q_i + \Delta q$ during the N years of record (this is called the discharge frequency), and summation is over the number of discharge bins.

If soil conservation reduces sediment load L then the right hand side of equation (6) must also reduce. Discharge frequency will not change over a period of decades, and so it is the sediment concentration rating curve which must reduce.

Two instances of change in sediment concentration rating have been observed in New Zealand – the Motueka River (Basher et al. 2011) and the Waipaoa River (Hicks et al. 2000). In both cases, the rating curve moved parallel upwards in log-log space, indicating that sediment concentrations moved up by the same relative amount throughout the discharge range. We assume the same here; that is, when sediment loads are reduced by a fraction *p* the sediment concentration rating curve is also reduced by *p* throughout the discharge range.

As an example we will assume that the catchment-wide soil conservation reduces sediment loads by 50%. Then the percentiles of sediment concentration given in Table 2-6 are reduced by 50% to give those in Table 3-1.

Table 3-1: Suspended sediment concentration percentiles (g/m^3) of the Hatea, Waiarohia and Otaika Rivers after reduction of sediment loads by 50%. Sediment concentration is below the sediment concentration percentile for the percentile of time. For example, sediment concentration in the Hatea River is below 0.7 g/m^3 for 10% of the time.

Percentile	Hatea River	Waiarohia River	Otaika River
10%	0.7	0.8	0.7
50%	1.8	1.8	2.1
80%	3.0	3.7	5.7
95%	5.6	9.2	13.1

3.2 Turbidity

As shown in the previous section, reductions in sediment load following soil conservation will result in the same reduction in sediment concentration. The reduction in turbidity therefore will depend on the relationship between turbidity and sediment concentration.

There is usually a linear relationship in log-log space:

$$log10(turb) = a \, log10(s) + b \tag{7}$$

This may be rewritten as:

$$turb = 10^b s^a \tag{8}$$

Therefore, if sediment concentration is reduced to a fraction q of what it was then the turbidity will be reduced to:

$$turb' = q^{a}.turb \tag{9}$$

and turbidity will be reduced to a fraction q^a of what it was. This assumes that the character of the sediment, such as particle size, remains the same as before.

Table 3-2 shows how the reduced turbidity percentiles may be estimated from the reduced sediment loads.

Table 3-2: Estimation of decreased turbidity percentiles from reduced sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of a from Figure 2-10, Figure 2-11 and Figure 2-12	1.14	1.0	1.0
reduced sediment load as fraction of old	q	q	q
percentiles of sediment concentration as fraction of old	q	q	q
percentiles of turbidity as fraction of old	$q^{1.14}$	q	q

3.3 Water clarity

Water clarity is inversely linearly related to turbidity in log-log space (Figure 2-7, Figure 2-8, Figure 2-9):

$$log10(wc) = m\ log10(turb) + c \tag{10}$$

where m is a negative real number. This may be rewritten as:

$$wc = \ 10^{c}\ turb^{m} \tag{11}$$

Therefore if turbidity is reduced to a fraction p of what it was, then the water clarity will be increased to:

$$wc' = wc\ \ p^{m} \tag{12}$$

Table 3-3 shows how the increased water clarity percentiles may be estimated from the reduced sediment loads.

Table 3-3: Estimation of increased water clarity percentiles from reduced sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of m from Figure 2-7, Figure 2-8, Figure 2-9	-0.95	-0.78	-0.95
reduced sediment load as fraction of old	q	q	q
percentiles of sediment concentration as fraction of old	q	q	q
percentiles of turbidity as fraction of old	$q^{1.14}$	q	q
ratio of new over old water clarity percentiles	1/(*q***1.14)**0.95	1/*q***0.78	1/*q***0.95

Table 3-4 gives an example of how to estimate increases in water clarity as a result of a 50% reduction in sediment loads.

Table 3-4: Estimation of increased water clarity percentiles from 50% reduction in sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of *m* from Figure 2-7, Figure 2-8, Figure 2-9	-0.95	-0.78	-0.95
reduced sediment load as fraction of old	0.5	0.5	0.5
percentiles of sediment concentration as fraction of old	0.5	0.5	0.5
percentiles of turbidity as fraction of old	0.454 (= $0.5^{1.14}$)	0.5	0.5
ratio of new over old water clarity percentiles	2.12 (= 1/(0.454)**0.95 (i.e., 112% increase)	1.71 (= 1/0.5**0.78) (i.e., 71% increase)	1.93 (= 1/0.5**0.95 (i.e., 93% increase)

3.4 Euphotic depth

Euphotic depth is a power relationship of turbidity as given by equation 1. Therefore, if turbidity is reduced to a fraction p of what it was, then the water clarity will be increased to:

$$ED' = ED/sqrt(p) \tag{13}$$

Table 3-5 shows how the increased euphotic depth percentiles may be estimated from the reduced sediment loads.

Table 3-5: Estimation of increased euphotic depth percentiles from reduced sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of *m* from Figure 2-7, Figure 2-8, Figure 2-9	-0.95	-0.78	-0.95
reduced sediment load as fraction of old	q	q	q
percentiles of sediment concentration as fraction of old	q	q	q
percentiles of turbidity as fraction of old	$q^{1.14}$	q	q
ratio of new over old euphotic depth percentiles	1/(q**1.14)**0.5	1/q**0.5	1/q**0.5

Table 3-6 gives an example of how to estimate increases to euphotic depth percentiles from 50% percent reduction in sediment loads.

Table 3-6: Estimation of increased euphotic depth percentiles from 50% reduction in sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of *m* from Figure 2-7, Figure 2-8, Figure 2-9	-0.95	-0.78	-0.95
reduced sediment load as fraction of old	0.5	0.5	0.5
percentiles of sediment concentration as fraction of old	0.5	0.5	0.5
percentiles of turbidity as fraction of old	0.454 (= $0.5^{1.14}$)	0.5	0.5
ratio of new over old euphotic depth percentiles	1.48 (= 1/(0.454)**0.5 (i.e., 48% increase)	1.41 (= 1/0.5**0.5) (i.e., 41% increase)	1.41 (= 1/0.5**0.5) (i.e., 41% increase)

3.5 Embeddedness

Embeddedness is given by the sediment concentration at one quarter of the mean annual flood. Hence, when sediment load becomes a fraction q of what it was (due to soil conservation works) then embeddedness becomes the same fraction q of what it was.

$$EB' = q.EB \tag{14}$$

4 References

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Appendix I: Derivation of turbidity percentiles from flow percentiles

The probability that flow is less than a given value x is given by

$$P(x) = \int_{-\infty}^{x} f(s)\mathrm{d}s \qquad \text{(A1-1)}$$

where s is the flow ranging from minus infinity to x. When turbidity y is a monotonic function of x, expressed as $y = g(x)$, then, equation (A1-1) may be rewritten as

$$P(y) = \int_{-\infty}^{y} f(g)\mathrm{d}g \qquad \text{(A1-2)}$$

This shows that for a given flow percentile x with probability P of non-exceedance, the turbidity $y = g(x)$ has the same probability of non-exceedance and is therefore the equivalent turbidity percentile.

This result relies on being able to equate $f(s)\mathrm{d}s$ with $f(g)\mathrm{d}g$. This requires $g(x)$ to be a monotonic function. If there are errors in $g(x)$ then they need to be small and evenly distributed if $f(s)\mathrm{d}s$ is to be approximately equated with $f(g)\mathrm{d}g$. If this is not the case then a Monte Carlo simulation of turbidity values from flow values could be used to estimate turbidity percentiles.