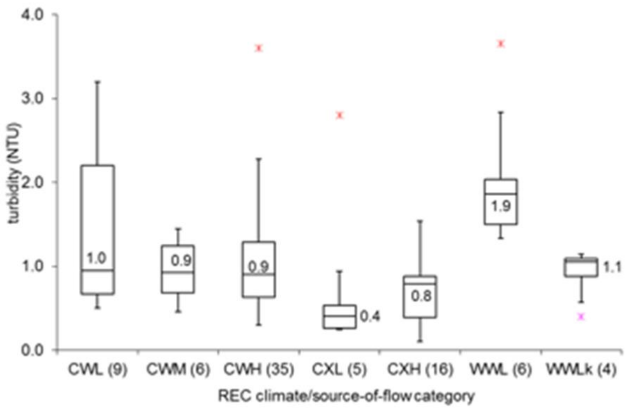
# Sediment Attribute Stage 1b

## Proposed classification for suspended sediment

*Prepared for Ministry for the Environment*

*March 2017*



Prepared by:
Craig Depree

For any information regarding this report please contact:

Craig Depree
Water Quality Scientist - Group Manager
Environmental Chemistry and Ecotoxicology
+64-7-856 1750
craig.depree@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 11115
Hamilton 3251

Phone +64 7 856 7026

NIWA CLIENT REPORT No: 2017076HN
Report date: March 2017
NIWA Project: MFE16211

| Quality Assurance Statement | | |
|---|---|---|
| Dr Neale Hudson | Reviewed by: | |
| Alison Bartley | Formatting checked by: | A. Bartley |
| Dr David Roper | Approved for release by: | |

*Cover photo: Redfin bully [S. Moore, Landcare] and Mayfly [N. Philips, NIWA]*

# Contents

## Tables

## Figures

# Executive summary

The purpose of Stage 1B was to develop a classification system that differentiates (i.e., classifies) New Zealand rivers according to "reference state" variation in environment state variable (ESV) characteristics.

Work was divided into suspended sediment (NIWA, this report) and deposited sediment (Cawthron), which is *reported separately* (Clapcott and Goodwin 2017).

To characterise reference state variation, we derived up-to-date land-cover information for the catchments of more than 800 sites where suspended sediment (SS) is measured. This was done using the latest version of the New Zealand Land-cover Database (v4.1). Using these data, a series of thresholds (or rules) were developed to define the upper bounds of minimally disturbed condition (MDC) sites that were used to define the extent of 'reference state' variation. Having established the extent of reference state variation, determination of a classification system required to address natural state variation commenced. The approach followed made use of the six levels of information embedded in the River Environment Classification (REC) system.

The 'reference state variation' for suspended sediment (determined using MDC site medians) was relatively small, with maximum values of 6.0 g/m$^3$, 1.1 m and 3.3 NTU for TSS, clarity and turbidity respectively. Limiting the natural state variation to the 95$^{th}$ percentile of MDC sites, the respective maximum values for TSS, clarity and turbidity were 3.9 g/m$^3$, 1.5 m and 2.5 NTU; and median values were 2.0 g/m$^3$, 3.5 m and 0.8 NTU.

Warm REC climate classes had, on average, 2-times higher turbidity values. This finding was supported by the work of McDowell et al. (2013), who predicted reference site median values for 12 cool and 6 warm climate categories to be approximately 2.0 and 1.0 NTU, respectively. In the context of ecological relevance, however, this difference is arguably not meaningful – for example, >95% of MDC (i.e., 'reference') sites had clarity that exceeded 1.4 m, with turbidity values less than 2.5 NTU. Other work has demonstrated these latter values to be conservative biological effect thresholds, based on reaction distances of trout during drift feeding.

On balance, I recommend to not classify (i.e., differentiate) flowing waters in New Zealand for the purpose of managing SS for ecosystem health. That is, we recommend proceeding without a classification system for suspended sediment.

## With respect to redundancy of sediment ESVs (including turbidity)

Following extensive analysis of national data representing all regions, we concluded the following:

- Euphotic depth is largely irrelevant for the management of SS in flow waters.
- In general, TSS has a method detection limit that is too high to enable it to be used to determine reference state variation.
- Clarity and TSS are not routinely monitored by all councils.
- Turbidity is measured by all councils.
- Turbidity is more suited (relative to clarity) for managing in the 'dirtier end of the SS spectrum'.

- Correlations between TSS and turbidity and TSS and clarity were relatively weak (using site medians), which reduces confidence when converting between these metrics – this would be a potential limitation if TSS were adopted as the SS attribute.
- At national scale, clarity and turbidity correlated well ($R^2$=0.8), and for dirtier water, the conversion from turbidity to clarity was more robust than was conversion from clarity to turbidity.

Accordingly, we recommend that one ESV will be sufficient for managing suspended sediment in flowing waters for ecosystem health (analogous for deposited sediment). If a single suspended sediment metric (or ESV) is adopted, benefits may be realised from using one based on turbidity.

# 1 Introduction

## 1.1 Project context

Increased sediment input arising from human modification of the landscape and ongoing land use activities has the potential to impact significantly on freshwater values. Increased sediment inputs adversely impact freshwaters in several ways:

- Suspended fine sediments change visual clarity and light penetration, two key optical characteristics of water (Davie-Colley et al. 2014).
- Reduced visual clarity impairs the foraging efficiency of fish and birds that hunt by sight.
- Reduced light penetration can inhibit growth of aquatic plants and algae.
- Sediments suspended in the water column can clog or physically abrade gills, affect the migration of fish species and reduce food quality and quantity.
- Deposition of fine sediment on the beds of rivers, lakes and estuaries degrades benthic habitat.

The National Policy Statement for Freshwater Management (NPS-FM) requires regional councils, through their regional plans, to set freshwater objectives that provide for freshwater values, and to set limits and management actions to achieve those objectives. The NPS-FM includes the National Objectives Framework (NOF), which defines attributes that assist regional councils to set freshwater (i.e., numeric) objectives and justifiable policies (including limits) for achieving these.

The NOF does not currently include attributes for sediment despite the importance of this contaminant in freshwaters in New Zealand. The difficulties associated with defining nationally applicable freshwater objectives and attributes for sediment were not satisfactorily resolved when the 2014 NPS-FM was released. The development of sediment attributes has been identified as a priority for revision of the NPS-FM. A team of NIWA and Cawthron scientists is currently working on behalf of the Ministry for the Environment (MfE) to produce a set of attribute bands for sediment that will cover as many of New Zealand's riverine environments as possible.

## 1.2 Project structure

The project comprises three stages (or phases).

### Stage 1A:

- Update and extend the sediment environment state variable (ESV) data used in a previous sediment project (Hicks et al. 2016).
- Collate relevant biological data.
- Report the result of Part 1 of field work associated with the discharge of sediment from Waihi Dam and, if required, provide a plan for Part 2 of field work.

### Stage 1B:

- Derive a draft national classification system for deposited and suspended sediment ESVs.

### Stage 2:

- Analyse biological effects in response to sediment ESV gradients.
- Recommend new indicators suitable for determining sediment pressure.
- Recommend proposed sediment attributes.

## 1.3 Specific components of Stage 1B

This report is the contracted deliverable for Stage 1B of the project (item 4 below), which involves providing the following services to the Ministry:

1) Develop a classification system that differentiates New Zealand rivers according to "reference state" variation in ESV characteristics. A classification may apply to all ESVs, or different ESVs may require a separate classification (e.g., for one for deposited sediment and another for clarity). These classification(s) need to account for variations in catchment sediment yields and other characteristics that drive variation in ESVs. This includes sediment characteristics (e.g., in size distribution) and environmental influences, such as of channel hydraulics on deposited sediment. The spatial resolution of this classification system must be justified by an analysis of the precision with which ESVs can be characterised (e.g., mean or median values), given monitoring constraints. The classification(s) needs to account for the definition of "reference state", being aware that current natural land cover may be affected by legacy issues (e.g., historic land clearance) and ongoing disturbance (e.g., pigs and deer).
2) Summarise the relevant ESV characteristics (e.g., as mean, median or other exceedance value proposed as the frequency criterion), within classes defined by the classification system for both reference state and current conditions.
3) Following analysis, summarise the relationship(s) between the ESVs, considering whether any of the four ESVs are redundant or unnecessary. This analysis would be undertaken in the context of the classification system.
4) Prepare and provide a report for the Ministry (Stage 1B Report) by 28 February 2017 containing:
    a. the classification system set out in 1 above
    b. the analysis of ESV characteristics set out in 2 above
    c. the analysis of the relationship between the ESVs set out in 3 above, and
    d. provide recommendations to the Ministry regarding:
        i. the suitability/adequacy of the classification system, and
        ii. analysis of ESV characteristics that should continue to Stage 2.

Although the contracted delivery date for the Stage 1B report was 28 February 2017, the Ministry granted an extension to 17 March 2017.

## 1.4 Structure of report and clarification of scope

### 1.4.1 Report layout

The content of this report is limited to the three proposed suspended sediment ESV's (Section 2) and contains the required content outlined in Section 1.3 (point 4).

*Note, that the proposed classification system for deposited sediment in NZ flowing waters is presented in a separate Cawthron report (Clapcott and Goodwin 2017).*

### 1.4.2 Suspended sediment ESV's:

Whereas a single attribute has been recommended to manage the issues relating to the deposition of fine sediments on stream beds, three sediment ESVs were recommended to manage suspended sediment (i.e., within the water column). The three suspended sediment ESVs include:

- **Suspended sediment** – direct measure of suspended sediment concentration (SSC) or total suspended sediment (TSS). For the purposes of this report, TSS and SSC measurements are considered identical and are collectively referred to as TSS, and is reported as concentration units ($g/m^3$).
- **Clarity** – a measure of the horizontal viewing distance (m) of a black disc through the water column. Visual clarity is inversely related to TSS, and therefore provides an indirect (or proxy) measure of TSS.
- **Euphotic depth** – a measure of vertical light penetration, expressed as the depth (m) where photosynthetically available radiation (PAR) is 1% of the surface value.

At the first commissioning meeting, it was decided that euphotic depth is of low relevance when managing sediment (for ecosystem health purposes) in flowing waters (i.e., rivers and streams). Accordingly, euphotic depth was excluded as a potential suspended sediment ESV. A detailed justification of this decision is provided in Section 1.5.

### 1.4.3 Inclusion of turbidity data as a proxy measure for suspended sediment

Although not initially proposed as a potential sediment ESV for suspended sediment, turbidity is a widely used proxy measure of suspended sediment concentration (SSC). Previous studies have shown strong correlations between turbidity and TSS (e.g., Holliday et al. 2003, Davies-Colley et al. 2014). Given the amount of turbidity data available (from >800 sites over tens of years), it was decided that turbidity data would be included (along with visual clarity data) as a useful proxy measure of suspended sediment. It is acknowledged that there are some limitations regarding turbidity measurements, which are summarised in Davies-Colley and Smith (2001). The justification for including turbidity, for data exploration and to provide guidance on the classification system, are summarised below:

a. All regional councils (RC's) and unitary authorities monitor turbidity as part of their state of the environment monitoring, whereas almost a quarter do not regularly measure visual clarity – this includes Otago, Gisborne, Marlborough and Auckland councils.

b. Turbidity is used internationally for water quality assessments, and the biological effects of suspended sediment are generally expressed in terms of either TSS or turbidity.

c. Clarity measurements span a large range (e.g., 4-16 m) at the 'cleaner' end of the TSS spectrum, but are relatively compressed (<0.5 m) at the 'dirtier' end, for example where viewing distances are <0.5 m (Ausseil & Clark 2007). In contrast, turbidity spans a large range at the dirty end of the spectrum where adverse biological effects are likely. It is therefore potentially more useful for defining wide ranges of TSS concentrations (using turbidity as a proxy measure) when looking at biological responses along suspended sediment gradients.

### 1.4.4 Clarification of scope of the classification system

The contract wording is provided in Section 1.3 (item 1) in full. To ensure clarity, the key contractual requirements are discussed briefly in this section, with the contract wording shown in italics.

- *Develop a classification system that differentiates New Zealand rivers according to "reference state" variation in ESV characteristics.*

Deposited and suspended sediment measurements have high temporal variability. At a given site, suspended sediment can vary over 3-4 orders-of-magnitude depending on river flow. For suspended sediment, we have used the central tendency of the data (i.e., median) to characterise the 'reference state' variation, which in turn was used to inform the recommended approach to differentiate rivers into justifiable classes.

- *The classification(s) needs to account for the definition of "reference state" given that current natural land cover may be affected by legacy issues (e.g., historic land clearance) and ongoing disturbance (e.g., pigs and deer).*

The approach we have taken with suspended sediment is to use data from all available water quality (WQ) monitoring sites (i.e., regional state of the environment (SoE) and National River Water Quality Network (NRWQN) monitoring sites. Using upstream catchment landcover (LCDB v4.1) for all WQ sites, rules and/or thresholds were developed to define a subset of WQ sites that ranged from natural state to a minimally disturbed condition (MDC) sites. Sites defined as being in MDC were used by McDowell et al. (2013) to validate predicted reference state conditions for water quality variables. Using real data from MDC sites to characterise 'natural state' variation means that legacy issues such as land clearance (and hence regenerating native landscapes) and ongoing disturbance from introduced animals are taken into account. The use of this more permissive (as opposed to purist) definition of 'reference state' recognises the relevance of catchments where major landcover types are native, but not necessarily natural (e.g., where the undisturbed state would be undisturbed indigenous forest). Regenerating catchment landcover types are expected to yield (on average) higher TSS in flowing waters than undisturbed indigenous forest, but in the context of regulatory timeframes, these regenerating catchments may be regarded as *contemporary* or *pseudo* reference sites. However, in the interest of using consistent nomenclature (McDowell et al. 2013), the subset of *contemporary* reference sites is referred to in this report as *minimally disturbed condition* (MDC) sites.

- *The classification(s) needs to account for the variation in catchment sediment yields and other characteristics that drive variation in the ESVs. This include the sediment* *characteristics (e.g., size distribution) and environmental influences, such as channel hydraulics on deposited sediment.*

Accounting for the variation in catchment sediment yields was raised as an issue by the client at the November 10 (2017) progress meeting. The response of the project team was that the focus was on the 'natural state' variation in the instream sediment ESV values (including turbidity), rather than variation in catchment sediment yields. Basically, if two catchments had catchment sediment yields that differed by orders-of-magnitude, but where median visual clarity were comparable or similar, only the latter (i.e., the instream measure of sediment pressure on ecosystem health) would be considered relevant. In simple terms, organisms living in the water column or on the bed, only 'see' (i.e., experience) the pressure exerted by instream measures of suspended and deposited sediment, respectively. As such, if two rivers had similar median visual clarity, but 100-fold different sediment yields, it is anticipated that the biological response in these two rivers would reflect the similar instream ESV value. The link between sediment yields and instream sediment ESVs was considered in the Stage 1 sediment project (Hicks et al. 2015), whereas the current project is focussed exclusively on the instream values of sediment ESVs (suspended and deposited), and the effects of these values on ecosystem health (based on fish and macroinvertebrate responses).

- *Consideration of biological relevance when developing the classification systems for suspended and deposited sediment*

Although not included in the contract, this issue was discussed at the commissioning meeting and at progress meetings. Although the wording of the contract implies that the classification system would be prepared without considering biological responses, as Stage 1B work progressed it became apparent that differentiation of rivers according to natural state variation should consider whether the differences between proposed classes are meaningful with respect to likely biological response thresholds. Incorporating biological relevance in Stage 1B of the project (instead of Stage 2) is a pragmatic approach that should enable a more streamlined process when determining biological responses to suspended and deposited sediments in Stage 2 of the project.

For example, if the variation in 'reference state' was between 0.1 and 20 NTU (nephelometric turbidity units, widely used when expressing turbidity), and biological effects were anticipated at levels as low as 5 NTU, then a classification system is relevant. However, if the variation ranged between 0.1 and 2 NTU, then any differentiation of rivers, even if statistically significant, would not be ecologically significant because the entire natural state variation (based on central tendency of the data) is considerably less than the anticipated biological effects threshold. In this case, the classification system would not be meaningful, and therefore could not be justified.

## 1.5 Euphotic depth: Justification for excluding as a suspended sediment ESV for flowing waters

Justification for excluding euphotic depth as a suspended sediment ESV in flowing water is provided in Appendix A. The key findings of this technical discussion are presented below.

Davies-Colley and Nagels (2008) found that although suspended sediment was the main controller of light penetration into NZ rivers, coloured dissolved organic matter (CDOM) also limited light penetration. In NZ's generally shallow rivers, light 'shading' by the water column is seldom likely to be a major constraint on plant growth, unlike shading by riparian vegetation. Large (deep) rivers with more persistent loads of suspended materials (leading to higher light-attenuation) may be severely light-limiting (e.g., Julian et al. 2008). In NZ, such conditions are mostly confined to episodic and transient flood flows, which are deeper and more light-attenuating than baseflows.

Any suspended sediment attributes would apply more to baseflow conditions in flowing waters, making it reasonable to assume that adverse ecological effects arising from low light penetration is largely irrelevant (on a national-scale). To justify this assertion, the model framework from Davies-Colley and Nagels (2008) was used to estimate benthic irradiance (as a fraction of incident radiation) for 'average' and 'dirty' rivers at depths of 1 and 2 m (Table 1-1).

**Table 1-1: Irradiance (PAR) at the bed of a NZ river as a fraction of incident irradiance.**

| River state scenario (i.e., SS and CDOM) | Visual clarity (m) | CDOM ($g_{340}$, 1/m) | $K_d$ (PAR) (1/m) | Bed irradiance as a % of incident irradiance $E_{bed}/E_o$ | |
|---|---|---|---|---|---|
| | | | | 1 m depth | 2 m depth |
| average SS; average CDOM | 1.28 | 4.10 | 1.03 | 38 | 15 |
| High SS; average CDOM | 0.36 | 4.10 | 1.95 | 16 | 2.7 |
| High SS; high CDOM | 0.36 | 12.2 | 2.46 | 10 | 1.0 |

For a NZ river 1 m deep (average), exhibiting average light-attenuation (median clarity = 1.28 m), 38% of the incident light (i.e., light at the surface) reaches the stream bed. These conditions would not be light-limiting to most benthic plant communities. In a very 'dirty' and coloured NZ river (95$^{th}$ %ile clarity and CDOM), at 1 m depth 10% of incident light will reach the bed. Under these conditions the growth of some light-demanding benthic plants may start to be constrained (Duarte 1991). If the water was deeper, light limitation would be more severe. For example, if the depth of water in the previous example was increased to 2m, the proportion of incident light reaching the bed would decrease to 1%, extinguishing most benthic plants.

These simple calculations suggest that light limitation by water shading is not often an issue in NZ rivers, making specific protection of light penetration in rivers unnecessary.

# 2 Suspended Sediment

## 2.1 General approach used to develop the proposed classification system

The contract required development of a classification system for suspended sediment that differentiates New Zealand rivers according to variation in "reference state" ESV characteristics. The approach taken for the suspended sediment component aimed to find the simplest classification possible. To this end, the development of the suspended sediment classification system (Stage 1B) took the following approach:

1) Maximise the use of real data – national and regional river water quality monitoring networks comprise monthly measurement at more than 800 sites (turbidity).

2) Define 'reference state' in a manner that is relevant to anthropogenic drivers of suspended sediment in the contemporary New Zealand environmental setting. This involved using the latest land cover database (LCDB4) and defining a series of thresholds to identify a subset of sites representing minimal disturbed condition (MDC).

3) Characterise the 'reference state' variation using the subset of MDC sites defined in (2), and explore the *statistical significance* of reference state variation when grouped by relevant categories (e.g., REC-based levels such as climate, topography and geology).

4) Compare measured reference state variation (for MDC subset in 3) with modelled reference state for flowing waters in New Zealand. McDowell et al. (2015) modelled reference state for suspended sediment (TSS, turbidity and clarity) for rivers group by REC "climate" (1$^{st}$ level) and "topography" (2$^{nd}$ level) factors.

5) Consider *ecological significance* versus *statistical significance* of 'reference state' variation determined in (3). The approach taken for suspended sediment is that statistically significant differences in 'reference state' variation by relevant groupings, on their own, do not justify differentiating flowing waters into different classes. A necessary step is determining the ecological relevance of natural state variation by comparing it with estimated biological effects thresholds (i.e., taken from the literature).

6) Propose a justifiable classification system for suspended sediment.

## 2.2 Methods

### 2.2.1 Data

TSS data for the period 2004-2012 was obtained from the database compiled by Hicks et al. (2015), comprising 589 sites. Of these, 514 sites satisfied the criterion of having at least 18 data points between 2004 and 2012. Data were arranged by site via a pivot table (Excel) from which median value for each site were calculated.

Turbidity and visual clarity data for the period 2004-2013 was obtained from the database compiled by Larned et al. (2015) – this dataset was not updated by Hicks et al. (2015). This dataset comprised of 833 turbidity and 722 visual clarity sites. These data were supplied as a file containing summary statistics (median, means, and percentiles) for each water quality variable and site.

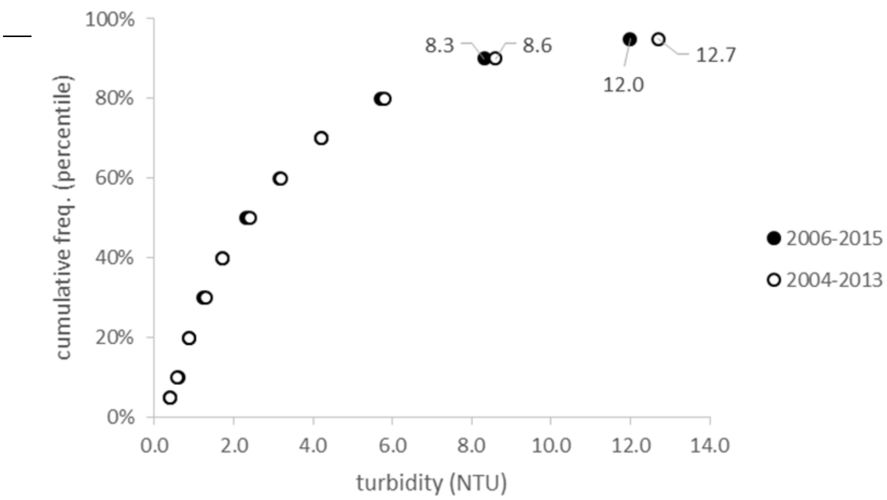
A summary of suspended sediment data, by regional authority, is provided in Table 2-1.

Efforts are underway to update the clarity and turbidity datasets to include data for the period 2006-2015. When comparing data for these two periods, it appears that there could be up to 100 additional sites in the latter period. However, there are several anomalies in the NZReach assignment of water quality sets in the 2016 LAWA data file, which are still being resolved. Turbidity and clarity data (not TSS) will be updated during preparation of the final (Stage 2) report. The main driver for updating the suspended sediment data is to capture additional reference sites (referred to as minimally disturbed condition (MDC) sites, Section 2.3). Using turbidity data (Figure 2-1), the distributions in suspended sediment ESVs for the two time periods (i.e., 2004-2013 and 2006-2015) are not expected to differ significantly.

**Table 2-1: Summary of the number of water quality (WQ) sites with suspended sediment ESV data (including turbidity) used for Stage 1B.**

| Regional authority[1] | | Number of WQ sites by variable | | |
|---|---|---|---|---|
| | | TSS[2] | Clarity | Turbidity[3] |
| AC | Auckland Council | 29 | 26 | 29 |
| BOP | Bay of Plenty Regional Council | 19 | 32 | 35 |
| ECAN | Environment Canterbury | 79 | 89 | 91 |
| ES | Environment Southland | 67 | 67 | 67 |
| GDC | Gisborne District Council | 17 | | 18 |
| GWRC | Greater Wellington Regional Council | 52 | 52 | 52 |
| HBRC | Hawkes Bay Regional Council | 44 | 49 | 49 |
| HRC | Horizons Regional Council | 79 | 82 | 82 |
| MDC | Marlborough District Council | 30 | | 32 |
| NCC | Nelson City Council | 27 | 28 | 28 |
| NRWQN | National River Water Quality Network | | 77 | 77 |
| NRC | Northland Regional Council | 20 | 31 | 31 |
| ORC | Otago Regional Council | 41 | 1 | 44 |
| TDC | Tasman District Council | 10 | 43 | 43 |
| TRC | Taranaki Regional Council | | 10 | 10 |
| WCRC | West Coast Regional Council | | 37 | 37 |
| WRC | Waikato Regional Council | | 98 | 107 |
| **Total** | | **514** | **722** | **832** |

[1] NRWQN data set includes sites from the 16 regions. [2] only includes sites with ≥18 data. [3] excludes one site monitored by Christchurch City Council which would increase the total to 833.




| Statistic | Data period | |
|---|---|---|
| | 2006-2015 | 2004-2013 |
| min | 0.1 | 0.1 |
| 25th %ile | 1.1 | 1.1 |
| median | 2.3 | 2.4 |
| 75th %ile | 4.9 | 5.1 |
| max | 127.0 | 80.0 |
| IQR | 3.8 | 4.0 |

**Figure 2-1: Cumulative frequency (percentile) distribution of turbidity data for 2006-2015 (solid black circle) and 2004-2013 (open black circles).** Summary statistics in table.

### 2.2.2 Generating LCDB v4.1 land-cover data for suspended sediment sites

While developing an up-to-date definition of 'reference state', which involved setting land-cover thresholds to bound an acceptable level of catchment 'disturbance' (referred to as minimally disturbed condition or MDC sites), land-cover was determined using the latest version of the New Zealand Land Cover Database (LCDB v4.1).

Each site has a reach identifier 'NZReachID' assigned to it that links it to River Environment Classification (REC) streams. The REC reach (stream) data has nodes that link the reaches to form a drainage network. For a given site, all upstream reaches were selected using 'from' and 'to' node information available in the REC stream network dataset. Watershed polygons for the selected reaches from the REC database were then combined to make the upstream catchment polygon. Using a Geographic Information System, this catchment polygon was then intersected with the LCDB v4.1 dataset (layer) to generate the area of each land-cover class (a total of 35 – refer toTable D-7, Appendix D) for the upstream catchment of all 833 water quality sites. Validation of this method is provided in Appendix C.

## 2.3 Defining 'reference sites'

### 2.3.1 Using REC-based land use classifications

#### Stage 1A summary

The identification of possible reference sites, based on the REC land cover classification, were briefly explored as part of the Stage 1A report (Depree and Clapcott, 2016). Briefly, we tentatively proposed the idea of primary and secondary reference sites (Table 2-2). Primary reference sites comprised the indigenous forest (IF) class, while secondary sites consisted of scrub (S), tussock (T), and possibly exotic forest (EF) – given that EF showed a similar cumulative distribution to S and T classes (refer to Appendix A).

**Table 2-2: Summary of land cover classes (REC2) potentially relevant for identifying reference or MDC sites.** Turbidity and clarity data shown. Adapted for data in Stage 1a report (Depree and Clapcott, 2016).

| REC land cover | Reference | Number of sites | |
|---|---|---|---|
| | | Clarity | Turbidity |
| Indigenous forest (IF) | primary | 146 | 159 |
| Scrub (S) | secondary | 21 | 27 |
| Tussock (T) | secondary | 21 | 33 |
| Exotic forest (EF) | secondary[1] | 31 | 36 |

[1] suggested as a secondary reference because the cumulative distribution was similar to that of tussock (T) and scrub (S) land use classes.

Using these REC land cover definitions, the number of primary reference sites (IF) with clarity and/or turbidity data were 146 and 159, respectively – this corresponds to 20% of the total number of sites. Including secondary reference sites increased this to a maximum of 219 and 255 sites with clarity and/or turbidity respectively (30% of all sites).

In hindsight, EF should not be considered as a reference site because periods of high sediment yield occur during harvesting cycles resulting in increased suspended sediment concentrations. Excluding EF when using the REC definition of natural land cover (i.e., IF, S and T), the total number of clarity and turbidity 'reference' sites is 188 and 219, respectively. This corresponds to one-quarter of all the monitoring sites.

### Limitations of REC land cover classifier for sites

The REC land cover classification was based on information derived from the New Zealand Land Cover Database (LCDB). LCDB classes were simplified into 9 groupings (Table D-1, Appendix D), namely: bare-ground (B); indigenous forest (IF); Scrub (S); Tussock; (T); wetlands (W), exotic-forest (EF); pastoral (P); urban (U) and miscellaneous (M; includes mangrove, riparian willows, coastal sands). The REC defines IF, S and T as natural land-cover types.

The REC assigns an overall, or dominant, land-cover according to the dominant type of cover (expressed as percentage), with exceptions for catchments where the proportion of anthropogenic land-cover types exceed a threshold value. For urban (U) and pastoral (P), the threshold values are 15 and 25% respectively – so if an upstream catchment is 83% IF and 17% U, the predominant land-cover (i.e., overall REC category) assigned to that river site is urban (U).

For Stage 1B, the decision was made to not proceed with REC-based land-cover categories because of the following potential issues:

1) The 1997 LCDB used for the REC is out of date. LCDB v4.1 was released in 2015, providing land-cover for NZ for 20012/13 based on higher resolution, improved image analysis.

2) REC thresholds for proportion of urban and pastoral of 15 and 25%, respectively, are considered too permissive to define upper bounds of MDC sites.

3) Assignment of overall land-cover category is too coarse – for example, a catchment area comprising 76% IF and 24% pastoral would be categorised as 'IF' and hence a reference site. In contrast, a catchment comprising 74% IF and 26% pasture would be categorised as 'P' and would be an impact site.

4) REC scrub (S) category is defined as natural land-cover; however in LCDB4, scrub is differentiated into three native (e.g., *Manuka/kanuka*, *matagouri*, *broad-leaved indigenous hardwoods*) and one exotic (e.g., *mixed exotic shrubland* and *gorse and/or broom*) scrub types.

5) REC scrub (S) category is regarded as natural, but many scrub forms represent landscapes regenerating from pastoral use. It is hypothesised that such land cover types yield suspended sediment ESV values that are intermediate between true natural (i.e., IF) and pasture (P).

6) REC tussock (T) category is regarded as natural land-cover category, but makes no distinction between long-tussock and short tussock. In LCDB v4.1, short tussock is combined with exotic sward grassland into a category called *low producing grasslands*. It is unclear how the REC 'T' category relates to the v4.1 class, and whether this natural REC category contains significant areas of extensively grazed, poor quality pasture.

A list of the 35 land-cover classes used in LCDB v4.1 are provided in Table D-7, Appendix D.

When identifying reference benchmarks for macroinvertebrate community metrics, Clapcott et al. (2016) defined the following thresholds:

- >85% native cover
- <15% light pastoral cover
- <5% heavy pastoral cover
- 0% urban cover, and
- nil consented water abstraction.

The last two conditions, in particular, appear to be very specific to macroinvertebrates, as opposed to management of suspended sediment. The classes heavy pastoral and light pastoral are no longer used in LCDB (v4.1).

### 2.3.2 Land-cover thresholds for defining MDC sites (also known as reference sites)

To overcome limitations associated with the generality of the REC land-use (and out of date LCDB definitions), a new working definition for reference sites - one specifically related to a suspended sediment ESV - was developed. This working definition was based around defining land-cover type thresholds (LCDB v4.1) for MDC sites which would adequately characterise the 'natural state' variation in suspended sediment measures.

When developing thresholds for land cover types using LCDB v4.1, we focussed on turbidity because this measure of suspended sediment represented the largest number of sites (i.e., 833, compared to 722 and 514 for clarity and TSS respectively).

The proposed list of thresholds to define the upper bounds of MDC sites are summarised in Table 2-3.

**Table 2-3: LCDB v4.1 land-cover type thresholds for upper bound of minimally disturbed condition (MDC) sites.** Refer to Table D-1, Appendix D for descriptions of all LCDB v4.1 land-cover classes.

| Landcover type (LCDB v4.1 class) | Threshold | Comment/notes |
|---|---|---|
| **Natural**<br>Combination of 15 land-cover types (refer to comments/notes column) | >75% | Lower than Clapcott et al. 2016 of 85%, however this definition excludes short tussock and non-native types of scrub/shrublands. Accordingly, this threshold is difficult to compare with those derived using older versions of LCDB.<br>Natural land-cover types included: Indigenous Forest (69); Broadleaved Indigenous Hardwoods (54); Manuka and/or Kanuka (52); Matagouri or Grey Scrub (58); Sub Alpine Shrubland (55); Tall Tussock Grassland (43); Fernland (50); Flaxland (47); Permanent Snow and Ice (14); Sand or Gravel (10); Alpine Grass/Herbfield (15); Lake or Pond (20); River (21); Estuarine Open Water (22); Herbaceous Freshwater Vegetation (45). |
| **Heavy pastoral**<br>High producing exotic grassland (40) + short-rotation cropland (30) | <10% | Lower than REC threshold for pastoral land-cover (including horticultural cropping) of 25%. Greater than Clapcott et al. (2016) reference site definition of 5%. Settled on 10% as turbidity showed no apparent correlation with this combined land-cover type (Figure E-1, Appendix E). This is consistent with deposited sediment reference state definition (Section **Error! Reference source not found.**), where a 10% heavy pasture threshold is used. |
| **Light and heavy pastoral**<br>High producing exotic grassland (40) + short-rotation cropland (30) + Low Producing Grassland (41) | <15% | Somewhat arbitrary threshold. Introduced largely because of the relatively high heavy pastoral threshold used (10%). This combined 15% threshold attempts to recognise the additive pressure that different agricultural land-cover types may have on suspended sediment ESV's. |
| **Regenerating native**<br>Fernland (50) + Manuka and/or Kanuka (52) + Broadleaved Indigenous Hardwoods (54) | <40% | Somewhat arbitrary threshold, but aims to take into account that largely native catchments comprise of regenerating land-cover types (to ultimately form indigenous forest cover) are not natural – i.e., most likely reflects the slow reversion of 'disturbed land' (cleared for pasture) back to native forest. During this reversion, it is assumed that suspended sediment ESV's will be significantly higher (relative to the indigenous forest). As such, it was considered appropriate to have a maximum threshold for regenerating native land-types. |
| **Urban**<br>Built-up area (settlement) (1) + transport infrastructure (5) | <5% | More conservative than the REC threshold value of 15%, although the REC class included urban parks/open spaces – whereas LCDB4 v4.1 class *urban parkland/open space* (2) was excluded from the urban threshold. |
| **Mines/quarries**<br>Surface mine or dump (6) | 0% | Potential point source discharges having significant impact on downstream water quality monitoring site. Easiest way to manage uncertainty from this land-cover type (which represents very small areas) is to set zero threshold. |
| **Wetland**<br>Herbaceous Freshwater Vegetation (45) | <50% | The classification system applies to flowing waters – wetlands are a special, and have therefore sites with upstream catchments dominated by wetland land-cover (>50%) have been excluded. |
| **Permanent snow and ice (14)** | <10% | Attempt to eliminate rivers that have naturally high suspended sediment ESV values due to glacial flour. The intention is that the classification system for suspended sediment ESVs will not include glacial flour-impacted rivers. In Otago, these types of rivers (glacial source) are excluded from turbidity standards in the Regional Plan. |
| **Indigenous forest (69)** | na | Natural land-cover of upstream catchments vary depending on altitude and latitude. It was therefore considered to arbitrary to set a threshold for indigenous forest cover. |

### 2.3.3 Minimally disturbed condition (MDC) sites

The results of applying the LCDB v4.1 land-cover thresholds in Table 2-3 to TSS, clarity and turbidity data sets are summarised in Table 2-4. The number of MDC sites for TSS, clarity and turbidity was 51, 85 and 92, respectively, corresponding to between 10 and 12% of the total number of sites.

**Table 2-4: Summary of minimally disturbed condition (MDC) sites for different suspended sediment (SS) variables.**

| SS variable | Total no. of sites | No. of MDC sites | % MDC sites (of total) |
|---|---|---|---|
| TSS | 514 | 51 | 10 |
| Clarity | 722 | 85 | 12 |
| Turbidity | 833 | 92 | 11 |

Using turbidity MDC sites (because it is the largest, and all clarity MDC sites are coincident with turbidity), MDC sites were grouped by region (Figure 2-2), and the four main REC levels – climate, topography, geology and land-cover (Figure 2-3). The locations of the 92 MDC sites is shown in Figure 2-4.

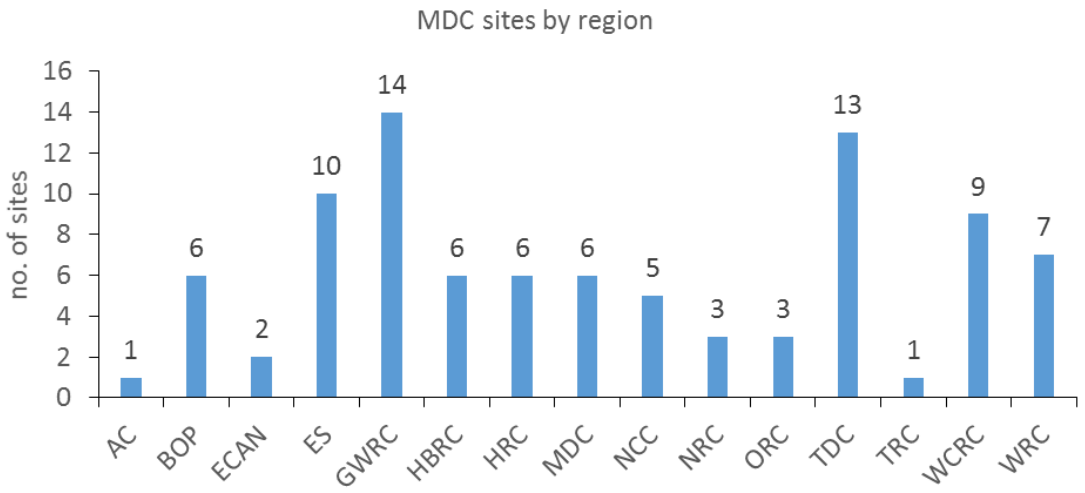



**Figure 2-2: MDC turbidity sites (n=92) grouped by region.** Regional totals include NRWQN sites.

The 92 turbidity MDC sites showed relatively good coverage across the country (Figure 2-2 and Figure 2-4), although 40% of the sites are concentrated around the bottom of the North Island (GWRC) and top of the South Island (NCC, MDC, TDC). Taranaki, East Cape, Canterbury, and northern regions are underrepresented.

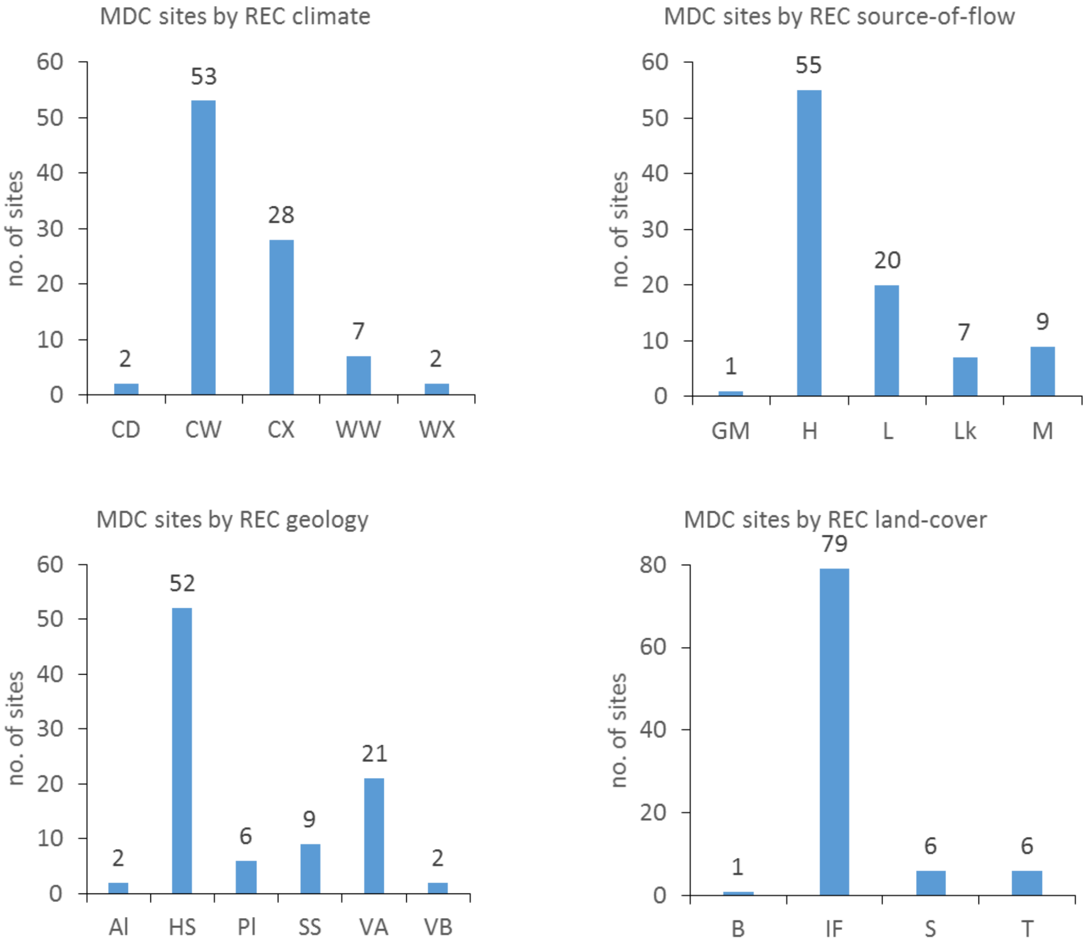



**Figure 2-3: Turbidity MDC sites grouped by REC levels: climate (top left); topography or source-of-flow (top right); geology (bottom left); dominant land-cover (bottom right).** Refer to Table D-1 to Table D-7, Appendix D for REC code definitions.

The distribution of turbidity MDC sites by REC classification levels (Figure 2-3) showed that the 'reference state' sites are dominated by:

- cool wet climates
- hill and low elevation sites
- hard sedimentary and volcanic acidic geologies (but with some soft sedimentary)
- indigenous forest land-cover (as expected for MDC sites).

Work presented in Section 2.4 shows that the only statistically significant difference in median turbidity values between various REC categories were for climate categories. Potential limitations from climate classes not represented by MDC sites were addressed by considering the work of McDowell et al. (2013), which established reference conditions for suspended sediment (TSS, turbidity and clarity) for 18 combined first (climate) and second (source-of-flow) level REC classes. This is discussed in Section 2.5.

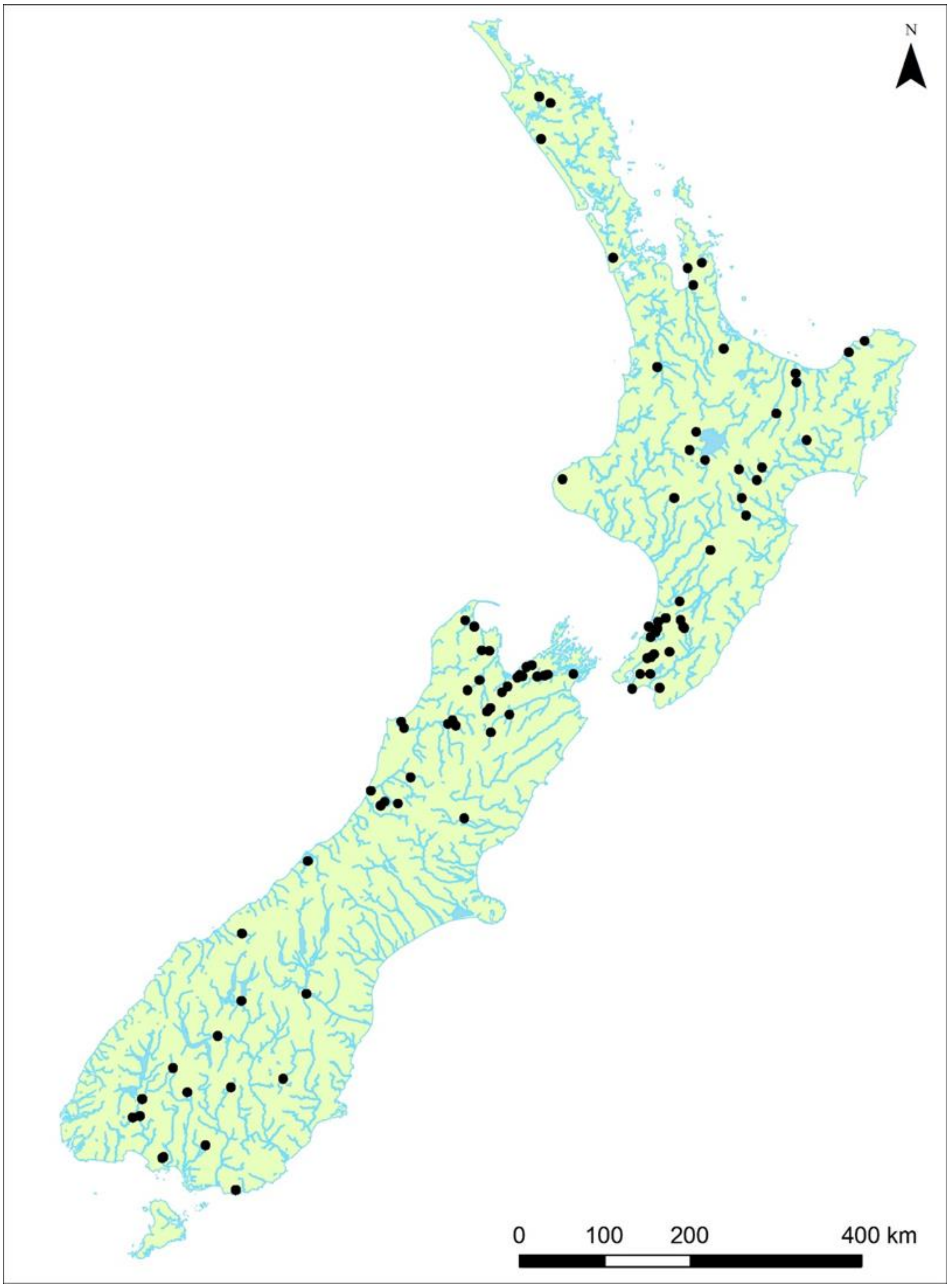



**Figure 2-4: Location of the 92 minimally disturbed condition (MDC) turbidity sites.**

### 2.3.4 Summary of suspended sediment ESV's for MDC sites: defining reference state variation

Summary statistics for MDC sites (defined using thresholds in Table 2-3) for TSS, visual clarity and turbidity are shown in Table 2-5 and Figure 2-5 (refer to Table F-1, Appendix F for full list of MDC sites). The variation of suspended sediment variables for different percentiles is summarised in Table 2-6.

**Table 2-5: Summary statistics for medians of suspended sediment ESV's at MDC sites: estimating reference state variation.** Based on median values for each of the MDC sites.

| Statistic | TSS ($g/m^3$) | Clarity (m) | Turbidity (NTU) | |
|---|---|---|---|---|
| | 2004-2012 | 2004-2013 | 2004-2013 | 2006-2015 |
| count | 51 | 85 | 92 | 92 |
| minimum | 0.3 | 1.1 | 0.1 | 0.1 |
| $5^{th}$ %ile | 0.5 | 1.5 | 0.3 | 0.2 |
| $10^{th}$ %ile | 0.6 | 1.7 | 0.4 | 0.4 |
| $25^{th}$ %ile | 2.0 | 2.6 | 0.6 | 0.6 |
| Median | 2.0 | 3.4 | 0.9 | 0.8 |
| $75^{th}$ %ile | 3.0 | 4.7 | 1.3 | 1.3 |
| $90^{th}$ %ile | 3.0 | 6.9 | 2.2 | 2.2 |
| $95^{th}$ %ile | 3.9 | 9.2 | 2.8 | 2.5 |
| maximum | 6.0 | 13.9 | 3.8 | 3.3 |
| IQR[1] | 1.0 | 2.2 | 0.7 | 0.7 |

[1] interquartile range.

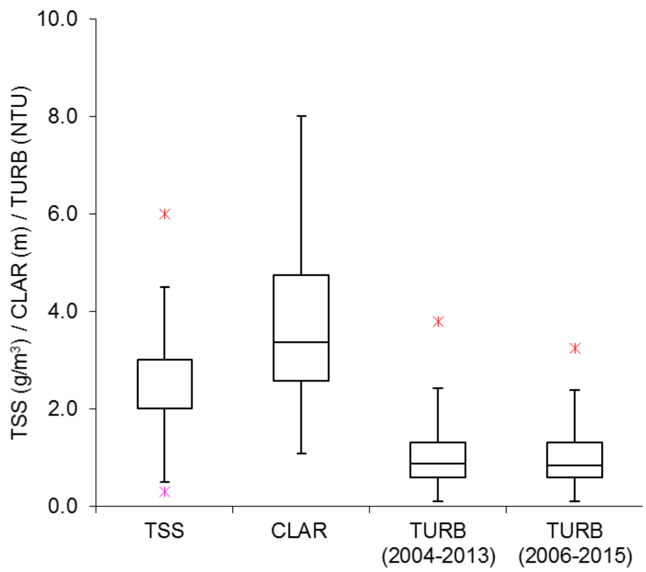



**Figure 2-5: Boxplot of natural state variation of median TSS ($g/m^3$, n=51), median visual clarity (m, n=85) and turbidity (NTU, n=92) as estimated at each MDC site. Data for two 10-year periods is shown for turbidity.** All data based on medians for each of the MDC sites.

**Table 2-6: Range of reference state data for suspended sediment variables, based of median values of MDC sites.**

| Variation between %ile range | TSS (n=51) | Clarity (n=85) (2004-2013) | Turbidity (n=92) | |
|---|---|---|---|---|
| | | | 2004-2013 | 2006-2015 |
| Min to max | 20-fold | 13-fold | 38-fold | 33-fold |
| 5th to 95th %ile | 8-fold | 6-fold | 9-fold | 13-fold |
| 10th to 90th %ile | 5-fold | 4-fold | 6-fold | 6-fold |
| 25th to 75th %ile | 1.5-fold | 2-fold | 2-fold | 2-fold |

## TSS

TSS values for MDC sites (n=51) ranged from 0.3 to 6 g/m$^3$. The median, lower and upper quartile TSS values were 2.0, 2.0 and 3.0 g/m$^3$, respectively. The maximum variation in TSS across MDC sites was 20-fold, reducing to around 8-fold and 5-fold, respectively for 5-95th and 10-90th percentile ranges (Table 2-6). The method detection limits for quantifying TSS are relatively high (i.e., typically 2-3 g/m$^3$ for most regions), and therefore it is not a suitable metric for assessing natural state variation in suspended sediment (discussed in Section 2.3.5).

## Clarity

Visual clarity values for MDC sites (n=85) ranged from 1.1 to 13.9 m. The median, lower and upper quartile clarity values were 2.6, 3.4 and 4.7 m, respectively. The maximum variation in clarity across MDC sites was 13-fold, reducing to around 6-fold and 4-fold, respectively for 5-95th and 10-90th percentile ranges (Table 2-6).

## Turbidity

Turbidity values ()2004-2013) for MDC sites (n=92) ranged from 0.1 to 3.8 NTU. The median, lower and upper quartile clarity values were 0.9, 0.6 and 1.3 NTU, respectively. The maximum variation in turbidity across MDC sites was 38-fold, reducing to around 13-fold and 6-fold, respectively for 5-95th and 10-90th percentile ranges (Table 2-6).

Results based on 2006-2015 data were similar, the main difference was a reduction in some of the highest median turbidity values for MDC sites (reducing the maximum turbidity from 3.8 to 3.3 NTU), resulting in a maximum variation of 33-fold (compared to 38-fold for 2004-2013).

The larger variation with turbidity (compared with clarity) reflects the inverse relationship of the two measurements. Turbidity measurements in clear water are near zero. With a typical detection limit of 0.1 NTU, a near zero denominator results in a large-fold difference when compared with a higher percentile statistic. In contrast, the lowest ‘denominator’ values for clarity at MDC sites is around 1 m (i.e., they are not near-zero).

## General comment of estimated reference state variation for clarity and turbidity

Overall, based on 10th and 90th percentile values, the variation in estimated ‘reference state’ (using MDC sites) for clarity and turbidity was 4- and 6-fold, respectively. This relatively low degree of variation is contrary to what was perhaps anticipated (i.e., outlined in the RfP), and along with the coherence of pattern between landscape variables (e.g., REC topography class presented in Section

2.4), suggests that a simple classification system may address natural state variation in suspended sediment in New Zealand's rivers.

### 2.3.5 Unsuitability of TSS as a suspended sediment ESV for defining natural state variation

The stepwise cumulative frequency (percentile) distribution of TSS data for MDC sites shows that the dataset is dominated by below detection limit (DL) data (Figure F-1, Appendix F). Across the 10 regions, MDC sites comprised a total 2,483 TSS data, and of these 1,337 (54%) were flagged as being at or below the method DL. Using the median value of DL flagged data, the majority of regions have a relatively high DL value of 2 to 3 g/m$^3$ (Figure 2-6). AC, NCC, HRC and ECAN appear to have method DL values of 0.3 to 1.0 g/m$^3$ – presumably this reflects slight methodological differences. Figure 2-5 shows that the median turbidity value for MDC sites is 0.8-0.9 NTU, which suggests DL <1 g/m$^3$ (preferably 0.3 g/m$^3$) would be required to collect meaningful TSS 'reference state' data.

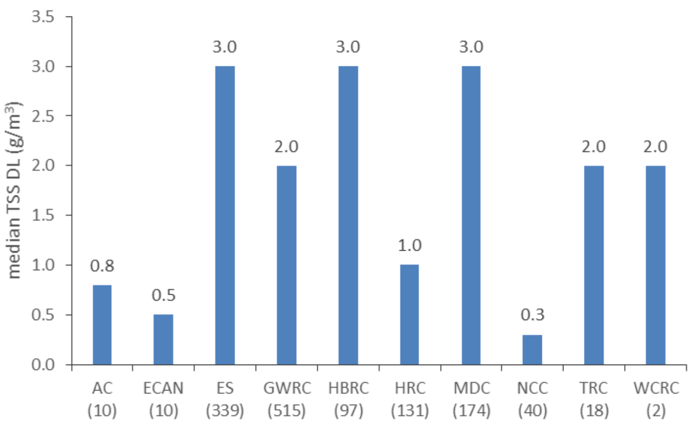



**Figure 2-6: Median TSS (of site medians) values for all data flagged as 'DL' (at or below detection limit).** The number of DL data for each region is shown in parentheses (x-axis).

Of the 51 MDC sites, 20 had greater than 50% of the data flagged as '<DL' (below detection limit)– for these sites (i.e., 40% of TSS MDC sites), the reported median is the method detection limit. At 6 sites, 100% of the reported TSS data was flagged 'DL'. Accordingly, for the purpose of defining reference state variation, TSS data is not fit-for-purpose and is not included in subsequent discussion/analyses.

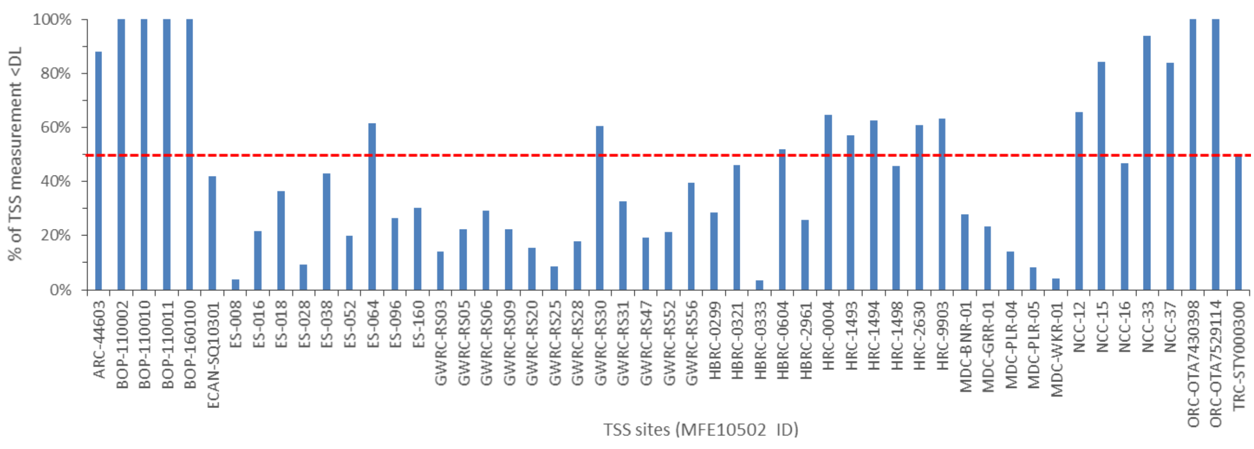



**Figure 2-7: The 51 MDC sites with TSS data showing the fraction (%) of data flagged as 'detection limit' (DL) for each site.** Values exceeding the red dashed line indicate sites where the median TSS would exceed the DL value. Site code on x-axis is a NIWA database site code (as used in project MFE10502).

## 2.4 'Reference state' variation grouped by REC levels/categories

In this interim report, this section is limited to turbidity because it had the greatest number of MDC sites (n=92), and all sites were coincident with the slightly smaller number of clarity MDC sites (n=85). To explore differentiation of rivers according to 'reference state' variation (albeit relatively small – refer to Figure 2-5), turbidity data from MDC sites were grouped by category for the main REC classification levels: climate, topography, geology, dominant land-cover, network position and valley landform.

### 2.4.1 REC climate

MDC sites included 5 climate categories, with three of these (CW, CX and WW) containing >5 sites. Almost 90% of the MDC sites were CW or CX. The median turbidity for all cold (C) categories ranged from 0.8 to 0.9 NTU. The median value of 2.3 NTU at WX comprises only 2 sites, with median turbidity values of 0.8 and 3.8 NTU. The median turbidity values for CW, CX and WW (those with >5 sites) were significantly different (Kruskal-Wallis test, $\alpha=0.05$, see Table 2-7). Box and whisker plot summary statistics are listed in Table G-1 (Appendix G).

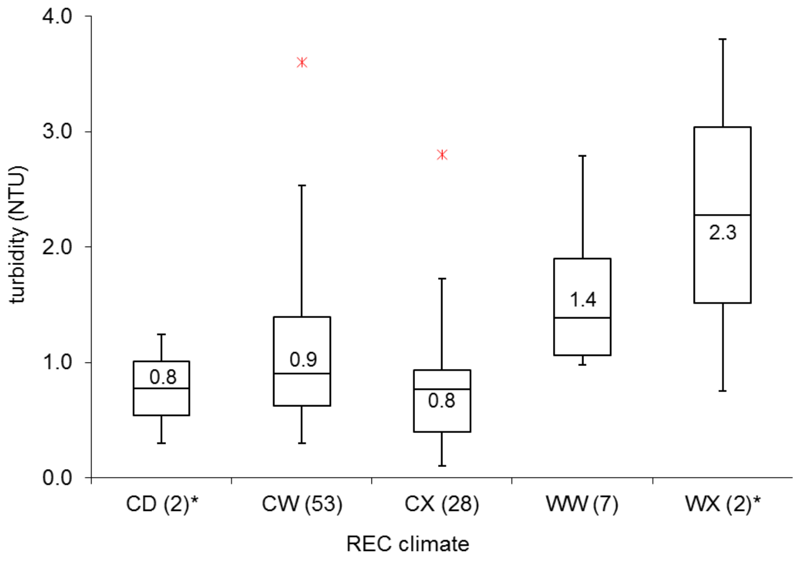



**Figure 2-8: Median turbidity data for each MDC site grouped by REC climate categories.** * indicates categories with <5 MDC sites. CD = cool-dry; CW = cool-wet; CX = cool-extremely-wet; WW = warm-wet; WX = warm extremely-wet. Description of REC climate is provided in Table D-3, Appendix D).

### 2.4.2 REC topography

The 92 MDC sites spanned 5 source-of-flow categories, 4 if the single glacial mountain site is excluded (Figure 2-9). The reference sites were dominated by hill and low elevation categories, accounting for 80% of the total. Median turbidity values for the 4 topography classes (where n>5) ranged from 0.7 to 1.0 NTU and were not statistically different (Kruskal-Wallis test, $\alpha=0.05$, see Table 2-7). Box and whisker plot summary statistics are listed in Table G-2 (Appendix G).

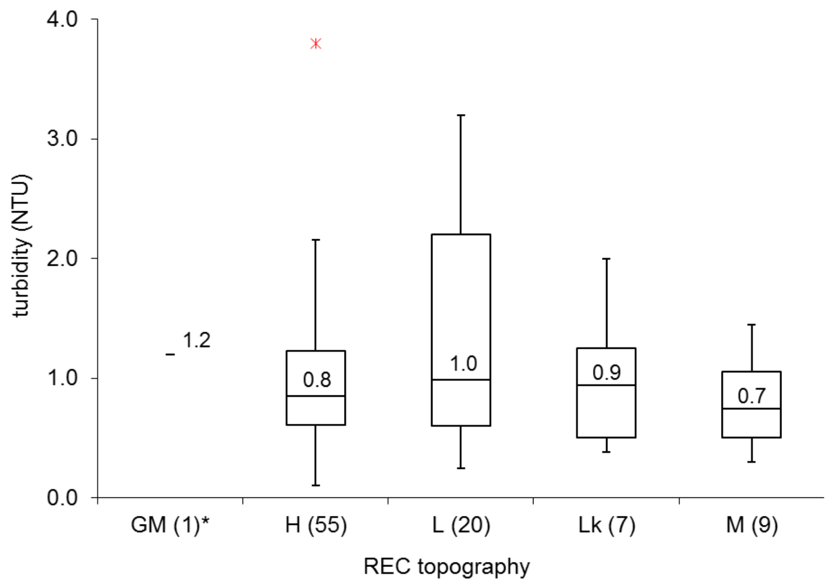



**Figure 2-9: Median turbidity data for each MDC site grouped by REC topography categories.** * indicates categories with <5 MDC sites. GM = glacial mountain; H = hill; L = low elevation; Lk = lake-fed; M = mountain. Description of REC topography is provided in Table D-2, Appendix D).

## 2.4.3 REC geology

Turbidity MDC sites included 4 REC geology categories with >5 sites, namely HS, Pl, SS and VA (Al and VB contained only 2 sites each). The two dominant geology types were HS (n=52) and VA (n=21), which together accounted for 80% of the total (Figure 2-10). The median turbidity for the 4 main geology types ranged from 0.8 to 1.3 NTU, but the differences were not statistically significant (Kruskal-Wallis test, $\alpha=0.05$, see Table 2-7). Box and whisker plot summary statistics are listed in Table G-3 (Appendix G).

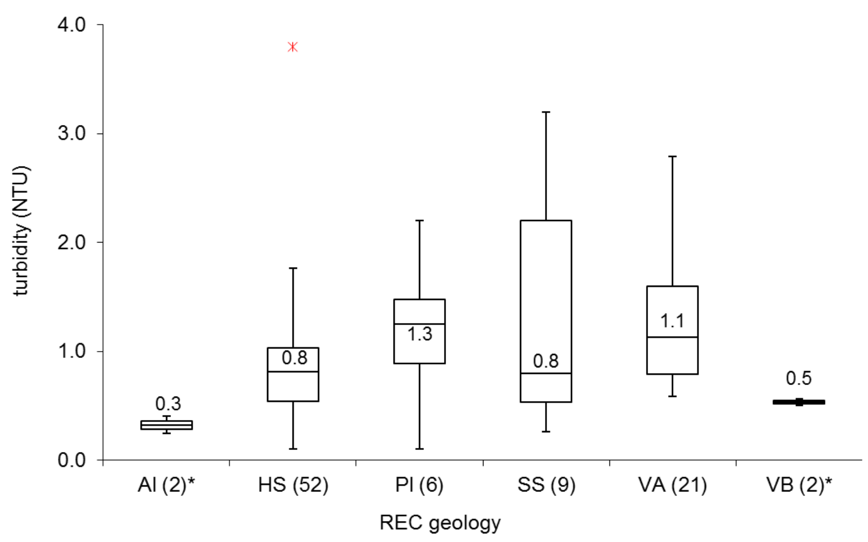



**Figure 2-10: Median turbidity data for each MDC site grouped by REC geology categories.** * indicates categories with <5 MDC sites. Al = alluvium; HS = hard sedimentary; Pl = plutonics; SS = soft sedimentary; VA = volcanic acidic; VB = volcanic basic. Description of REC geology is provided in Table D-4, Appendix D).

### 2.4.4 REC dominant land-cover

Perhaps not surprisingly (because threshold criteria favours forested catchments), indigenous forest (IF) land-cover accounted for 86% of the total (Figure 2-11). Both scrub and tussock were represented with 6 MDC sites. Ignoring the single site for 'B' (bare land), the median turbidity value for IF, S and T ranged from 0.8 to 1.1 NTU, and were not statistically significantly different (Kruskal-Wallis test, $\alpha$=0.05, see Table 2-7). Box and whisker plot summary statistics are listed in Table G-4 (Appendix G).

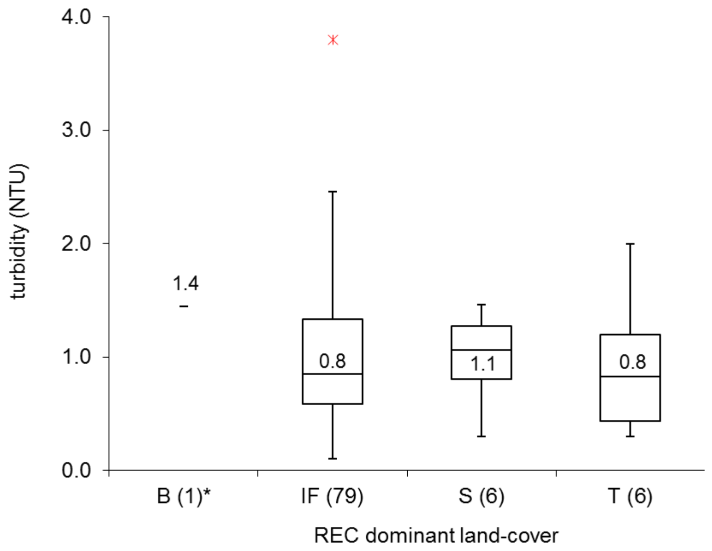



**Figure 2-11: Median turbidity data for each MDC site grouped by REC dominant land-cover categories.** * indicates categories with <5 MDC sites. B = bare; IF = indigenous forest; S = scrub; T = tussock. Description of REC land-cover level is provided in Table D-1, Appendix D).

### 2.4.5 REC network position

Network position indicates where the site is within the network– with lower order sites (LO) corresponding to low streams orders (1 and 2), dominated by small headwater streams, middle order (MO) sites are represented by tributaries to larger rivers with streams orders of 3 and 4, and finally high order (HO) are rivers, with stream orders of 5 or more. Further explanation of this REC level is provided in Table D-5, Appendix D.

All network position categories were represented, although the MDC sites were dominated by equal numbers of middle and high order sites. The median turbidity for the 3 site categories ranged from 0.8 to 0.9 NTU (Figure 2-12), and were not significantly different (Kruskal-Wallis test, $\alpha$=0.05, see Table 2-7). Box and whisker plot summary statistics are listed in Table G-5 (Appendix G).

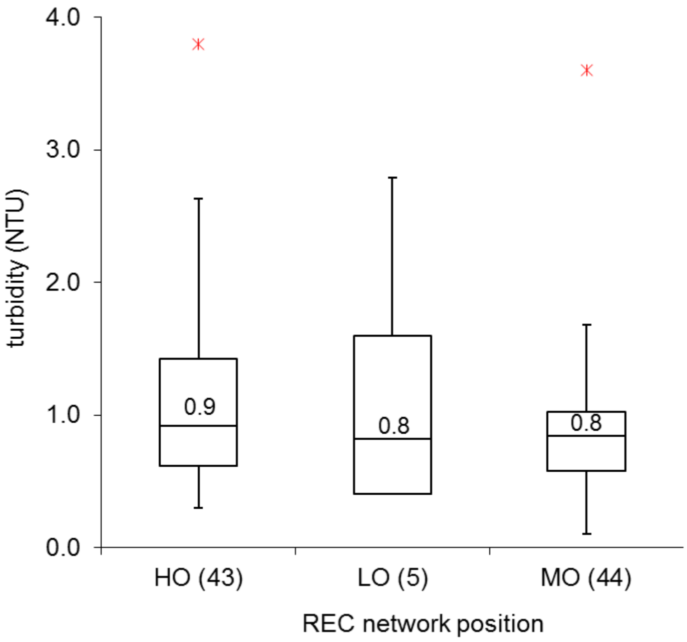



**Figure 2-12: Median turbidity data for each MDC site grouped by REC network position categories.** LO = low order; MO = middle order; HO = high order. Description of the REC network position classification is provided in Table D-5, Appendix D).

### 2.4.6 REC valley landform

This REC classification level is related to channel steepness. High gradient (HG) sites comprise steep channels and high water velocities. Medium gradient (MG) channel sites have more meandering and often pool-riffle-run structure. Low gradient (LG) channels are typically represented by highly meandering rivers with low water velocities. Additional explanation of this REC level is provided in Table D-6, Appendix D.

All gradient categories were represented, although sites were dominated by low gradient systems (>70% of sites). Median turbidity values for LG, MG and HG were 1.0, 0.7 and 0.8 NTU, respectively (Figure 2-13), which were not significantly different (Kruskal-Wallis test, $\alpha=0.05$, see Table 2-7). Box and whisker plot summary statistics are listed in Table G-6 (Appendix G).

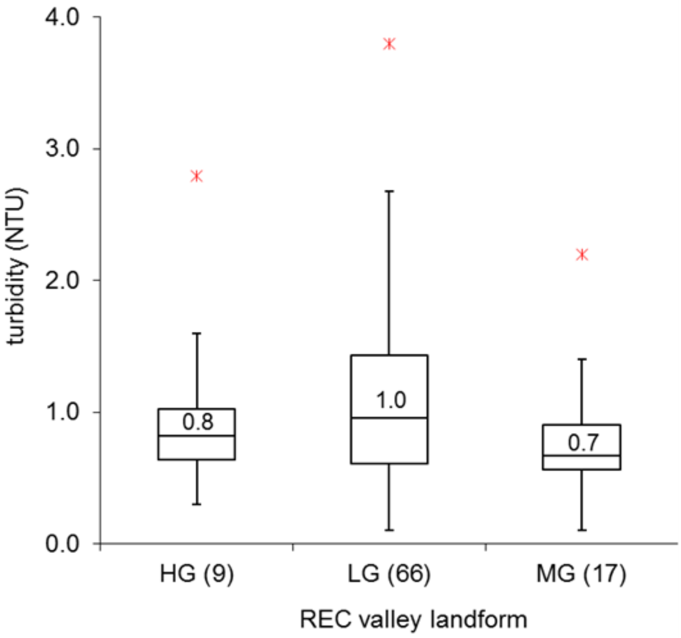



**Figure 2-13: Median turbidity data for each MDC site grouped by REC valley-landform categories.** LG = low gradient; MG = medium gradient; HG = high gradient. Description of REC land-cover level is provided in Table D-6, Appendix D).

### 2.4.7 Statistical significance of REC-based grouping of 'reference state' turbidity

The statistical significance of any observed differences in median 'reference state' (i.e., MDC) turbidity when grouped by different REC categories was determined using the Kruskal-Wallis test (adjusted for ties, and $\alpha = 0.05$). Kruskal-Wallis H-value, degrees of freedom and probability for each REC level is summarised in Table 2-7.

**Table 2-7: Summary of Kruskal-Wallis significance testing ($\alpha = 0.05$) on MDC medians when grouped by different REC level categories.**

| REC level | Degrees of freedom | H-value (adjusted for ties) | P-value | Significant difference in category medians |
|---|---|---|---|---|
| Climate | 2 | 11.55 | 0.003 | Yes |
| Source-of-flow | 3 | 1.89 | 0.595 | No |
| Geology | 3 | 7.23 | 0.065 | No |
| Land-cover | 2 | 0.33 | 0.85 | No |
| Network position | 2 | 0.58 | 0.75 | No |
| Valley landform | 2 | 5.28 | 0.071 | No |

Of the 6 individual REC classification levels included here only grouping 'reference state' turbidity by climate categories resulted in statistically significant differences in median values. The 3 represented climate categories CW, CX and WW (where $n \geq 5$) had median turbidity values of 0.9, 0.8 and 1.4 NTU, which were all significantly different ($\alpha = 0.05$, refer to Table G-7, Appendix G).

## 2.5 Comparison with modelled reference state for REC climate/source-of-flow categories (McDowell et al. 2013)

### 2.5.1 MDC turbidity results grouped by REC climate/topography

Applying the same REC-based ‘climate and topography’ grouping to the MDC sites resulted in 6 categories being represented by >5 sites – namely CWL, CWM, CWH, CXL, CXH and WWL – and these account for 84% of the total. The distributions of MDC turbidity medians for these REC categories are shown in Figure 2-14. The most obvious feature of the plot is the median value for WWL, which is approximately 2-fold higher (with non-overlapping interquartile ranges) than the ‘cool’ classes (<1 NTU). Because MDC sites do not represent ‘warm’ climate classes very well, the 4 sites representing WWLk (warm wet lake-fed) are included (despite normally excluding classes which were represented by <5 MDC sites), which had a median clarity similar to the ‘cool’ categories.

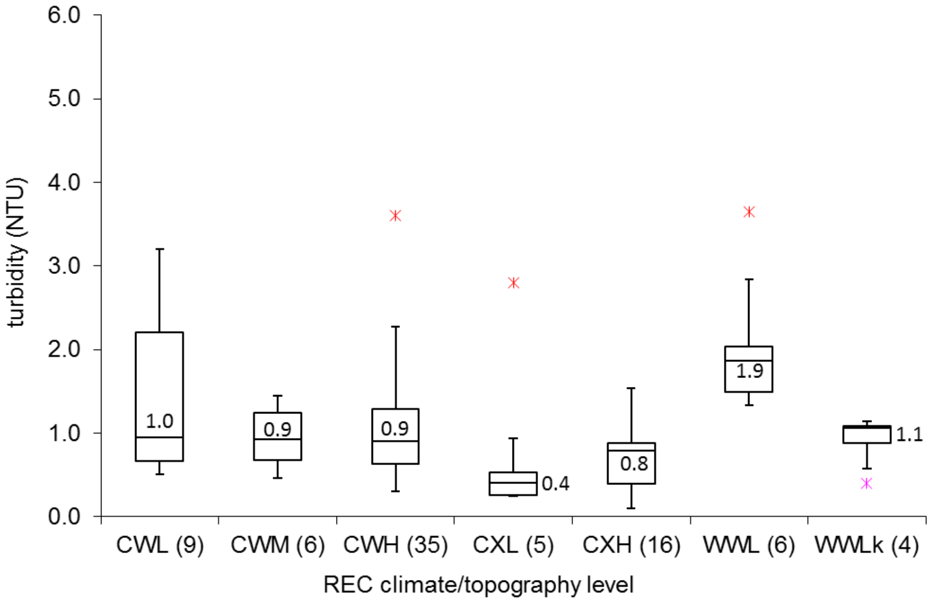



**Figure 2-14: Median turbidity for each MDC site grouped by REC climate and topography categories.**

It is also worth pointing out that although the median for CWL (cool wet low) was 1 NTU, the 75$^{th}$ percentile value was 2.2 NTU. This variation meant that the medians for CWL and WWL classes (1.0 and 1.9 NTU, respectively) were not significantly different ($\alpha$=0.05, df=1, H-value=0.682, P-value=0.409). It is therefore difficult to determine whether there is sufficient justification to differentiate ‘reference state’ sites based on REC climate (i.e., cool vs warm), and within the warm wet climate class, potentially distinguishing between lake and non-lake sites.

McDowell et al. (2013) modelled reference condition by plotting the variable (i.e., turbidity) on the y-axis and heavy pasture (%) on the x-axis. After having taken into account landscape-scale variations defined by the hierarchical REC classes as random-effects in a mixed-effects model, curve was then fitted to the data to interpolate to 0% heavy pasture, which corresponds to the predicted reference condition. The strength of this approach is that for catchment types where reference site data are sparse (i.e., warm climate classes), ‘impact’ data can be used to estimate reference state. This method requires several assumptions, and is highly dependent on the reference state variable being strongly correlated with the single anthropogenic driver used in the study (i.e., % heavy pasture). It is also dependent on the impact sites providing a gradient of percent heavy pasture. A potential strength and limitation of the method is the use of splines to fitted curves – these are intended to 'pull' the line down (or up in the case of clarity) to near reference sites (i.e., MDC sites). This effectively gives more 'weighting' to sites that approximate reference condition. While this makes sense generally, the results may be questionable where unsuitable MDC sites (i.e., where near zero percent heavy pasture was not a good predictor of reference state SS for NZ flowing waters) were included in the regression analysis. For example, when checking raw data, it was found that inclusion of two wetland sites resulted in a reference condition prediction for CDL clarity of 0.9 m, whereas, if data from these sites were excluded, the reference clarity value would increase to around 2.5 m (McDowell pers. comm.).

Table 2-8 compares the MDC results (this study) with the predicted reference condition for the same climate-SoF categories. Excluding the predicted reference conditions for CWM and WWLk because of limited data available for their derivation, the MDC medians and predicted reference state showed relatively good agreement. For WWL, the high MDC median (1.9 NTU) was consistent with the modelled median reference condition of 2.3 NTU (Table 2 8).

**Table 2-8: Comparison of turbidity results between MDC sites (this work) and predicted reference condition (McDowell et al. 2003) for REC climate/SoF categories.**

| Statistic | CWL | CWM | CWH | CXL | CXH | WWL | WWLk |
|---|---|---|---|---|---|---|---|
| **Current work (MDC sites)** | | | | | | | |
| No. sites | 9 | 6 | 35 | 5 | 16 | 6 | 4[1] |
| **median** | **1.0** | **0.9** | **0.9** | **0.4** | **0.8** | **1.9** | **1.1** |
| 25th %ile | 0.7 | 0.7 | 0.6 | 0.3 | 0.4 | 1.5 | 0.9 |
| 75th %ile | 2.2 | 1.2 | 1.3 | 0.5 | 0.9 | 2.0 | 1.1 |
| **McDowell et al. modelled reference condition** | | | | | | | |
| No. sites[2] | 77 | 7[3] | 123 | 20 | 24 | 106 | 5[3] |
| **median** | **1.2** | **1.6** | **1.0** | **1.3** | **0.7** | **2.3** | **2.1** |
| -CI | 0.8 | 0.9 | 0.8 | 0.7 | 0.4 | 1.6 | 0.6 |
| +CI | 1.7 | 2.6 | 1.3 | 2.1 | 1.1 | 3.3 | 4.3 |

[1] <5 MDC sites for this REC category. [2]based on no. of sites for clarity data (turbidity sites not provided), and these are the total number of sites used to fit curve to interpolate to reference state conditions (it is not the number of minimally disturbed condition sites). [3] Although somewhat arbitrary, a threshold of 20 sites was determine as being more likely to yield a reliable curve fit – these predicted reference state conditions are therefore considered to be less reliable.

McDowell et al. (2013) estimated reference conditions for 18 climate-SoF categories, consisting of 12 'cool' and 6 'warm'. The median estimated turbidity for 'cool' climate categories ranged from 0.5 to 1.6 NTU, with an overall median (median of 12 medians) of 1.0 NTU. The 'warm' categories had median turbidity values ranging from 1.2 to 2.5 NTU, with an overall median (n=6) of 2.0 NTU.

These findings were similar for estimated reference conditions of TSS and clarity (refer to Table H-1, Appendix H). Accordingly, if 1 vs 2 NTU is meaningful with respect to ecosystem health effect, then a classification system would need to differentiate between key 'warm' and 'cool' climate-SoF categories.

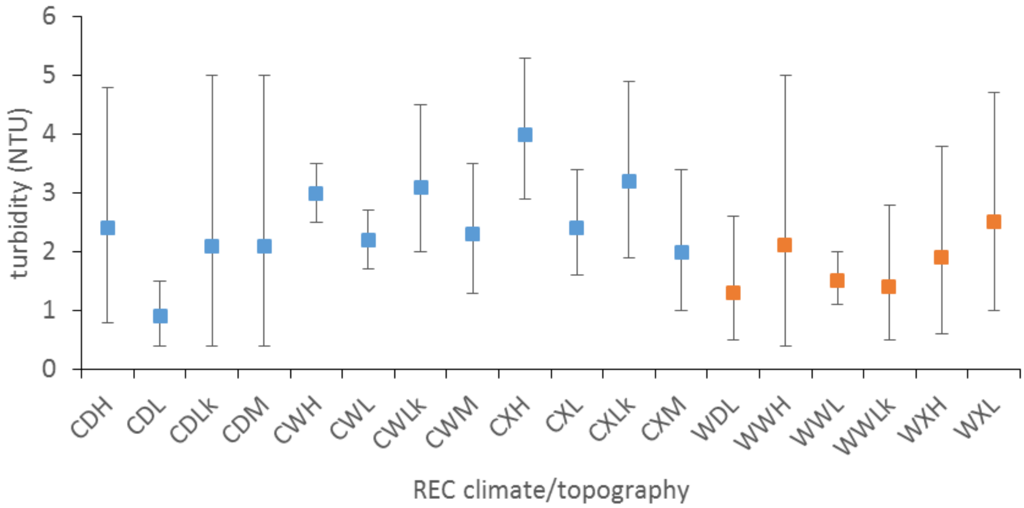



**Figure 2-15: Predicted reference condition (turbidity, NTU) for REC climate/source-of-flow categories.** Based on data provided from authors of McDowell et al. 2013. Blue and orange data reflect cool and warm climate categories, respectively.

## 2.6 Ecological vs statistical significance

Previous sections have explored 'reference state' variation (using turbidity data from MDC sites) and the possibility of using REC-based classification approaches to reduce the extent of reference state variation. This would then provide some justification for differentiating NZ flowing waters into 'classes'. Of the six REC classifications, only climate resulted in statistical significant differences in grouped data (i.e., CW, CX and WW climates). An important consideration (prior to progressing with Stage 2 – biological responses and proposed threshold values) is to determine whether the magnitude of these statistically significant differences (between potential reference state 'classes') is relevant with respect to likely ecological/biological effects thresholds. If not, then statistically significant groupings would not (by itself) be a justified reason for differentiating reference condition between flowing waters.

### 2.6.1 Likely ecological effects thresholds for suspended sediment: literature

Table 2-9 summarises the lowest suspended sediment concentrations known to have adverse effects on macroinvertebrates and fish. Most of these data are derived from short (acute) test durations, whereas sediment thresholds will be based on chronic effects. The bioenergetics model of Hay et al. (2006) is based on optimum reaction distances for 12 mm prey (which is the size of the majority of drift insects in New Zealand). Using the regression between clarity and turbidity for MDC sites (refer to Section 2.7), a visual clarity of 1.4 m corresponds to a turbidity of around 2.5 NTU. The relevance of this relatively low turbidity is uncertain because it involves a threshold for the optimised feeding of a non-native fish species. Whether trout should be included in (or excluded from) the sediment attribute process is still yet to be resolved.

**Table 2-9: The lowest turbidity required for an ecological response as reported in a selection of international literature.**

| Organism | SS measure | Duration of exposure | Effect | Reference |
|---|---|---|---|---|
| Benthic invertebrates | ~8 NTU (8 g/m$^3$) | 2.5 h | Increased rate of drift | Rosenberg and Wiens (1978) |
| Sable fish | 5-10 NTU | 70 min | Reduced prey consumption | De Robertis et al. (2003) |
| Rainbow trout | 15-30 NTU | 1 h | Reduced reactive distance by 20-55% | Barrett et al. (1992) |
| Trout | 1.4 m clarity (~2.5 NTU) | - | Bioenergetics model – reduced reaction distance | Hay et al. (2006) |

### 2.6.2 Comparison of possible thresholds with 'natural state' variation (i.e., MDC sites)

Figure 2-16 compares selected literature-reported thresholds (2.5 and 5 NTU) with the distribution in turbidity (MDC sites) for different climate categories. Of the 92 MDC sites, no turbidity median values exceed the indicative 5 NTU threshold. The maximum MDC site median value for the 2004-2013 and 2006-2015 datasets was 3.8 and 3.3 NTU, respectively. This suggest that when setting a national bottom line (i.e., a relatively high value) for suspended sediment (for ecosystem health), it would be difficult to justify a classification system to differentiate New Zealand streams and rivers because any separation into classes would be below the values required to negatively influence ecosystem health.

With respect to the relatively conservative threshold of 2.5 NTU (converted from the 1.4 m clarity value indicated by the bioenergetics model), the summary in Table 2-10 shows that the majority of sites with median turbidity value >2.5 NTU are from cold climates. This is not unexpected, given that the MDC dataset is heavily biased towards cool climate sites. The presence of several exceedances at cold sites indicates that managing for 100% of the variation in TSS at MDC sites would not be achieved using an REC climate-based classification system for 'reference state' sites. That being said, any classification system will not explain explain/represent 100% of the variation, and it is therefore anticipated that a climate-based (and perhaps topography) classification will be revisited during phase 2 of the project.

If managing reference state (i.e., MDC sites) for 95$^{th}$ percentile values, then no sites would exceed the indicative threshold of 2.5 NTU used here as an example of a very conservative threshold (i.e., derived to maintain trout fishery values, Hay et al. 2006).

**Table 2-10: Summary of MDC sites that exceed a 2.5 NTU turbidity or 1.4 m clarity, including the REC climate/SoF category.**

| SS measure | Dataset | No. > threshold | Exceedance values | Climate/SoF categories |
|---|---|---|---|---|
| Turbidity (2.5 NTU) | 2004-2013 | 7 | 3.8, 3.6, 3.2, 2.8, 2.8, 2.7, 2.6 | CWH (2), CWL (2), CXL, WXH, WWL |
| Turbidity (2.5 NTU) | 2006-2015 | 4 | 3.3, 3.1, 3.1, 2.6 | CWL (2), CWH, WX |
| Clarity (1.4 m) | 2004-2013 | 3 | 1.1, 1.2, 1.23 | CWL, CWH, WWL |

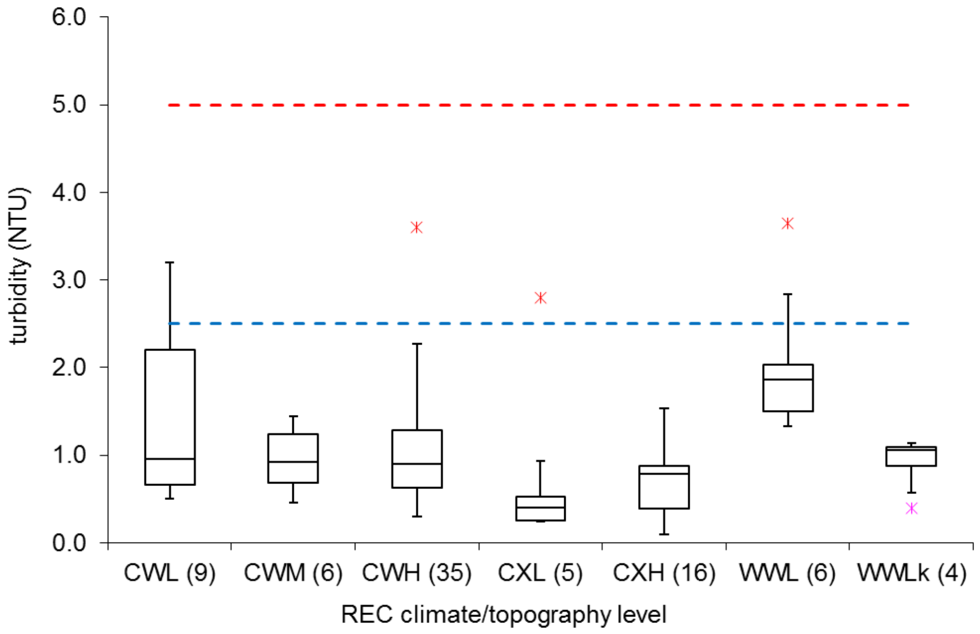



**Figure 2-16: Median turbidity for MDC sites grouped by REC climate and SoF categories in relation to possible conservative biological effects thresholds.** Red dashed line (5 NTU) based on De Robertis et al. (2003) and 2.5 NTU derived from 1.4 m value of Hay et al. (2006).

## 2.7 Sediment ESV redundancy

In this section, the term redundancy refers largely to two outcomes:

1) Redundancy arising from robust correlation between multiple important SS metrics (Davies-Colley et al. 2014). The metrics in their own right are all required to manage SS in flowing waters (for ecosystem health), but the ability to reliably convert between metrics effectively means that only one is required as an attribute.

2) Redundancy arising from one or more SS metrics (ESVs) being irrelevant or superfluous. Using multiple metrics to manage the ecosystem health risks of SS in flowing water creates the potential for superfluous measurements.

The initially proposed suspended sediment ESVs included:

1) euphotic depth (Light penetration)

2) total suspended sediment (TSS)

3) visual clarity.

For reasons discussed in Section 1.5 (with additional technical justification in Appendix A), we recommend removing euphotic depth as a sediment ESV for managing SS in flowing waters.

TSS and visual clarity remaining as candidate SS ESVs, although as discussed in Section 1.4.3, we recommend including turbidity as a useful suspended sediment metric (or ESV). Reasons for including turbidity are:

a. all councils monitor turbidity

b. currently 4 councils (AC, MDC, GDC and ORC) do not regularly monitor clarity

c. turbidity is used internationally – useful as biological effects thresholds, often reported in turbidity units (NTU)

d. potentially a regulatory 'appetite' for turbidity-based thresholds exists because of familiarity with turbidity limits in resource consents

e. turbidity has a better range at the 'dirtier' end of the SS spectrum in river waters, which reflect conditions where SS concentrations are likely to exert biological effects and where management issues are focussed.

With respect to TSS, although a direct measurement of SS, it has at least two limitations:

a. it is the least monitored SS metric (based on number of sites) – it does not appear to be routinely monitored by TDC, WCRC, WRC and TRC (based on 2004-2012 data)

b. method detection limits for TSS are generally too high for meaningful monitoring of sites representing reference state conditions.

Point b) is a limitation for using TSS to determine reference state variation of SS in New Zealand flowing waters. But assuming that proposed SS threshold values would be greater than TSS detection limits (typically around 2-3 g/m$^3$), then a TSS-based attribute could be used to manage SS in flowing waters.

### 2.7.1 Regressions for TSS, clarity and turbidity

TSS, clarity and turbidity are generally correlated with each other, however the strength of the correlation is often site-specific, and 'one size fits all' regressions may not be sufficiently robust to allow interconversions to be carried out with confidence (Davies-Colley & Smith 2001). This limitation indicates that when going from a single site, to regional/organisational, or to national datasets, it should be anticipated that regressions between SS metrics will be less robust.

Assuming that robust regression exist at site and regional scale, and assuming that the SS attribute was clarity, regional or unitary authorities not monitoring clarity would with confidence be able to converted threshold values of turbidity and/or TSS into clarity values (or convert their data into clarity values to assess against attribute threshold values). If sufficiently robust regressions do not exist however, and if the SS attribute selected was a metric not monitoring by some councils, then the only way those councils would be able to assess compliance against the attribute thresholds would be to start monitoring that metric (as was the case with the periphyton attribute).

There would therefore be significant advantages in selecting a SS sediment attribute that is currently monitored by all regions.

## NRWQN regressions between TSS, turbidity and clarity

NRWQN data (2011-2015) indicate strong correlations ($R^2$ of 0.84 to 0.93) between SS metrics, indicating that interconversion between three SS metrics may be undertaken with reasonable confidence (Figure 2-17, from Hicks et al. 2016). Note that these figures are based on discrete data (approximately 60 data points per site), as opposed to site medians (1 data point per site). These data include stormflows, which is why the axes span a large range of SS values.

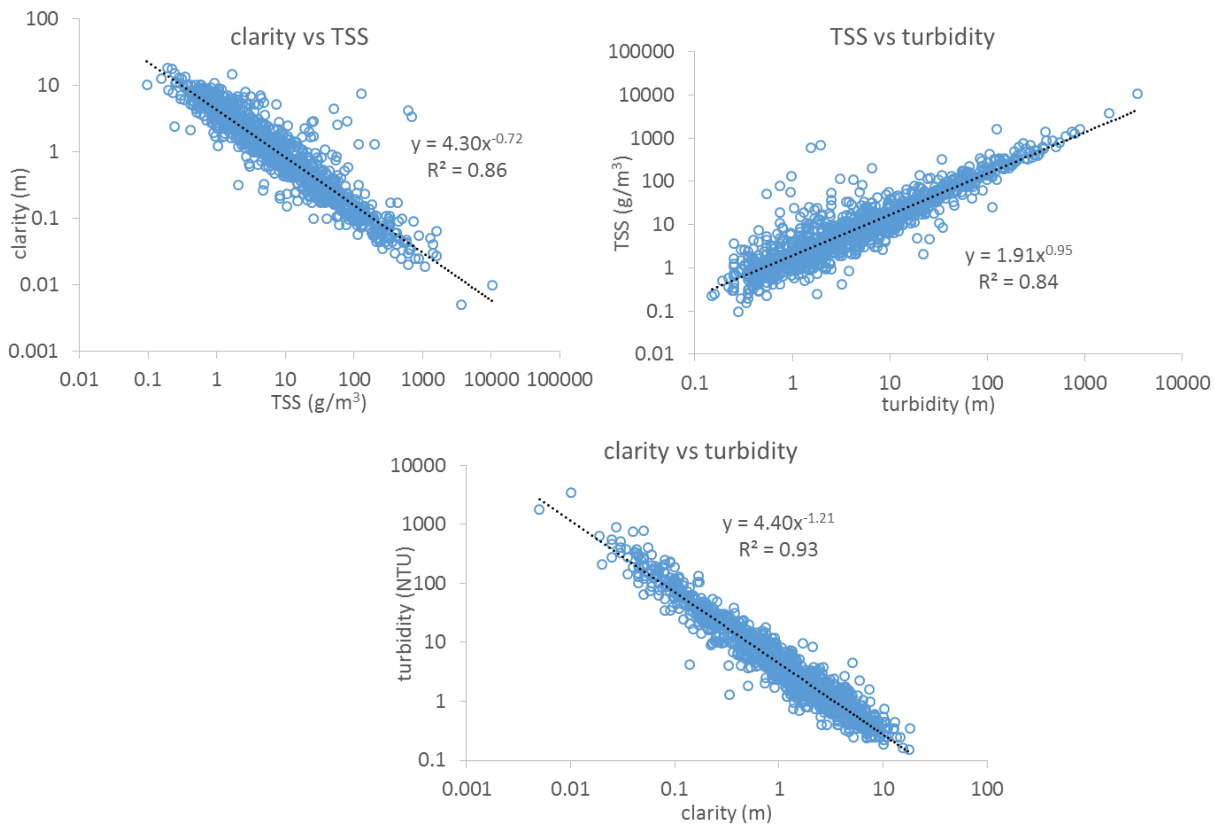



**Figure 2-17: Regression of TSS, clarity and turbidity using NRWQN data (2011-2015).**Note data shown is all monthly data, as opposed to site medians.

## Regional monitoring datasets (using site medians)

Using the dataset summarised in Table 2-1 (Section 2.2.1), the regression of TSS vs turbidity and clarity vs TSS (Figure 2-18) has correlation coefficients ($R^2$) of 0.69 and 0.52, respectively. It is unlikely that these regression equations would provide sufficient confidence to convert from TSS into either turbidity or clarity. This uncertainty would be a limitation when implementing a TSS attribute.

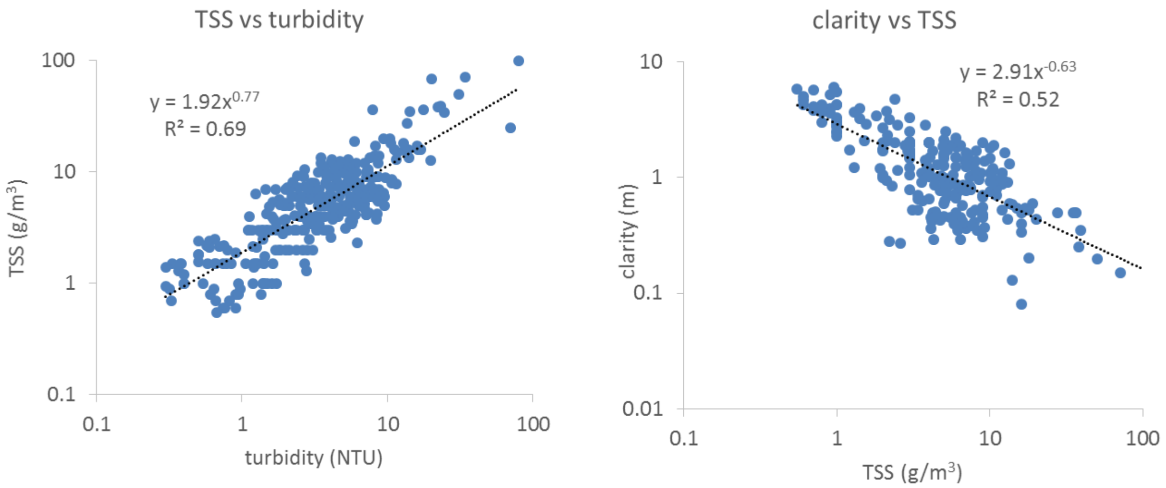



**Figure 2-18: Regression of TSS with clarity and turbidity, using site medians for all available monitoring data (refer to Table 2-1).** Data points represent site medians – usually derived from 7-10 years of monthly monitoring data.

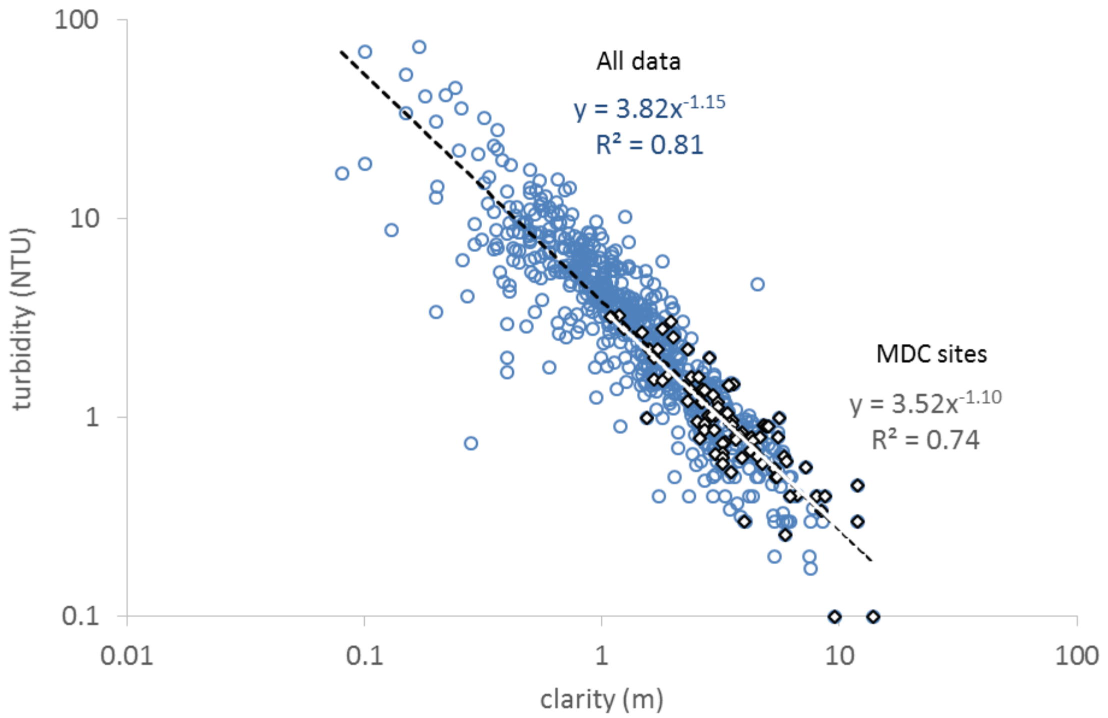



**Figure 2-19: Regression of turbidity and clarity using site medians for all sites.** For all sites, n=722 (blue circles) and for MDC sites, n=83 (black diamonds).

In contrast, using 722 paired turbidity and clarity data (derived from regional and NRWQN monitoring), the regression yielded a correlation coefficient of 0.81 (compared to 0.93 for NRWQN sites, Figure 2-17). Limiting the number of sites to the subset of MDC sites (n=83), the regression equation was similar and with an only slightly weaker $R^2$ value of 0.74. Using the three regression equations (for NRWQN, all sites and MDC sites respectively), a range of clarity and turbidity values may be interconverted (Table 2-11). These data show that because of the inverse relationship between turbidity and clarity, the compression of clarity at the 'dirtier' end of the spectrum results in greater absolute uncertainty when low clarity values (e.g., <0.5 m) are converted to turbidity. For example, 0.5 m clarity converted to turbidity values that ranged between 7.5 and 10.2 NTU; and 0.3 m clarity converted to turbidity values that ranged between 13.2 to 18.9 NTU, dependent on the regression equation used.

In contrast, when using the same regression equation to convert turbidity to clarity, the large range of turbidity is converted into the compressed range of clarity, resulting in less variability (or sensitivity) to the regression equation selected. For example, a turbidity of 5 NTU converted to clarity values that ranged between 0.9 and 1.1 m; and a turbidity of 20 NTU converted to clarity values that ranged between 0.2 and 0.3 m. At ecological relevant levels of SS, the results in Table 2-11 suggest that measured turbidity may be converted to clarity values with greater confidence than converting clarity to turbidity. When this advantage is combined with ones listed previously (the main one being that it is measured by all councils), turbidity appears to be a strong candidate as an attribute to manage SS for ecosystem health in flowing waters.

**Table 2-11: Conversion of clarity into turbidity (left side) and turbidity into clarity (right side) using three regression equations.** The grey shaded area represent where management of SS is likely to focus, and hence where greater confidence is required when inter-converting values derived from different metrics.

| Clarity (m) value to convert | Turbidity (NTU) via regression eqn. | | | Turbidity (NTU) value to convert | Clarity (m) via regression eqn. | | |
|---|---|---|---|---|---|---|---|
| | All | MDC | NRWQN | | All | MDC | NRWQN |
| 0.3 | 15.3 | 13.2 | 18.9 | 0.5 | 5.9 | 5.9 | 6.0 |
| 0.5 | 8.5 | 7.5 | 10.2 | 1.0 | 3.2 | 3.1 | 3.4 |
| 0.6 | 6.9 | 6.2 | 8.2 | 1.5 | 2.3 | 2.2 | 2.4 |
| 0.8 | 4.9 | 4.5 | 5.8 | 2.0 | 1.8 | 1.7 | 1.9 |
| 1.0 | 3.8 | 3.5 | 4.4 | 2.5 | 1.4 | 1.4 | 1.6 |
| 1.4 | 2.6 | 2.4 | 2.9 | 3.0 | 1.2 | 1.2 | 1.4 |
| 1.6 | 2.2 | 2.1 | 2.5 | 4.0 | 1.0 | 0.9 | 1.1 |
| 2.0 | 1.7 | 1.6 | 1.9 | 5.0 | 0.8 | 0.7 | 0.9 |
| 3.0 | 1.1 | 1.1 | 1.2 | 10 | 0.4 | 0.4 | 0.5 |
| 5.0 | 0.6 | 0.6 | 0.6 | 20 | 0.2 | 0.2 | 0.3 |

# 3 Conclusions

*Note: conclusions regarding deposited sediment are reported separately (Clapcott and Goodwin 2017).*

### 3.1.1 Classification system for suspended sediment

The 'reference state variation' for suspended sediment (determined using MDC site medians) was relatively small, with maximum values of 6.0 g/m$^3$, 1.1 m and 3.3 NTU for TSS, clarity and turbidity respectively. Limiting the natural state variation to the 95$^{th}$ percentile of MDC sites, the respective maximum values for TSS, clarity and turbidity were 3.9 g/m$^3$, 1.5 m and 2.5 NTU; and median values were 2.0 g/m$^3$, 3.5 m and 0.8 NTU.

The number of reference data was a limitation, but it is suggested (and was supported by modelled reference condition data McDowell et al. 2013) that, for MDC sites, warm REC climate classes have, on average, 2-times higher turbidity values. For example, MDC sites categorised as WWL had a median turbidity of 1.9 NTU, compared to 0.8-0.9 NTU for cool REC climate/SoF categories. This was supported by McDowell et al. (2013), where the median (of predicted reference site medians) for 12 cool and 6 warm climate categories was approximately 2.0 and 1.0 NTU, respectively (there is also some indication that within warm climate categories, lake and non-lake topography categories may be important). However, on balance, we are recommending (at least initially) to not differentiate flowing waters in New Zealand for the purpose of managing SS for ecosystem health. That is, we recommend proceeding without a classification system for suspended sediment. Reasons supporting this recommendation include:

- Uncertainty about reference state variation for warm REC climate class – this includes uncertainty in the predicted reference conditions (McDowell et al. 2013).
- 95% of MDC sites are within 1.4 m clarity (2.5 NTU), which is a conservative biological effect threshold based on optimal reaction distances for trout feeding on 12 mm macroinvertebrate (Hay et al. 2006).

It is often inferred that certain regions have geologies that cause rivers to have naturally higher SS values. We were unable to find a parameter that could account for this supposition.

### With respect to redundancy of sediment ESVs (including turbidity)

Following detailed assessment of available data, we conclude the following:

- Euphotic depth is largely irrelevant for the management of SS in flow waters, and therefore it should not be considered as a potential SS ESV.
- TSS has a method detection limit that is too high to enable it to be used to determine reference state variation, and therefore it should not be used for this purpose.
- Clarity and TSS are not routinely monitored by all councils, and if either is incorporated as an attribute, some councils would not be able to assess compliance against proposed thresholds.
- Turbidity is measured by all councils, and while there are some limitations of this proxy measure of TSS (Davie-Colley & Smith 2001), these appear to be related to the absence

of particulate materials, which is likely to only be an issue at the cleaner end of the TSS spectrum (i.e., related to waters having very low SS loads).

- Turbidity is potentially more suited (relative to clarity) for managing waters at the dirtier end of the SS spectrum. It is challenging to measure clarity (without bankside dilution) in waters providing less than approximately 0.5 m sighting range, which corresponds to a turbidity of around 8-10 NTU.
- NRWQN data provide good regression equations for interconverting turbidity, clarity and TSS values; however for regional datasets (based on site medians), the correlations were weaker (although it is important to note that the NRWQN TSS dataset is for a single year, 2011). As presented in this report, the simply regressions using site medians from regional SoE data, are probably not sufficiently robust for converting between TSS and turbidity or TSS and clarity.
- Clarity and turbidity correlated well ($R^2$=0.8), and the inverse relationship meant in the area of interest (i.e., higher SS range) the conversion from turbidity to clarity showed less variability (than conversion from clarity to turbidity).

With the caveat that only site medians were investigated for characterising reference state variation, we recommend that one ESV will be sufficient for managing SS in flowing water for ecosystem health (analogous for deposited sediment). Although it is acknowledged that SS may have different modes of action impairing ecosystem health, the limiting mode of action can be expressed as either turbidity or clarity. There is benefit in adopting a turbidity-based SS attribute, because:

- the working range in 'dirtier' water is larger than for clarity, and principally
- all councils measure turbidity, and hence have long-term SoE monitoring data available for compliance testing.

# 4 Acknowledgements

I gratefully acknowledge the ongoing assistance from regional and unitary councils and LAWA with data enquires, advice regarding reference site assignments, NZReach assignments (and a multitude of other enquiries) and assistance with the second part of the project's field work. I thank Neale Hudson for formerly reviewing the report; and, in addition, Doug Booker and Andrew Hughes for providing valuable comments/feedback, and Rob Davies-Colley for providing the technical appendix on light penetration. Last, but certainly not least, I thank Sanjay Wadhwa for his excellent GIS support, in particular, generating the LCDB v4.1 land-cover data for all 833 water quality monitoring sites which was an essential component of the work.

# 5 Glossary of abbreviations and terms

| | |
|---|---|
| Clarity | Water clarity refers to light transmission through water, and has two important aspects: visual clarity (sighting range for humans and aquatic animals) and light penetration for growth of aquatic plants.<br>Clarity in this report refers only to visual clarity. |
| ESV | Environment state variable. |
| Euphotic depth | The depth at which light has fallen to 1% of the light available at the surface. |
| LCDB4 | Land cover database version 4. |
| MDC | Minimally disturbed condition - referring to sites that are below a threshold of anthropogenic disturbance, and can therefore be used as proxies to define at least a pseudo reference state range of conditions. |
| NRWQN | National River Water Quality Monitoring Network (run by NIWA). |
| ORC | Otago Regional Council. |
| PAR | Photosynthetic available radiation. |
| RC | Regional Council. |
| REC | River Environment Classification. Refer to Snelder et al. (2004). |
| REC2 | River Environment Classification - version 2. |
| SoE | State of the Monitoring water quality sites undertaken by regional and unitary authorities. For the purposes of this report, it also includes NRWQN sites. |
| SSC | Suspended sediment concentration. |
| TSS | Total suspended sediment. |

# 6 References


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

Ausseil, O., Clark, M. (2007) Recommended Water Quality Standards for the Manawatu Wanganui Region: Technical Report to support policy development. *Horizon's Regional Council,* Report No. 2007/EXT/806.

Barrett, J.C., Grossman, G.D., Rosenfeld, J. (1992) Turbidity-induced changes in reactive distance of rainbow trout. *Transactions of the American Fisheries Society,* 121: 437–443.

Clapcott, J.E., Goodwin, E.O., Snelder, T.H., Collier, K.J., Neale, M.W. (2016) Finding reference: a comparison of modelling approaches for predicting benchmarks for macroinvertebrate community metrics. *New Zealand Journal of Marine and Freshwater Research*.

Clapcott, J.E., Goodwin, E.O. (2017) Technical report on developing a deposited sediment classification for New Zealand streams. Prepared for Ministry for the Environment. *Cawthron Report,* No. 2994: 36 plus appendices.

Davies-Colley, R.J., Ballantine, D.J., Elliot, S.H., Swales, A., Hughes, A.O., Gall, M.P. (2014) Light attenuation – a more effective basis for the management of fine sediment than mass concentration? *Waster Science & Technology*, 69(9): 1867-1874.

Davies-Colley, R.J., Nagels, J.W. (2008) Predicting light penetration into river waters. *Journal of Geophysical Research-Biogeosciences,* 113: G03028. doi10.1029/2008JG000722.

Davies-Colley, R.J., Smith, D.G. (2001) Turbidity, suspended sediment, and water clarity: a review. *Journal of the American Water Resources Association,* 37(5): 1085-1101.

Duarte, C.M (1991) Seagrass depth limits. *Aquatic Botany,* 40: 363-377.

De Robertis, A., Ryer, C.H., Veloza, A., Brodeur, R.D. (2003) Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. *Canadian Journal of Fisheries and Aquatic Sciences,* 60: 1517–1526.

Hay, J., Hayes, J., Young, R. (2006) Water quality guidelines to maintain trout fishery values. Prepared for Horizons Regional Council. *Cawthron Report,* No. 1205: 17.

Julian, J.P., Doyle, M.W., Stanley, E.H. (2008) Empirical modeling of light availability in rivers. *Journal of Geophysical Research-biogeosciences*, 113: G03022. doi:10.1029/2007JG000601

Holliday, C.P., Rasmussen, T.C., Miller, W.P. (2003) In: *Proceedings of the 2003 Georgia Water Resources Conference*, University of Georgia (April 23-24, 2003). Ed. Kathryn J. Hatcher. Institute of Ecology, University of Georgia, Athens, Georgia.

McDowell, R.W., Snelder, T.H., Cox, N. (2013) Establishment of reference conditions and trigger values for chemical, physical and microbiological indicators in New Zealand streams and rivers. *AgResearch Client Report prepared for Ministry for the Environment* (February 2013).

Rosenberg, D.M., Wiens, A.P. (1978) Effects of sedimentation on macrobenthic invertebrates on a northern Canadian river. *Water Research*, 12: 753–763.

Snelder, T., Biggs, B., Weatherhead, M. (2004) *New Zealand River Environment Classification User Guide.* Ministry for the Environment, Wellington, NZ (first published in March 2004, revised September 2010).

# Appendix A Technical justification for excluding euphotic depth as a suspended sediment ESV for flowing waters

**Light penetration and euphotic depth.**
(Notes for the sediment NOF, Stage 2 work)

Rob Davies-Colley, NIWA, March 2017


## Summary

Suspended sediment attenuates light, leading to effects on aquatic ecosystems via two different aspects of water clarity: (reduced) *visual clarity* (restricting visual range of aquatic animals) and (reduced) *light penetration* (constraining aquatic plant photosynthesis). Visual clarity is relatively simply (linearly) related to concentration of suspended sediment of a particular type by its light beam attenuation, although the overall correlation with suspended sediment is weakened by a fairly wide range (~20-fold) in light beam attenuation per unit mass due to variation in particle size, shape and composition. Light penetration is more complicatedly (and non-linearly) related to suspended sediment concentration, because diffuse (sun)light attenuation reflects interaction of light scattering by fine particles with light absorption. Simple calculations suggest that light penetration into NZ rivers is not often limiting of benthic plants, and it is *downstream* waters (lakes, estuaries) where protection of light fields may be necessary. But protection of visual clarity by prospective NOF-objectives for fine sediment suspended in waters may also serve to protect light penetration in all but very 'unusual' cases.


## Optical basis of water clarity

Two aspects of visual clarity in waters are important to ecology and human values: light penetration and visual clarity (Davies-Colley et al. 2003).

Visual clarity controls the sighting distance of aquatic animals, including fish and aquatic birds, as well as strongly affecting human use of waters for recreation (e.g., Smith et al. 1995) Visual clarity is quantified by the beam attenuation coefficient, $c$ ($m^{-1}$), *the proportional loss of light energy from a perfectly collimated light beam per unit (small[1]) length of light path* by two optical processes:

- *absorption* (conversion of light energy to another form, ultimately heat, symbol $a$), and
- *scattering* (change in direction but not energy of light photons, symbol $b$).

These optical properties are associated as follows:

$$c = a + b,$$

The beam attenuation, absorption and scattering coefficients are all *inherent* optical properties (IOPs) (e.g., Kirk 2011), dependent only on the properties of the water and not on incident light.

Penetration of sunlight (diffuse light or irradiance) into waters, combined with water depth, controls the light field of benthic plants that are 'competing' for light with phytoplankton circulating through the overlying water column. Sunlight penetration is quantified by the irradiance attenuation

[1] The path length has to be small so that the proportional change in incident light does not change much. See formal definitions in standard texts like Davies-Colley et al. (2003) and Kirk (2011).

coefficient $K$(m$^{-1}$), usually measured to detect down-welling irradiance with a cosine response[2] – denoted by subscript-d (Kirk 2011). Analogous to beam attenuation, irradiance attenuation can be defined as the *proportional change in irradiance over a (small) depth interval in water*. Irradiance attenuation can be measured using detectors having different spectral responses. The most commonly used device, particularly with regard to aquatic plant light fields, is a photosynthetically available radiation (PAR) sensor – one that is equally sensitive to all photons in the PAR band of 400-700 nm wavelength. Down-welling irradiance attenuation in the PAR band is denoted $K_d$(PAR). Irradiance attenuation is an *apparent* optical property (AOP) that depends (albeit weakly) on incident sunlight (Kirk 2011). One important consequence of this 'apparent' character is that it is not strictly correct to add the contributions of different light-attenuating constituents in water (such as fine sediment and phytoplankton) in order to estimate total irradiance attenuation.

## Effects of fine sediment on water clarity

Both light penetration and visual clarity of waters are strongly affected by fine sediment (e.g., Davies-Colley et al. 2015) – which typically dominates light scattering in water and sometimes also contributes strongly to light absorption. Absorption of light by fine sediment is usually due to organic material sorbed onto mineral surfaces, rather than to intrinsic mineral 'colour', but counter examples of practical importance, notably (yellow to red-coloured) ferric sesquioxides exist.

Visual clarity is rather simply related to the amount of sediment suspended in waters. Beam attenuation (controlling visual clarity) depends linearly on suspended fine sediment concentration. However, fine sediment varies greatly in physical size and surface properties, and thus the light beam attenuation per unit mass concentration

$$c^* = c/\text{TSS},$$

units m$^2$/g, hence often referred to as an 'optical cross-section') also varies appreciably. So sediment 'quality' (physical properties) are almost equally important as sediment 'quantity' (concentration) as regards light beam attenuation. 'Fine' sediment, may be defined for current purposes as particles in the 0.1 to 10 μm diameter range, and in that range the attenuation cross-section (for equidimensional particles) varies roughly 20-fold (peaking at an intermediate size of about 1.2 μm; Davies-Colley et al. 2003: fig 2.9). Particle shape is also important, with layer clay minerals having, as could be expected, appreciably higher optical cross-sections than equidimensional particles (e.g., Gibbs 1978). Hicks et al. (2016) reported an approximate 20-fold range in average optical cross-section of fine sediment in NZ rivers in the NRWQN – which is most strongly due to variation in particle size but also particle shape. Unfortunately, the predictability of optical cross-section in NZ rivers was found to be weak, with only %silt-clay in catchment soils having any useful predictive power (Hicks et al. 2016), so visual clarity will probably have to be related empirically (locally) to suspended sediment concentration by pairing visual clarity with TSS measurements.

The relationship between light penetration and suspended sediment is more complex than that between visual clarity and suspended sediment. A classic paper by Kirk (1985) elucidated the mechanism:

- light absorption is what actually extinguishes light photons moving down through the water column, such that irradiance attenuation is proportional to absorption, but

[2] Response proportional to the cosine of the angle of incidence. Light detectors fitted with flat plate diffusers typically closely approach the ideal cosine response (Kirk 2011).

- light scattering contributing indirectly to irradiance attenuation by forcing light photons to take a tortuous path, thereby increasing the probability of absorption over a given depth interval.

In a series of papers, Kirk showed that light attenuation was proportional to the square root of light scattering (Kirk 2011). For example, Kirk (1981) used stochastic modelling to derive the following expression for irradiance attenuation at the mid-point of the euphotic zone (i.e., the 10% light level):

$$K_d(z_m) = (a^2 + 0.256ab)^{0.5}$$

So if fine sediment is light-scattering, but negligibly light-absorbing (for example glacial flour), we expect a square-root relationship between $K_d$ and TSS. More often fine sediment is light-*absorbing* as well as light-scattering, and, if the light absorption is comparatively strong ($a \sim b$), $K_d$ is nearly linearly dependent on TSS. More often, fine sediment is more strongly light-scattering than absorbing ($b > a$), and the relationship between these $K_d$ and TSS is best described by a power law with an empirical exponent between 0.5 and 1.0. Some studies have found a near-linear dependence (e.g., Vant 1990, and Gall et al. 2017 in prep. for estuaries), but more often the dependence is better fitted empirically by a power law with an exponent between 0.5 and 1.0 (e.g., Davies-Colley and Nagels 2008 reported an exponent of 0.50 for NZ rivers).

Note that fine sediment interacts with dissolved light absorption, primarily by coloured dissolved organic matter (CDOM, humic matter), to increase overall irradiance attenuation by the same mechanism discussed by Kirk (1985) – i.e., light scattering by suspended particles increases effective path and the likelihood of absorption of photons. This insight was the basis for development of a simple semi-empirical model of irradiance attenuation in NZ rivers as a function of beam attenuation and CDOM by Davies-Colley and Nagels (2008).

### Protecting NZ waters from optical and non-optical impacts of fine suspended sediment

There is little doubt that visual clarity is a valued attribute of NZ waters, including rivers, and important to the habitat quality of higher animals (fish and birds). Therefore, visual clarity should be protected by national standards (NOF-bands). Given development of national standards for visual clarity, two further questions arise:

- Are NOF bands (standards) also required to manage the *non*-optical effects of suspended sediment?

- Are NOF bands (standards) also required to manage the light penetration effects of suspended sediment?

### Non-optical effects of fine suspended sediment

In my opinion, because light beam attenuation per unit mass (attenuation cross-section, $m^2/g$) of sediment in NZ rivers varies appreciably (about 20-fold), we cannot rely on visual clarity (or suspended sediment concentration) alone, despite the good overall correlation of these quantities (e.g., Davies-Colley et al. 2014). It may be inconvenient, but New Zealand would ideally have standards for *both* visual clarity and suspended mass concentration to adequately protect from both optical and non-optical effects of fine suspended matter. (This assumes, in the absence of specific knowledge to the contrary, that non-optical effects will scale with mass concentration. That assumption should, ideally, be tested).

## Different optical effects of fine suspended sediment

The two main optical effects of fine suspended sediments, as we have seen, are reduced visual clarity and reduced light penetration. However, it should be noted that fine sediment also affects water colour and thereby, human aesthetic response to waters and, potentially, spectral light fields in waters, which are likely to affect plant photosynthesis and aquatic animal vision. For the moment we will ignore water colour and spectral effects and concentrate solely on water clarity.

## Can standards for visual clarity adequately protect light penetration?

Davies-Colley and Nagels (2008) found that suspended sediment was the main controller of light penetration into NZ rivers, but CDOM (dissolved humic matter) also contributed, apparently by interacting with the light scattering of suspended matter via the process discussed by Kirk (1985). In waters downstream, that is, estuaries and lakes, phytoplankton may be expected to become important as a light-attenuating constituent (Davies-Colley et al. 2003), as has been shown for lakes (e.g., Vant and Davies-Colley 1984). Vant (1990) and Gall et al. (2017 in prep.) found that phytoplankton chlorophyll *a* contributed negligibly to irradiance attenuation in northern North Island estuaries.

In NZ's mostly shallow, small rivers light 'shading' by the water column is probably seldom a major constraint on plant growth, unlike shading by riparian vegetation (see calculations below and summarised in Table A-1). Deep, highly light-attenuating rivers can be severely light-limiting (e.g., Julian et al. 2008), but in NZ rivers such conditions are probably mostly confined to episodic and transient flood flows, which are both deeper and more light-attenuating than baseflows.

Furthermore, it is difficult to imagine a situation where visual clarity would not be changed to the extent that recommended standards were exceeded, but light penetration would be, because both aspects of clarity depend on light-attenuation, including by sediment, albeit in different ways.

So it is reasonable to hypothesise that controlling light beam attenuation (to protect visual clarity) will also protect irradiance attenuation (and thus light penetration) in New Zealand rivers.

To check this hypothesis, a model of benthic lighting for different NZ rivers would ideally be constructed, based on the BLAM (benthic light availability model) framework of Julian et al. (2008), with irradiance at the bed given by

$$E_{bed} = 0.93sE_o\exp(-K_\mathrm{d}z),$$

where $E_o$ is incident irradiance, $z$ is water depth, and the factor 0.93 accounts for an average of about 7% loss of irradiance by reflection at the water surface. (As a 'worst case' we neglect bank and riparian shading, $s$.) The model framework would use:

- the simple statistical model of $K_d$(PAR) (as a function of c and CDOM) from Davies-Colley and Nagels (2008), together with
- statistical models (to be constructed from available water quality and morphological data) of both
  - optical properties (c, CDOM; Smith et al. 1997), and
  - depth distribution ($z$) as a function of flow

- to estimate benthic lighting as a function of flow and thus time (using the flow-duration curve).

As a (very) rough indicator of how this kind of modelling would 'work', we can illustrate benthic irradiance as a fraction of incident for some particular cases (Table A-1).

1. For an averagely light-attenuating NZ river (median visibility = 1.28 m; $g_{340}$, an index of CDOM, = 4.1/m; Smith et al. 1997), the semi-empirical statistical model of Davies-Colley and Nagels (2008) predicts $K_d$(PAR) = 1.03/m.  In 1 m water depth (average), the ratio $E_{bed}/E_o$ = 38% (Table A-1), which would not be light-limiting for most benthic plant communities.

2. In a very 'dirty' and coloured NZ river with 95percentile visibility = 0.36 m and 95percentile CDOM, $E_{bed}/E_o$ at 1 m depth is 10% – which is starting to constrain growth of some (light-demanding) benthic plants.

3. Obviously if the water was even deeper the light limitation would be more severe.  For example, for a dirty and coloured river water at 2 m depth, the bed is approximately at the euphotic depth (irradiance has fallen to ~1% of surface value; Table A-1), extinguishing most benthic plants.

These simple calculations suggest that light limitation by water shading is generally not an issue in NZ rivers, and that specific protection of light penetration in rivers should not be needed.

Light penetration will need to be considered in lake and estuary receiving waters. There is ample evidence that keystone benthic plants in lakes (macrophytes) and estuaries (seagrasses) have declined historically in NZ because of reduction in euphotic depth (depth of the 1% light level, a useful rough index of the maximum depth of light growth – e.g., Vant et al. 1986), caused by increased suspended sediment concentrations.  However, in particular cases it is difficult to decide whether increased suspended sediment and light attenuation is a symptom or a cause of the decline in keystone plant population (often probably both – Schallenberg and Sorrell 2009).  But even in lakes and estuaries, protecting visual clarity (light beam attenuation) – depending on how the standards are formulated numerically – may also serve to adequately protect benthic light fields (irradiance attenuation) in all but very 'unusual' cases.

**Table A-1: Irradiance (PAR) at the bed of a NZ river as a fraction of incident irradiance.** Calculations used Model 1b of Davies-Colley and Nagels (2008) to calculate irradiance attenuation (Kd(PAR)) from visual clarity and g340 (CDOM index) statistics from the NRWQN as summarised by Smith et al. (1997). The benthic light availability model framework (BLAM) of Julian et al. (2008) was used to calculate the irradiance at the bed as a fraction of incident irradiance, assuming a 1 m and 2 m average depth (ignoring riparian shade and allowing for 7% loss of light by water surface reflection).

| NZ rivers | Visual clarity (m) | CDOM ($g_{340}$, 1/m) | $K_d$(PAR) (1/m) | Bed irradiance as a % of incident irradiance $E_{bed}/E_o$ | |
|---|---|---|---|---|---|
| | | | | 1m depth | 2m depth |
| Median values | 1.28 | 4.10 | 1.03 | 38 | 15 |
| Dirty (95%ile clarity) | 0.36 | 4.10 | 1.95 | 16 | 2.7 |
| Dirty & coloured (95%ile) | 0.36 | 12.2 | 2.46 | 10 | 1.0 |

# References


Davies-Colley, R.J., Nagels, J.W. (2008) Predicting light penetration into river waters. *Journal of Geophysical Research-Biogeosciences,* 113: G03028. doi10.1029/2008JG000722.

Davies-Colley, R.J., Vant, W.N., Smith, D.G. (2003) Colour and clarity of natural waters*. Science and management of optical water quality.* Reprinted by Blackburn Press, Caldwell, New Jersey: 310.

Davies-Colley, R.J., Ballantine, D.J., Elliott, A.H., Swales, A., Hughes, A.O., Gall, M.P. (2014) Light attenuation – a more effective basis for the management of fine suspended sediment than mass concentration? *Water science and technology*, 69(9): 1867-1874. doi: 10.2166/wst.2014.096.

Davies-Colley, R.J., Hicks, D.M., Hughes A.O., Clapcott, J., Kelly, D., Wagenhoff, A. (2015) Fine sediment effects on freshwaters, and the relationship of environmental state to sediment load. *NIWA Client Report* (HAM2015-154), for the Ministry for the Environment, November 2015: 99.

Gall, M.P., Swales, A., Davies-Colley, R.J., Bremner, D. (2017 in prep.) Light penetration and optical water quality of northern North Island, New Zealand estuaries. *Estuarine, coastal and shelf science*.

Gibbs, R.J. (1978) Light scattering from particles of different shapes. *Journal of Geophysical Research*, 83C1: 501-502.

Hicks, D.M., Clapcott, J., Davies-Colley, R.J., Dymond, J., Greenwood, M., Hughes A.O., Shankar, U., Walter, K. (2016) Sediment attributes Stage I. *NIWA Client Report* (CHC2016-058), for the Ministry for the Environment, June 2016: 166 + Appendices.

Julian, J.P., Doyle, M.W., Stanley, E.H. (2008) Empirical modeling of light availability in rivers. *Journal of Geophysical Research-biogeosciences*, 113: G03022. doi:10.1029/2007JG000601

Kirk, J.T.O. (1981) Monte Carlo study of the nature of the underwater light field in, and the relationships between optical properties of, turbid yellow waters. *Australian journal of marine and Freshwater Research*, 32: 517-532.

Kirk, J.T.O. (1985) Effects of suspensoids (turbidity) on penetration of solar radiation in aquatic ecosystems. *Hydrobiologia*, 125: 195-208.

Kirk, J.T.O. (2011) *Light and photosynthesis in aquatic ecosystems*. Cambridge University Press, New York, NY: 649.

Schallenberg, M., Sorrell, B. (2009) Regime shifts between clear and turbid water in New Zealand lakes: Environmental correlates and implications for management and restoration. *New Zealand Journal of Marine and Freshwater Research*, 43(3): 701-712. DOI: 10.1080/00288330909510035

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

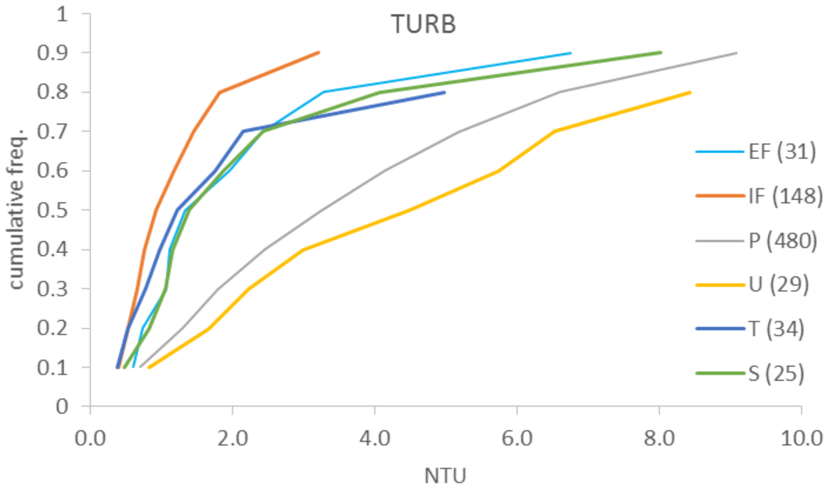
Smith, D.G., Davies-Colley, R.J., Knoeff, J., Slot, G.W.J. (1997) Optical characteristics of New Zealand rivers in relation to flow. *Journal of the American Water Resources Association*, 33: 301-312.

Vant, W.N. (1990) Causes of light attenuation in nine New Zealand estuaries. *Estuarine, Coastal and Shelf Science*, 31: 125-137.

Vant, W.N., Davies-Colley, R.J. (1984) Factors affecting clarity of New Zealand lakes. *New Zealand Journal of Marine and Freshwater Research*, 18: 367-377.

Vant, W.N., Davies-Colley, R.J., Clayton, J.S., Coffey, B.T. (1986) Macrophyte depth limits in North Island (New Zealand) lakes of differing clarity. *Hydrobiologia*, 137: 55-60.

# Appendix B Cumulative frequency (percentile) distribution of turbidity for different REC land-use classifications (Stage 1A report)



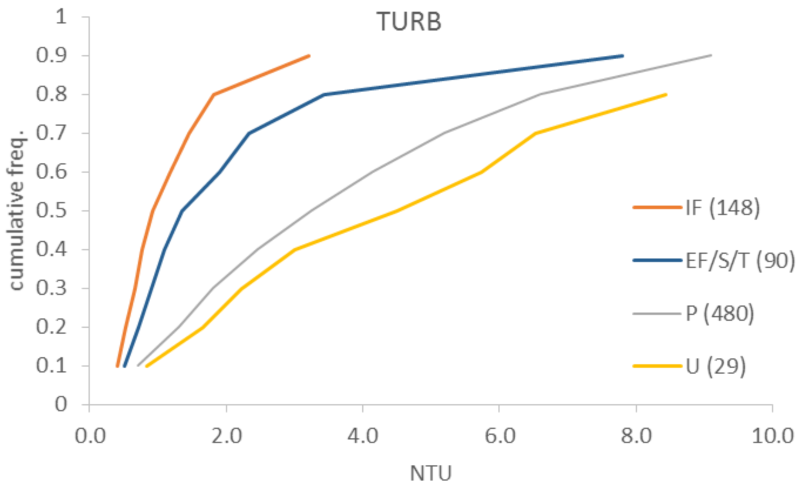




**Figure B-1: Cumulative frequency distributions curves of different REC landcover classes for TURB sites.** Upper figure shows separate curves for all REC landcover class; lower figure shows EF, S and T classes replaced with a single merged curve (EF/S/T). Wetland (W) and bare (B) classes have been excluded (Figure 3-1, p. 13 – Stage 1A report – Depree and Clapcott, 2016).

# Appendix C Assignment of LCDB v4.1 land-cover classes to upstream catchments of 833 water quality sites

Revision of the definition of 'reference state' involved setting land-cover thresholds to bound an acceptable level of catchment 'disturbance'. This made use of recent land-cover data derived from the latest version of the New Zealand Land Cover Database (LCDB v4.1).

Each monitoring site has a corresponding unique reach identifier ('NZReachID') that links it to the River Environment Classification (REC) system. The REC system links individual reaches to form a drainage network. For each monitoring site:

- all upstream reaches were selected using 'from' and 'to' node information available in the REC stream network dataset
- watershed polygons defined for each associated reach in the REC database were then combined to create a single polygon that represented the catchment upstream of each monitoring site.
- Using a Geographic Information System, this catchment polygon was then intersected with the LCDB v4.1 dataset (layer), thereby
- generating the area of each land-cover class of the upstream catchment for each of 833 water quality sites.

This process was done using an automated script-driven analytical method within GIS. Given the importance of the intended use of this information (these data were used to define 'reference state' according to land-cover thresholds), several individual monitoring sites were selected to manually repeat the process and check the results.

The results obtained for three randomly selected sites (selected from the total of 833) were checked to determine if the areas calculated using the procedure outlined above were correct, and whether the area of the catchment polygons derived from the REC reaches matched those derived from the LDCB areas. Key data included:

1) The total area calculated for the sum of the REC polygons upstream of the monitoring site.
2) Total calculated area values derived from assigned LCDB v4.1 land-coverage.
3) The accuracy of the intersection of the polygons derived from the LCDB v4.1 data with catchment areas derived from GIS using the REC sub-catchment polygons initially.
4) Whether the differences in catchment areas estimated from these two processes were tolerable.

The three randomly-selected sites are listed in Table C-1, along with key information.

**Table C-1: Details of sites randomly selected for method validation.**

| Site no. | NEMaR_ID | LAWA_ID | RC_ID | Site name | NZReach |
|---|---|---|---|---|---|
| 8 | ARC-07811 | ARC-00017 | AC | Oteha Stream at Days Bridge | 2004535 |
| 323 | EW-1293-009 | EW-00111 | EW | Whangamarino River at Jefferies Rd Br | 3008516 |
| 698 | NRC-109098 | NRC-00029 | NRC | Waimamaku River @ SH12 | 1014099 |

## Validation of results for site #8 (ARC-00017)

Referring to Figure C-1:

- the sub-catchments defined by the thin yellow lines are defined by the REC reach assignments
- the red line identifies the catchment boundary derived from GIS incorporating all the REC sub-catchments.
- Visual inspection indicates:
  - the sub-catchments for all upstream reaches for site #8 appeared to be captured, and are inside the catchment polygon (red bold line)
  - the stream lines do not cross the catchment boundary.

The results of an intersection between the catchment polygon and the LCDB4 landcover overlay (indicated by the black line in Figure C-1, right) were exported to a .txt file that was opened in Excel for more detailed evaluation. The total areas ($m^2$) for the different classes for site #8 are summarised in Table C-2. These results indicate:

- total area of the polygon following overlay with LCDB4 was 11,975,407 $m^2$
- total area of the polygon derived from GIS was 11,978,100 $m^2$
- the difference in areas calculated manually was 0.02%.

The difference in area estimated from these two sources is negligible. Although no difference might be expected, the processes used to assign land cover class may lead to minor overlaps or gaps between areas. The difference observed here is within the error expected for the land cover assignment.

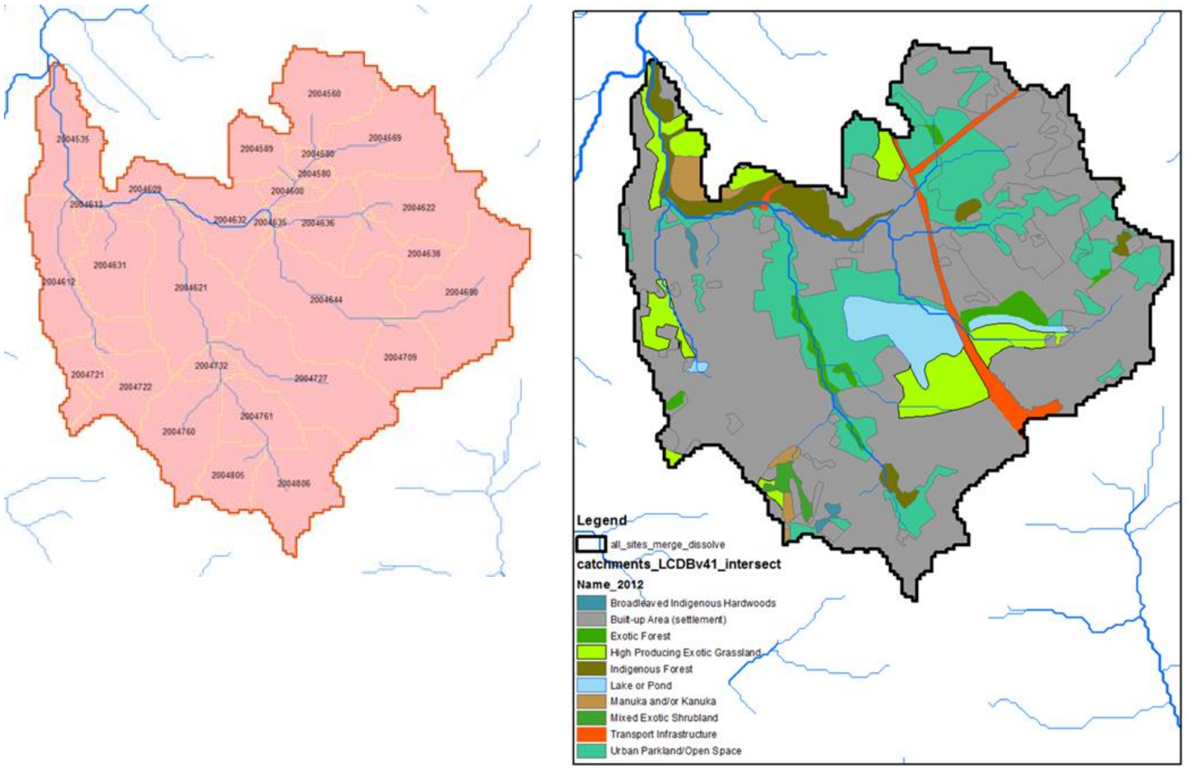



**Figure C-1: Polygon map of the catchment upstream of site #8 (left), with LCDB v4.1 land-cover overlay (right).** In the left-hand figure, the yellow lines identify catchments defined by the REC reaches, and the red line indicates the catchment boundary defined by GIS. The right-hand figure indicates the land cover classes across the entire monitoring site catchment area (denoted by the black outline).

**Table C-2: Summary of LCDB v4.1 land-cover output for site #8 (ARC-00017).**

| LCDB v4.1 landcover (description) | LCDB v4.1 code | Area ($m^2$) |
|---|---|---|
| Built-up Area (settlement) | 1 | 7,520,159 |
| Urban Parkland/Open Space | 2 | 2,061,352 |
| Transport Infrastructure | 5 | 259,267 |
| Lake or Pond | 20 | 422,150 |
| High Producing Exotic Grassland | 40 | 802,904 |
| Manuka and/or Kanuka | 52 | 147,966 |
| Broadleaved Indigenous Hardwoods | 54 | 44,106 |
| Mixed Exotic Shrubland | 56 | 55,851 |
| Indigenous Forest | 69 | 456,182 |
| Exotic Forest | 71 | 205,471 |
| **TOTAL** | | **11,975,407** |

## Validation of results for Site #323 (EW-00111)

Water quality monitoring site #323 corresponds to NZReach 3008516. The catchment upstream of this site is more complex, comprising 236 individual watershed polygons defined by the REC.

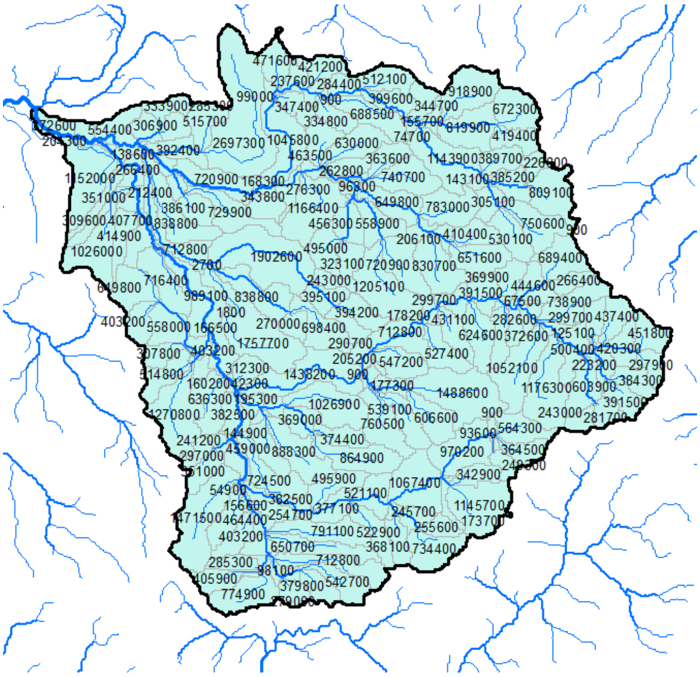


**Figure C-2: Upstream reaches and catchment polygon for site #323 (EW-00111).**

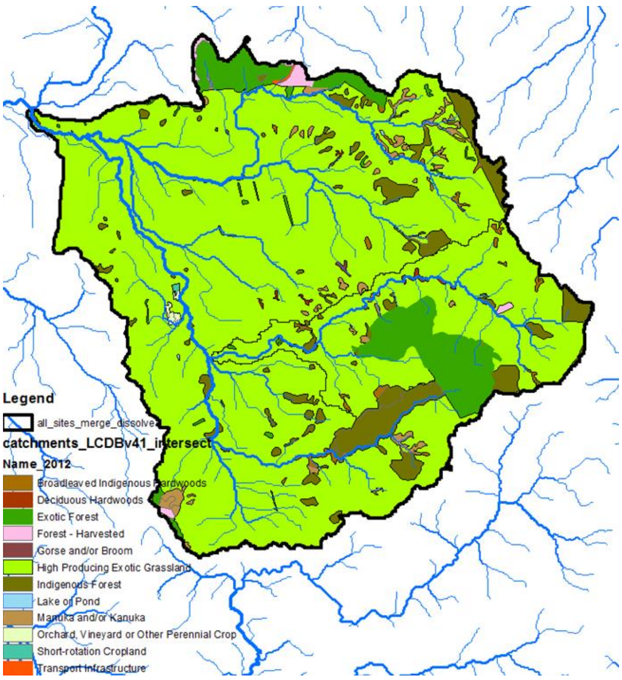



**Figure C-3: LCDB v4.1 overlay on upstream catchment polygon of site #323.**

Visual inspection of Figure C-2 shows that all upstream sub-reaches appear to be accurately captured within the overall catchment polygon (black line). The catchment polygon (in black) also appears to represent the catchment accurately.

The results of an intersection between the land cover classes and catchment boundary (Figure C-2 and Figure C-3) were assessed in Excel.  The areas derived from this process are summarized in Table C-3.

**Table C-3: Summary of LCDB v4.1 land-cover output for site #323 (EW-00111).**

| LCDB4 landcover (description) | LCDB4 code | Area ($m^2$) |
|---|---|---|
| Transport Infrastructure | 5 | 36,383 |
| Lake or Pond | 20 | 14,656 |
| Short-rotation Cropland | 30 | 28,148 |
| Orchard, Vineyard or Other Perennial Crop | 33 | 129,456 |
| High Producing Exotic Grassland | 40 | 80,237,404 |
| Gorse and/or Broom | 51 | 41,277 |
| Manuka and/or Kanuka | 52 | 1,490,799 |
| Broadleaved Indigenous Hardwoods | 54 | 548,539 |
| Forest - Harvested | 64 | 505,425 |
| Deciduous Hardwoods | 68 | 220,149 |
| Indigenous Forest | 69 | 6,647,475 |
| Exotic Forest | 71 | 6,607,176 |
| **TOTAL** | | **96,506,887** |

The total area estimated from LCDB4 was 96,506,887 $m^2$, 43,800 $m^2$ larger than the catchment polygon area derived from GIS.  This represents a difference less than 0.05%

## Validation of results for Site #698 (NRC-00029)

Water quality monitoring site #698 corresponds to NZReach 1014099. The catchment upstream of this site is the most complex of the three tested, comprising 332 individual watershed polygons defined by the REC.

Visual inspection of Figure C-4 shows that all upstream sub-reaches appear to be accurately captured within the overall catchment polygon (black line).  The catchment polygon (in black) also appears to represent the catchment accurately.

The results of an intersection between the land cover classes and catchment boundary (Figure C-4 and Figure C-5) were assessed in Excel.  The areas derived from this process are summarized in Table C-4.

The total area estimated from LCDB4 was 102,430,081 $m^2$,  115,920 $m^2$ smaller (0.1%) than the catchment polygon area derived from GIS (102,546,000 $m^2$).

In all cases the difference in area estimated by two independent techniques was less than or equal to 0.1%.  In view of the processes used to generate catchment areas and areas of discrete land use (satellite and aerial photography, automated land use assignment with expert input etc., each of which has measurable error), we are confident that the method used to define 'reference state' in terms of land-cover thresholds to bound an acceptable level of catchment 'disturbance' is defensible, repeatable and introduces negligible error when defining reference states.

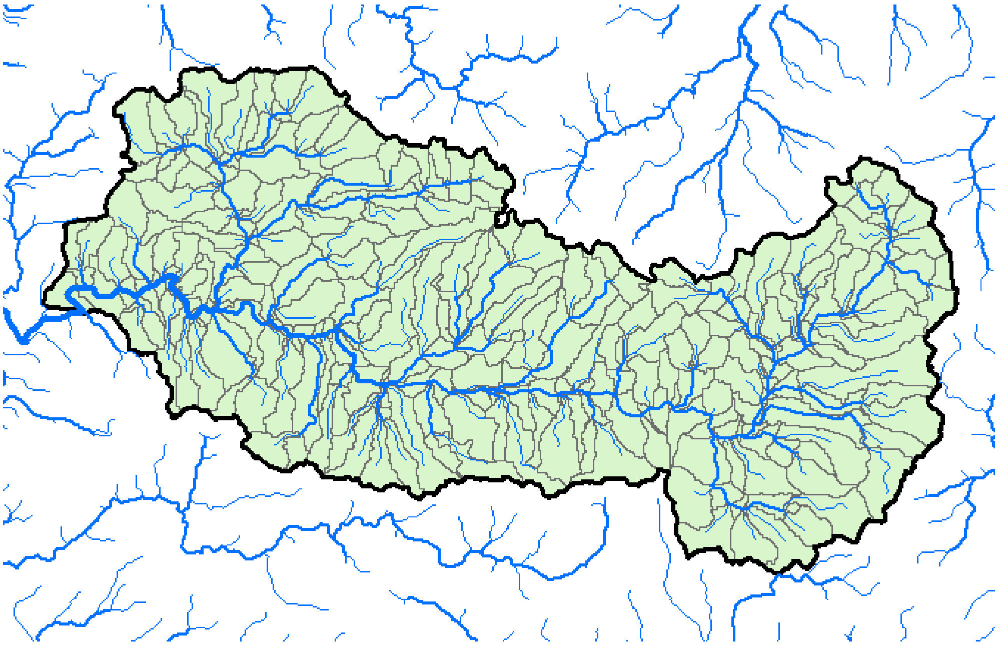


**Figure C-4: Upstream reaches and catchment polygon for site #698 (EW-00029).**

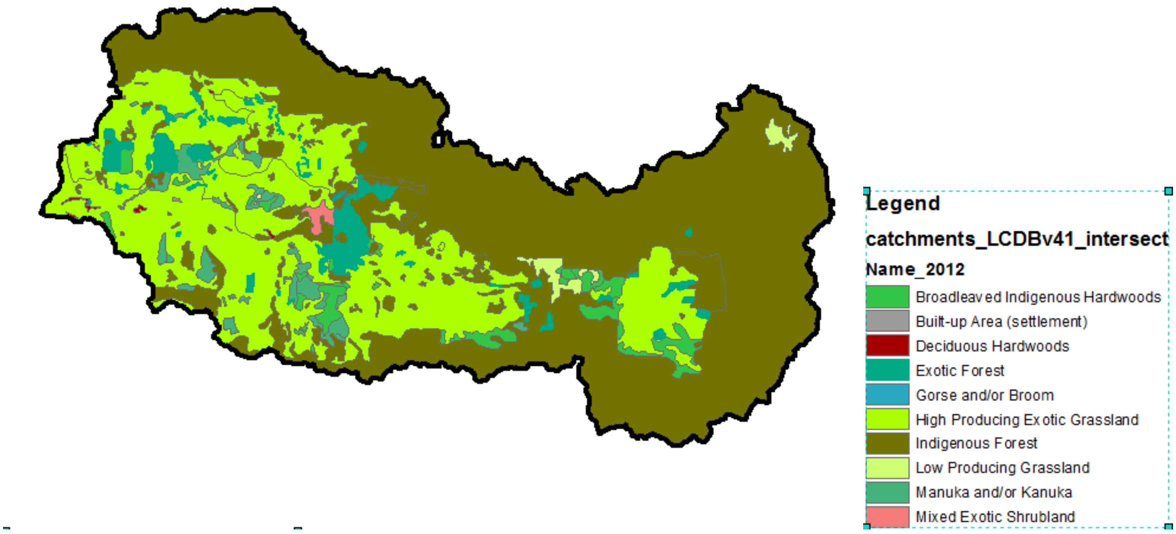



**Figure C-5: LCDB v4.1 overlay on upstream catchment polygon of site #698.**

**Table C-4: Summary of LCDB v4.1 land-cover output for site #698 (EW-00029).**

| LCDB4 landcover (description) | LCDB4 code | Area ($m^2$) |
|---|---|---|
| Built-up Area (settlement) | 1 | 12,460 |
| High Producing Exotic Grassland | 40 | 32,549,876 |
| Low Producing Grassland | 41 | 866,079 |
| Gorse and/or Broom | 51 | 834 |
| Manuka and/or Kanuka | 52 | 2,301,317 |
| Broadleaved Indigenous Hardwoods | 54 | 29,094,867 |
| Mixed Exotic Shrubland | 56 | 280,963 |
| Deciduous Hardwoods | 68 | 113,233 |
| Indigenous Forest | 69 | 59,696,786 |
| Exotic Forest | 71 | 3,699,045 |
| **TOTAL** | | **102,430,081** |

# Appendix D REC level/category definitions (Snelder et al. 2004) and New Zealand Land-Cover Database version 4.1 (LCDB v4.1)

**Table D-1: Simplified land-cover categories used for REC and the associated LCDB classes.** (Table 2.6 from Snelder et al. 2004).

| Land-Cover Category | Notation | LCDB Types |
|---|---|---|
| Bare-Ground | B | Bare Ground |
| Indigenous-Forest | IF | Indigenous-Forest |
| Scrub | S | Scrub |
| Tussock | T | Tussock |
| Wetlands | W | Inland Wetlands, Coastal Wetlands |
| Exotic-Forest | EF | Planted Forest |
| Pastoral | P | Primarily Pastoral, Primarily Horticultural |
| Urban | U | Urban, Urban Open Space |
| Miscellaneous | M | Mangrove, Riparian Willows, Coastal Sands |

**Table D-2: REC topography categories (Snelder et al. 2004).**

| Source-of-Flow category | Notation | Characteristics of category |
|---|---|---|
| Glacial-Mountain | GM | Similar to the Mountain category. Low flows in winter, high flows extend further into summer. High turbidity due to fine glacial sediment. |
| Mountain | M | Strong seasonal pattern of flows: low flows in winter, high flows in summer. High suspended solids and sediment load. Very frequent high flood flows lead to unstable substrates and channels with wide, active gravel bed flood plains. |
| Hill | H | Strong seasonal pattern: low flows in late summer, high flows in spring due to rainfall and snow melt. High to medium sediment loads depending on catchment geology and land use. Where the valley is broad so that the river channel is unconstrained, the channel morphology is characterized by unstable substrates and wide, active gravel bed flood plains. |
| Low-Elevation | L | Very marked seasonal flow patterns: high in winter, low in summer (see Figure 1.6). Low sediment supply. Stable, Low-Gradient, entrenched channels with low flow velocity and silty-sandy substrates. Flood flow velocities are low due to low channel slope. |
| Lake | Lk | Stable flow regime. Low suspended solids and sediment load. Stable channel and substrates, which may be 'armoured' (i.e. large stable stones due to winnowing of fine material and lack of sediment supply). |

Table D-3: REC climate categories (Snelder et al. 2004).

| Climate category | Notation |
|---|---|
| Warm-Extremely-Wet | WX |
| Warm-Wet | WW |
| Warm-Dry | WD |
| Cool-Extremely-Wet | CX |
| Cool-Wet | CW |
| Cool-Dry | CD |

Table D-4: REC geology categories (Snelder et al. 2004).

| Geology category | Notation | Characteristics of category |
|---|---|---|
| Alluvium | Al | Rainfall infiltration is high which tends to reduce flood frequency. There tends to be a high degree of surface water and ground water interaction. Base flows may be sustained by seepage or springs or may reduce in the downstream direction as water flows into the groundwater system. Water chemistry reflects the nature of the parent material. Note that the source information on catchment geology, the LRI, does not discriminate the parent material for alluvium. This makes the geochemistry of the Alluvium category variable. |
| Hard sedimentary rocks (greywacke, schist) | HS | Infiltration of rainfall is variable. Where geology is fractured, infiltration is high, resulting in infrequent floods but sustained base flow. Low natural nutrient concentration. Low suspended sediment. Relatively coarse substrates (cobble, gravel, sands) depending on local morphology. |
| Soft sedimentary (siltstone, mudstone and limestone) | SS | Low infiltration resulting in increased floods and low base flow. High natural phosphorus concentration. Because of the relatively soft parent material suspended sediment concentrations tend to be high. In addition, substrates tend to be relatively fine (silts and mud). |
| Volcanic basic | VB | This is a broad category within which considerable variation may exist. Phosphorus concentration tends to be high relative to other geology categories. Substrates tend to be angular, well packed and stable. |
| Volcanic acidic | VA | This is a broad category within which considerable variation may exist. Very high infiltration in areas of tephra or scoria resulting in low flood frequency and sustained base flow. Concentration of phosphorus tends to be high. Substrates tend to be fine (sands, silts and mud), unless the stream channel is steep and eroding. |

**Table D-5: REC network-positon categories (Snelder et al. 2004).**

| Network-Position category | Notation | Characteristics of river environment |
|---|---|---|
| Low-Order | LO | Headwater streams (Stream order 1 and 2) with little upstream storage. Fluxes of water and water borne constituent (e.g. sediment) move rapidly through with little attenuation. |
| Middle-Order | MO | Tributaries (Stream order 3 and 4) |
| High-Order | HO | Main stems (Stream order greater than 4). Main stems have large upstream catchments with appreciable storage. The response of the river to rainfall is 'damped' and variation in concentrations or fluxes of inputs, such as sediment or other contaminants are smoothed by the homogenising effect of catchment storage and upstream mixing. |

**Table D-6: REC valley-landform categories (Snelder et al. 2004).**

| Valley-Landform category | Notation | Characteristics of river environment |
|---|---|---|
| High-Gradient | HG | Steep channels with high water velocities. Substrates tend to be coarse relative to the lower gradient Valley Land form classes. |
| Medium-Gradient | MG | Medium-Gradient channels. These are typically broad and shallow with some meandering pattern resulting in varied morphology typically a pool-riffle-run sequence. The characteristics are, however, dependent on higher order classes. |
| Low-Gradient | LG | Low-Gradient channels. For given higher order classes, LG categories are characterised by relatively greater meandering, greater depth relative to width and lower water velocities. |

**Table D-7: 35 land-cover classes used in LCDB v4.1.**

| Class Code | Class Name | Class Description |
|---|---|---|
| 1 | Built-up Area (settlement) | Commercial, industrial or residential buildings, including associated infrastructure and amenities, not resolvable as other classes. Low density 'lifestyle' residential areas are included where hard surfaces, landscaping and gardens dominate other land covers. |
| 2 | Urban Parkland/Open Space | Open, mainly grassed or sparsely-treed, amenity, utility and recreation areas. The class includes parks and playing fields, public gardens, cemeteries, golf courses, berms and other vegetated areas usually within or associated with built-up areas. |
| 5 | Transport Infrastructure | Artificial surfaces associated with transport such as arterial roads, rail-yards and airport runways. Skid sites and landings associated with forest logging are sometimes also included. |
| 6 | Surface Mine or Dump | Bare surfaces arising from open-cast and other surface mining activities, quarries, gravel-pits and areas of solid waste disposal such as refuse dumps, clean-fill dumps and active reclamation sites. |
| 10 | Sand or Gravel | Bare surfaces dominated by unconsolidated materials generally finer than coarse gravel (60mm). Typically mapped along sandy seashores and the margins of lagoons and estuaries, lakes and rivers and some areas subject to surficial erosion, soil toxicity and extreme exposure. |
| 12 | Landslide | Bare surfaces arising from mass-movement erosion generally in mountain-lands and steep hill-country. |
| 14 | Permanent Snow and Ice | Areas where ice and snow persists through late summer. Typically occurring above 1800m but also at lower elevations as glaciers. |
| 16 | Gravel or Rock | Bare surfaces dominated by unconsolidated or consolidated materials generally coarser than coarse gravel (60mm). Typically mapped along rocky seashores and rivers, sub-alpine and alpine areas, scree slopes and erosion pavements. |
| 15 | Alpine Grass/Herbfield | Typically sparse communities above the actual or theoretical treeline dominated by herbaceous cushion, mat, turf, and rosette plants and lichens. Grasses are a minor or infrequent component, whereas stones, boulders and bare rock are usually conspicuous. |
| 20 | Lake or Pond | Essentially-permanent, open, fresh-water without emerging vegetation including artificial features such as oxidation ponds, amenity, farm and fire ponds and reservoirs as well as natural lakes, ponds and tarns. |
| 21 | River | Flowing open fresh-water generally more than 30m wide and without emerging vegetation. It includes artificial features such as canals and channels as well as natural rivers and streams. |
| 22 | Estuarine Open Water | Standing or flowing saline water without emerging vegetation including estuaries, lagoons, and occasionally lakes occurring in saline situations such as inter-dune hollows and coastal depressions. |
| 30 | Short-rotation Cropland | Land regularly cultivated for the production of cereal, root, and seed crops, hops, vegetables, strawberries and field nurseries, often including intervening grassland, fallow land, and other covers not delineated separately. |
| 33 | Orchards, Vineyards or Other Perennial Crops | Land managed for the production of grapes, pip, citrus and stone fruit, nuts, olives, berries, kiwifruit, and other perennial crops. Cultivation for crop renewal is infrequent and irregular but is sometimes practiced for weed control. |
| 40 | High Producing Exotic Grassland | Exotic sward grassland of good pastoral quality and vigour reflecting relatively high soil fertility and intensive grazing management. Clover species, ryegrass and cocksfoot dominate with lucerne and plantain locally important, but also including lower-producing grasses exhibiting vigour in areas of good soil moisture and fertility. |
| 41 | Low Producing Grassland | Exotic sward grassland and indigenous short tussock grassland of poor pastoral quality reflecting lower soil fertility and extensive grazing management or non-agricultural use. Browntop, sweet vernal, danthonia, fescue and Yorkshire fog dominate, with indigenous short tussocks (hard tussock, blue tussock and silver tussock) common in the eastern South Island and locally elsewhere. |
| 43 | Tall Tussock Grassland | Indigenous snow tussocks in mainly alpine mountain-lands and red tussock in the central North Island and locally in poorly-drained valley floors, terraces and basins of both islands. |

| | | |
|---|---|---|
| 44 | Depleted Grassland | Areas, of mainly former short tussock grassland in the drier eastern South Island high country, degraded by over-grazing, fire, rabbits and weed invasion among which *Hieracium* species are conspicuous. Short tussocks usually occur, as do exotic grasses, but bare ground is more prominent. |
| 45 | Herbaceous Freshwater Vegetation | Herbaceous wetland communities occurring in freshwater habitats where the water table is above or just below the substrate surface for most of the year. The class includes rush, sedge, restiad, and sphagnum communities and other wetland species, but not flax nor willows which are mapped as Flaxland and Deciduous Hardwoods respectively. |
| 46 | Herbaceous Saline Vegetation | Herbaceous wetland communities occurring in saline habitats subject to tidal inundation or saltwater intrusion. Commonly includes club rush, wire rush and glasswort, but not mangrove which is mapped separately. |
| 47 | Flaxland | Areas dominated by New Zealand flax usually swamp flax (harakeke) in damp sites but occasionally mountain flax (wharariki) on cliffs and mountain slopes. |
| 50 | Fernland | Bracken fern, umbrella fern, or ring fern, commonly on sites with low fertility and a history of burning. Manuka, gorse, and/or other shrubs are often a component of these communities and will succeed Fernland if left undisturbed. |
| 51 | Gorse and/or Broom | Scrub communities dominated by gorse or Scotch broom generally occurring on sites of low fertility, often with a history of fire, and insufficient grazing pressure to control spread. Left undisturbed, this class can be transitional to Broadleaved Indigenous Hardwoods. |
| 52 | Manuka and/or Kanuka | Scrub dominated by mānuka and/or kānuka, typically as a successional community in a reversion toward forest. Mānuka has a wider ecological tolerance and distribution than kānuka with the latter somewhat concentrated in the north with particular prominence on the volcanic soils of the central volcanic plateau. |
| 54 | Broadleaved Indigenous Hardwoods | Lowland scrub communities dominated by indigenous mixed broadleaved shrubs such as wineberry, mahoe, five-finger, *Pittosporum* spp, fuchsia, tutu, titoki and tree ferns. This class is usually indicative of advanced succession toward indigenous forest. |
| 55 | Sub Alpine Shrubland | Highland scrub dominated by indigenous low-growing shrubs including species of *Hebe*, *Dracophyllum*, *Olearia*, and *Cassinia*. Predominantly occurring above the actual or theoretical treeline, this class is also recorded where temperature inversions have created cooler micro-climates at lower elevations e.g. the 'frost flats' of the central North Island. |
| 56 | Mixed Exotic Shrubland | Communities of introduced shrubs and climbers such as boxthorn, hawthorn, elderberry, blackberry, sweet brier, buddleja, and old man's beard. |
| 58 | Matagouri or Grey Scrub | Scrub and shrubland comprising small-leaved, often divaricating shrubs such as matagouri, *Coprosma* spp, *Muehlenbeckia* spp., *Casinnia* spp., and *Parsonsia* spp. These, from a distance, often have a grey appearance. |
| 80 | Peat Shrubland (Chatham Is) | Low-growing shrubland communities usually dominated by *Dracophyllum* spp. in association with *Cyathodes* spp. and ground ferns. Mapped only on the Chatham Islands. |
| 81 | Dune Shrubland (Chatham Is) | Low-growing shrubland communities dominated by *Leucopogon* spp., *Pimelia arenaria* and *Coprosma* spp., in association with sedges and scattered herbs and grasses. Mapped only on the Chatham Islands. |
| 70 | Mangrove | Shrubs or small trees of the New Zealand mangrove (*Avicennia marina* subspecies *australascia*) growing in harbours, estuaries, tidal creeks and rivers north of Kawhia on the west coast and Ohiwa on the east coast. |
| 64 | Forest - Harvested | Predominantly bare ground arising from the harvesting of exotic forest or, less commonly, the clearing of indigenous forest. Replanting of exotic forest (or conversion to a new land use) is not evident and nor is the future use of land cleared of indigenous forest. |
| 68 | Deciduous Hardwoods | Exotic deciduous woodlands, predominantly of willows or poplars but also of oak, elm, ash or other species. Commonly alongside inland water (or as part of wetlands), or as erosion-control, shelter and amenity plantings. |
| 69 | Indigenous Forest | Tall forest dominated by indigenous conifer, broadleaved or beech species. |
| 71 | Exotic Forest | Planted or naturalised forest predominantly of radiata pine but including other pine species, Douglas fir, cypress, larch, acacia and eucalypts. Production forestry is the main land use in this class with minor areas devoted to mass-movement erosion-control and other areas of naturalised (wildling) establishment. |

# Appendix E Land-cover thresholds for defining upper bounds of minimally disturbed condition (MDC) sites

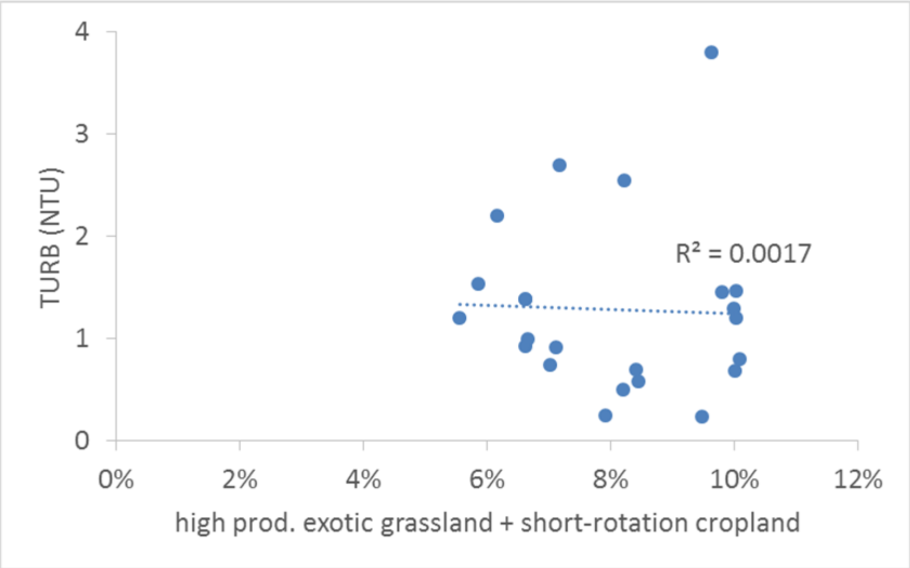



**Figure E-1: Relationship between turbidity (NTU) and land use at selected MDC sites.** Sites reflect combinations of high producing pasture + cropping land-cover of 5 to 10% (of upstream catchment area).

# Appendix F Characterising natural state variation using MDC sites

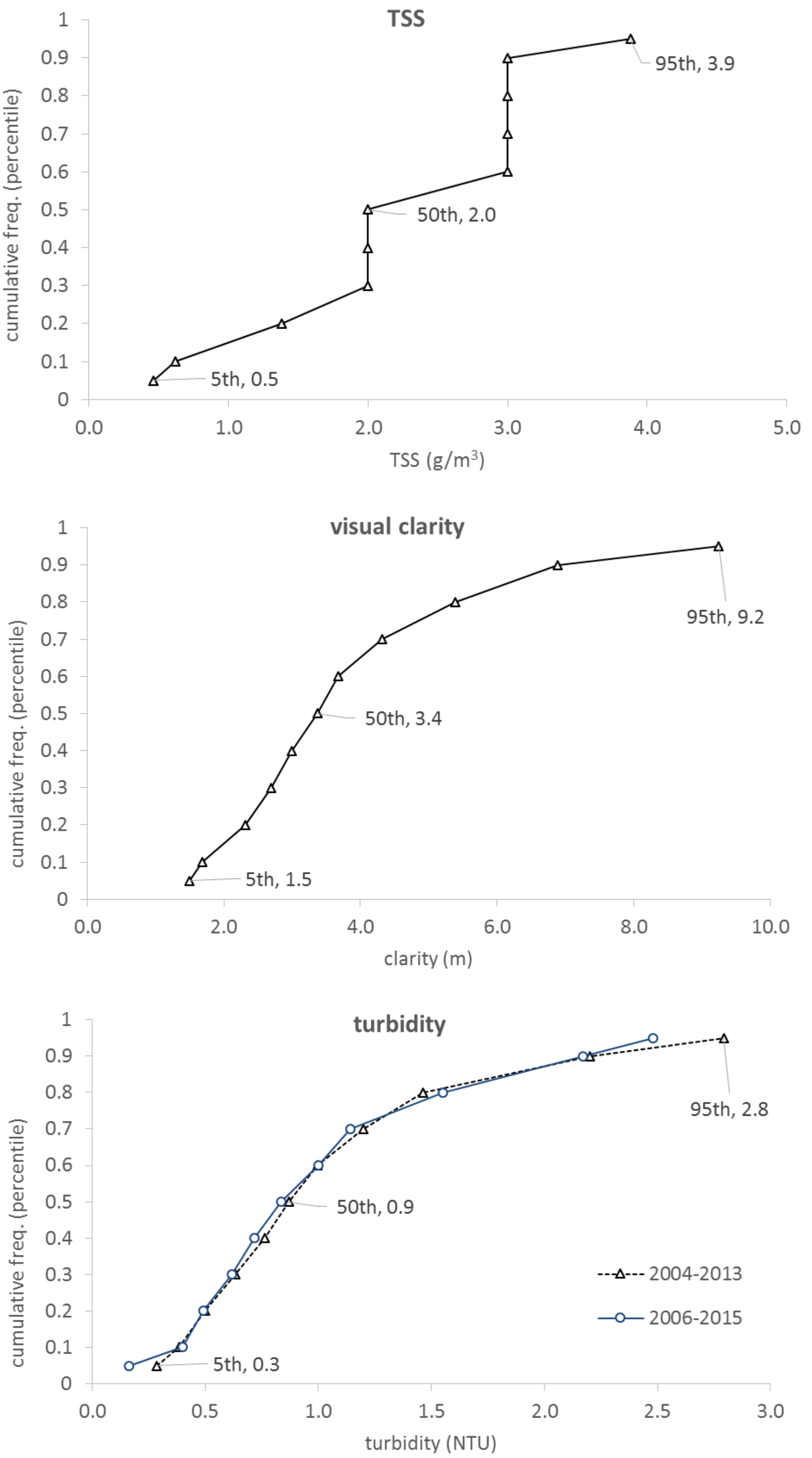



**Figure F-1: Cumulative frequency (percentile) distributions of median values of potential sediment attributes for MDC sites.** TSS (top), clarity (middle) and turbidity (bottom).

**Table F-1: Details of minimally disturbed condition (MDC) sites for turbidity (n=92) and visual clarity (n=85).**

| NZreach | NEMaR_ID | LAWA_ID | region | Site name | No. years | N | Median values | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Turbidity 2004-2013 | Turbidity 2006-2015 | Clarity 2004-2013 |
| 2005866 | ARC-44603 | ARC-00001 | AC | Cascade Stream at Confluence | 10 | 115 | 2.79 | 2.44 | 1.23 |
| 4003934 | BOP-160100 | EBOP-00002 | BOP | Haparapara River at SH35 Bridge | 7 | 41 | 1.00 | 0.90 | 5.57 |
| 4002930 | BOP-110035 | EBOP-00009 | BOP | Ngamuwahine at Old Ngamuwahine Bridge | 7 | 37 | 0.75 | 0.82 | 3.30 |
| 4001560 | BOP-110002 | EBOP-00022 | BOP | Raukokore at S.H.35 Bridge | 7 | 41 | 3.80 | 3.05 | 1.94 |
| 4013670 | BOP-110010 | EBOP-00041 | BOP | Whakatane at Ruatoki Bridge | 5 | 29 | 2.00 | 1.70 | 2.85 |
| 4010027 | BOP-110011 | EBOP-00042 | BOP | Whakatane at Pekatahi Bridge | 10 | 116 | 2.55 | 2.05 | 2.00 |
| 13519343 | ECAN-SQ10301 | ECAN-00124 | ECAN | Otematata River at SH83 | 9 | 42 | 0.30 | 0.40 | 3.98 |
| 15016464 | ES-008 | ES-00003 | ES | Mararoa River at South Mavora Lake | 10 | 103 | 0.60 | 0.55 | 5.99 |
| 15056487 | ES-016 | ES-00006 | ES | Cascade Stream at Pourakino Valley Road | 10 | 108 | 2.20 | 2.10 | 1.71 |
| 15056201 | ES-018 | ES-00007 | ES | Pourakino River at Ermedale Road | 10 | 105 | 2.70 | 2.40 | 1.47 |
| 15027427 | ES-028 | ES-00012 | ES | Cromel Stream at Selbie Road | 10 | 106 | 0.90 | 1.01 | 4.88 |
| 15051163 | ES-038 | ES-00016 | ES | Dunsdale Stream at Dunsdale Reserve | 10 | 105 | 2.20 | 2.20 | 1.58 |
| 15024871 | ES-052 | ES-00026 | ES | Waikaia River u/s Piano Flat | 10 | 108 | 1.05 | 1.02 | 3.37 |
| 15062800 | ES-064 | ES-00033 | ES | Waikopikopiko Stream at Haldane Curio Bay | 10 | 105 | 3.20 | 3.10 | 1.09 |
| 15038276 | ES-096 | ES-00041 | ES | Waiau River at Sunnyside | 10 | 105 | 1.20 | 1.04 | 2.65 |
| 15030310 | ES-160 | ES-00060 | ES | Waiau River at Duncraigen Road | 10 | 105 | 1.30 | 1.07 | 2.94 |
| 3004722 | EW-0234-011 | EW-00009 | EW | Kauaeranga River at Smiths Cableway/Recorder | 10 | 120 | 1.12 | 1.14 | 3.06 |
| 3047456 | EW-0282-004 | EW-00013 | EW | Kuratau River at SH41 Moerangi | 10 | 120 | 1.60 | 1.54 | 2.37 |
| 3023179 | EW-0477-010 | EW-00034 | EW | Mangauika Stm at Te Awamutu Borough W/S Intake | 10 | 119 | 1.47 | 1.52 | 3.60 |
| 3002756 | EW-0954-005 | EW-00066 | EW | Tapu River at Tapu-Coroglen Rd | 10 | 120 | 0.97 | 0.94 | 3.55 |
| 3043927 | EW-1106-004 | EW-00074 | EW | Waihaha River at SH32 | 10 | 120 | 0.58 | 0.58 | 3.22 |
| 3002276 | EW-1257-003 | EW-00106 | EW | Waiwawa River at SH25 Coroglen | 10 | 120 | 1.38 | 1.20 | 2.63 |
| 9001170 | GWRC-RS03 | GW-00003 | GWRC | Waitohu Stream at Forest Park | 10 | 118 | 0.87 | 0.94 | 2.70 |

| NZreach | NEMaR_ID | LAWA_ID | region | Site name | No. years | N | Median values | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Turbidity 2004-2013 | Turbidity 2006-2015 | Clarity 2004-2013 |
| 9002382 | GWRC-RS05 | GW-00005 | GWRC | Otaki River at Pukehinau | 10 | 120 | 1.02 | 0.92 | 2.89 |
| 9000731 | GWRC-RS06 | GW-00006 | GWRC | Otaki River at Mouth | 10 | 120 | 1.39 | 1.10 | 2.34 |
| 9003697 | GWRC-RS09 | GW-00009 | GWRC | Waikanae River at Mangaone Walkway | 10 | 120 | 0.66 | 0.71 | 3.23 |
| 9009042 | GWRC-RS20 | GW-00020 | GWRC | Hutt River at Te Marua Intake Site | 10 | 120 | 0.87 | 0.77 | 2.98 |
| 9009342 | GWRC-RS25 | GW-00025 | GWRC | Akatarawa River at Hutt Confluence | 10 | 120 | 0.62 | 0.57 | 3.23 |
| 9013597 | GWRC-RS28 | GW-00028 | GWRC | Wainuiomata River at Manuka Track | 10 | 118 | 0.95 | 1.01 | 2.51 |
| 9016841 | GWRC-RS30 | GW-00030 | GWRC | Orongorongo River at Orongorongo Station | 10 | 120 | 3.60 | 3.25 | 1.18 |
| 9000758 | GWRC-RS31 | GW-00031 | GWRC | Ruamahanga River at McLays | 10 | 120 | 0.92 | 0.66 | 3.52 |
| 9007799 | GWRC-RS47 | GW-00047 | GWRC | Waiohine River at Gorge | 10 | 120 | 0.81 | 0.74 | 3.68 |
| 9016703 | GWRC-RS52 | GW-00052 | GWRC | Tauanui River at Whakatomotomo Rd | 10 | 118 | 1.02 | 0.78 | 3.00 |
| 9013660 | GWRC-RS56 | GW-00056 | GWRC | Waiorongomai River at Forest Park | 10 | 121 | 1.02 | 0.86 | 2.81 |
| 8024159 | HBRC-0299 | HBRC-00021 | HBRC | Ngaruroro River at Whanawhana | 10 | 52 | 1.46 | 1.67 | 3.40 |
| 8013017 | HBRC-0321 | HBRC-00026 | HBRC | Mokomokonui Stream U/S Waipunga | 10 | 49 | 1.37 | 1.42 | 2.70 |
| 8003529 | HBRC-0333 | HBRC-00030 | HBRC | Aniwaniwa Stream at Aniwaniwa | 10 | 46 | 0.94 | 1.14 | 3.47 |
| 8013661 | HBRC-2961 | HBRC-00062 | HBRC | Mohaka River U/S Taharua River Confluence | 6 | 70 | 0.68 | 0.69 | 4.22 |
| 8017485 | HBRC-0604 | HBRC-00071 | HBRC | Mohaka River D/S Ripia Confluence | 10 | 68 | 1.20 | 1.34 | 2.30 |
| 7048086 | HRC-1498 | HRC-00021 | HRC | Mangatainoka at Putara | 6 | 66 | 0.66 | 0.64 | 3.00 |
| 7016679 | HRC-0004 | HRC-00029 | HRC | Mangawhero at DOC Headquarters | 9 | 96 | 0.79 | 0.67 | 2.57 |
| 7047475 | HRC-1493 | HRC-00030 | HRC | Ohau at Gladstone Reserve | 9 | 100 | 0.69 | 0.65 | 4.36 |
| 7030815 | HRC-9903 | HRC-00036 | HRC | Oroua at Apiti Gorge Bridge | 6 | 59 | 0.80 | 0.80 | 4.27 |
| 7042760 | HRC-1494 | HRC-00054 | HRC | Tokomaru River at Horseshoe bend | 9 | 103 | 1.20 | 1.16 | 3.07 |
| 7048450 | HRC-2630 | HRC-00056 | HRC | Waikawa at North Manakau Road | 7 | 75 | 0.59 | 0.60 | 4.75 |
| 11024066 | MDC-BNR-01 | MDC-00005 | MDC | Branch River at Weir Intake | 5 | 52 | 1.30 | 1.14 | |
| 11011033 | MDC-GRR-01 | MDC-00010 | MDC | Graham River at Road Bridge | 7 | 77 | 0.50 | 0.60 | |
| 11011349 | MDC-PLR-04 | MDC-00020 | MDC | Pelorus River at Fishermans Flat | 9 | 79 | 0.70 | 0.69 | |

| NZreach | NEMaR_ID | LAWA_ID | region | Site name | No. years | N | Median values | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Turbidity 2004-2013 | Turbidity 2006-2015 | Clarity 2004-2013 |
| 11011819 | MDC-PLR-05 | MDC-00021 | MDC | Pelorus River at Kahikatea Flat | 9 | 85 | 0.50 | 0.45 | |
| 11011667 | MDC-WKR-01 | MDC-00031 | MDC | Wakamarina River at SH6 | 9 | 86 | 0.35 | 0.40 | |
| 10012097 | NCC-12 | NCC-00012 | NCC | Brook at Motor Camp | 10 | 40 | 0.63 | 0.48 | 4.50 |
| 10011551 | NCC-15 | NCC-00015 | NCC | Maitai at Groom Rd | 10 | 41 | 0.90 | 0.72 | 5.05 |
| 10011665 | NCC-16 | NCC-00016 | NCC | Maitai South Branch at Intake | 10 | 38 | 0.56 | 0.40 | 7.25 |
| 10009267 | NCC-33 | NCC-00033 | NCC | Pitchers at 890m | 10 | 40 | 0.76 | 0.71 | 4.30 |
| 10009017 | NCC-37 | NCC-00037 | NCC | Graham at SH6 | 10 | 38 | 0.82 | 0.62 | 3.80 |
| 1016578 | NRC-103304 | NRC-00007 | NRC | Waipoua River @  SH12 | 10 | 113 | 2.20 | 2.20 | 2.30 |
| 1006091 | NRC-108978 | NRC-00022 | NRC | Mangamuka River @ Iwitaua Rd Bridge | 7 | 68 | 1.00 | 1.57 | 1.55 |
| 14011901 | ORC-OTA7529114 | ORC-00015 | ORC | Hawea at Camphill Bridge | 8 | 48 | 0.38 | 0.40 | |
| 14048641 | ORC-OTA7430398 | ORC-00074 | ORC | Taieri at Linnburn Runs Road | 10 | 58 | 1.24 | 1.29 | |
| 12011819 | TDC-0422 | TDC-00005 | TDC | Mangles at Gorge | 10 | 36 | 0.63 | 0.75 | 3.87 |
| 10005729 | TDC-0880 | TDC-00013 | TDC | Takaka at Harwoods | 10 | 35 | 0.50 | 0.60 | 5.40 |
| 10013104 | TDC-0916 | TDC-00017 | TDC | Wangapeka at Walter Peak | 10 | 41 | 0.50 | 0.50 | 5.43 |
| 10015334 | TDC-0417 | TDC-00020 | TDC | Lee @ Meads Br | 10 | 41 | 0.40 | 0.40 | 8.65 |
| 10017554 | TDC-0911 | TDC-00021 | TDC | Wairoa @ Pig Vly | 10 | 40 | 0.40 | 0.40 | 8.02 |
| 12011297 | TDC-0809 | TDC-00022 | TDC | Matakitaki @ SH6 Murchison | 10 | 38 | 0.85 | 1.00 | 3.88 |
| 10005780 | TDC-0868 | TDC-00026 | TDC | Riwaka @ Northbranch Source | 10 | 41 | 0.30 | 0.30 | 11.98 |
| 10023488 | TDC-0403 | TDC-00032 | TDC | Hunters @ Kikiwa | 9 | 32 | 0.80 | 0.85 | 5.48 |
| 10016609 | TDC-0919 | TDC-00036 | TDC | Wangapeka @ 5km u-s Dart | 9 | 37 | 0.34 | 0.30 | 8.37 |
| 10001434 | TDC-0839 | TDC-00045 | TDC | Onekaka @ u-s Ironstone | 10 | 40 | 0.40 | 0.40 | 6.17 |
| 10000810 | TDC-0407 | TDC-00048 | TDC | Kaituna @ 500m u-s Track start | 3 | 4 | 0.53 | 0.60 | 3.49 |
| 6005935 | TRC-STY000300 | TRC-00008 | TRC | Stony River at Mangatete Road | 10 | 120 | 0.92 | 1.00 | 2.69 |
| 12028930 | WCRC-WCS32 | WCRC-00008 | WCRC | Sawyers Ck @ Bush Fringe | 10 | 37 | 2.80 | 2.55 | 1.79 |
| 12010633 | WCRC-WCS29 | WCRC-00019 | WCRC | Orowaiti Rv @ Keoghans Rd | 10 | 32 | 0.26 | 0.20 | 5.90 |

| NZreach | NEMaR_ID | LAWA_ID | region | Site name | No. years | N | Median values | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Turbidity 2004-2013 | Turbidity 2006-2015 | Clarity 2004-2013 |
| 12041401 | WCRC-WCS27 | WCRC-00024 | WCRC | Okutua Ck @ New Rd Br-Okarito Forest | 10 | 32 | 0.40 | 0.10 | 2.27 |
| 12031538 | WCRC-WCS11 | WCRC-00033 | WCRC | Crooked Rv @ Rotomanu-Bell Hill Rd | 10 | 42 | 0.10 | 0.10 | 9.50 |
| 12031547 | WCRC-WCS41 | WCRC-00036 | WCRC | Hohonu Rv @ Mitchells-Kumara Rd Br | 6 | 31 | 0.10 | 0.10 | 13.90 |
| 12031252 | WCRC-WCS42 | WCRC-00040 | WCRC | Hohonu Rv @ Mouth | 9 | 40 | 0.24 | 0.10 | 4.16 |
| 4022892 | NAT-RO04 | | BOP | Whirinaki @ Galatea | 10 | 120 | 1.62 | 1.60 | 1.88 |
| 13020391 | NAT-CH01 | | ECAN | Hurunui @ Mandamus | 10 | 120 | 1.56 | 1.98 | 1.65 |
| 15038952 | NAT-DN10 | | ES | Monowai below Control Gates | 10 | 119 | 0.41 | 0.46 | 6.65 |
| 3048532 | NAT-TU02 | | EW | Tongariro @ Turangi | 10 | 120 | 0.74 | 0.80 | 3.21 |
| 9008427 | NAT-WN02 | | GWRC | Hutt @ Kaitoke | 10 | 120 | 0.55 | 0.60 | 5.35 |
| 9000872 | NAT-WN05 | | GWRC | Ruamahanga @ Mt Bruce | 10 | 120 | 0.80 | 0.73 | 4.63 |
| 8021350 | NAT-HV04 | | HBRC | Ngaruroro @ Kuripapango | 10 | 120 | 0.64 | 0.75 | 5.85 |
| 11029639 | NAT-NN03 | | MDC | Wairau @ Dip Flat | 10 | 120 | 1.45 | 1.31 | 3.42 |
| 1007423 | NAT-WH01 | | NRC | Waipapa @ Forest Ranger | 10 | 120 | 1.60 | 1.61 | 2.56 |
| 14027448 | NAT-AX02 | | ORC | Kawarau @ Chards Rd | 10 | 119 | 2.00 | 2.20 | 1.65 |
| 10022270 | NAT-NN02 | | TDC | Motueka @ Gorge | 10 | 120 | 0.45 | 0.47 | 11.97 |
| 12010223 | NAT-NN05 | | TDC | Buller @ Longford | 10 | 120 | 0.92 | 1.00 | 4.82 |
| 12012463 | NAT-GY01 | | WCRC | Buller @ Te Kuha | 10 | 120 | 1.53 | 1.89 | 1.80 |
| 12025991 | NAT-GY03 | | WCRC | Grey @ Waipuna | 10 | 119 | 0.78 | 0.91 | 3.67 |
| 12052272 | NAT-GY04 | | WCRC | Haast @ Roaring Billy | 10 | 120 | 1.20 | 1.48 | 2.60 |

# Appendix G Summary turbidity statistics of MDC sites group by REC categories

**Table G-1: Summary turbidity statistics for MDC sites grouped by REC climate categories.** * indicates categories where the number of sites was <5.

| Statistic | Cold dry (2)* | Cold wet (53) | Cold extremely wet (28) | Warm wet (7) | Warm extremely wet (2)* |
|---|---|---|---|---|---|
| Minimum | 0.3 | 0.3 | 0.1 | 1.0 | 0.8 |
| 25th %ile | 0.5 | 0.6 | 0.4 | 1.1 | 1.5 |
| Median | 0.8 | 0.9 | 0.8 | 1.4 | 2.3 |
| 75th %ile | 1.0 | 1.4 | 0.9 | 1.9 | 3.0 |
| Maximum | 1.2 | 3.6 | 2.8 | 2.8 | 3.8 |
| IQR | 0.5 | 0.8 | 0.5 | 0.8 | 1.5 |

**Table G-2: Summary turbidity statistics for MDC sites grouped by REC source-of-flow categories.** * indicates categories where the number of sites is <5.

| Statistic | Glacial mountain (n=1)* | Hill (n=55) | Low-elevation (n=20) | Lake-fed (n=7) | Mountain (n=9) |
|---|---|---|---|---|---|
| Minimum | | 0.1 | 0.2 | 0.4 | 0.3 |
| 25th %ile | | 0.6 | 0.6 | 0.5 | 0.5 |
| Median | 1.2 | 0.8 | 1.0 | 0.9 | 0.7 |
| 75th %ile | | 1.2 | 2.2 | 1.3 | 1.1 |
| Maximum | | 3.8 | 3.2 | 2.0 | 1.4 |
| IQR | | 0.6 | 1.6 | 0.7 | 0.6 |

**Table G-3: Summary turbidity statistics for MDC sites grouped by REC geology categories.** * indicates categories where the number of sites is <5.

| Statistic | Alluvium (2)* | Hard sedimentary (52) | Plutonics (6) | Soft sedimentary (9) | Volcanic acidic (21) | Volcanic basic (2)* |
|---|---|---|---|---|---|---|
| Minimum | 0.2 | 0.1 | 0.1 | 0.3 | 0.6 | 0.5 |
| 25th %ile | 0.3 | 0.5 | 0.9 | 0.5 | 0.8 | 0.5 |
| Median | 0.3 | 0.8 | 1.3 | 0.8 | 1.1 | 0.5 |
| 75th %ile | 0.4 | 1.0 | 1.5 | 2.2 | 1.6 | 0.5 |
| Maximum | 0.4 | 3.8 | 2.2 | 3.2 | 2.8 | 0.6 |
| IQR | 0.1 | 0.5 | 0.6 | 1.7 | 0.8 | 0.0 |

**Table G-4: Summary turbidity statistics for MDC sites grouped by REC dominant land-cover categories.** * indicates categories where the number of sites is <5.

| Statistic | Bare (1)* | Indigenous forest (79) | Scrub (6) | Tussock (6) |
|---|---|---|---|---|
| Minimum | 1.4 | 0.1 | 0.3 | 0.3 |
| 25th %ile | 1.4 | 0.6 | 0.8 | 0.4 |
| Median | 1.4 | 0.8 | 1.1 | 0.8 |
| 75th %ile | 1.4 | 1.3 | 1.3 | 1.2 |
| Maximum | 1.4 | 3.8 | 1.5 | 2.0 |
| IQR | 0.0 | 0.7 | 0.5 | 0.8 |

**Table G-5: Summary turbidity statistics for MDC sites grouped by REC network position categories.**

| Statistic | High order (43) | Low order (5) | Middle order (44) |
|---|---|---|---|
| Minimum | 0.3 | 0.4 | 0.1 |
| 25th %ile | 0.6 | 0.4 | 0.6 |
| Median | 0.9 | 0.8 | 0.8 |
| 75th %ile | 1.4 | 1.6 | 1.0 |
| Maximum | 3.8 | 2.8 | 3.6 |
| IQR | 0.8 | 1.2 | 0.4 |

**Table G-6: Summary turbidity statistics for MDC sites grouped by REC valley landform categories.**

| Statistic | High-gradient (9) | Low-gradient (66) | Medium gradient (17) |
|---|---|---|---|
| Minimum | 0.3 | 0.1 | 0.1 |
| 25th %ile | 0.6 | 0.6 | 0.6 |
| Median | 0.8 | 1.0 | 0.7 |
| 75th %ile | 1.0 | 1.4 | 0.9 |
| Maximum | 2.8 | 3.8 | 2.2 |
| IQR | 0.4 | 0.8 | 0.3 |

**Table G-7: Pairwise comparisons of median turbidity (MDC sites) when grouped by REC climate categories CW, CX and WW ($\alpha$=0.05).** Kruskal-Wallis test (d.f =1, equivalent to Mann-Whitney U-test). H-values adjusted for ties.

| Climate category pair | Degrees of freedom | H-value (adjusted for ties) | P-value | Significant difference in category medians |
|---|---|---|---|---|
| CW-CX | 1 | 5.15 | 0.023 | yes |
| CW-WW | 1 | 4.44 | 0.035 | yes |
| CX-WW | 1 | 9.32 | 0.002 | yes |

# Appendix H Data from McDowell et al. 2013: establishment of reference conditions in New Zealand streams and rivers

**Table H-1: Predicted reference state condition for clarity, turbidity and TSS for different REC climate-SoF categories.**

| Indicator | REC | Median | Median - CI | Median + CI |
|---|---|---|---|---|
| Clarity (m) | CDH | 2.4 | 0.8 | 4.8 |
| | CDL | 0.9 | 0.4 | 1.5 |
| | CDLk | 2.1 | 0.4 | 5 |
| | CDM | 2.1 | 0.4 | 5 |
| | CWH | 3 | 2.5 | 3.5 |
| | CWL | 2.2 | 1.7 | 2.7 |
| | CWLk | 3.1 | 2 | 4.5 |
| | CWM | 2.3 | 1.3 | 3.5 |
| | CXH | 4 | 2.9 | 5.3 |
| | CXL | 2.4 | 1.6 | 3.4 |
| | CXLk | 3.2 | 1.9 | 4.9 |
| | CXM | 2 | 1 | 3.4 |
| | WDL | 1.3 | 0.5 | 2.6 |
| | WWH | 2.1 | 0.4 | 5 |
| | WWL | 1.5 | 1.1 | 2 |
| | WWLk | 1.4 | 0.5 | 2.8 |
| | WXH | 1.9 | 0.6 | 3.8 |
| | WXL | 2.5 | 1 | 4.7 |
| Turbidity (NTU) | CDH | 0.5 | 0.3 | 0.8 |
| | CDL | 0.7 | 0.4 | 1.1 |
| | CDLk | 0.9 | 0.1 | 2.3 |
| | CDM | 1.4 | 0.4 | 2.8 |
| | CWH | 1 | 0.8 | 1.3 |
| | CWL | 1.2 | 0.8 | 1.7 |
| | CWLk | 0.8 | 0.5 | 1.3 |
| | CWM | 1.6 | 0.9 | 2.6 |
| | CXH | 0.7 | 0.4 | 1.1 |
| | CXL | 1.3 | 0.7 | 2.1 |
| | CXLk | 0.7 | 0.4 | 1.2 |
| | CXM | 1.3 | 0.5 | 2.6 |
| | WDL | 2.5 | 0.8 | 5.2 |
| | WWH | 1.5 | 0.4 | 3.2 |
| | WWL | 2.3 | 1.6 | 3.3 |
| | WWLk | 2.1 | 0.6 | 4.3 |
| | WXH | 1.9 | 0.6 | 3.8 |
| | WXL | 1.2 | 0.4 | 2.2 |

| Indicator | REC | Median | Median - CI | Median + CI |
|---|---|---|---|---|
| Suspended solids ($g/m^3$) | CDH | 1 | 0.6 | 1.5 |
| | CDL | 1.4 | 0.8 | 2.1 |
| | CDLk | 1.5 | 0.3 | 3.7 |
| | CDM | 1.9 | 0.7 | 3.7 |
| | CWH | 1.2 | 0.9 | 1.6 |
| | CWL | 1.2 | 0.7 | 1.7 |
| | CWLk | 1.4 | 0.7 | 2.3 |
| | CWM | 3.9 | 1.7 | 7 |
| | CXH | 1.4 | 0.4 | 2.8 |
| | CXL | 1.2 | 0.4 | 2.4 |
| | CXLk | 1.3 | 0.5 | 2.4 |
| | CXM | 1.9 | 0.2 | 5.1 |
| | WDL | 2.3 | 0.8 | 4.5 |
| | WWH | 1.9 | 0.2 | 5.1 |
| | WWL | 3.2 | 1.8 | 5.1 |
| | WWLk | 3.6 | 1.1 | 7.3 |
| | WXH | 3.4 | 1.1 | 6.7 |
| | WXL | 3.2 | 1 | 6.4 |