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Temporal disaggregation of sediment loads in the Whangarei Harbour Catchment and response to soil conservation

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Contents

Executive Summary

The SedNetNZ model has been implemented for the Whangarei Harbour Catchment. Annual sediment loads (t/yr) for 11 reporting zones were estimated for the current land cover: Hatea river (4482), Waiarohia river (4932), Limeburners creek (1038), Otaika creek (11204), northern-inner harbour (2143), southern-inner harbour (2424), northern-middle harbour (2944), southern-middle harbour (555), northern-outer harbour A (1238), northern-outer harbour B (781), southern-outer harbour (0). For pre-human vegetation, sediment loads were estimated to be about 45% of the current sediment loads.

Temporal disaggregration of sediment loads would normally be done through a sediment concentration rating curve. A measured time distribution of water flow (i.e. flow duration curve) may then be converted to a time distribution of sediment concentration. However, insufficient sediment concentration data is available for rivers in the Whangarei Harbour Catchment to derive a robust sediment concentration curve. Also, the sediment concentration data is surface sampled, rather than depth –integrated and not suitable for load estimates. Hence disaggregation was achieved through the more numerous turbidity samples. In addition time distributions are derived for water clarity and euphotic depth. Embeddedness is estimated by the sediment concentration occurring at one quarter of the mean annual flow and does not vary in time.

A time distribution of turbidity was generated through a turbidity rating curve. A time distribution of sediment concentration was inferred from the relationship between sediment concentration and turbidity and the turbidity time distribution . Similarly a time distribution was inferred for water clarity, and also euphotic depth, using a relationship between euphotic depth and turbidity given by Davies Colley and Nagels (2008) rather than fit a curve to data as there was no measured data on euphotic depth. Embeddedness estimated by the sediment concentration occurring at one quarter of the mean annual flow was 122 g/m3 for the Waiarohia River gravel bed river. The Otakia and Hatea rivers are not gravel bed.

The percentiles of these time distributions depend on sediment loads through the impact of sediment loads on sediment concentration. It is assumed any percentage reduction of sediment load as a result of land use change or soil conservation in a catchment will result in the same percentage reduction of percentiles of sediment concentration. The relationship of turbidity, water clarity, and euphotic depth to sediment concentration will then control the percentage change in their percentiles. For the Hatea, Waiarohia, and Otaika rivers, a 50% reduction in sediment load will give reductions in the percentiles of sediment concentration by 50% and reductions in the percentiles of turbidity by 55%, 50%, and 50% for each river respectively. A 50% reduction in sediment load will give increases in the percentiles of water clarity by 112%, 71%, and 93% respectively. A 50% reduction in sediment load will give increases in the percentiles of euphotic depth by 48%, 41%, and 41% respectively. A 50% reduction in sediment load will also reduce embeddedness in rivers with gravel beds by 50%.

1 Introduction

The purpose of this report is to show how sediment loads as modelled by SedNetNZ (Dymond et al. 2016) may be disaggregated into a time distribution of sediment concentration and other sediment attributes of importance to freshwater ecology. We use the Whangarei Harbour Catchment as a case study to demonstrate the method. We briefly introduce freshwater sediment attributes, give a summary of the SedNetNZ model in the Whangarei Harbour, and then show how the sediment loads may be disaggregated. We also show how soil conservation works influence the time distributions of the sediment attributes.

1.1 Ecological effects of fine sediment in running waters

Fine sediment is a natural feature of rivers (Suttle et al., 2004). However, human activities such as forest clearance and agriculture have increased the amount of fine sediment delivered to rivers (Waters, 1995). There have been negative impacts on rivers in New Zealand (Ryan, 1991; Clapcott et al., 2011) and worldwide (Newcombe and MacDonald, 1991; Waters, 1995; and Wood and Armitage, 1997). Affected freshwater organisms include fish, benthic invertebrates and algae.

1.1.1 Suspended fine sediment

Ecological effects of suspended fine sediment in rivers (Newcombe and MacDonald, 1991) have been researched less than those of deposited fine sediment. Physical effects of suspended sediment include increased water turbidity, reduced water clarity and reduced euphotic depth (section 1.2 defines these attributes). Higher turbidity and reduced clarity reduces the foraging efficiency of visual hunting fish and birds (Julian et al., 2013; Davies-Colley et al., 2014), may cause migratory fish to avoid turbid rivers (Boubée et al., 1997; Rowe and Dean, 1998), and can increase drift rates of benthic invertebrates (Shaw and Richardson, 2001; Bond and Downes, 2003). Suspended sediment can also damage the gills of fish, which can limit their growth and make them more susceptible to disease (Waters, 1995). Reduced euphotic depth is likely to negatively affect growth of periphyton and macrophytes on the river bed (Julian et al., 2013; Davies-Colley et al., 2014).

1.1.2 Deposited fine sediment

Benthic invertebrates

The most common mechanism driving the responses of benthic invertebrates to deposited fine sediment is change in habitat (Clapcott et al., 2011). Invertebrate responses to increased sediment range widely and include changes in feeding and growth rates, behaviour, community composition, diversity and abundance (Ryan, 1991; Waters, 1995; Wood and Armitage, 1997). Invertebrate feeding can be directly affected by clogging of the feeding apparatus (e.g., 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).

Fish

Deposited fine sediment influences fish indirectly via impacts on habitat and food supply (Clapcott et al., 2011). Deposited sediment limits the amount of habitat available for spawning and reducing the viability of egg survival (Wood and Armitage, 1997; Harvey et al., 2009). Salmonids are particularly susceptible to excess sediment suffocating eggs in redds (Hay, 2005). Deposited fine sediment also reduces the amount of habitat and cover available to juvenile and adult fish. In terms of food availability, sediment can alter the benthic invertebrate community in favour of less preferred food items for some fish species, i.e., a reduction in drifting species. Consequently, sediment can affect the small-scale distribution of fishes and hence fish density and richness.

Benthic algae

Compared to benthic invertebrates, effects of deposited fine sediment on benthic algae in running waters are less well understood. In New Zealand, several recent experiments have shown that sediment can have widespread and strong effects on algal communities (Piggott et al., 2012; Magbanua et al., 2013; Wagenhoff et al., 2013; Piggott et al., 2015a). However, both negative and positive algal responses are common (depending on whether biomass accrual, algal functional guilds or taxonomical community composition are considered), and results are not always consistent across studies.

Multiple stressors

Most farmland streams are affected by multiple stressors acting simultaneously, and recent research in New Zealand has shown that deposited fine sediment often interacts with other agricultural stressors when affecting stream communities. Interacting stressors include nutrient enrichment, flow reduction due to water abstraction and raised water temperature due to removal of shading riparian vegetation, and such interactions occur both for benthic invertebrates (Townsend et al., 2008; Matthaei et al., 2010; Wagenhoff et al., 2011, 2012; Piggott et al., 2012, Lange et al., 2014, Piggott et al., 2015b) and benthic algae (Piggott et al., 2012; Wagenhoff et al., 2013, Piggott et al., 2015a). However, due to the pervasiveness and strength of its effects, deposited fine sediment can be regarded as a "master stressor" for farmland streams in New Zealand: its effects are often negative in their own right, and interactions with other stressors make these effects even worse.

1.2 Sediment attributes

1.2.1 Sediment concentration

Sediment concentration, *s*, is defined as the ratio of the mass of dry sediment in a water-sediment mixture to the volume of the mixture. Common units are gm/m^3 or mg/litre. It is commonly measured by weighing the sediment collected in a sample of surface water or a depth profile of water. Sediment concentration is highly variable with high values during floods and low values during low flows. Therefore its ecological impact is also variable. It is useful to characterise the time distribution of sediment concentration by relating it to water flow *w* (in m^3/s), which is often measured on a semi-continuous basis (logged every 15 minutes). A relationship between *w* and *s* is derived by plotting measurements of sediment concentration, which are taken sporadically, versus flow (Hicks et al., 2004). This relationship is called the sediment concentration rating curve. Sediment concentration will also vary with water depth with higher concentrations being closer to the channel. Average values of sediment concentration in a cross section may be obtained using a depth-integrating sampler with samples at multiple locations across the channel (Hicks et al., 2004).

1.2.2 Suspended sediment load

Suspended sediment load is the average mass of sediment that flows past a point in the river in a year. We denote it by *L*. It has units of tonnes/yr. It is estimated by summing up the sediment discharge over a number of years to get the total tonnes of sediment discharge and then dividing by the number of years (the longer the record the better as annual sediment load is highly variable). The sediment discharge is estimated by multiplying the water flow, *flow* (m^3/s), by the sediment concentration as estimated from the sediment concentration rating curve, which is a function of water flow. (Note that depth-integrated concentration is required to estimate suspended sediment load). Suspended sediment load is modelled by SedNetNZ. When land use is changed or soil conservation works are implemented then SedNetNZ will predict a change in the suspended sediment load of a river. The question addressed in this report is what influence will that have on the time distribution of other important sediment attributes, such as turbidity, sediment concentration, water clarity, euphotic depth, and embeddedness.

1.2.3 Turbidity

Turbidity, *turb*, is the cloudiness of water caused by scattering of light from suspended particles. It is measured with a nephelometer which measures the intensity of light scattered at 90 degrees from a beam of light passing through a water sample. The scattering attenuation of light through water is then given by exp(-*turb x*) where *turb* is the turbidity in Nephelometric Turbidity Units and *x* is the distance travelled through the water. Turbidity is closely related to sediment concentration and is also highly variable depending on water flow. The turbidity at a site is therefore often characterised by a time distribution. Often there will be more measurements of turbidity available than sediment concentration because turbidity can be measured immediately and on site, whereas for sediment concentration samples must be processed at a laboratory. Because turbidity can be measured semi-continuously it is often used as a surrogate for sediment concentration.

1.2.4 Water clarity

Water clarity, *WC*, is the distance which an object can be clearly seen through water . The object may be a black target or a so-called Secchi disk (white disk) which is usually viewed horizontally through water using a simple viewer equipped with a 45 degree mirror (Davies-Colley, 1988). Like sediment concentration and turbidity, water clarity is highly variable and depends strongly on water flow. Water clarity is a direct measure of the immediate foraging range of fish.

1.2.5 Euphotic depth

Euphotic depth, *ED*, is the distance of water through which light travels and becomes attenuated to 1% of the surface light intensity. The distance defines the euphotic zone in which there is sufficient light for photosynthesis and periphyton and macrophytes may be sustained (Julian et al., 2013; Davies-Colley et al., 2014). Euphotic depth is rarely measured directly but may be inferred from measurements of turbidity (Davies-Colley and Nagels, 2008).

1.2.6 Embeddedness

Embeddedness, *EB*, is a measure of the fine sediment trapped in channel gravel. It is the one measure we have of deposited fine sediment. Clapcott et al. (2011) characterised it with the fraction of channel surface as fines. Here we follow Green et al. (2015) who 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). It is a direct measure of deposited fine sediment. Green et al. (2015) hypothesised 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 and can therefore be estimated from the sediment concentration rating curve.

2 SedNetNZ in the Whangarei Harbour Catchment

SedNetNZ had previously been implemented for the Kaipara Harbour Catchment (Dymond et al., 2016, give technical details of the SedNetNZ model). The model was implemented as four raster layers for landslide, earthflow, gully, and surficial erosion, and a subcatchment file (REC2 subcatchments). The subcatchment file completes all erosion processes with the addition of floodplain deposition and bank erosion. The large spatial rectangular extent of the Kaipara Harbour included the Whangarei Harbour Catchment, so SedNetNZ was able to be implemented for the Whangarei Harbour Catchment merely by clipping out the appropriate spatial extent from the Kaipara Harbour SedNetNZ implementation. The Beta version (7/10/15) of SedNetNZ has been used in this report, replacing the Alpha version (20/11/14). Beta has improved landslide density versus slope angle relationship for Northland and improved cover factors for urban bare ground.

Land cover is a major driver of soil erosion. Figure 1 shows the land cover in the Whangarei Harbour catchment as given by the LCDB 4.0. Figure 2 shows the intersection of land cover with erosion terrains (Dymond et al., 2010) to give the susceptibility of the land to mass-movement erosion. There are significant areas of earthflow and gully erosion needing soil conservation work. There are also some areas susceptible to landsliding. Figure 3 shows the REC2 subcatchments for which sediment budgets are constructed, and Figure 4 shows the mean total erosion for each subcatchment. Figure 5 shows the reporting zones as constructed in the Northland Sediment Study (Green et al., 2015) and their sediment loads to the Whangarei Harbour as predicted by SedNetNZ.

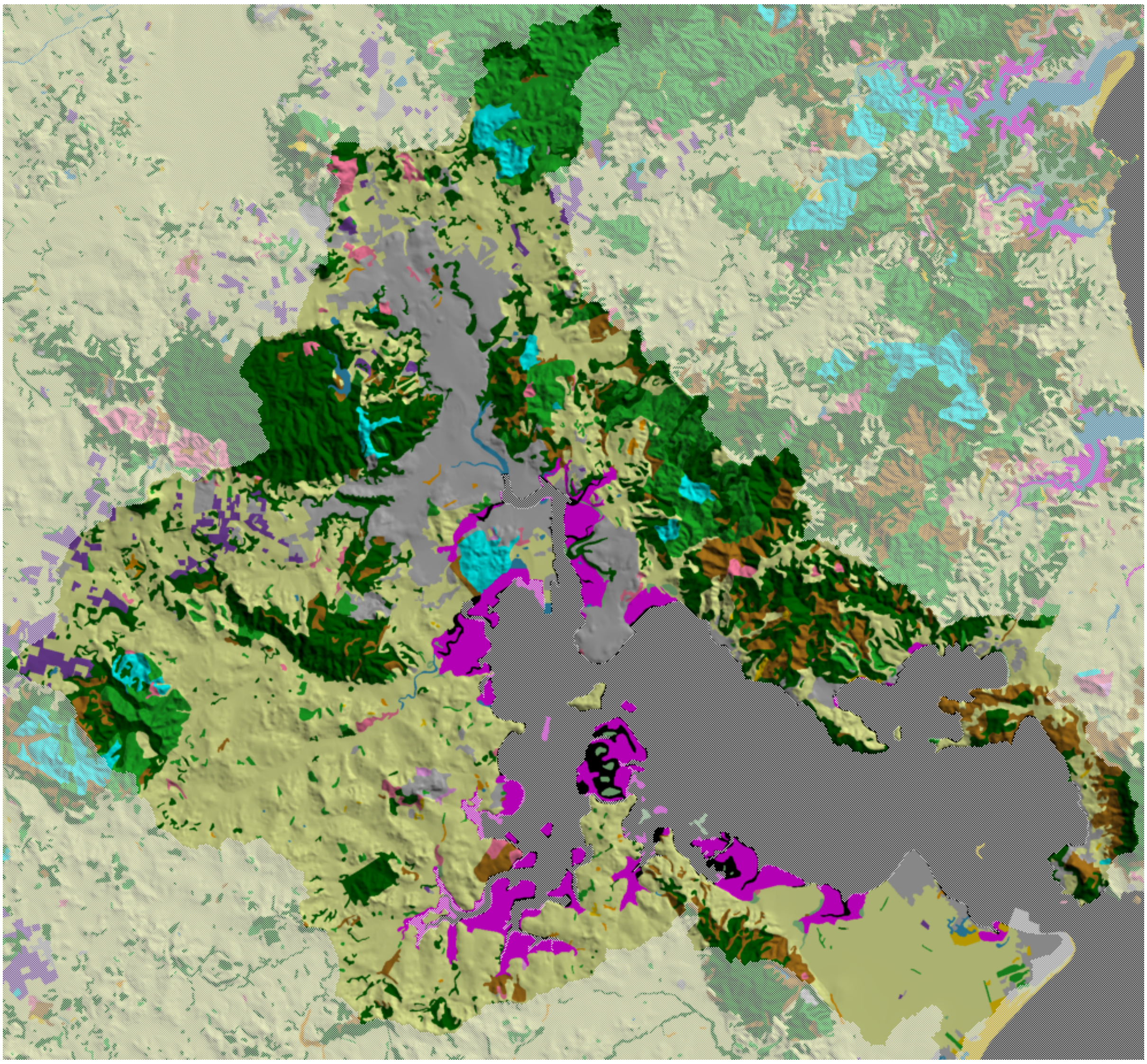

Figure 1 Land cover in the Whangarei Harbour Catchment. Light gray is urban. Dark green is indigenous forest. Light green is exotic forest. Magenta is mangroves. Cyan is harvested exotic forest. Brown is Manuka/Kanuka. Yellow is pasture. Purple is orchards/vineyards. Pink is indigenous shrublands.

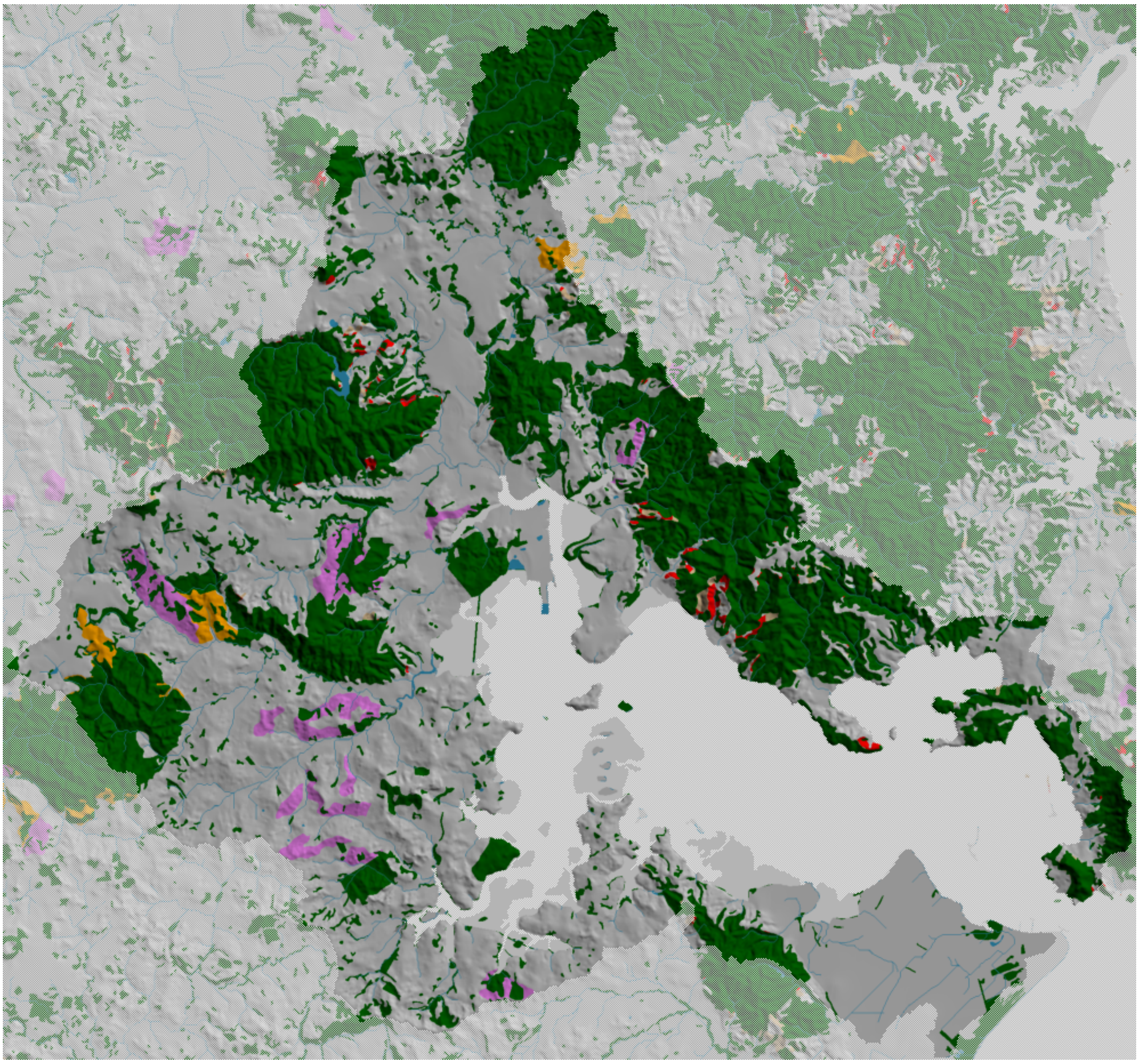

Figure 2 Highly erodible land in the Whangarei Harbour Catchment. Red shows land susceptible to landsliding. Magenta shows land susceptible to earthflow erosion. Gold shows land susceptible to gully erosion. Dark green shows forested land which protects the land from mass-movement erosion.

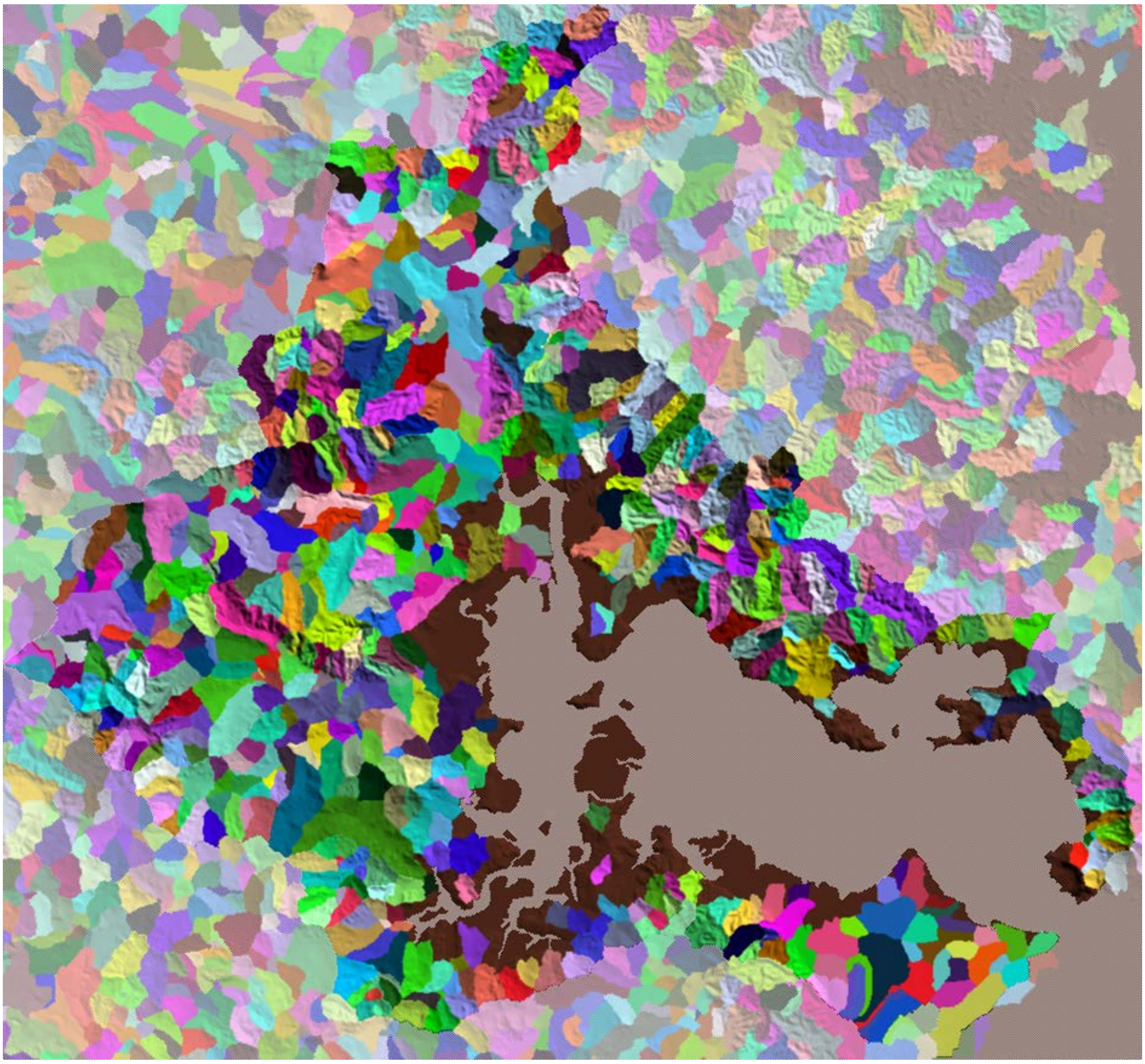

Figure 3 REC2 subcatchments for which sediment budgets are constructed. Dark brown areas adjacent to coast show infill required to match true coast.

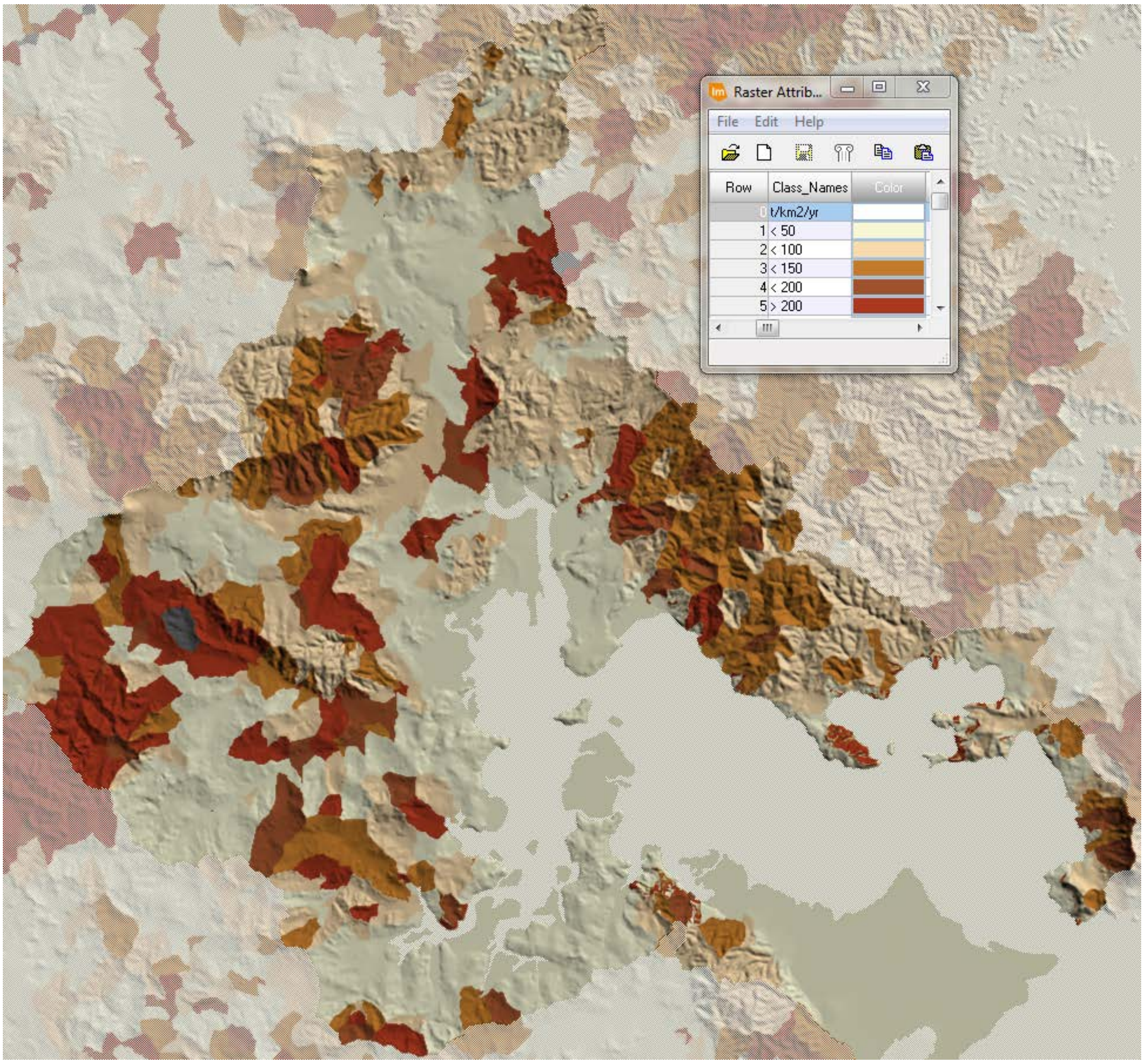

Figure 4 Mean total erosion of all processes (landsliding, earthflow, gully, surficial, net bank erosion, and floodplain deposition) as modelled by SedNetNZ for each REC2 subcatchment in the Whangarei Harbour Catchment.

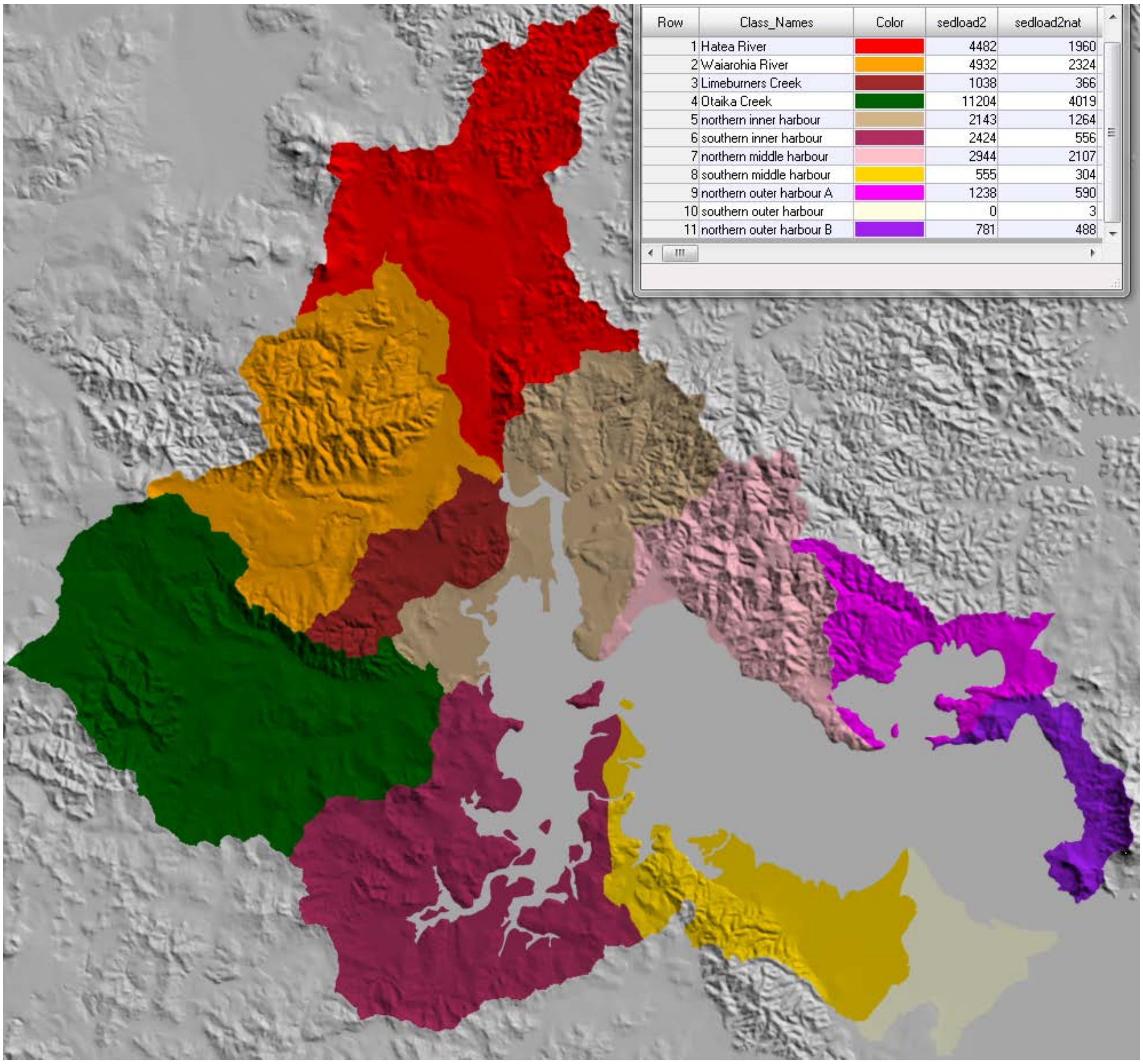

Figure 5 Reporting zones in Whangarei Harbour Catchment. Current sediment loads derived from SedNetNZ(tonnes/yr) to Whangarei Harbour from reporting zones are shown in column "sedload2". Historic sediment loads before human settlement are shown in column "sedload2nat".

3 Data

There are three water-level recorders in the Whangarei Harbour catchment which are rated for flow. From these recorders, average hourly water flow (m^3/s) may be derived from the beginning to the end of the record (see Table 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 (Figures 6-8).

At sites near the water-level recorders, measurements 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 suspended sediment concentration have been taken occasionally at the same time as the turbidity and water clarity samples.

Table 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 concurrent with turbidity samples	No of sediment concentration samples concurrent 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

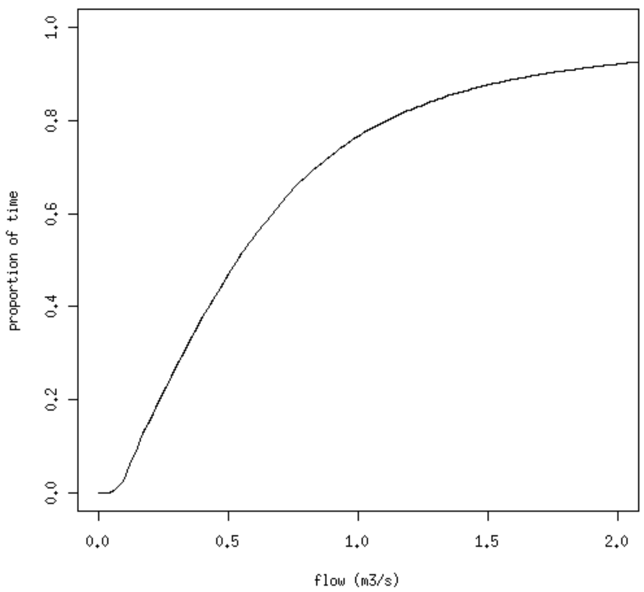

Figure 6 Time distribution of water flow in the Hatea River at Whareora Rd (1986-2014). y-axis shows fraction of time that river is below water flow on x-axis.

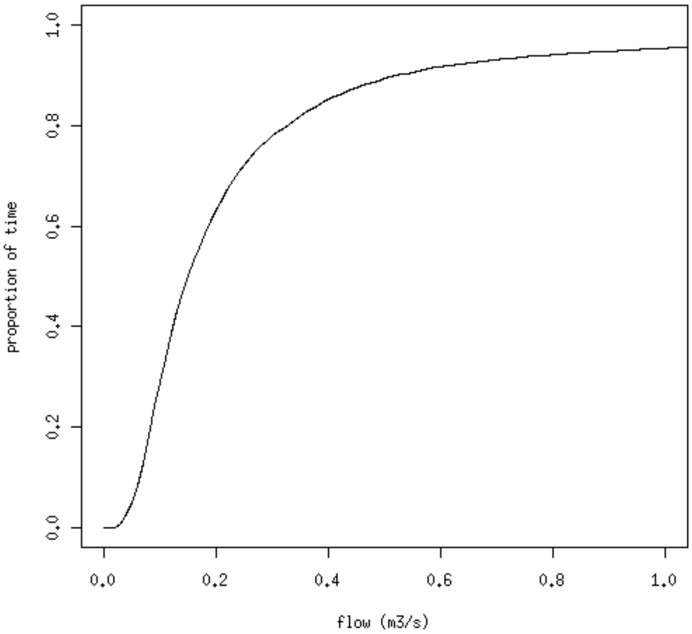

Figure 7 Time distribution of water flow in the Waiarohia River at Lovers Lane (1979-2014). y-axis shows fraction of time that river is below water flow on x-axis.

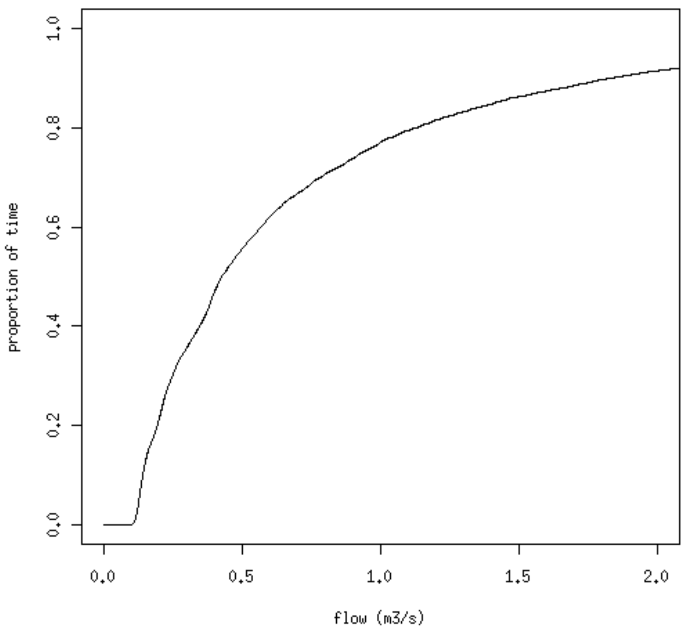

Figure 8 Time distribution of water flow in the Otaika River at Kay (2011-2015). y-axis shows fraction of time that river is below water flow on x-axis.

3.1 Flow

Flow percentiles are simply read off the derived time distribution of flow. Low, medium, high, and very high flows are characterised by the 10, 50, 80, and 95 percentiles.

Table 2 shows the flow percentiles.

Table 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

3.2 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) 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 9, Figure 10 and Figure 11 show the relationships of turbidity with flow for the Hatea, Waiarohia, and Otaika Rivers, respectively.

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

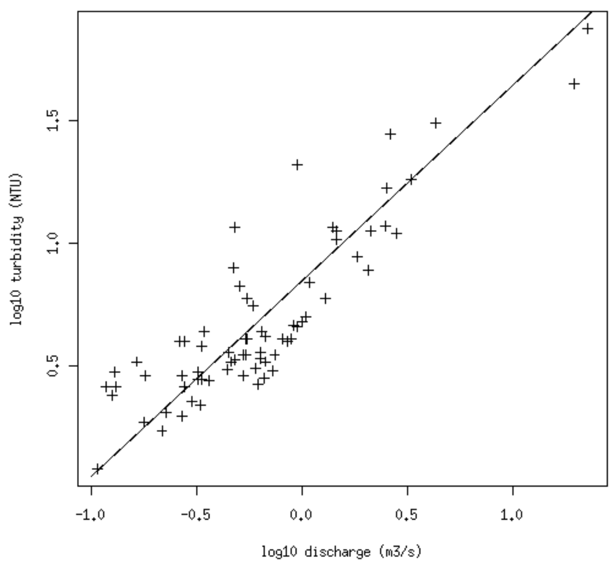

Figure 9 Log-log plot of turbidity versus flow for the Hatea River at Whareora Rd. Fitted line is given by $\log_{10}(turbidity) = 0.8 \log_{10}(flow) + 0.85$.

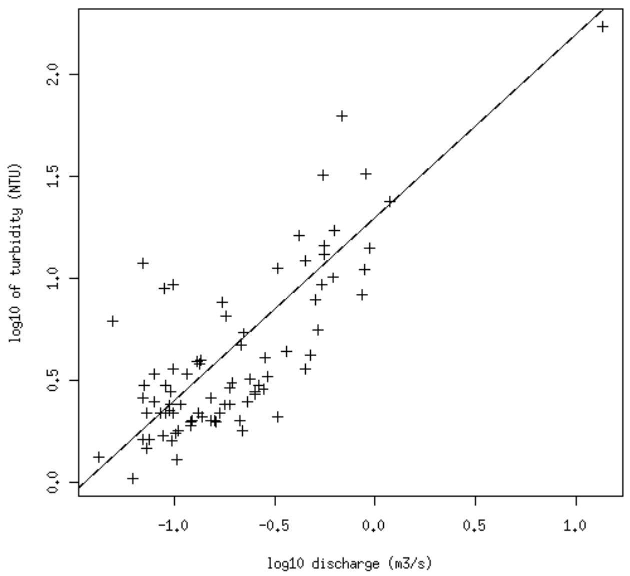

Figure 10 Log-log plot of turbidity versus flow for the Waiarohia River at Lovers Lane. Fitted line is given by $\log_{10}(turbidity) = 0.9 \log_{10}(flow) + 1.3$.

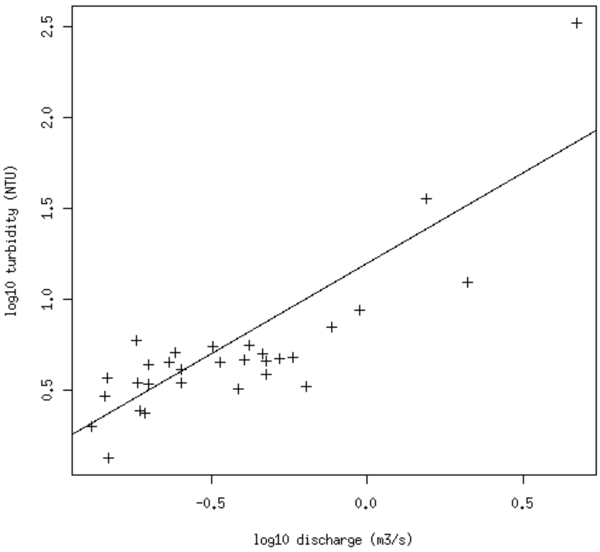

Figure 11 Log-log plot of turbidity versus flow for the Otaika River at Kay. Fitted line is given by $\log_{10}(turbidity) = 1.0 \log_{10}(flow) + 1.2$.

Table 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

3.3 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 scattering).

Therefore, we derive the relationship between turbidity and water clarity and infer water clarity percentiles from the turbidity percentiles. Figure 12, Figure 13 and Figure 14 show the relationships of turbidity with water clarity for the Hatea, Waiarohia and Otaika Rivers, respectively.

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

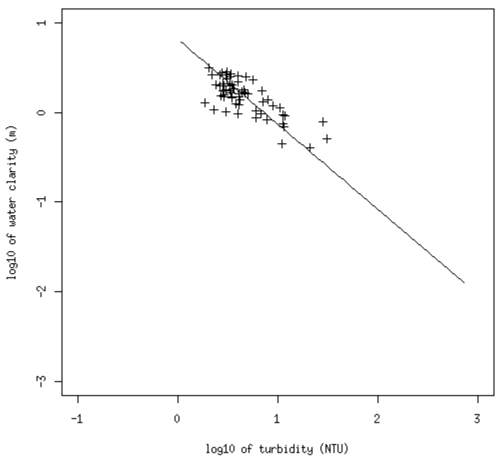

Figure 12 Log-log plot of water clarity versus turbidity for the Hatea River at Whareora Rd. Fitted line is given by $\log_{10}(\textit{water clarity}) = -0.95 \log_{10}(\textit{turbidity}) + 0.82$.

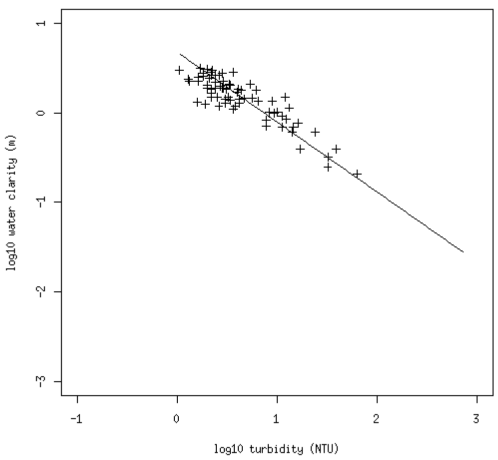

Figure 13 Log-log plot of water clarity versus turbidity for the Waiarohia River at Lovers Lane. Fitted line is given by $\log_{10}(\textit{water clarity}) = -0.78 \log_{10}(\textit{turbidity}) + 0.6$.

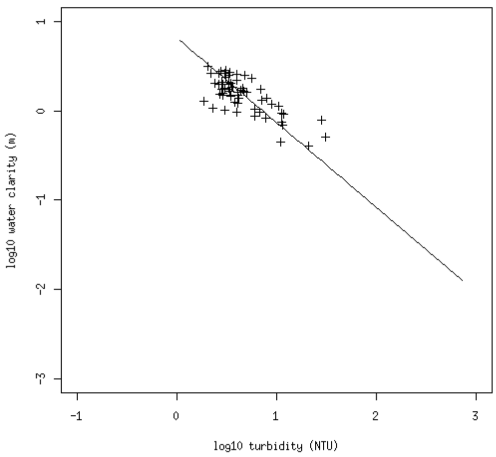

Figure 14 Log-log plot of water clarity versus turbidity for the Otaika River at Kay. Fitted line is given by $\log_{10}(\textit{water clarity}) = -0.95 \log_{10}(\textit{turbidity}) + 0.82$.

Table 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

3.4 Euphotic depth

There are no samples of euphotic depth from which to estimate percentiles. However, Davies-Colley and Nagels (2008) found that light 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

$$ED = 4.6/sqrt(turb) \qquad (1)$$

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

Table 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

3.5 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 15, Figure 16 and Figure 17 show the relationships of turbidity with sediment concentration.

Table 6 shows the inferred sediment concentration percentiles.

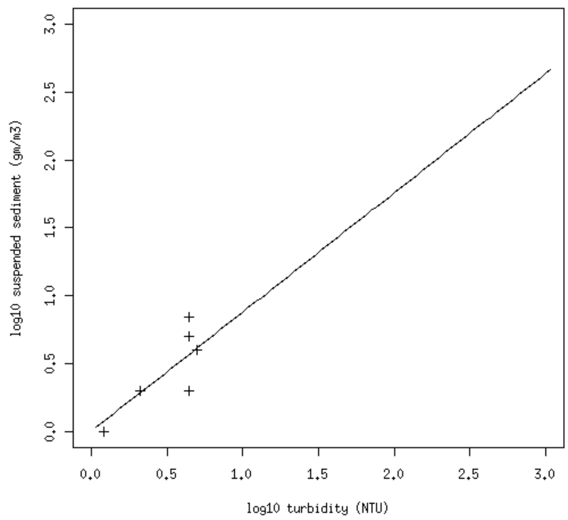

Figure 15 Log-log plot of suspended sediment concentration versus turbidity for the Hatea River at Whareora Rd. Fitted line is given by $\log_{10}(\textit{suspended sediment}) = 0.88 \log_{10}(\textit{turbidity})$.

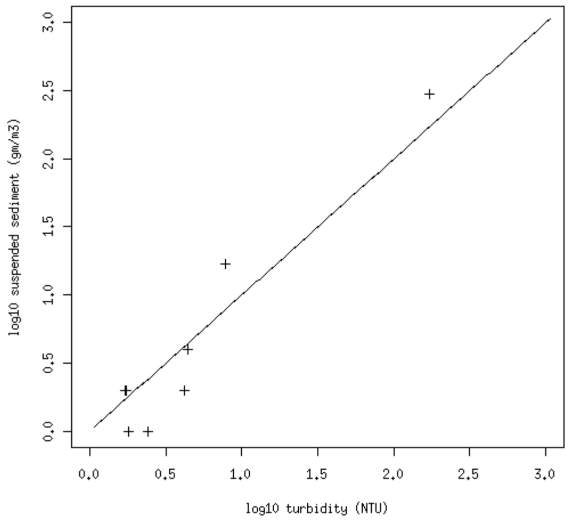

Figure 16 Log-log plot of suspended sediment concentration versus turbidity for the Waiarohia River at Lovers Lane. Fitted line is given by $\log_{10}$(*suspended sediment*) = $\log_{10}$(*turbidity*).

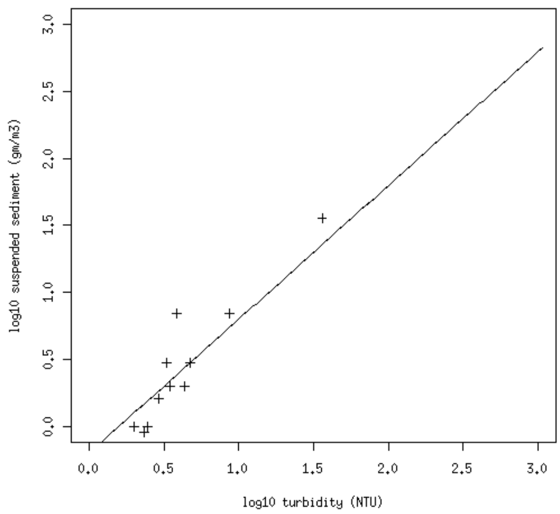

Figure 17 Log-log plot of suspended sediment concentration versus turbidity for the Otaika River at Kay. Fitted line is given by $\log_{10}$(*suspended sediment*) = $\log_{10}$(*turbidity*) - 0.2.

Table 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

3.6 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 flow at which channel gravel stops moving is approximately equal to one quarter of the mean annual flood. Therefore it follows that:

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

where *EB* is embeddedness (g/m^3), *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 flow (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 flow 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 10 as 122 NTU. Then, Figure 16 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.

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

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

4.1 Sediment concentration

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

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

where L is the sediment load in t/yr, $flow_j$ is the water flow in m^3/s at time interval j, s_j is the suspended sediment concentration in g/m^3 at time interval j, $\sum$ is the summation over N years of record, and 10^6 is a conversion factor for converting grams to tonnes.

In rivers, there is normally a strong relationship between flow and suspended sediment concentration s:

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

This is called the sediment concentration rating curve, and is often used for estimating sediment loads in rivers. This curve is the means by which sediment loads may be disaggregated into a time distribution of sediment concentrations.

Substitution of (4) into (3) gives:

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

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

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

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

If soil conservation reduces sediment load L then the right hand side of equation (6) must also reduce. Flow 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). (These were in response to storm impacts and not land use change). 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 flow range. We assume the same here; that is, when sediment loads are reduced to a fraction p of what they were, then the sediment concentration rating curve is also reduced to a fraction p of what they were throughout the flow 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 6 are reduced by 50% to give those in Table 7.

Table 7 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

4.2 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 p of what it was then the turbidity will be reduced to:

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

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

Table 8 shows how the reduced turbidity percentiles may be estimated from the reduced sediment loads.

Table 8 Estimation of decreased turbidity percentiles from reduced sediment loads

	Hatea River	Waiarohia River	Otaika River
value of *a* from Figure 15, Figure 16 and Figure 17	1.14	1.0	1.0
reduced sediment load as fraction of old	*p*	*p*	*p*
percentiles of sediment concentration as fraction of old	*p*	*p*	*p*
percentiles of turbidity as fraction of old	$p^{1.14}$	*p*	*p*

4.3 Water clarity

Water clarity is inversely linearly related to turbidity in log-log space (Figure 12, Figure 13, Figure 14):

$$log10(wc) = m\ log10(turb) + c \quad (10)$$

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

$$wc = 10^c\ turb^m \quad (11)$$

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

$$wc' = wc\ \ q^m \quad (12)$$

Table 9 shows how the increased water clarity percentiles may be estimated from the reduced sediment loads.

Table 9 Estimation of increased water clarity percentiles from reduced sediment loads

	Hatea River	Waiarohia River	Otaika River
value of *m* from Figure 12, Figure 13, Figure 14	-0.95	-0.78	-0.95
reduced sediment load as fraction of old	*p*	*p*	*p*
percentiles of sediment concentration as fraction of old	*p*	*p*	*p*
percentiles of turbidity as fraction of old	$p^{1.14}$	*p*	*p*
ratio of new over old water clarity percentiles	1/(*p***1.14)**0.95	1/*p***0.78	1/*p***0.95

Table 10 gives an example of how to estimate increases in water clarity as a result of a 50% reduction in sediment loads.

Table 10 Estimation of increased water clarity percentiles from 50% reduction in sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of *m* from Figure 12, Figure 13, Figure 14	-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)

4.4 Euphotic depth

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

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

Table 11 shows how the increased euphotic depth percentiles may be estimated from the reduced sediment loads.

Table 11 Estimation of increased euphotic depth percentiles from reduced sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of *m* from Figure 12, Figure 13, Figure 14	-0.95	-0.78	-0.95
reduced sediment load as fraction of old	*p*	*p*	*p*
percentiles of sediment concentration as fraction of old	*p*	*p*	*p*
percentiles of turbidity as fraction of old	$p^{1.14}$	*p*	*p*
ratio of new over old euphotic depth percentiles	1/(*p***1.14)**0.5	1/*p***0.5	1/*p***0.5

Table 12 gives an example of how to estimate increases to euphotic depth percentiles from 50% percent reduction in sediment loads.

Table 12 Estimation of increased euphotic depth percentiles from 50% reduction in sediment loads.

	Hatea River	Waiarohia River	Otaika River
value of *m* from Figure 12, Figure 13, Figure 14	-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)

4.5 Embeddedness

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

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

5 Summary/discussion

The SedNetNZ model has been implemented for the Whangarei Harbour Catchment. Annual sediment loads (t/yr) for 11 reporting zones were estimated for the current land cover: Hatea river (4482), Waiarohia river (4932), Limeburners creek (1038), Otaika creek (11204), northern-inner harbour (2143), southern-inner harbour (2424), northern-middle harbour (2944), southern-middle harbour (555), northern-outer harbour A (1238), northen-outer harbour B (781), southern-outer harbour (0). Annual sediment loads (t/yr) were also estimated for pre-human vegetation (i.e. indigenous forest everywhere): Hatea river (1960), Waiarohia river (2324), Limeburners creek (366), Otaika creek (4019), northern-inner harbour (1264), southern-inner harbour (556), northern-middle harbour (2107), southern-middle harbour (304), northern-outer harbour A (590), northern-outer harbour B (488), southern-outer harbour (3). On average the pre-human sediment loads are about 45% of the current sediment loads.

There are only three sites in the Kaipara Harbour Catchment where sediment loads have been measured. These are Kaipara at Waimauku, Kaukapakapa at Taylors, and Hoteo at Gubbs (Curran-Cournane et al., 2013). Table 5 compares the measured sediment loads with those predicted by SedNetNZ. Modelled sediment load is about the same as measured for Kaukapakapa, 50% more for Hoteo, and about twice for the Kaipara river. These ratios show reasonable agreement given that the measurement records are only for several years and don't include major events yet and are based on surface sampling of sediment concentration which will generally underestimate sediment loads.

Table 13 Comparison of measured sediment loads with those predicted by SedNetNZ

	Kaipara at Waimauku	Kaukapakapa at Taylors	Hoteo at Gubbs
Measured sediment load (t/yr)	5200	4700	19800
Modelled sediment load (t/yr)	10000	3700	33300
Length of record (yr)	1.0	2.6	2.6

Temporal disaggregration of sediment loads would normally be done through a sediment concentration rating curve. A measured time distribution of water flow may then be converted to a time distribution of sediment concentration. However, insufficient sediment concentration data is available for rivers in the Whangarei Harbour Catchment to derive a robust sediment concentration curve. Hence disaggregation was achieved through the more numerous turbidity samples.

A time distribution of turbidity was generated through a turbidity rating curve. A time distribution of sediment concentration was inferred from the turbidity time distribution and the relationship between sediment concentration and turbidity. Similarly a time distribution was inferred for water clarity, and also euphotic depth, except we use a relationship between euphotic depth and turbidity given by Davies-Colley and Nagels (2008) rather than fit a curve to data (as there was no measured data on euphotic depth). Embeddedness as defined here does not vary in time and is given by the sediment concentration occurring at one quarter of the mean annual flow. This is 122 g/m3 for the Waiarohia River gravel bed river. The Otakia and Hatea rivers are not gravel bed.

The percentiles of these time distributions depend on sediment loads through the impact of sediment loads on sediment concentration. Any percentage reduction of sediment load as a result of land use change or soil conservation in a catchment will result in the same percentage reduction of percentiles of sediment concentration. The relationship of turbidity, water clarity, and euphotic depth to sediment concentration will then control the percentage change in their percentiles. For the Hatea, Waiarohia, and Otaika rivers, a 50% reduction in sediment load will give reductions in the percentiles of sedment concentration by 50% and reductions in the percentiles of turbidity by 55%, 50%, and 50% respectively. A 50% reduction in sediment load will give increases in the percentiles of water clarity by 112%, 71%, and 93% respectively. A 50% reduction in sediment load will give increases in the percentiles of euphotic depth by 48%, 41%, and 41% respectively. A 50% reduction in sediment load will reduce embeddedness also by 50%.

Two important assumptions are required in these methods. The first is that the sediment concentration curve is proportional to the sediment load in the river. Hence percentiles of sediment concentration will change by the same percentage change as sediment load. Certainly, this is true for the average sediment concentration as the sediment load is just the summation of sediment discharge, which in turn is the product of sediment concentration and flow. However, it is uncertain whether this holds at low and high flows as well. 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 instances the sediment concentration rating curve changed by the same relative amount over the full range of flow. However, the changes were in response to storm impacts and not land use change. The second assumption is that the relationships between turbidity and water clarity, euphotic depth, and sediment concentration, do not change at a site. This would be expected if the source of sediment is much the same, so that particle size of sediment stays the same. However, if land use change/soil conservation brings about a reduction of sediment load, then the source of sediment might change and may also bring about a change in particle size of sediment. Both these assumptions need to be tested in future research.

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Appendix – Derivation of turbidity percentiles from flow percentiles

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

$$P(x) = \int_0^x f(s)\mathrm{d}s \qquad \text{(A1-1)}$$

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

$$P(y) = \int_0^y f(g)\mathrm{d}g \qquad \text{(A1-2)}$$

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.