Manaaki Whenua
Landcare Research

Modelling baseline suspended sediment loads and load reductions required to achieve Draft Freshwater Objectives for Southland

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Modelling baseline suspended sediment loads and load reductions required to achieve Draft Freshwater Objectives for Southland

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Contents

Summary

Project and Client

- Environment Southland (ES) contracted Manaaki Whenua – Landcare Research (MWLR) to model mean annual suspended sediment loads and the reductions in load required to meet draft Freshwater Objectives (FWOs) for visual clarity developed through the 'Values and Objectives' workstream and supplied to MWLR by Land Water People (LWP).
- This work contributes to Stage 1 for the Southland Regional Forum (Phase 3) workstream, led by LWP.

Objectives

- Model mean annual suspended sediment loads for the Southland region using the SedNetNZ model under a) a contemporary landcover scenario representing a baseline for FWO setting, and b) a natural landcover scenario.
- Assess the sensitivity of SedNetNZ baseline suspended sediment load estimates to changes in the spatial distribution of mapped winter forage cropping.
- Quantify reductions required in mean annual suspended sediment loads with respect to the baseline mean annual suspended sediment loads to achieve draft FWOs for visual clarity (recreational objectives) and suspended fine sediment (ecosystem health objectives).
- Provide end-of-catchment load data for the baseline mean annual suspended sediment loads as input to an estuary model developed by NIWA.
- Advise on potential mitigation scenarios that could be modelled in Stage 2 of the Regional Forum (Phase 3) workstream.

Methods

- Develop a regional application of the SedNetNZ model for Southland that builds on a revised version of the model applied to the Ōreti and Aparima catchments (Smith et al. 2019b).
- Further revisions were made to the surficial erosion component of SedNetNZ to incorporate 1) a spatially variable *K* factor for the NZUSLE, utilising S-map data, where available, and 2) the impact of winter forage cropping on mean annual suspended sediment loads. The sediment routing component of SedNetNZ was also updated to represent the sediment trapping effect of significant water bodies in the region.
- An evaluation of the sensitivity of modelled mean annual sediment loads to variations in the extent and location of winter forage cropping was conducted using maps of winter forage cropping from 2014 and 2017.
- Baseline mean annual suspended sediment loads were calculated using land cover from LCDB v5.0 and the 2017 winter forage cropping map to represent the 2017 landcover. The impact of pre-existing riparian stock exclusion on mean annual suspended sediment loads was included where data was available on the location of

existing stock exclusion fencing. This is used as baseline for calculating the mean annual suspended sediment load reductions required to achieve draft FWOs.

- Mean annual suspended sediment loads were also modelled under a natural landcover scenario, where land below the treeline was modelled as having woody-vegetation cover. Landcover above the treeline was modelled as represented in LCDBv5. No changes in channel configuration or hydrology were modelled. This scenario therefore represents loads under a natural landcover for the contemporary catchment configuration and climate, and should not be interpreted as pre-human suspended sediment loads.
- The mean annual suspended sediment load reductions required to meet FWOs were calculated using national-scale empirical models of the relationship between SSC and visual clarity, based on modelled baseline visual clarity provided by LWP. Uncertainty estimates for the load reductions required to achieve the draft FWOs are provided based on the national-scale variance in the relationships between reduction in suspended sediment and visual clarity reported by Hicks et al. (2019).

Results

- Under the baseline scenario, mean annual suspended sediment loads are estimated to be 490,000 t y^{-1} for the Matāura catchment, 295,000 t y^{-1} for the Ōreti catchment, 67,000 t y^{-1} for the Aparima catchment, and 457,000 t y^{-1} for the Waiau catchment. The total load for the modelled area is 1.343 Mt y^{-1}. This reduced to 0.823 Mt yr^{-1} in the natural landcover scenario, where the greatest proportional reductions are seen in the Aparima and Waiau catchments.
- Mean annual suspended sediment loads were found to be relatively insensitive to total extent, or the variations in mapped winter forage crop distributions at the catchment scale, with <1% difference in total end-of-catchment loads between scenarios using the 2014 and 2017 maps of winter foraging cropping, and <5% increase from loads estimated with no inclusion of winter forage. Sensitivity of suspended sediment loads to winter forage cropping is more pronounced in low order lowland streams, where absolute loads are relatively small.
- The impact of forage cropping is more pronounced at the river segment scale, particularly in low-order lowland streams, where absolute loads are relatively small, so forage cropping has a large impact proportionally.
- Across the region, suspended fine sediment objectives are achieved for a greater length of the REC2 stream network than for visual clarity objectives (≥58% vs ≥32%, respectively).
- Maximum required load reductions to achieve bottom of envelopes range from 33% to 84% for visual clarity, and 2% to 73% for suspended fine sediment between reporting zones.
- Under the natural landcover scenario visual clarity objectives are achieved along ≥81% of the REC2 network. Suspended fine sediment objectives are achieved along ≥85% of the network. The top of the envelope is achieved along 42% of the network for visual clarity, and 78% of the network for suspended fine sediment.

Conclusions and Recommendations

- End-of-catchment mean annual suspended sediment loads were found to be relatively insensitive to winter forage cropping. Winter forage cropping has the greatest impact on sediment loads in the Aparima catchment and FMU, and on low order lowland streams.
- Mean annual suspended sediment loads in the modelled area are dominated by surficial erosion in the headwaters of main catchments. Bank erosion becomes the dominant source of local erosion in higher order stream segments.
- The Indigenous Forest and Conservation land use class is the largest contributor of sediment loads in the Waiau, Ōreti, and Aparima. Sheep and Beef is the largest contributor in the Matāura.
- Future work to look at mitigation scenarios to achieve the draft FWOs is likely to focus on the use of stock exclusion, and may include afforestation or reversion of steep slopes. Scenarios could be run to include stock exclusion on different stream orders or land use types.

1 Introduction

The Ministry for the Environment (MfE) announced changes to the National Policy Statement for Freshwater Management (NPS-FM) and National Objectives Framework (NOF) that will set requirements for water quality attributes for freshwater in New Zealand. The new policy will require a minimum standard to be achieved (a bottom line) for all water bodies, along with a requirement for no further degradation for water bodies which already exceed the bottom line. Councils will be required to develop plans to achieve these standards. Environment Southland (ES) has begun this process under the People, Water and Land programme which consists of three workstreams: the 'Action on the Ground workstream', the 'Values and Objectives' workstream, and the 'Regional Forum' workstream. The objectives for water quality and estuaries are being developed under the 'Values and Objectives' workstream. The 'Regional Forum' workstream involves providing advice on how the objectives should be achieved.

ES, in partnership with Te Ao Marama Incorporated (TAMI), have developed draft Freshwater Objectives (FWOs) for the Southland region that identify region-specific objectives for water quality attributes under the 'Values and Objectives' workstream. Under Stage 1 of the 'Regional Forum' workstream (Phase 3), Land Water People (LWP) are leading modelling to identify the reductions in contaminants required to achieve the draft FWOs. Scenario testing to identify mitigation options to achieve the required reductions will then be completed under Stage 2.

ES engaged Manaaki Whenua – Landcare Research (MWLR) to provide modelled mean annual suspended sediment loads at reach and catchment scales as well as estimates of the reductions in load required to achieve the draft FWOs for visual clarity (recreational objectives, defined using visual clarity metrics) and suspended fine sediment (ecosystem health) objectives relating to the NPS-FM 2020, also defined using visual clarity metrics). Achievement of the draft FWOs will be assessed at river segment scale, and results aggregated by reporting catchment. This modelling will contribute to the 'Regional Forum' workstream, along with modelling of the reductions required to meet the draft FWOs for other contaminants led by LWP.

2 Background

SedNetNZ (Dymond et al. 2016) was identified as the most appropriate model for these objectives. SedNetNZ is a steady-state sediment budget model designed to represent the diversity of erosion processes that occur in the New Zealand landscape and predict mean annual suspended sediment yields (Dymond et al. 2016). SedNetNZ represents individual erosion processes, allowing direct targeting of erosion processes with appropriate mitigations during mitigation scenario modelling. This improves on the national-scale modelling framework employed by Neverman et al. (2019) that utilised the NZeem model (Dymond et al. 2010). NZeem does not represent individual erosion processes, and therefore required uniform partitioning of load to differentiate hillslope and river bank erosion derived loads nationally for targeted treatment during mitigation scenario modelling.

A revised version of SedNetNZ was previously developed for application in Southland and applied in the Ōreti and Aparima catchments (Smith et al. 2019b). Further improvements have since been implemented as part of the present regional application of SedNetNZ. We sought to represent the impact of winter forage cropping, which is a significant land management practice in Southland affecting soil erosion. We also represent the spatial variability in soil erodibility arising from different soil types using S-map and the Fundamental Soils Layers (FSL) when calculating the *K* factor in the NZUSLE (Dymond 2010), as opposed to the uniform soil erodibility employed in previous SedNetNZ applications. In addition, Gill's (1979) approximation of Brune's (1953) trap efficiency model has been incorporated into the sediment routing component of SedNetNZ to account for the trapping effect of lakes on suspended sediment loads, which is particularly relevant in the Waiau catchment.

Dymond et al. (2017) identified relationships between suspended sediment concentration and visual clarity and turbidity. Hicks et al. (2019) used these relationships to develop nationally fitted models to predict the reductions required in mean annual suspended sediment loads to achieve visual clarity and turbidity bottom lines. Following a similar approach to Neverman et al. (2019), these models have been applied to estimate the reductions in the SedNetNZ baseline mean annual suspended sediment loads required to achieve the draft FWOs for Southland.

The results and outputs from this work may form the basis for modelling mitigation scenarios similar to those used by Neverman et al. (2019) to identify which mitigations may feasibly achieve the draft FWOs for Southland under the `Regional Forum` workstream.

3 Objectives

- Develop a contemporary landcover layer from LCDB v5.0 and mapped locations of paddocks with winter forage cropping in 2017 to model baseline mean annual suspended sediment loads.
- Develop a natural landcover layer, where woody-vegetation covers all land below the tree line.
- Model mean annual suspended sediment loads for the Southland region using the SedNetNZ model at reach and catchment scales under contemporary and natural landcover.
- Run scenarios with SedNetNZ using landcover layers with different spatial configurations of winter forage cropping to assess the sensitivity of SedNetNZ suspended sediment load estimates to changes in the spatial distribution of winter forage cropping at reach and catchment scales.
- Quantify reductions required in mean annual suspended sediment loads at draft assessment sites with respect to the 2017 baseline mean annual suspended sediment loads to achieve draft FWOs for visual clarity and suspended fine sediment, and uncertainty in the required reductions, using national-scale empirical models developed by Hicks et al. (2019).

- Provide end-of-catchment load data for the baseline mean annual suspended sediment loads as input to an estuary model developed by NIWA.
- Advise on potential mitigation scenarios that could be modelled in scenario testing for the Regional Forum, or for plan development.

4 Methods

4.1 Regional SedNetNZ model description

4.1.1 Surficial Erosion

Surficial erosion processes in SedNetNZ (Dymond et al. 2016) are represented by the NZUSLE (Dymond 2010) model:

$$ES = a\,P^2 KLSC \tag{1}$$

where ES denotes surficial erosion in t km^{-2} yr^{-1}; a is a constant (t km^{-2} yr^{-1} mm^{-2}) calibrated against measurements (Dymond 2010) with a value of 1.2 x 10^{-3}; P is mean annual rainfall (mm); K is the soil erodibility factor (dimensionless), L is the slope length factor, estimated as $\left(\frac{\lambda}{22}\right)^{0.5}$ with λ assumed globally = 200 m; S is the slope steepness factor, estimated by 0.065 + 4.56 θ + 65.41 θ^2, where θ denotes the dimensionless slope gradient; and C represents the impact of vegetation cover (dimensionless) (1.0 for bare ground, 0.01 for pasture, and 0.005 for forest and scrub).

In this study, we use a revised representation of surficial erosion processes as part of the SedNetNZ model. Following Smith et al. (2019b), this includes replacing the uniform slope length factor (L) of the NZUSLE (Dymond 2010) with a factor that better represents the effect of topography on the size of convergent upslope areas contributing overland flow and surficial erosion, as described by Desmet and Govers (1996):

$$L = \frac{(A + D^2)^{m+1} - A^{m+1}}{D^{m+2} * x^m * 22.13^m} \tag{2}$$

where L is slope length factor for a given raster cell (pixel), A is the upstream catchment area (m^2) at the cell inlet, D is the raster cell width (m), m is the slope length exponent, x = $\sin a + \cos a$, with α being the slope aspect.

The slope length exponent m is calculated depending on the rill to inter-rill ratio β and the slope gradient θ (Foster et al. 1977 and McCool et al. 1989, cited in Renard et al. 1997). Here we assume moderate susceptibility to rill erosion (Renard et al. 1997) based on soil characteristics (dominantly weakly structured silty soils from loess, colluvium, and alluvium):

$$\beta = \frac{\frac{\sin\theta}{0.0896}}{3 * (\sin\theta)^{0.8} + 0.56} \tag{3}$$

$$m = \frac{\beta}{1+\beta} \tag{4}$$

We also apply a revised slope factor, S, which is calculated according to a threshold in slope gradient sp (%) (Rendard et al. 1997):

$$S = \begin{cases} 10.8 * \sin\theta + 0.03 & with\, sp < 9\% \\ 16.8 * \sin\theta - 0.5 & with\, sp \geq 9\% \end{cases} \tag{5}$$

Furthermore, we apply a spatially variable *K* factor in the NZUSLE to better represent the spatial variability of soil erodibility, utilising S-map and FSL data available for Southland. We adapted the *K* factor equations in Wang et al. (2001) and Yang et al. (2018) to the NZUSLE:

$$K = \frac{2.1(12 - OM)M^{1.14}10^{-4} + 3.25(SS - 2) + 2.5(PP - 3)}{7.59\, x\, 10} \tag{6}$$

where *OM* is the soil organic matter content, *M* is the particle size parameter, *SS* is the soil structure code, and *PP* is the soil profile permeability code. We use 6 *PP* classes, adapted from Rosewell & Loch (2002). The soil structure code was set at *SS* = 2 as neither the S-map nor FSL have sufficient data on soil structure to relate to the *SS* classes used for calculating *K*. We found the magnitude of *K* was not sensitive to the choice of *SS* class value. *M* is calculated as a function of the proportion silt and clay:

$$M = Silt(100 - Clay) \tag{7}$$

where *Silt* and *Clay* are the percent of silt and clay in the soil, respectively.

Silt was limited to a range of 15–70%, and *OM* was capped at 4% to fit the nomograph of Wischmeier et al. (1971) used to derive Equation 6 for organic soils.

4.1.2 Representation of bank erosion in SedNetNZ

SedNetNZ represents bank erosion at the reach-scale where the river network is divided into stream segments based on the River Environment Classification (REC). The total mass of material eroded from riverbanks each year is a function of bank height, reach length, and bank migration rate (Dymond et al. 2016):

$$B_j = \rho M_j H_j L_j \tag{8}$$

where B_j is the total eroded mass for the j-th stream segment (t y^{-1}), ρ is the bulk density of the bank material (t m^{-3}), M_j is the bank migration rate (m y^{-1}), H_j is the mean bank height (m) and L_j is the length (m) of the j-th stream segment. Bank height is derived from a regional relationship with mean annual discharge and bulk density is estimated at 1.5 t m^{-3} (Dymond et al. 2016).

The predicted mass of material eroded from riverbanks represents the gross contribution of sediment supplied to the river channel per year. This does not account for redeposition and storage of eroded bank material on banks, within the channel bed, or the lateral accretion of material on bars with channel migration. Hence, net bank erosion in SedNetNZ is estimated as one-fifth of gross bank erosion based on results from the

Waipaoa River catchment (De Rose & Basher 2011). Overbank vertical accretion of fine sediment on floodplains beyond the active channel is represented separately (Dymond et al. 2016).

The original bank migration rate (M_j) component of Equation 8 described by Dymond et al. (2016) was based on a simple empirical relationship with mean annual flood only. This has since been replaced by an improved bank migration model that better represents the spatial variability in factors influencing migration rates (Smith et al 2019a). The improved approach represents the mean annual bank migration rate as a function of six factors as follows:

$$M_j = SP_j Sn_j T_j V_j \left(1 - PR_j\right)\left(1 - PW_j\right) \tag{9}$$

where M_j is the bank migration rate (m y^{-1}) of the j-th stream segment, SP_j is the stream power of the mean annual flood for the j-th stream segment, Sn_j is the channel sinuosity rate factor of the j-th segment, T_j is the soil texture-based erodibility factor of the j-th segment, V_j is the valley confinement factor of the j-th segment, PR_j is the proportion of riparian woody vegetation of the j-th segment, and PW_j is the fraction of bank protection works for the j-th segment.

Stream power (SP_j) for the mean annual flood (MAF_j, m^3 s^{-1}) is estimated for each stream segment by the product of mean annual flood and channel slope (S_j). MAF is estimated from a fitted power relationship ($MAF = aq^b$) with mean annual discharge (q, m^3 s^{-1}) using data from long-term river flow gauging within the catchment or region of interest:

$$SP_j = MAF_j S_j = a{q_j}^b S_j \tag{10}$$

Various studies report increasing bank migration rates with increasing bankfull discharge and stream power (Hooke 1979; Nanson & Hickin 1986; Walker & Rutherfurd 1999; Alber & Piégay 2017). The mean annual flood (Equation 10) is used in both the original and improved model versions, and while it has been shown to relate to bank erosion rates (Dymond et al. 2016), other factors such as channel sinuosity (Nanson & Hicken 1983), the cohesiveness of bank materials (Julian & Torres, 2006), valley confinement (Hall et al. 2007), and riparian woody vegetation (Abernethy & Rutherfurd 2000) are also important, resulting in high levels of spatial variability in bank erosion.

We use the log-normal probability density function to represent the relationship between channel sinuosity and migration rate, which we term the sinuosity rate factor. This function allows us to represent the positive-skew observed in the relationship between channel sinuosity and migration rate (Crosato 2009). The dimensionless channel sinuosity rate factor (Sn_j) is calculated as

$$Sn_j = \frac{1}{(Sinu_j - 1)\sigma\sqrt{2\pi}}\, e^{\left(-\frac{(ln\,(Sinu_j - 1) - \mu)^2}{2\,\sigma^2}\right)} \tag{11}$$

where $Sinu_j$ is sinuosity of the j-th stream segment of the River Environment Classification v2 (REC2) network, and μ and σ are the mean and standard deviation parameters that determine the location and scale of the distribution. The μ and σ parameters are fitted using measurements of reach-scale bank migration rates.

The texture of bank material influences bank migration rates (Hickin & Nanson 1984; Julian & Torres 2006; Wynn & Mostaghimi 2006). Our approach is based on an empirical relationship between percent silt + clay content (*SC*) and soil critical shear stress (τ_c) derived by Julian and Torres (2006) using data from Dunn (1959) as follows:

$$\tau_c = 0.1 + 0.1779SC + 0.0028SC^2 - 0.0000234SC^3 \qquad (12)$$

SC is obtained from spatial data on soil textural classes compiled from the Fundamental Soil Layers (FSL) (Newsome et al. 2008), which provide national coverage. The soil texture-based erodibility factor (T_j) is represented by a power function to characterise the relationship between τ_c and bank erodibility for the *j*-th stream segment:

$$T_j = c\tau_{c,j}{}^{-d} \qquad (13)$$

where the *c* and *d* parameters are fitted using available bank migration rate data. The choice of a power function is based on experimental (Arulanandan et al. 1980) and field (Hanson & Simon 2001; Julian & Torres 2006) observations of the relationship between stream bank or bed critical shear stress and erodibility.

Floodplain extent and the level of valley confinement are factors that may limit lateral bank migration (Hall et al. 2007; De Rose & Basher 2011). The presence of steep valley sides and/or exposure of bedrock influence spatial patterns of erosion and deposition (Fryirs et al. 2016). Here, we adapt the Australian SedNet model approach to estimate a valley confinement factor (V_j) by using the mean slope (SB_j) in degrees of a buffer zone (4 × 15 m DEM pixel width) either side of the *j*-th stream segment:

$$V_j = \left(1 - e^{\left(-15/SB_j\right)}\right)^{11} \qquad (14)$$

Woody riparian vegetation typically increases bank stability via the effects of root reinforcement and root cohesion (Abernethy & Rutherfurd 2000; Hubble et al. 2010; Polvi et al. 2014; Konsoer et al. 2015). Woody vegetation can also increase roughness and flow resistance, thereby reducing the boundary shear stress acting on the bank surface (Thorne 1990). In addition, woody vegetation has hydrological effects on bank stability. For example, woody vegetation was found to be more effective than grass cover in lowering soil water content due to increased canopy interception and evapotranspiration, thus improving bank stability (Simon & Collison 2002).

We represent the effect of riparian woody vegetation (PR_j) in reducing bank migration rates at the reach scale. Bank migration rates are reduced proportionally to the extent of woody riparian vegetation along the *j*-th stream segment (Equation 9). Stream segments with complete riparian woody vegetation cover are assumed to erode at 5% of the migration rate with no woody cover (De Rose et al. 2003). Spatial information on woody vegetation is obtained from satellite imagery and intersected with the Land Information New Zealand (LINZ) digital stream network obtained from 1:50,000 topographic mapping. The mapped stream network was used in preference to the DEM-derived channel network because it tends to exhibit better planform accuracy which should improve spatial correspondence between channel position and riparian woody vegetation. The proportion of riparian woody vegetation is computed from the intersection of the digital stream network with a 15-m buffer and a classified map of 2002 woody vegetation cover (called EcoSat Woody) which was derived from Landsat TM at 15 m resolution (Dymond & Shepherd 2004).

We also include representation of channel protection works (PW_j) that are designed to reduce bank erosion (e.g. rock riprap, willow edge protection) as well as stopbanks employed for flood protection, where such data are available. We assume that over the multi-decadal model timescale, erosion mitigation would be targeted to where migrating riverbanks approach stopbanks, or that such interventions have already been implemented to protect stopbank integrity. The proportional length of bank erosion control measures (PEC_j) and stopbanks (PSB_j) is summed to give the proportion of channel works (PW_j) for the j-th stream segment. PEC_j is computed as the length of erosion control measures within a stream segment relative to the total length of that segment. This assumes erosion control measures are targeted to the eroding bank side. Stopbanks may be located on either side of the channel irrespective of the direction of bank migration. Therefore, PSB_j is computed as the length of stopbanks in a segment relative to 2 × segment length.

4.1.3 Sediment routing

To account for sediment trapping through lakes, we apply a revised SedNetNZ sediment routing algorithm. The revised routing algorithm applies a lake-specific sediment passing factor (SPF) to the net routed sediment load at the end of a REC2 sub-catchment draining to a lake. SPF was calculated using an adaptation of Gill's (1979) approximation of Brune's (1953) trap efficiency (the inverse of passing factor) curve for medium sediment:

$$SPF = 1 - \frac{{}^{V}\!/_{I}}{1.02\left({}^{V}\!/_{I}\right) + 0.012} \tag{15}$$

where V is the lake volume and I is the annual inflow to the lake. This is similar to the approach of Hicks et al. (2019).

4.2 Application to Southland

The area modelled for this report comprises the Waiau, Ōreti, Aparima, and Matāura Freshwater Management Units (FMUs) (Fig. 1). FMUs are a concept described in the National Policy Statement for Freshwater Management (NPS-FM) as a management unit comprising one or multiple freshwater bodies, and are defined by the regional council as the appropriate spatial scale for managing freshwater objectives and limits. FMUs differ from catchments as catchment boundaries are hydrologically defined, while FMU boundaries are politically defined and may not follow a hydrological boundary. The modelled FMUs encompass the main Waiau, Ōreti, Aparima, and Matāura catchments, plus smaller surrounding catchments, and are described in the proposed Southland Land and Water Plan.

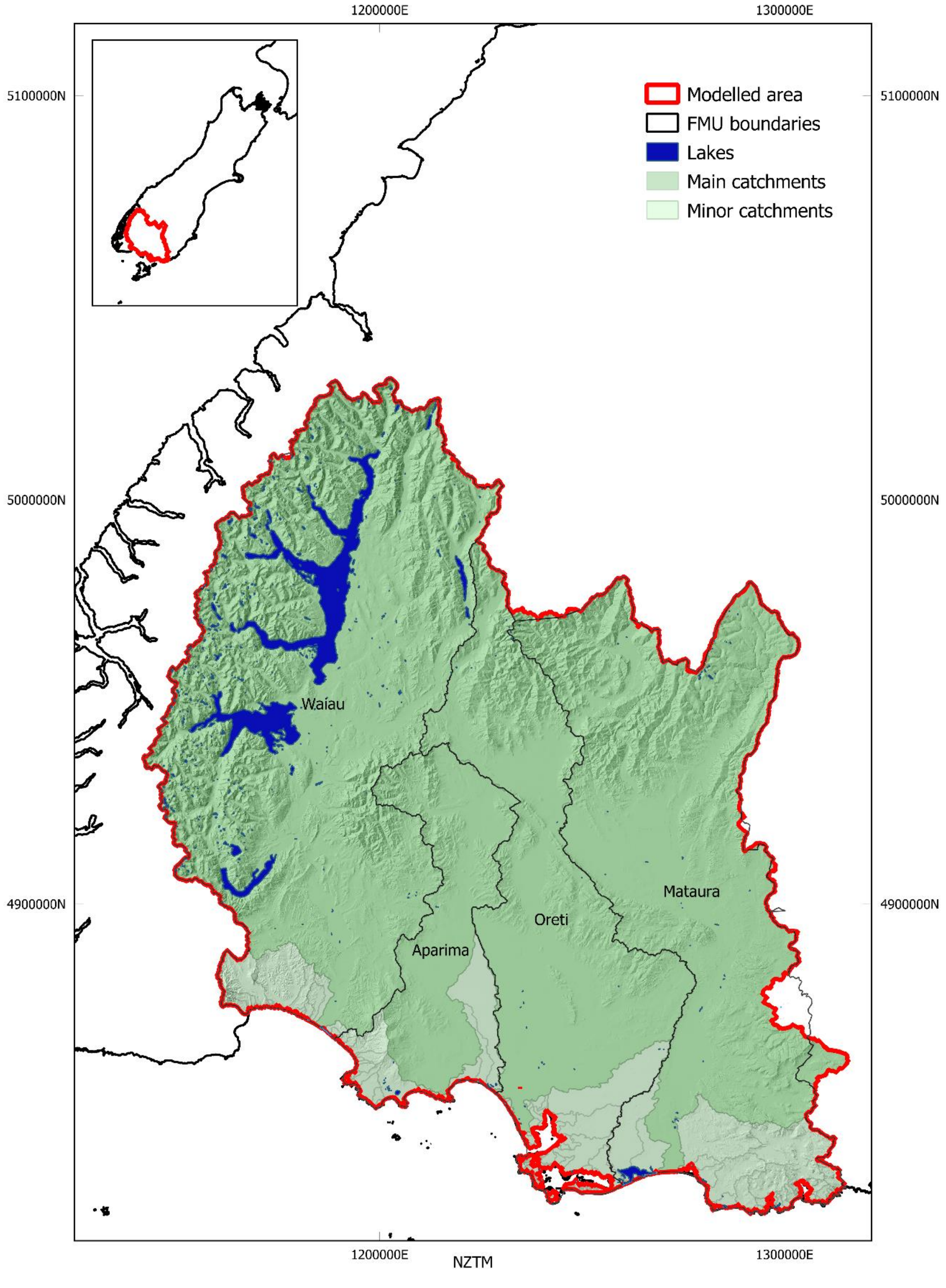

Figure 1. Modelled area (red boundary), comprising the Waiau, Ōreti, Aparima, and Matāura FMUs (thick black lines). The main catchments within each FMU are shown in dark green, and the minor catchments making up the remainder of each FMU are shown in light green. The FMUs take the same name as the main catchment in each.

In applying SedNetNZ to the Southland region we consider loads to be primarily driven by surficial and bank erosion, and do not include representation of shallow landsliding or gully erosion, as evidence suggests relatively minor contribution from these sources in the Ōreti and Aparima (Brown 2018, Smith et al. 2019). We acknowledge these processes do occur within in the region, particularly in Fiordland headwater catchments, but their contribution to loads in the lowlands is likely to be minor as a major portion of load from these areas is trapped in lakes. We consider the application of the surficial and bank erosion components of SedNetNZ to a provide a suitable approximation of mean annual suspended sediment loads in the region.

4.2.1 Surficial erosion

Spatial input data used to apply the revised surficial erosion component comprised the national 15 m DEM for the calculation of the L and S factors and a national rainfall layer interpolated to 15 m resolution to calculate P^2 in the NZUSLE. Individual REC2 sub-catchments were used to summarise pixel-based modelling results.

Soil data processing

Soil data inputs for the revised NZUSLE K factor were obtained from S-map data where available. In areas where S-map is not available (Fig. 2), the FSL were used. Where S-map data is available, a K factor was calculated for each soil map unit (SMU) using data from up to 5 siblings. OM, percent silt, and percent clay were calculated from data for the uppermost functional horizon (FH1) in each sibling (equivalent to the topsoil). Where available, S-map data was used for OM, otherwise OM was calculated as:

$$OM = 1.72C \tag{16}$$

where C is soil carbon. For S-map, soil carbon is supplied as median topsoil carbon, derived from the New Zealand Soil Classification (NZSC).

PP represents the profile permeability. Permeability codes were mapped to the six PP classes using Table 1.

Table 1. Profile permeability classes used to calculate *K*

PermeabilityCode	Profile permeability class (*PP*)
r	1
r/m	2
r/s	2
m	3
m/r	3
m/s	4
s/r	5
s/m	5
s	6

A weighted average for each parameter was calculated for the SMU, weighted by the proportion of the SMU containing each sibling:

$$\bar{x}_{SMUj} = \frac{\sum_{i=1}^{n} p_{ij}\, x_{ij}}{\sum_{i=1}^{n} p_{ij}} \tag{17}$$

where $\bar{x}_{SMUj}$ is the weighted average of any parameter, x, for the j-th SMU, x_{ij} is the value of the parameter for the i-th sibling in the j-th SMU, and p_{ij} is the proportion of ith sibling in the j-th SMU.

Where S-map data were not available, data from the FSL were used to calculate K. OM was calculated using Equation 16, with the median soil carbon used for C for consistency with the S-map calculation.

Particle size in the FSL is represented by particle size classes, which have a range for sand, silt, and clay proportions within the fine earth fraction of the soil, except in skeletal soils with >35% coarse fraction, where sand, silt, and clay are represented as a proportion of the whole soil. To get a single value for silt and clay in each FSL particle size class, sibling codes from S-map were mapped to each FSL particle size class. The loamy class, *L*, was split into loam (*L*, silt ≤70%) and silt (*Z*, silt > 70%) classes.

The proportion of silt and clay in each sibling code were averaged to provide an estimate of the proportion of silt and clay in the respective FSL particle size class:

$$\bar{x}_{FSLj} = \frac{1}{n}\sum_{i=1}^{n} x_{SMAPi} \tag{18}$$

where $\bar{x}_{FSLj}$ is the average sand, silt, or clay (x), for the j-th FSL particle size class, and x_{SMAPi} is the particle size for x from the i-th S-map particle size class mapped to the j-th FSL particle size class. For skeletal soils where the coarse fraction exceeds 35%, sand was set to 35%, and silt and clay set to 15%.

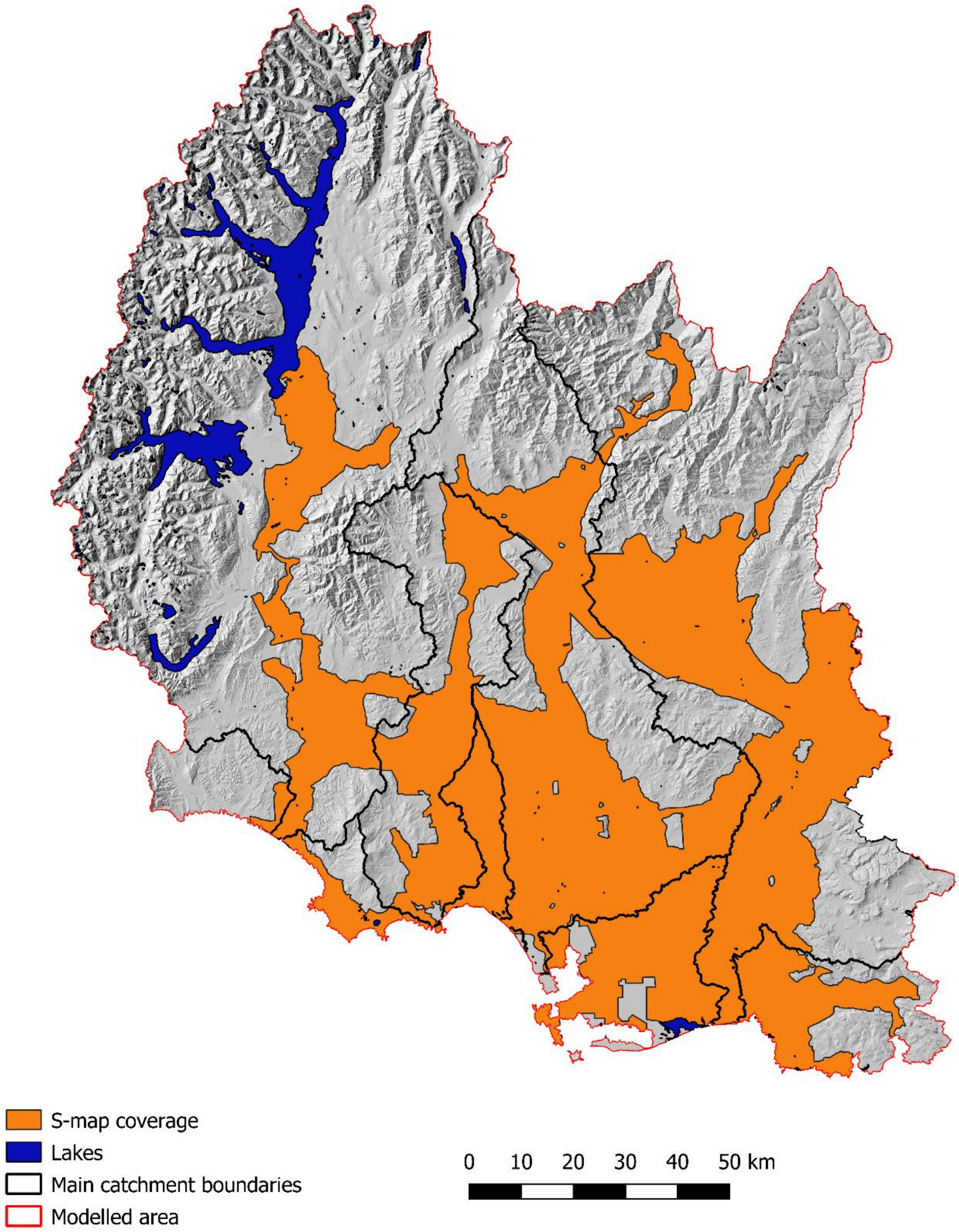

Figure 2. S-map coverage in the modelled area.

Winter forage cropping

To incorporate the impact of winter forage cropping on surficial erosion a modified C factor was used in winter forage cropping paddocks (C_{WF}) to represent the temporal variability in cover. Where forage cropping occurs, it is assumed the average paddock has vegetation cover with a C factor equivalent to pasture for 9 months of the year, and equivalent to bare ground for 3 months of the year as a result of the sowing and grazing cycles. C_{WF} is therefore calculated as:

$$C_{WF} = 0.75C_P + 0.25C_B \tag{19}$$

where C_P is the C factor for pasture and C_B is the C factor for bare ground. This gives a C factor of 0.2575 for winter forage cropping.

The location of winter forage cropping was available for the Southland region as a raster for 2014 and as a vector layer for 2017 using paddock boundaries (North & Belliss 2014; North et al. 2018). The 2014 data were vectorised following North et al. (2018) to make it coherent with the 2017 data. Each layer was separately merged with LCDB v5.0 to create different landcover layers (Table 2).

Table 2. Discrete landcover scenarios run separately in SedNetNZ to test the sensitivity of suspended sediment loads to the spatial distribution of winter forage cropping

Landcover layer name	Description
LCDB5	LCDB v5.0 with no winter forage class
$LCDB_{WF2014}$	LCDB v5.0 with the 2014 winter forage crop map from North & Belliss (2014) incorporated
$LCDB_{WF2017}$	LCDB v5.0 with the 2017 winter forage crop map from North et al. (2018) incorporated

To test the sensitivity of SedNetNZ mean annual suspended sediment loads to the spatial distribution of winter forage cropping, SedNetNZ was run with the three different landcover layers. Three sensitivity scenarios (Table 3) were then created by comparing the loads estimated under the three different landcover layers.

Table 3. Winter forage cropping sensitivity scenarios

Sensitivity scenario	Description	Calculation
Scenario 1	Difference in loads between *LCDB5* and $LCDB_{WF2014}$	Subtraction of *LCDB5* landcover loads from the $LCDB_{WF2014}$ loads
Scenario 2	Difference in loads between *LCDB5* and $LCDB_{WF2017}$	Subtraction of *LCDB5* landcover loads from the $LCDB_{WF2017}$ loads
Scenario 3	Difference in loads between $LCDB_{WF2014}$ and $LCDB_{WF2017}$	Subtraction of $LCDB_{WF2014}$ landcover loads from the $LCDB_{WF2017}$ loads

4.2.2 Bank erosion

Inputs to the bank erosion model component of SedNetNZ were obtained from national-scale spatial datasets comprising the REC2 and LINZ stream networks, 15 m DEM, FSL for soil data, and EcoSat Woody for 2002 woody vegetation cover. LCDB v5.0 was not used, despite being more recent, because it has a minimum mapping unit of 10,000 m^2 compared with 225 m^2 for EcoSat. This makes LCDB less suitable for characterising narrow corridors of woody vegetation often found along channel banks.

Hydrological data were obtained from Environment Southland's Environment Data website (http://envdata.es.govt.nz/?c=flow&tab=hydro). This comprises flow data from 24 gauging stations across the region that were used to fit a relationship (Fig. 3) between mean annual discharge and mean annual flood ($MAF = 20q^{0.9}$, $R^2 = 0.91$). The diversion of flow to Doubtful Sound via the Manapouri Power station significantly reduced the mean annual discharge on the Waiau River. This diversion corresponds to a reported reduction in mean flow from 561 to 157 $m^3 s^{-1}$ in the Waiau River at Tuatapere (Duncan & Woods 2013). To account for this loss of flow, we apply an equivalent proportional reduction to the modelled mean annual discharge (Woods et al. 2006) along the main river channel downstream from Lake Manapouri to the coast.

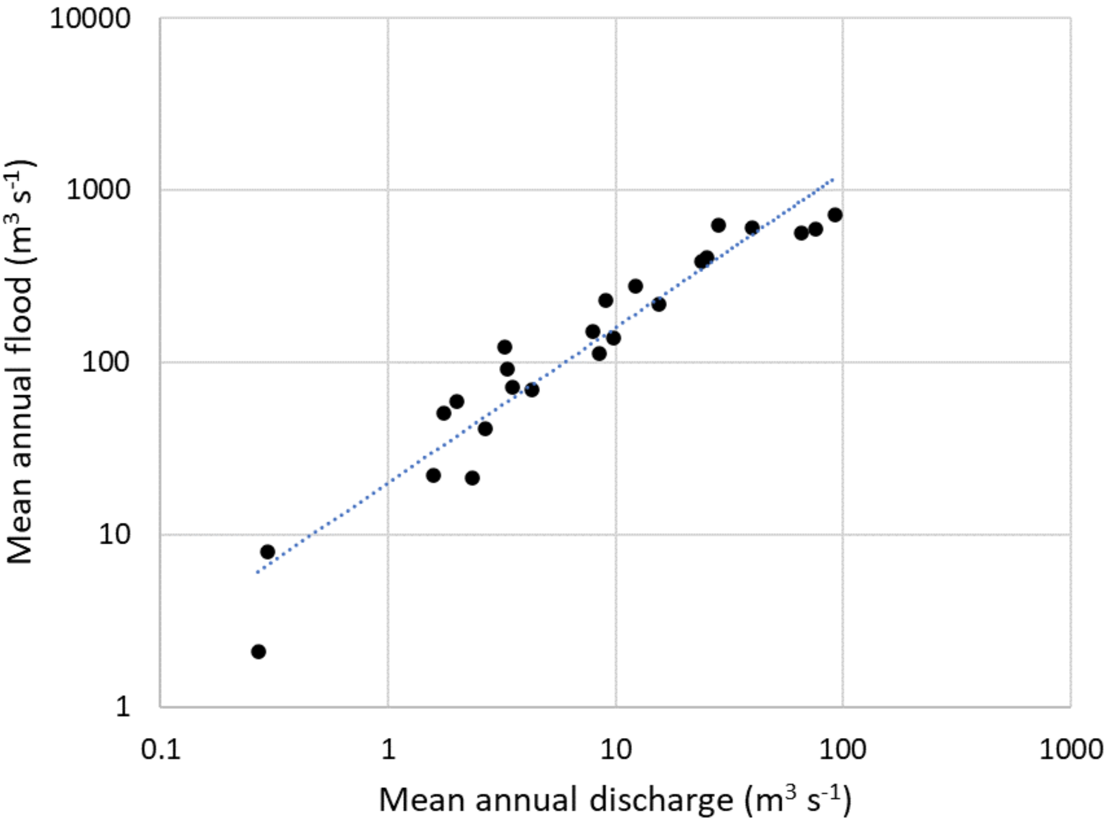

Figure 3. Fitted power law relationship between mean annual discharge and mean annual flood (MAF) based on data from 24 gauging stations across Southland (catchment area range: 21–5,109 km^2).

In the absence of mapped reach-scale channel changes within the Southland region, we used a combined dataset comprising measured bank migration rates from the Manawatu and Kaipara catchments to calibrate the bank erosion model (Spiekermann et al. 2017; Smith et al. 2019a). This calibration dataset was also used in the previous application of the improved bank erosion model to the Ōreti and Aparima catchments (Smith et al. 2019b).

Calibration of the bank migration model was performed by minimising the mean square error (MSE) between predicted and observed data by optimising parameter values for the sinuosity (μ and σ) and soil texture (c and d) factors in Equations 11 and 13, respectively. This was achieved using the optim() function in R with the L-BFGS-B method (Byrd et al. 1995) that allows parameters to be given upper and lower bounds. The search range in parameter values for the sinuosity rate factor were constrained (μ: 0–1 and σ: 1–1.5) to preserve the positive-skewed form of the sinuosity-migration rate relationship, which has been observed in studies of river channel change and is considered to have a physical basis (Crosato 2009). Parameter ranges for the soil texture erodibility factor were only loosely constrained (c: 0–100 and d: 0–3) to accommodate the range in observed bank migration rates.

The revised bank migration model was found to significantly improve prediction, once calibrated, compared to the previous SedNetNZ bank migration model (Smith et al. 2019a; Fig. 4).

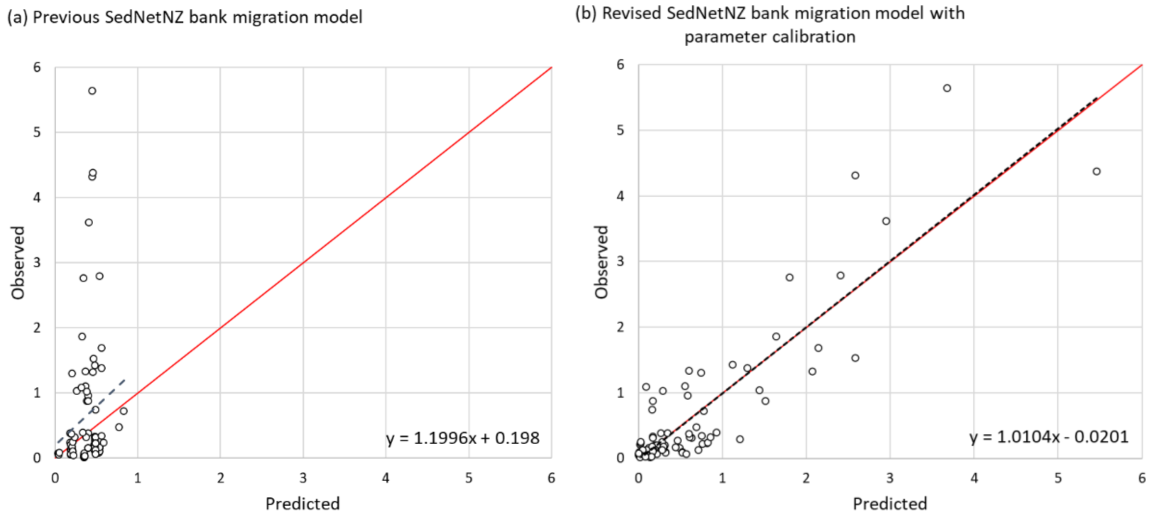

Figure 4. Comparison of predicted versus observed bank migration rates (m y^{-1}) for (a) original (Dymond et al. 2016) and (b) revised SedNetNZ bank migration models (Smith et al. 2019a). Red line indicates the 1:1 line.

Since the previous application of the bank erosion model to the Ōreti and Aparima catchments (Smith et al. 2019b), we have refined the procedure for pre-processing LINZ stream network data used to determine the extent of riparian woody vegetation. We found that the LINZ river polygons provided poor representation of channel width for some wider braided reaches. To address this issue, the spatial union of the LINZ river polygons with LCDB v5.0 ‘river’ and ‘gravel and rock’ land cover classes was used to produce a revised river polygon. Mapped ‘gravel and rock’ areas located beyond the extent of the channel network were removed. This approach enabled better representation of wide channels with exposed gravel beds and improved the alignment between channel banks and mapped woody vegetation when quantifying the reach-scale extent of riparian woody vegetation cover.

4.2.3 Sediment routing

We obtained a GIS layer of the Water Bodies of National Importance (WONI), including associated lake attribute data from LWP. *SFP* was calculated for 453 lakes based on the “Amended Volume” field for *V*, and “Catch flow” for *I*. The lakes ranged in volume from $3.9e^4$ to $4.8e^{10}$ m^3, with sediment passing factors ranging from 0.02 to 0.97. The mean lake size is $1.3e^6$ m^2. The majority of lakes have a residence time <1 year, with a maximum residence time of 11 years.

4.3 Contemporary baseline scenario

ES and LWP agreed 2017 would be used as the baseline year for visual clarity and suspended fine sediment, which aligns with the baseline year used for other contaminants, as this is when the most recent data is available for most input datasets. The 2017 baseline corresponds to the mean annual suspended sediment load that would be expected to occur over a multi-decadal timescale if the 2017 landcover and pre-existing mitigations were to remain constant.

To represent the 2017 landcover for the Southland region, LCDB v5.0 was used, as this was mapped ~2018. The 2017 winter forage crop vector layer produced by North et al. (2018) was incorporated with LCDB to represent the spatial distribution of forage cropping in 2017 ($LCDB_{wf2017}$). While we have used the 2017 distribution of winter forage cropping in the landcover layer used to estimate baseline loads, we recognise winter forage cropping varies spatially and in extent from year to year making it difficult to represent in a steady-state model such as SedNetNZ. We have therefore also modelled loads using the 2014 distribution of forage cropping, and no forage cropping, to assess sensitivity of mean annual suspended sediment loads to spatial representation of winter forage cropping.

4.3.1 Incorporating the effect of pre-existing mitigations

Following the approach of Neverman et al. (2019), the effect of pre-existing mitigations was included in the calculation of baseline mean annual suspended sediment loads. The only data available on pre-existing mitigations in Southland were a spatial layer provided by ES representing existing and planned fencing.

A reduction of 80% in net suspended sediment load from bank erosion may be attributable to riparian fencing and stock exclusion (Dymond et al. 2016). This reflects the effect of reduced stock trampling and foraging on banks (Trimble 1994), as well as the potential for riparian woody and herbaceous vegetation to become better established in the absence of livestock over the longer-term. For surficial erosion, our modelling assumes stock are excluded from the buffer between the fence and channel, allowing vegetation to establish which intercepts sediment entrained in overland flow and stabilises banks. The effectiveness of the buffer for intercepting sediment is a function of the buffer width.

We estimate the fraction of REC2 stream segment length that has been fenced (FR_j) as the length of fence relative to 2 x stream segment length, which approximates the maximum extent of fencing when present on both sides of a channel in a given segment. The reduced net suspended sediment load from bank erosion due to fencing and stock exclusion (B_{F_j}) is computed as:

$$B_{F_j} = B_j \times \left(1 - 0.8FR_j\right) \tag{20}$$

where B_j is the net suspended sediment load from bank erosion without the effect of fences in reducing erosion.

The sediment passing factor, the inverse of the trapping efficiency, applied to surface erosion load of the buffer for the *j*-th segment (PF_{Fj}) was calculated using Equation 21, from Zhang et al. (2010):

$$PF_{F_j} = 1 - k\left(1 - e^{-bw}\right) \tag{21}$$

where *k* and *b* are fitted parameters, and equal 90.9 and 0.446 (Zhang et al., 2010), respectively, and *w* is the buffer width (Table 4). Estimates of the average width of buffers by REC2 stream order were provided by ES for stream orders 2-6. Buffer widths for orders 1 and 7 were taken to be the same as orders 2 and 7, respectively. These values were used to represent *w* based on the REC2 stream order of the *j*-th stream segment.

Table 4. Estimated buffer widths by stream order derived from unpublished data supplied by ES

Stream order	Buffer width (m)
1	3
2	3
3	3
4	4
5	5
6	10
7	10

The reduction in suspended sediment load from surficial erosion due to the fencing and stock exclusion in a reach (S_{F_j}) is a function of the proportion fenced and the buffer passing factor:

$$S_{F_j} = ES_j \times \left(1 - FR_j PF_{Fj}\right) \tag{22}$$

where ES_j is the load from surficial erosion for the *j*-th reach.

We use spatial data on fences supplied by ES to estimate the reduction in bank erosion due to riparian fencing. The data included both existing and planned fences, so the data were filtered to include only those fences with “Existing” or “Completed” in the “Status” field. This dataset included fences located beyond riparian areas, so we applied a 30-m buffer to the REC2 stream segments to select those fences in the vicinity of the channel. This buffer is designed to accommodate some positional error evident in REC2 stream segments relative to mapped fence lines.

Spatial data on riparian plantings or channel protection works were unavailable, whereas data on stopbank locations are available and have been included in model simulations.

4.4 Natural landcover scenario

ES and LWP requested a natural reference scenario to be modelled, against which achievement of FWOs would be assessed. Given the challenges of representing the natural catchment state, and the likely significant affect this would have on the relationship between loads and visual clarity (which could not be parameterised), a natural reference scenario was developed which represents naturalised landcover within the contemporary catchment setting (i.e. contemporary channel network and catchment hydrology). This scenario is therefore referred to as the natural landcover scenario. This scenario should not be interpreted as producing pre-human suspended sediment loads or visual clarity, but instead provides an estimate of loads where woody vegetation cover spans all areas below the tree line (defined as 1,000 m elevation based on observation).

To represent a naturalised landcover, land below the tree line (modelled as occurring at 1,000 m a.s.l) was modelled as having native forest cover. Land above the tree line was represented by alpine landcover as represented in LCDB v5.0.

4.5 Reductions in mean annual suspended sediment loads required to achieve draft Freshwater Objectives

To identify the reductions in mean annual suspended sediment loads required to achieve the draft Freshwater Objectives for visual clarity and suspended fine sediment in the baseline and natural landcover scenarios, the relationships between required reductions in mean visual clarity and suspended sediment loads simplified by Hicks et al. (2019) from Dymond et al. (2017) were used. The proportional reduction in load required to achieve the objective is calculated as a function of the difference between the baseline median and the objective for each parameter:

$$PR_v = 1 - (V_o/V_b)^{1/a} \tag{23}$$

where PR_v is the proportional reduction in load required to achieve the objective (reduction factor), V_o is the objective median visual clarity. As minimum thresholds are given for the draft FWOs, PR_v therefore represents the minimum load reduction that will be required to meet the objective. V_b is the baseline median visual clarity. a was assumed to take the national average reported by Hicks et al. (2019) as –0.76. Uncertainty in PR_v was estimated by calculating PR_v with a altered by ± one standard deviation, using the standard deviation reported by Hicks et al. (2019) for the national dataset (± 0.13). PR_v was therefore calculated with a set to -0.63 and -0.89, providing an upper and lower bound for the uncertainty range for PR_v at each REC2 segment. The minimum, median, and maximum uncertainties for the REC2 segments are presented in Appendix 1.

Baseline median visual clarity for Southland was provided by LWP for the REC2 network (Figure 5). These baseline values were estimated by LWP for the Southland region using random forest regression models, based on a range of catchment characteristics as predictors, and fitted to all sites where appropriate data were available. The draft Freshwater Objectives for Southland were also provided by LWP, and are reproduced here in Tables 5, 6, 7 and 8. Two sets of FWOs have been developed which use visual clarity as their attribute unit, but have different numeric attribute states for each respective attribute band. One set of FWOs relates to recreational values, referred to as "visual clarity" objectives, and one set relates to ecosystem health values, referred to as "suspended fine sediment" objectives. The objectives are defined as a Decision Envelope and Hauora (health and well-being) Envelope, which have a lower bound and upper bound objective (bottom and top of envelope, respectively). Envelopes are defined for each river management class of the REC2 segment (defined by ES). The numeric attribute states are assigned based on those proposed for the 4 Climate, Topography and Geology (CTG) classes defined by Franklin et al. (2019) for the NOF.

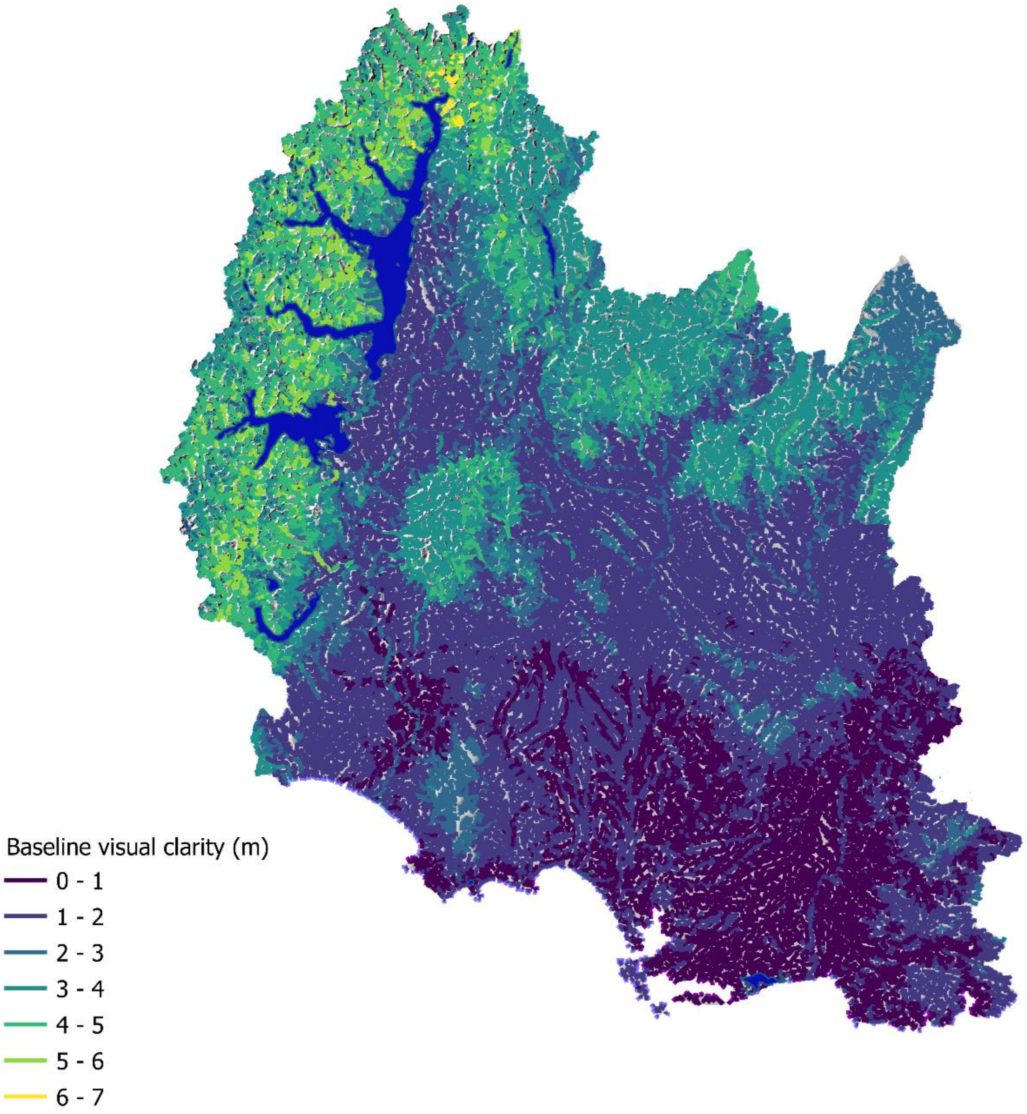

Figure 5. Modelled baseline visual clarity across the modelled area. Note the low visual clarity in the lowland reaches despite low local sediment yields. This may result for a number of reasons, including lower dilution due to lower flows, differences in sediment properties between steepland and lowland areas producing different effects on visual clarity, different phasing of sediment delivery (and therefore differences in whether or not interval sampling captures visual clarity peaks), biases in sampling between steepland and lowland sites, or between low and high order streams.

Table 5. Numeric attribute state for the Southland visual clarity (recreational) Freshwater Objective bands

Attribute band	Numeric attribute state – visible distance (m)
A	≥3.0
B	≥1.6 and ≤3.0
C	≥1.3 and ≤1.6
D	<1.3

Table 6. Draft visual clarity (recreational) Freshwater Objectives for Southland by river management class. The "Lowland" class is an amalgamation of the "Lowland Soft Bed" and "Lowland Hard Bed" segments.

River Management Class	Bottom of Decision Envelope	Bottom of Hauora Envelope	Top of Envelopes
Natural State	No change	No change	No change
Lowland Soft Bed	C	B	A
Lowland Hard Bed	B	B	A
Lowland	B	B	A
Hill	B	B	A
Mountain	A	A	A
Lake Fed	A	A	A
Spring Fed	A	A	A

Table 7. Numeric attribute state for the Southland suspended fine sediment (ecosystem health) Freshwater Objective bands

Attribute band and description	Numeric attribute state by suspended sediment class (visual clarity(m))			
	1	2	3	4
A	≥1.78	≥0.93	≥2.95	≥1.38
B	<1.78 and ≥1.55	<0.93 and ≥0.76	<2.95 and ≥2.57	<1.38 and ≥1.17
C.	<1.55 and ≥1.34	<0.76 and ≥0.61	<2.57 and ≥2.22	<1.17 and ≥0.98
D	<1.34	<0.61	<2.22	<0.98

Table 8. Draft suspended fine sediment (ecosystem health) Freshwater Objectives for Southland by river management class

River Management Class	Bottom of Decision Envelope	Bottom of Hauora Envelope	Top of Envelopes
Natural State	No change	No change	No change
Lowland Soft Bed	C	C	A
Lowland Hard Bed	C	C	A
Hill	C	C	A
Mountain	A	A	A
Lake Fed	C	C	A
Spring Fed	C	C	A

The absolute reduction in baseline and natural landcover mean annual suspended sediment load required to achieve each of the objectives at a segment is then calculated following Neverman et al. (2019) by multiplying the baseline load by the proportional reduction factor:

$$LR_v = PR_v L_b \tag{25}$$

where LR_v is the absolute load reduction required to meet the objective, and L_b is the baseline mean annual suspended sediment load for the segment.

The reductions required to achieve the draft FWOs are summarised for 12 reporting catchments, supplied by LWP.

5 Results

5.1 Baseline sediment loads

SedNetNZ modelled baseline mean annual suspended sediment loads are presented for the Waiau, Ōreti, Aparima, and Matāura catchments in Table 9, along with previous modelled estimates for these catchments by Hicks et al. (2011, 2019). The total load for the modelled area is 1.343 Mt yr^{-1}. Loads are also presented for each FMU in Table 10.

Table 9. SedNetNZ modelled baseline mean annual suspended sediment loads for the four major catchments estimated using SedNetNZ. Previous estimates by Hicks et al. (2011, 2019) provided for comparison

Catchment	SedNetNZ modelled mean annual suspended sediment load (t yr^{-1})	Mean annual suspended sediment load estimated by Hicks et al. 2011 (t yr^{-1})	Mean annual suspended sediment load estimated by Hicks et al. 2019 (t yr^{-1})
Matāura	490,000	690,000	280,000
Ōreti	295,000	260,000	180,000
Aparima	67,000	90,000	65,000
Waiau	451,000	780,000	333,000[1]

Table 10. Baseline mean annual suspended sediment loads for the modelled FMUs

FMU	SedNetNZ modelled mean annual suspended sediment load (t yr^{-1})
Matāura	509,000
Ōreti	296,000
Aparima	72,000
Waiau	465,000

The highest rates of erosion occur in the headwaters and along the main channel in the middle to lower reaches of the main catchments (Fig. 5). Of suspended sediment load in the modelled area, 8% is derived from bank erosion, with 92% from surficial erosion. In the main catchments, surficial erosion contributes 75% of the load to the Matāura, 66% of the load to the Aparima, 83% of the load to the Ōreti, and 95% of the load to the Waiau. These proportions also hold for the FMUs.

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[1] Outputs for the Waiau catchment are misreported in Hicks et al. (2019) with results from the Waiau River in Canterbury being reported instead. The estimated load from the Waiau River, Southland, has therefore been retrieved from the SSYE shapefile for reporting here. The data are available from https://data.mfe.govt.nz/layer/103686-updated-suspended-sediment-yield-estimator-and-estuarine-trap-efficiency-model-results-2019/

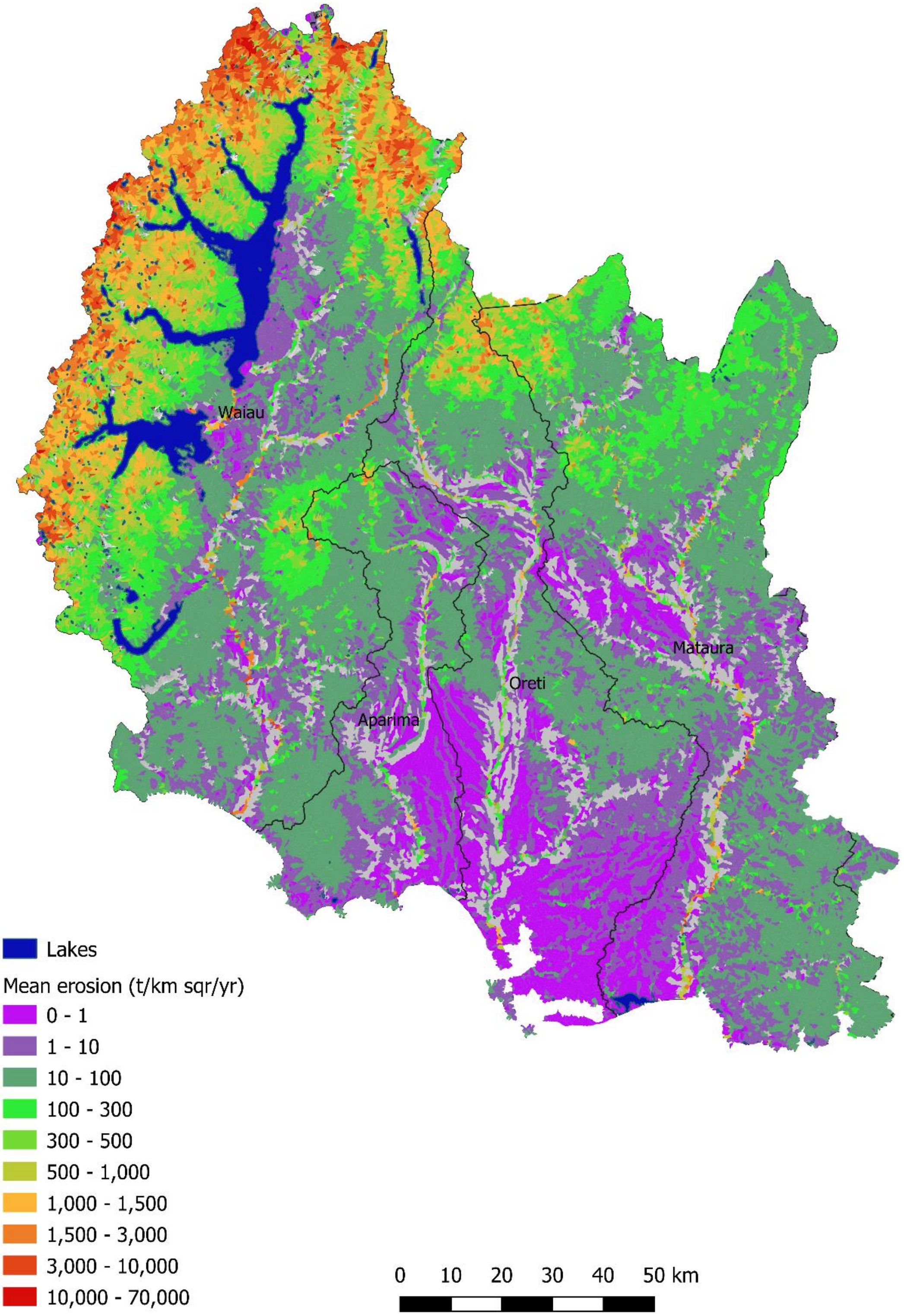


Figure 6. Spatial distribution of erosion averaged across the modelled area (sediment yield, t km^2 y^{-1}) by REC2 watershed.

In the Waiau FMU, 94% of sediment yield is derived from Indigenous Forest and Conservation land, which comprises 71% of the FMU by area (Table 11). Indigenous Forest and Conservation land contributes 35–54% of sediment yield from 13 to 17% of the land area in the other FMUs. Sheep and Beef is the second largest contributor, contributing 49% in the Matāura, 25% in the Aparima, and 36% in the Ōreti. The high contribution from Indigenous Forest and Conservation land to sediment yields across the region is largely due to its areal extent, and occurrence in areas of steep slopes and high rainfall which increase erosion rates. However, due to the extent of sediment trapping in lakes along the river network these areas may not contribute significantly to lowland loads, particularly in the Waiau catchment.

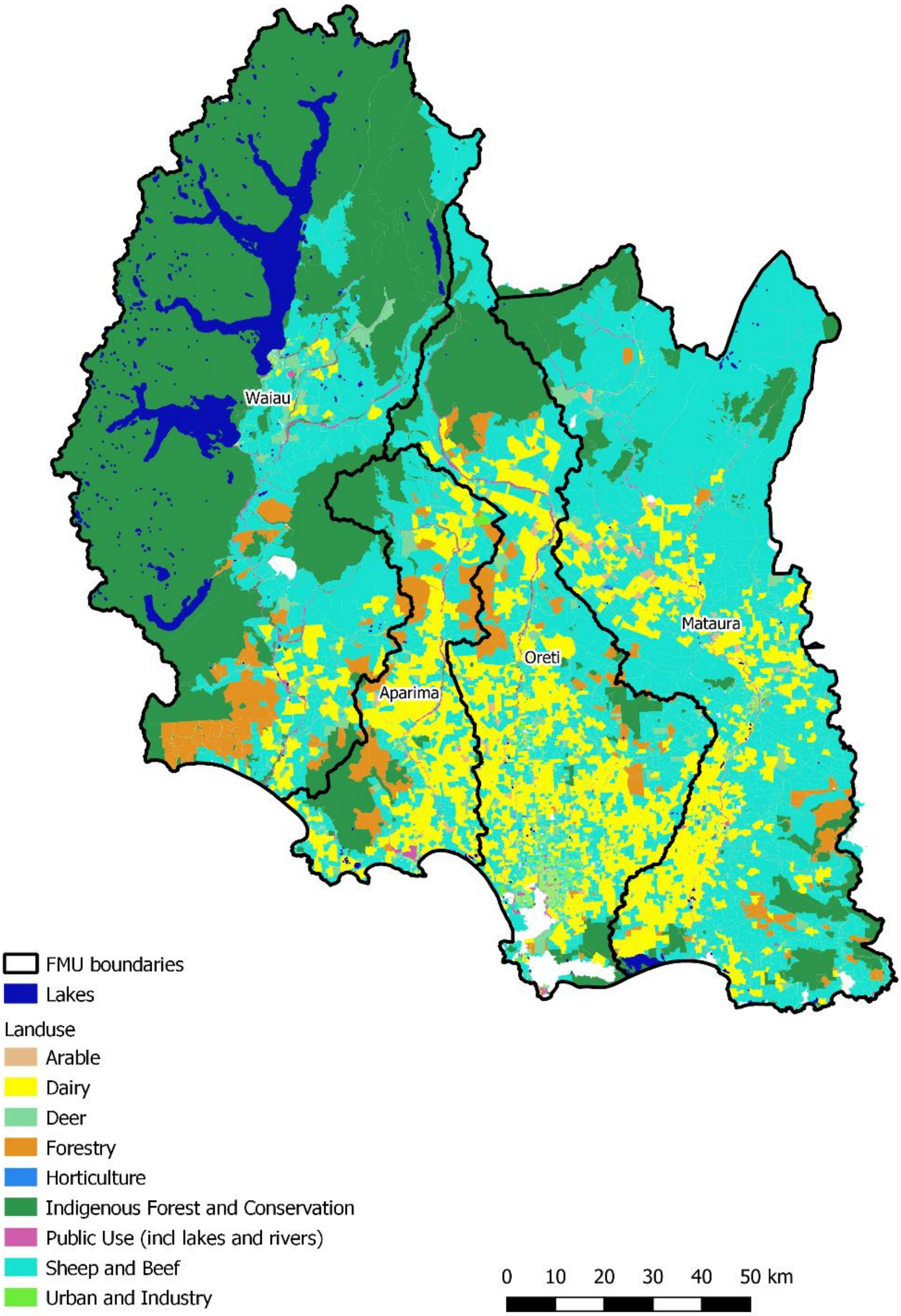


Figure 7. Distribution of land use within the modelled area. GIS layer of land use supplied by ES.

Table 11. Proportion of each FMU under each landuse class, and proportional contribution to load from each land use class

Landuse Class	Matāura		Waiau		Ōreti		Aparima	
	Extent as proportion of FMU (%)	Proportional contribution to load (%)	Extent as proportion of FMU (%)	Proportional contribution to load (%)	Extent as proportion of FMU (%)	Proportional contribution to load (%)	Extent as proportion of FMU (%)	Proportional contribution to load (%)
Arable	1	<1	0	<1	0	<1	0	<1
Dairy	16	7	3	<1	29	3	31	11
Deer	1	<1	1	<1	2	<1	2	1
Forestry	3	1	4	<1	5	1	11	5
Horticulture	0	<1	0	<1	0	<1	0	N/A
Indigenous Forest and Conservation	13	35	71	94	17	54	17	49
Public Use (incl. lakes and rivers)	1	5	1	1	1	4	1	7
Sheep and Beef	64	49	19	4	41	36	34	25
Urban and Industry	2	3	1	<1	4	1	2	2

5.1.1 Sensitivity of baseline sediment load to winter forage cropping extent and distribution

Inclusion of winter forage cropping increased mean annual suspended sediment loads ≤5% in the major catchments under each scenario, except in the Aparima under Scenario 2, which had an 8.5% increase under the 2014 winter forage map compared with loads modelled with no representation of winter forage cropping. This equates to <4% increase in the total load from the four catchments. The sensitivity of mean annual suspended sediment loads to the extent of winter forage cropping (see Fig. 7) is summarised in Table 12 for the four major catchments. The difference in end-of-catchment loads between the 2014 and 2017 distribution of winter forage cropping is <1%, except in the Aparima where the load was 3.5% higher under the 2014 distribution. This equates to a 0.05% difference in total load summed across the four catchments between the 2014 and 2017 distribution of winter forage cropping.

FMU loads increased 2.9 – 9.7% with inclusion of winter forage cropping (Table 14). Loads varied ≤1% between the 2014 and 2017 distribution of forage cropping, except in the Aparima, which varied by 4%.

Under Scenario 3, which represents the difference between the 2014 and 2017 distribution of forage crops, 48.7% of segments had a difference in load between the two scenarios. The mean difference in load between these scenarios is 35.7% and 5.7% of stream segments have a difference >100%. The majority of these segments are low order streams (Table 15) in the lowlands (Fig. 8). Excluding these segments, the mean difference is 10.3%.

The higher loads in Aparima and Waiau in the 2014 scenario, despite lower area of winter foraging, likely represents the location of winter foraging on land more prone to high erosion rates, such as steeper slopes, or with less existing stock exclusion or smaller riparian buffers.

Table 12. Area of forage cropping in 2014 and 2017 per FMU and major catchment

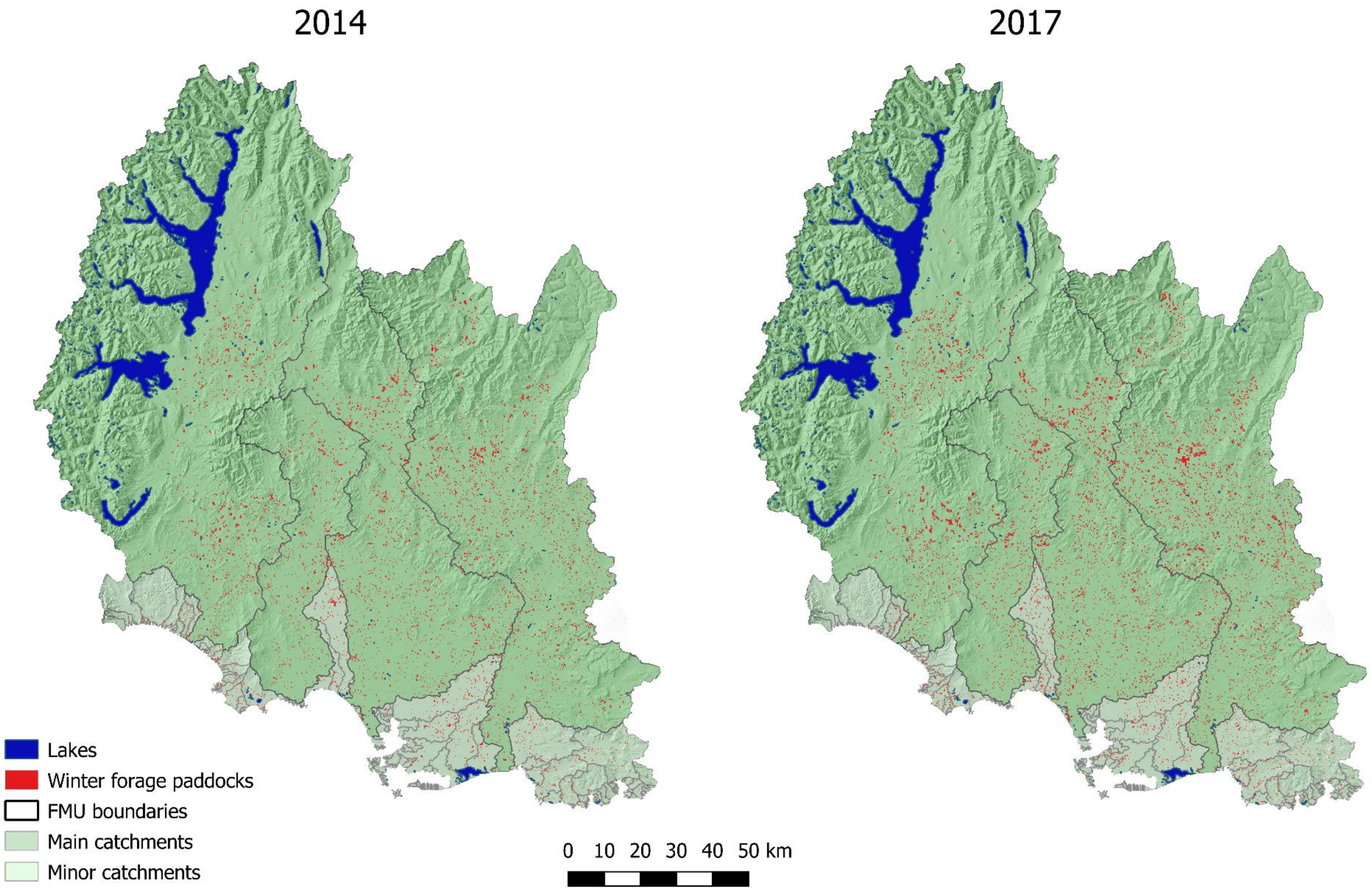
FMU	Area Of winter forage cropping in 2014 (km^2)	Area Of winter forage cropping in 2017 (km^2)	Catchment	Area Of winter forage cropping in 2014 (km^2)	Area Of winter forage cropping in 2017 (km^2)
Matāura	174	246	Matāura	149	207
Ōreti	117	163	Ōreti	103	147
Aparima	57	75	Aparima	39	52
Waiau	83	109	Waiau	79	106

Table 13.Contemporary catchment loads under each landcover layer, and difference in loads under each sensitivity scenario. The differences with Scenario 1 demonstrate the increase in load estimates when winter forage cropping is included as a landcover class in the C factor

Catchment	***LCDB5***	$LCDB_{WF2014}$	$LCDB_{WF2017}$	Scenario 1		Scenario 2		Scenario 3	
				$LCDB_{WF2014} - LCDB5$		$LCDB_{WF2017} - LCDB5$		$LCDB_{WF2017} - LCDB_{WF2014}$	
	Catchment load ($t\ y^{-1}$)	**Catchment load ($t\ y^{-1}$)**	**Catchment load ($t\ y^{-1}$)**	**Change in load ($t\ y^{-1}$)**	**Percent change**	**Change in load ($t\ y^{-1}$)**	**Percent change**	**Change in load ($t\ y^{-1}$)**	**Percent change**
Matāura	466,814	487,515	490,233	20,701	4.4	23,419	5.0	2,718	0.6
Ōreti	284,717	293,950	294,880	9,233	3.2	10,163	3.6	930	0.3
Aparima	64,344	69,798	67,339	5,454	8.5	2,995	4.7	–2,459	–3.5
Waiau	443,866	458,775	456,904	14,909	3.4	13,038	3.0	–1,871	–0.4
Total	**1,259,741**	**1,310,038**	**1,309,356**	**50,297**	**4.0**	**49,615**	**3.9**	**–682**	**–0.05**

Table 14. Contemporary FMU loads under each landcover layer, and difference in loads under each sensitivity scenario. The differences with Scenario 1 demonstrate the increase in load estimates when winter forage cropping is included as a landcover class in the *C* factor

FMU	***LCDB5***	$LCDB_{WF2014}$	$LCDB_{WF2017}$	Scenario 1		Scenario 2		Scenario 3	
				$LCDB_{WF2014} - LCDB5$		$LCDB_{WF2017} - LCDB5$		$LCDB_{WF2017} - LCDB_{WF2014}$	
	Catchment load ($t\ y^{-1}$)	**Catchment load ($t\ y^{-1}$)**	**Catchment load ($t\ y^{-1}$)**	**Change in load ($t\ y^{-1}$)**	**Percent change**	**Change in load ($t\ y^{-1}$)**	**Percent change**	**Change in load ($t\ y^{-1}$)**	**Percent change**
Matāura	481,934	504,457	509,457	22,524	4.7	27,524	5.7	5,000	1.0
Ōreti	285,827	295,177	296,141	9,350	3.3	10,314	3.6	964	0.3
Aparima	68,437	75,043	72,071	6,607	9.7	3,634	5.3	–2,972	–4.0
Waiau	452,139	468,018	465,423	15,879	3.5	13,284	2.9	–2,595	–0.6
Total	**1,288,336**	**1,342,696**	**1,343,092**	**54,360**	**4.2**	**54,756**	**4.3**	**396**	**0.03**


2014

2017

Figure 8. Distribution of winter forage cropping in 2014 and 2017.

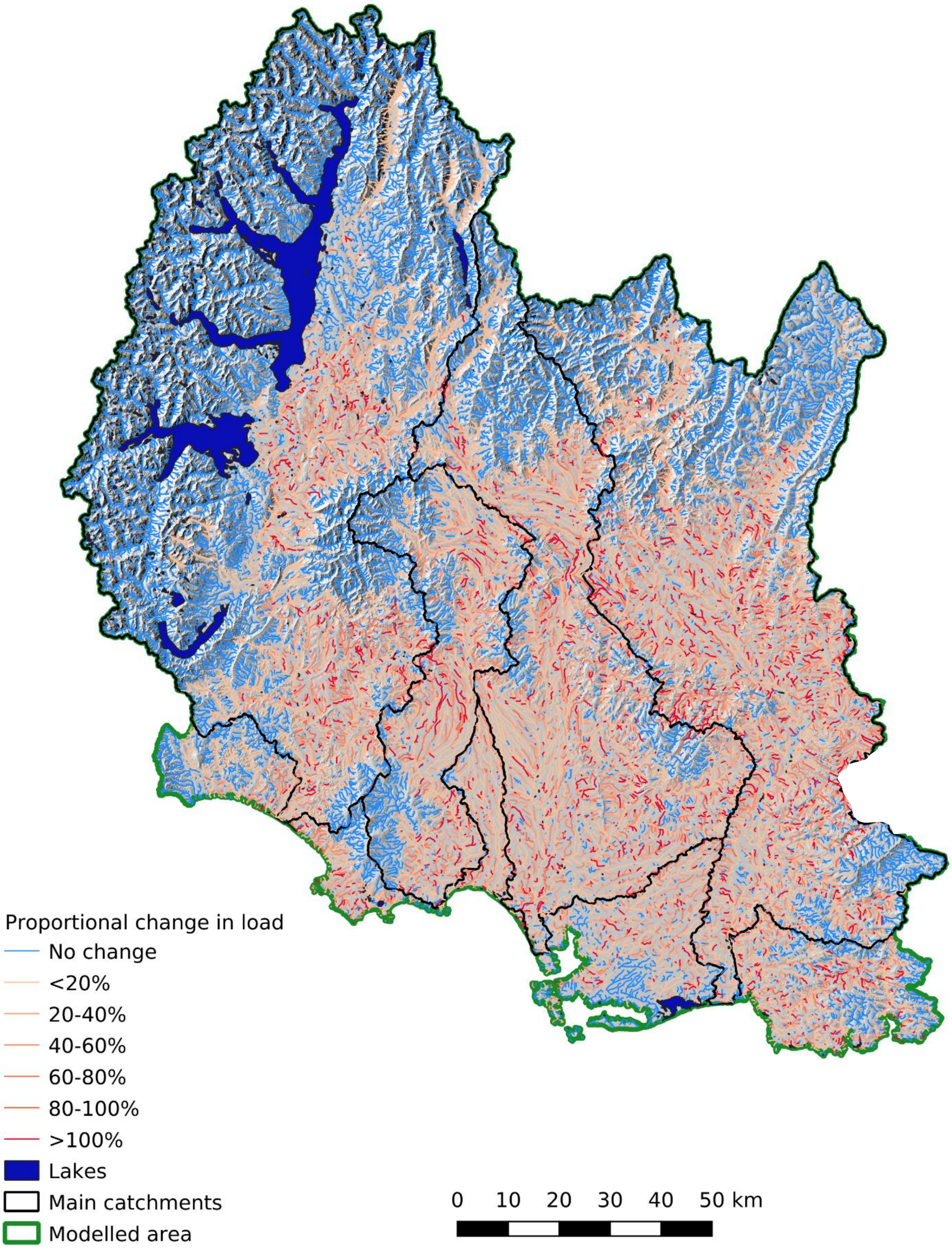


Figure 9. Proportional differences in mean annual suspended sediment loads for Scenario 3 (LCDB$_{WF2017}$ - LCDB$_{WF2014}$) at the REC2 segment scale.

Table 15. Summary of segment scale differences in mean annual suspended sediment load by stream order for Scenario 3

Stream order	No. of segments	No. of segments with a difference in load	Proportion of segments with a difference in load	Mean proportional difference in load
1	22,123	8,558	39%	54%
2	10,345	5,113	49%	26%
3	5,707	3,316	58%	14%
4	3,125	2,137	68%	6%
5	1,662	1,391	84%	4%
6	383	339	89%	3%
7	480	480	100%	1%
8	24	24	100%	0%

Differences in load under Scenario 3 tend to be relatively low at all site classes compared with Scenarios 2 and 3, except in the Rivermouth and Estuary classes, due to the relatively low effect of forage cropping on end-of-catchment loads.

Table 16. Mean proportional differences in loads under each sensitivity scenario by assessment site management class (includes sites with 0% difference). All values presented are percentages

Management class	Scenario 1 mean proportional difference	Scenario 2 mean proportional difference	Scenario 3 mean proportional difference
Hill	3	4	<1
Lake fed	19	27	5
Lowland hard bed	29	31	3
Lowland soft bed	38	67	28
Mountain	<1	<1	<–1
Spring fed	156	54	–16

5.2 Sediment loads under natural landcover

Mean annual suspended sediment loads for the natural landcover scenario are presented for the Waiau, Ōreti, Aparima, and Matāura catchments in Table 17. The total load for the modelled area is 823,000 t yr^{-1}. Loads are also presented for each FMU in Table 18.

Table 17. Natural landcover mean annual suspended sediment loads for the four major catchments estimated using SedNetNZ

Catchment	Natural landcover mean annual suspended sediment load (t yr^{-1})	Baseline mean annual suspended sediment load (t yr^{-1})	Proportional difference in natural landcover loads relative to baseline loads
Matāura	268,000	490,000	-45%
Ōreti	212,000	295,000	-28%
Aparima	35,000	67,000	-48%
Waiau	287,000	451,000	-36%

Table 18. Natural landcover mean annual suspended sediment loads for the modelled FMUs

FMU	Mean annual suspended sediment load (t yr^{-1})
Matāura	277,000
Ōreti	213,000
Aparima	79,000
Waiau	294,000

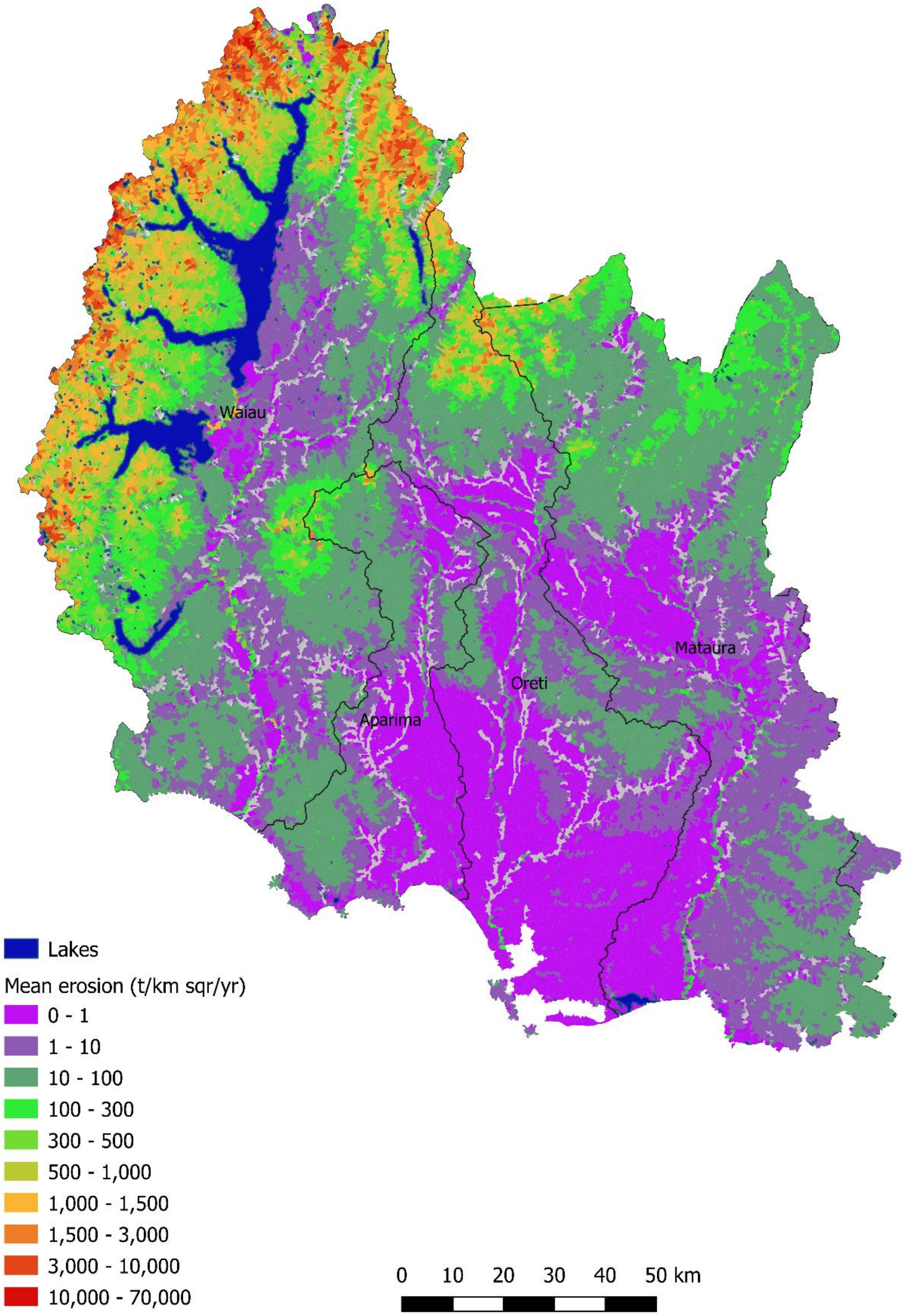


Figure 10. Spatial distribution of erosion averaged across the modelled area (sediment yield, t km2 y–1) by REC2 watershed for the natural cover scenario.

5.3 Achievement of draft Freshwater Objectives

5.3.1 Baseline scenario

The absolute and proportional reductions in mean annual suspended sediment loads required to achieve the draft FWOs are summarised in Tables 19 and 20.

Maximum required load reductions to achieve bottom of envelopes range from 33% to 84% for visual clarity, and 2% to 73% for suspended fine sediment between reporting zones.

The length of REC2 segments achieving the visual clarity and suspended fine sediment FWOs are reported in Tables 21-24. The “Lowland” class results are not included in the total rows as this class is an amalgamation of the “Low land Soft Bed” and “Lowland Hard Bed” segments. Across the region, suspended fine sediment objectives are achieved along more of the REC2 network than visual clarity objectives.

The “Hill” management class has the highest proportion of segments by length achieving at least the bottom of the envelopes for the visual clarity objectives. “Spring fed” has the lowest proportional achievement of the visual clarity objectives, whilst “Lowland Hard Bed” has the lowest proportional achievement of suspended fine sediment objectives. 65% of the length of “Mountain” classed segments exceed the top of the envelopes for visual clarity, with 99% achieving the suspended fine sediment objectives.

The Te Waewae Bay Western Coastal Zone has the highest proportion of segments by length achieving the bottom of decision envelope for visual clarity (88%), and second highest achievement for the bottom of decision and hauora envelopes for suspended fine sediment (90%), after the Caitlins Zone (93%). The Waiau Catchment had the greatest proportion of segments by length achieving the bottom of the visual clarity hauora envelope (48%). The Matāura Catchment has the greatest proportional length of segments achieving above the visual clarity top of the envelopes (19%), whilst the Te Waewae Bay Western Coastal Zone has the greatest proportional length of segments achieving above the suspended fine sediment top of the envelopes (72%).

The areal extent of reporting zones are presented in Appendix 2 for context.

Table 19. Summary of absolute and proportional reductions in load required at each REC2 segment to achieve visual clarity freshwater objectives in each reporting zone. The table reports mean values (including 0 values), with min and max reported in brackets, respectively

	Bottom of Decision Envelope		Bottom of Hauora Envelope		Top of Envelopes	
Reporting Zone	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**
Aparima & Pourakino Catchment	30 (0 - 4,100)	17 (0 - 77)	30 (0 - 4,100)	22 (0 - 77)	1,000 (0 - 39,000)	59 (0 - 82)
Bluff Zone	2 (0 - 50)	52 (0 - 73)	2 (0 - 50)	56 (12 - 73)	3 (0 - 70)	81 (61 - 88)
Catlins Zone	4 (0 - 60)	8 (0 - 33)	20 (0 - 200)	19 (0 - 49)	100 (1 - 600)	62 (8 - 78)
Matāura Catchments	1,200 (0 - 170,000)	16 (0 - 84)	1,300 (0 - 170,000)	22 (0 - 84)	3,900 (0 - 340,000)	45 (0 - 87)
Orepuki Coastal Zone	10 (0 - 400)	29 (0 - 82)	10 (0 - 400)	39 (0 - 82)	60 (0 - 1,000)	72 (38 - 82)
Ōreti & Invercargill Catchments	400 (0 - 142,000)	24 (0 - 78)	400 (0 - 142,000)	32 (0 - 78)	2,600 (0 - 188,000)	62 (0 - 88)
Te Waewae Bay Western Coastal Zone	0 (0 - 10)	2 (0 - 48)	6 (0 - 100)	10 (0 - 51)	100 (0 - 1,500)	57 (0 - 78)
Tokanui Coastal Zone	60 (0 - 1,200)	30 (0 - 56)	80 (0 - 1,600)	45 (0 - 67)	100 (0 - 2,200)	76 (37 - 85)

	Bottom of Decision Envelope		Bottom of Hauora Envelope		Top of Envelopes	
Reporting Zone	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**
Waiau Catchment	2,000 (0 - 177,000)	9 (0 - 81)	2,000 (0 - 177,000)	14 (0 - 81)	2,200 (0 - 177,000)	48 (0 - 81)
Waikawa Catchment	200 (0 - 3,200)	25 (0 - 54)	300 (0 - 4,300)	39 (0 - 58)	500 (0 - 6,100)	73 (29 - 82)
Waimatuku & Taunamau Catchments	6 (0 - 100)	35 (5 - 77)	7 (0 - 100)	46 (27 - 77)	10 (0 - 200)	76 (68 - 82)
Waituna Catchments	7 (0 - 100)	45 (23 - 74)	9 (0 - 200)	55 (41 - 74)	10 (0 - 200)	80 (74 - 89)

Table 20. Summary of absolute and proportional reductions in load required at each REC2 segment to achieve suspended fine sediment freshwater objectives in each reporting zone. The table reports mean values (including 0 values), with min and max reported in brackets, respectively

	Bottom of Decision Envelope		Bottom of Hauora Envelope		Top of Envelopes	
Reporting Zone	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**
Aparima & Pourakino Catchment	100 (0 - 15,000)	16 (0 - 69)	100 (0 - 15,000)	16 (0 - 69)	200 (0 - 26,000)	32 (0 - 79)
Bluff Zone	0 (0 - 10)	15 (0 - 62)	0 (0 - 10)	15 (0 - 62)	1 (0 - 20)	37 (0 - 74)
Catlins Zone	0 (0 - 3)	0 (0 - 2)	0 (0 - 3)	0 (0 - 2)	5 (0 - 70)	10 (0 - 38)
Matāura Catchments	1,500 (0 - 241,000)	6 (0 - 72)	1,500 (0 - 241,000)	6 (0 - 72)	3,100 (0 - 302,000)	18 (0 - 80)
Orepuki Coastal Zone	5 (0 - 100)	25 (0 - 73)	5 (0 - 100)	25 (0 - 73)	10 (0 - 200)	42 (0 - 81)
Ōreti & Invercargill Catchments	500 (0 - 85,000)	14 (0 - 66)	500 (0 - 85,000)	14 (0 - 66)	1,500 (0 - 142,000)	26 (0 - 76)
Te Waewae Bay Western Coastal Zone	0 (0 - 10)	6 (0 - 68)	0 (0 - 10)	6 (0 - 68)	0 (0 - 100)	9 (0 - 78)
Tokanui Coastal Zone	30 (0 - 600)	13 (0 - 68)	30 (0 - 600)	13 (0 - 68)	70 (0 - 1,300)	40 (0 - 78)
Waiau Catchment	100 (0 - 41,000)	10 (0 - 70)	100 (0 - 41,000)	10 (0 - 70)	1,800 (0 - 170,000)	20 (0 - 79)

	Bottom of Decision Envelope		Bottom of Hauora Envelope		Top of Envelopes	
Reporting Zone	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**	**Load Reduction (t/yr)**	**Proportional Reduction (%)**
Waikawa Catchment	80 (0 - 1,400)	6 (0 - 72)	80 (0 - 1,400)	6 (0 - 72)	200 (0 - 3,600)	29 (0 - 80)
Waimatuku & Taunamau Catchments	4 (0 - 70)	24 (0 - 41)	4 (0 - 70)	24 (0 - 41)	7 (0 - 100)	40 (0 - 60)
Waituna Catchments	0 (0 - 20)	16 (0 - 60)	0 (0 - 20)	16 (0 - 60)	2 (0 - 40)	30 (0 - 73)

Table 21. Length of REC2 segments achieving visual clarity FWOs by river class

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
River Management Class	**Achieving objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Hill	4,446,000	694,000	86	4,446,000	694,000	86	1,379,000	3,761,000	27
Lake Fed	62,000	157,000	28	62,000	157,000	28	62,000	157,000	28
Lowland Hard Bed	710,000	3,965,000	15	710,000	3,965,000	15	5,000	4,669,000	<1
Lowland Soft Bed	2,299,000	7,986,000	22	979,000	9,307,000	10	0	10,285,000	0
Lowland	1,688,000	13,271,000	11	1,688,000	13,271,000	11	6,000	14,954,000	0
Mountain	952,000	521,000	65	952,000	521,000	65	952,000	521,000	65
Spring Fed	10,000	561,000	2	10,000	561,000	2	10,000	561,000	2
Total	8,479,000	13,884,000	38	7,159,000	15,205,000	32	2,408,000	19,954,000	11

Table 22. Length of REC2 segments achieving suspended fine sediment FWOs by river class

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
River Management Class	**Achieving objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Hill	3,852,000	1,288,000	75	3,852,000	1,288,000	75	2,565,000	2,575,000	50
Lake Fed	168,000	52,000	76	168,000	52,000	76	83,000	137,000	38
Lowland Hard Bed	1,537,000	3,137,000	33	1,537,000	3,137,000	33	513,000	4,161,000	11
Lowland Soft Bed	5,859,000	4,427,000	57	5,859,000	4,427,000	57	3,886,000	6,399,000	38
Mountain	1,454,000	18,000	99	1,454,000	18,000	99	1,454,000	18,000	99
Spring Fed	197,000	374,000	35	197,000	374,000	35	97,000	474,000	17
Total	13,067,000	9,296,000	58	13,067,000	9,296,000	58	8,598,000	13,764,000	38

Table 23. Length of REC2 segments achieving visual clarity FWOs by reporting catchment

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Aparima & Pourakino Catchment	839,000	1,415,000	37	753,000	1,500,000	33	86,000	2,167,000	4
Bluff Zone	1,000	82,000	1	0	83,000	0	0	83,000	0
Catlins Zone	33,000	20,000	62	11,000	42,000	21	0	53,000	0
Matāura Catchments	3,361,000	5,181,000	39	3,061,000	5,482,000	36	1,604,000	6,938,000	19
Orepuki Coastal Zone	44,000	251,000	15	28,000	266,000	10	0	294,000	0
Ōreti & Invercargill Catchments	1,298,000	4,087,000	24	1,151,000	4,234,000	21	281,000	5,104,000	5
Te Waewae Bay Western Coastal Zone	252,000	35,000	88	88,000	198,000	31	4,000	283,000	1
Tokanui Coastal Zone	16,000	243,000	6	4,000	255,000	2	0	259,000	0

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Waiau Catchment	2,568,000	1,714,000	60	2,046,000	2,236,000	48	434,000	3,848,000	10
Waikawa Catchment	69,000	228,000	23	16,000	281,000	5	0	297,000	0
Waimatuku & Taunamau Catchments	0	359,000	0	0	359,000	0	0	359,000	0
Waituna Catchments	0	250,000	0	0	250,000	0	0	250,000	0
Total	8,481,000	13,865,000	38	7,158,000	15,186,000	32	2,409,000	19,935,000	11

Table 24. Length of REC2 segments achieving suspended fine sediment FWOs by reporting catchment

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Aparima & Pourakino Catchment	872,000	1,381,000	39	872,000	1,381,000	39	524,000	1,729,000	23
Bluff Zone	55,000	28,000	66	55,000	28,000	66	6,000	77,000	7
Catlins Zone	50,000	4,000	93	50,000	4,000	93	29,000	24,000	55
Matāura Catchments	5,692,000	2,851,000	67	5,692,000	2,851,000	67	3,761,000	4,782,000	44
Orepuki Coastal Zone	162,000	132,000	55	162,000	132,000	55	48,000	246,000	16
Ōreti & Invercargill Catchments	2,599,000	2,786,000	48	2,599,000	2,786,000	48	1,811,000	3,574,000	34
Te Waewae Bay Western Coastal Zone	257,000	30,000	90	257,000	30,000	90	206,000	81,000	72
Tokanui Coastal Zone	83,000	176,000	32	83,000	176,000	32	11,000	248,000	4

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Waiau Catchment	2,928,000	1,354,000	68	2,928,000	1,354,000	68	2,030,000	2,252,000	47
Waikawa Catchment	151,000	146,000	51	151,000	146,000	51	56,000	241,000	19
Waimatuku & Taunamau Catchments	70,000	289,000	19	70,000	289,000	19	68,000	291,000	19
Waituna Catchments	143,000	107,000	57	143,000	107,000	57	45,000	205,000	18
Total	13,062,000	9,284,000	58	13,062,000	9,284,000	58	8,595,000	13,750,000	38

5.3.2 Natural landcover scenario

The length of REC2 segments achieving the visual clarity and suspended fine sediment FWOs are reported in Tables 25 and 26 for the natural cover scenario. Across the region, suspended fine sediment objectives are achieved along more of the REC2 network than visual clarity objectives.

The “Hill” management class has the highest proportion of segments by length achieving at least the bottom of the envelopes for the visual clarity objectives (97%). “Spring fed” has the highest achievement of suspended fine sediment objectives (96%). Across the region, 42% of the network exceeds the top of the envelopes for visual clarity, and 78% for suspended fine sediment.

The Waituna Catchments zone has the highest proportion of segments by length achieving the bottom of decision envelope for visual clarity (94%), and for suspended fine sediment (96%). The Waimatuku & Taunamau Catchments zone has the greatest length of segments achieving above the visual clarity top of the envelopes (61%), whilst the Waituna Catchments zone has the greatest length of segments achieving above the suspended fine sediment top of the envelopes (90%).

Table 25. Length of REC2 segments achieving visual clarity FWOs by river class for the natural landcover scenario

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
River Management Class	Achieving Objective (m)	Not achieving objective (m)	Proportion achieving objective (%)	Achieving Objective (m)	Not achieving objective (m)	Proportion achieving objective (%)	Achieving Objective (m)	Not achieving objective (m)	Proportion achieving objective (%)
Hill	5,005,000	135,000	97	5,005,000	135,000	97	3,003,000	2,137,000	58
Lake Fed	172,000	48,000	78	172,000	48,000	78	172,000	48,000	78
Lowland Hard Bed	3,902,000	772,000	83	3,902,000	772,000	83	1,718,000	2,956,000	37
Lowland Soft Bed	9,016,000	1,269,000	88	7,682,000	2,604,000	75	3,206,000	7,080,000	31
Lowland	11,584,000	3,376,000	77	11,584,000	3,376,000	77	4,923,000	10,036,000	33
Mountain	934,000	538,000	63	934,000	538,000	63	934,000	538,000	63
Spring Fed	369,000	202,000	65	369,000	202,000	65	369,000	202,000	65
Total	19,398,000	2,964,000	87	18,064,000	4,299,000	81	9,402,000	12,961,000	42

Table 26. Length of REC2 segments achieving suspended fine sediment FWOs by river class for the natural landcover scenario

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
River Management Class	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Hill	4,679,000	461,000	91	4,679,000	461,000	91	3,929,000	1,211,000	76
Lake Fed	209,000	11,000	95	209,000	11,000	95	184,000	36,000	84
Lowland Hard Bed	3,967,000	707,000	85	3,967,000	707,000	85	3,459,000	1,215,000	74
Lowland Soft Bed	9,215,000	1,070,000	90	9,215,000	1,070,000	90	8,310,000	1,976,000	81
Mountain	1,062,000	411,000	72	1,062,000	411,000	72	1,062,000	411,000	72
Spring Fed	551,000	20,000	96	551,000	20,000	96	529,000	42,000	93
Total	19,683,000	2,680,000	85	19,683,000	2,680,000	88	17,473,000	4,891,000	78

Table 27. Length of REC2 segments achieving visual clarity FWOs by reporting catchment for the natural landcover scenario

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Aparima & Pourakino Catchment	1,873,000	381,000	83	1,826,000	428,000	81	808,000	1,446,000	36
Bluff Zone	56,000	27,000	67	55,000	28,000	66	35,000	48,000	42
Catlins Zone	42,000	11,000	79	21,000	32,000	40	1,000	52,000	2
Matāura Catchments	7,401,000	1,142,000	87	6,988,000	1,554,000	82	4,040,000	4,503,000	47
Orepuki Coastal Zone	214,000	80,000	73	173,000	121,000	59	38,000	256,000	13
Ōreti & Invercargill Catchments	4,799,000	586,000	89	4,589,000	796,000	85	2,211,000	3,173,000	41
Te Waewae Bay Western Coastal Zone	222,000	65,000	77	103,000	184,000	36	7,000	280,000	2

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Tokanui Coastal Zone	190,000	69,000	73	112,000	147,000	43	31,000	228,000	12
Waiau Catchment	3,840,000	442,000	90	3,536,000	746,000	83	1,840,000	2,441,000	43
Waikawa Catchment	178,000	119,000	60	102,000	195,000	34	18,000	279,000	6
Waimatuku & Taunamau Catchments	333,000	26,000	93	321,000	38,000	89	218,000	141,000	61
Waituna Catchments	237,000	14,000	94	223,000	27,000	89	148,000	103,000	59
Total	19,385,000	2,962,000	87	18,049,000	4,296,000	81	9,395,000	12,950,000	42

Table 28. Length of REC2 segments achieving suspended fine sediment FWOs by reporting catchment for the natural landcover scenario

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Aparima & Pourakino Catchment	1,767,000	487,000	78	1,767,000	487,000	78	1,457,000	796,000	65
Bluff Zone	67,000	16,000	81	67,000	16,000	81	60,000	23,000	72
Catlins Zone	44,000	9,000	83	44,000	9,000	83	39,000	14,000	74
Matāura Catchments	7,663,000	879,000	90	7,663,000	879,000	90	6,956,000	1,587,000	81
Orepuki Coastal Zone	211,000	83,000	72	211,000	83,000	72	157,000	137,000	53
Ōreti & Invercargill Catchments	4,936,000	449,000	92	4,936,000	449,000	92	4,409,000	976,000	82
Te Waewae Bay Western Coastal Zone	208,000	78,000	73	208,000	78,000	73	179,000	107,000	63

	Bottom of Decision Envelope			Bottom of Hauora Envelope			Top of Envelopes		
Reporting Zone	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**	**Achieving Objective (m)**	**Not achieving objective (m)**	**Proportion achieving objective (%)**
Tokanui Coastal Zone	216,000	43,000	83	216,000	43,000	83	151,000	108,000	58
Waiau Catchment	3,743,000	538,000	87	3,743,000	538,000	87	3,353,000	929,000	78
Waikawa Catchment	239,000	58,000	80	239,000	58,000	80	160,000	137,000	54
Waimatuku & Taunamau Catchments	334,000	25,000	93	334,000	25,000	93	313,000	46,000	87
Waituna Catchments	239,000	11,000	96	239,000	11,000	96	225,000	26,000	90
Total	19,667,000	2,676,000	88	19,667,000	2,676,000	88	17,459,000	4,886,000	78

6 Discussion

6.1 Model evaluation

Longer-term suspended sediment load data spanning several decades are unavailable for the modelled catchments, or for sites within the catchments. Therefore, we are unable to directly assess performance of the model for the Southland region. Instead, we compare the SedNetNZ mean annual suspended sediment loads with previous estimates by Hicks et al. (2011, 2019) using an empirical model based on precipitation and terrain classification (Hicks et al. 2011, 2019), and vegetation cover (Hicks et al. 2019).

The SedNetNZ baseline loads for the four major catchments fall within the range of previous estimates for the Aparima, Matāura, and Waiau catchments, with the Ōreti being 13% higher than the Hicks et al. (2011) estimate, and 63% higher than the Hicks et al. (2019) estimate. The total load estimated from the modelled area of 1.34 Mt/y falls within the range of previous estimates for loads delivered to the South coast of 2.1 and 0.98 Mt/y (Hicks et al. 2011, 2019). The general convergence in suspended sediment load predictions with the empirical results of Hicks et al. (2011, 2019) provides some support to the results presented here, particularly given SedNetNZ was not locally calibrated to the region.

6.2 Model Limitations

There are a range of limitations in SedNetNZ modelling of baseline loads, and in the calculation of the load reductions required to meet the draft Freshwater Objectives. We outline these limitations in terms of each modelling component below. Model outputs should be interpreted in the context of these limitations.

6.2.1 Surficial Erosion

The key limitations in the surficial erosion component of SedNetNZ relate to the calculation of the C and K factors in the NZUSLE, and the availability of suitable input data.

We have made significant improvements to the calculation of the K factor within the Southland region by utilising S-map and FSL data to calculate a spatially variable K factor instead of the uniform K factor previously used in the NZUSLE. While this enables us to better represent the spatial variation in sediment supply as it relates to soil types, some assumptions needed to be made to utilise the available datasets, particularly in the case of the FSL. Both datasets lack suitable data to calculate the soil structure class. We have therefore used a uniform class of 2, which essentially cancels the soil structure parameter from Equation 6, meaning soil structure is not represented.

While organic matter data are available from S-map and the FSL, Equation 6 was developed from nomographs with $OM \leq 4\%$ (Wischmeier et al. 1971). We have therefore implemented Equation 6 with a limit of 4% on OM. For organic soils, we set K=0, as the nomographs in Wischmeier et al. (1971) are not suited to organic soils. Similarly, silt is limited to ≤ 70% in Wischmeier et al. (1971). In future the NZUSLE may seek to develop methods to calculate *K* for those New Zealand soils with parameters that extend beyond the nomographs in Wischmeier et al. (1971), such as the approaches taken by Auerswald et al. (2014).

Particle size is represented in the FSL as size classes that span a range for silt and clay. To provide a more explicit estimate of particle size, each size class was mapped to similar soil type classes in S-map, and the average particle sizes for those S-map classes were assigned to the respective FSL class. The main limitation of this approach is that S-map data are available for the lowlands, but do not extend to the full range of terrains covered by the FSL. As the FSL data were used where S-map is not available, the S-map data may be less applicable in these areas. However, the S-map data do directly correspond with the topsoil, as opposed to the soil profile as described in the FSL, so better relate to the process of surface erosion.

We have attempted to incorporate the effect of the seasonal variability in landcover caused by winter forage cropping by introducing a fourth *C* factor class to those used by Dymond (2010) and Dymond et al. (2016) to account for the temporal variability in landcover where winter forage cropping occurs. This *C* factor requires an estimate to be made for the period that the forage crop area has little or no cover. This “bare ground” period is likely to vary between paddocks and from year to year, depending on whether the paddock is grazed early or late in the season. As suitable data on the period that winter forage crop paddocks are bare are not available for Southland, we have assumed 3 months to be a reasonable estimate. During this period, a *C* factor of 1 is applied, which is maximum limit for the *C* factor, representing base ground. This estimate could be improved in future if regional data were collected for a season on the period of low cover/bare ground in winter grazed paddocks.

The spatial distribution of winter forage cropping is temporally variable and challenging to capture in a multi-decadal model. We have included the spatial distribution of forage cropping from one year into our baseline landcover. While it has been demonstrated that this does not significantly affect end-of-catchment loads, it may have implications in low order sub-catchments. If further regional mapping of winter forage cropping is conducted, a spatial averaging of the location of forage cropping may be possible, allowing a spatio-temporal weighting of the forage cropping *C* factor that may better capture the multi-decadal mean annual load.

6.2.2 Bank Erosion

There are several limitations related to the revised bank erosion component that require consideration when analysing results at the sub-catchment scale. In the absence of local data on riverbank migration rates, it was necessary to calibrate the bank migration model using available measurements from the Manawatu and Kaipara catchments in the North Island. We recognise this potentially introduces additional and unquantified error into model predictions for Southland catchments. However, the dataset from Manawatu and Kaipara does span a large range in observed bank migration rates, riparian woody vegetation extents, soil textures, channel slope, and sinuosity variables for the mapped reaches (Spiekermann et al. 2017; Smith et al. 2019a). One important point of difference is the absence of braided channel reaches from this calibration dataset. This indicates the need to develop a calibration dataset for this channel form.

Representation of riparian woody vegetation has been derived from EcoSat Woody (Dymond & Shepard, 2004) as LCDB is less suitable for representing narrow strips of riparian corridor. Predictions of bank migration rates are therefore based on woody vegetation presence/absence in 2002, which may differ from contemporary woody vegetation. A further challenge results from the spatial correspondence of mapped channel location and woody vegetation resulting from the alignment of REC2 to the channel, and changes in channel planform since mapping occurred. Availability of catchment-wide LiDAR data would enable improved spatial representation of riparian woody vegetation and coherence with channel locations.

We were unable to include representation of channel works designed to reduce bank erosion, other than stopbanks. While such works have been undertaken, digital spatial information was not available for inclusion in model representation of bank erosion. It is therefore likely that our predictions of bank erosion rates and net bank-derived suspended sediment loads are over-estimated for some reaches where erosion mitigation works have been applied.

6.2.3 Pre-existing mitigations

It is important to include the effect of pre-existing mitigations in the baseline scenario, not only to estimate baseline loads more accurately, but also to understand better where further mitigations can or cannot be incorporated to achieve required reductions. The only data available to represent existing mitigations in Southland were a spatial dataset on the location of fences, and estimates of associated buffer widths. There were several challenges implementing these data into the model. First, it was difficult to derive from the metadata whether a section of fence was providing stock exclusion from nearby streams. We attempted to account for this by including any fence segment within a 30-m buffer of the REC2 segments, and assuming these are in place to exclude stock. This approach is complicated by the potential misalignment of the REC2 network and the true channel location, which is particularly challenging in low order streams. This may lead to incorrect fencing lengths at any given REC2 segment. However, this approach is spatially explicit, and is a better spatial representation of existing stock exclusion than the regionally uniform estimate used by Neverman et al. (2019), and therefore better represents the spatial variation in the effect of pre-existing mitigations, particularly at larger scales. Future modelling could be improved with remote sensing approaches to detecting fences within the riparian corridor. Inclusion of an attribute field in fencing databases to demarcate fences providing stock exclusion would also help with future implementation of fencing data in mitigation models.

Buffer width is the key variable driving the mitigation of surficial erosion by stock exclusion in Equation 22. Spatial data on the width of buffers were not available. We therefore estimated the width of buffer for each stream order using average widths for most stream orders provided by ES. Buffer slope has also been shown to be a driver of buffer effectiveness for mitigation of surficial erosion (Zhang et al. 2010) but buffer slope data are not available at sufficient resolution to incorporate in this model. These are avenues for future improvement in the model and could be improved with remote sensing using high resolution input data, particularly in the case of slope being derived from regional scale LiDAR. However, the inputs used do provide some spatial representation of the effect of riparian buffers for the interception of surficial erosion, and are an improvement over the use of homogenous buffer widths in Neverman et al. (2019).

The composition of the buffer is also an important variable for interception of sediment in overland flow, and the stabilisation of banks. Spatial heterogeneity in buffer composition has not been represented in this model. This model has assumed that where fencing occurs and stock are excluded, a vegetated buffer will develop comprising vegetation that intercepts surficial erosion and has a stabilising effect on banks. This effect is not explicitly captured in the surficial erosion mitigation component, but is conceptually represented in the bank erosion reduction factor of Dymond et al. (2016), which considers a reduction effect less than full woody vegetation cover due to a mixture of vegetation covers and maturity of the buffer. This may be improved in future by having different reduction factors for different buffer compositions, but suitable relationships between erosion reduction effectiveness and buffer composition are not presently available in the literature, and empirical research to address this gap is challenging.

Whilst tile or artificial drains are widely used throughout the region, these have not been explicitly represented in the model, and therefore cannot be identified as sediment sources, although a number of surface drains are included within the REC2 stream network. Further development of SedNetNZ could seek to represent drains, but would require spatial information on their location, and would require data to parameterise their erosion contribution.

6.2.4 Calculating required load reductions

Mean annual suspended sediment load reductions to achieve visual clarity and suspended fine sediment objectives were estimated using equations developed by Hicks et al. (2019) from simplifications in the relationships reported by Dymond et al. (2017). The key assumption for calculating required load reductions to meet objectives is the relationship between sediment load and flow remain constant at a site. In reality, this relationship may change due to changes in catchment hydrology leading to changes in the relationship between a given flow and suspended sediment concentration (Hicks et al. 2019). As data is not presently available to predict these changes, we assume that the associated relationships remain constant. This assumption is particularly important when modelling changes in visual clarity between the baseline and natural landcover scenarios. Because this scenario significantly changes the landcover, and this would result in changes in hydrology, it is likely the relationship between visual clarity and sediment load would differ at a given site compared to that in the contemporary landcover scenario.

We have estimated the required load reductions using empirical models fitted to a national dataset. This should result in the models being fitted to a wide range of catchment variables and therefore representing the variability across Southland, and sites from Southland were used in the national dataset (see Hicks et al. 2019), but may lead to under or over estimation of required reductions at any one location. Future improvements could be made by locally calibrating the models, but at present suitable datasets are not available for local model fitting.

6.3 Stage 2 Phase 3 modelling options

During the development phase of this work we were asked by ES to provide an outline of possible mitigation scenarios we could model with SedNetNZ to assess the feasibility of the draft Freshwater Objectives as part of future work for the Southland Regional Forum workstream. National scale mitigation scenario modelling to assess the feasibility of national freshwater objectives by Neverman et al. (2019) focused on three main scenarios: space-planting of trees on highly erodible pasture, afforestation (retirement) of highly erodible pasture, or riparian exclusion on streams >1 m wide.

Space-planting and afforestation scenarios are aimed at mitigating erosion from shallow landsliding (soil slips). Shallow landsliding in pasture is considered to be a minor contributor to sediment loads in the Southland region due to the relatively stable pasture slopes in the region compared to other regions with more highly erodible, soft rock hill country, and therefore have not been explicitly captured as an erosion source. Mitigation scenarios for Southland are therefore likely to focus on riparian stock exclusion, which reduces both surficial erosion and bank erosion, the two key contributors to sediment loads in Southland, and afforestation or reversion in steeper headwater catchments. The latter is likely going to be necessary given the significant proportion of load coming from hill country.

We could run a range of scenarios to apply different spatial configurations of stock exclusion, which assumes an accompanying buffer, with variable or set buffer widths based on-land or stream classifications. This could be driven by assigning stock exclusion to certain land use classes, and/or different stream orders, or stream classes such as Dairy Accord streams, as in Neverman et al. (2019). Taking the Land and Water Plan as an example, we could assign stock exclusion to REC2 segments intersecting all dairy and sheep and beef polygons from the Southland land use layer on major streams (>1 m, see Neverman et al. 2019), and run scenarios with different buffer widths. We could run scenarios with fixed or variable buffer widths, applying stock exclusion to landuse classes on certain average slopes. These scenarios would likely assume the full REC2 segment intersecting the land use is fenced.

Given the relatively high contribution of hill country and sheep and beef in the Ōreti, Aparima, and Matāura FMUs, we could also apply afforestation/scrub reversion to certain land classes, using classifications derived from slope, land use, and/or landcover. For example, Neverman et al. (2019) applied afforestation to pasture in steep slope classes. This could be done using national datasets such as the Land Resource Inventory (LRI), LCDB, or HEL (Highly Erodible Land, Dymond & Shepherd 2004), or regional datasets where available and appropriate.

Given the dominant contribution of sediment from headwater catchments in Southland, scenarios focusing on applying mitigations primarily to low order headwater streams in pastured catchments may also want to be considered, as Neverman et al. (2019) demonstrate the benefit applying mitigations in headwater stream segments may have, as the reductions are routed and affect a greater number of downstream segments than applying equivalent mitigations in higher order stream segments.

7 Conclusions

This report uses the SedNetNZ model to estimate baseline mean annual suspended sediment loads and reductions in load required to meet draft Freshwater Objectives for Stage 1 of the Southland Regional Forum workstream. A natural landcover scenario was also modelled against which achievement of FWOs was assessed. Revisions were made to SedNetNZ to better account for the spatial and temporal variability of erosion and sediment transport in Southland by incorporating the impact of winter forage cropping, a key land management variable in the region, the trapping effect of lakes on mean annual sediment loads, and the spatial variability of soil erodibility.

Under the baseline scenario, mean annual suspended sediment loads are estimated at 509,000 t yr^{-1} for the Matāura FMU, 296,000 t yr^{-1} for the Ōreti FMU, 72,000 t yr^{-1} for the Aparima FMU, and 465,000 t yr^{-1} for the Waiau FMU. For the major catchments in each FMU, mean annual suspended sediment loads are estimated to be 490,000 t y^{-1} for the Matāura catchment, 295,000 t y^{-1} for the Ōreti catchment, 67,000 t y^{-1} for the Aparima catchment, and 457,000 t yr^{-1} for the Waiau catchment. The total modelled load across the region is 1.343 Mt yr^{-1}. This reduced to 0.823 Mt yr^{-1} (a 39% reduction) in the natural landcover scenario. The greatest proportional reductions in the natural landcover scenario are seen in the Aparima and Waiau catchments.

Mean annual suspended sediment loads were found to be relatively insensitive to the variations in mapped winter forage crop distributions, with <1% difference in end-of-catchment loads between the 2014 and 2017 mapped distributions, and <5% increase from loads estimated with no inclusion of winter forage, in the majority of major catchments and FMUs. Variations become more pronounced at the segment scale, particularly in low order lowland streams, where absolute loads are relatively small, so forage cropping has a large impact proportionally, but the cumulative effect of these changes is minor at the catchment outlet.

Surficial erosion is the dominant source of sediment in the modelled area, with Indigenous Forest and Conservation being the dominant contributor of sediment in the Waiau, Ōreti, and Aparima. Sheep and Beef is the largest contributor in the Matāura. Bank erosion becomes the dominant source of local erosion in higher order stream segments.

Maximum required load reductions to achieve bottom of envelopes range from 33% to 84% for visual clarity, and 2% to 73% for suspended fine sediment between reporting zones. Across the region, suspended fine sediment objectives are achieved along more of the REC2 network than visual clarity objectives.

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Appendix 1 – Uncertainties

The uncertainty in the calculation of PR_v in Equation 23 has been calculated at each REC2 segment and is supplied in the dataset accompanying this report. The range in uncertainties are summarised in Tables 29-32. These tables report the minimum, median, and maximum uncertainties estimated at REC2 segments across the river management classes and reporting zones. The uncertainty in PRv has also been reported as an absolute load by multiplying the load at each REC2 segment by the proportional uncertainty. These values are also presented in the Tables 29-32.

Table 29. Summary of uncertainties for proportional (reported as percentage points) and absolute load reductions required across REC2 segments to achieve objectives for visual clarity by river management class

	Minimum		Median		Maximum	
River Management Class	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**
Hill	<1	<1	3	1	6	22,000
Lake Fed	<1	<1	4	6,400	7	27,000
Lowland Hard Bed	<1	<1	6	<1	7	24,000
Lowland Soft Bed	<1	<1	5	<1	7	8,100
Lowland	<1	<1	6	<1	7	24,000
Mountain	<1	<1	4	3	6	3,600
Spring Fed	<1	<1	6	<1	7	24,000

Table 30 Summary of uncertainties for proportional (reported as percentage points) and absolute load reductions required across REC2 segments to achieve objectives for suspended fine sediment by river management class

	Minimum		Median		Maximum	
River Management Class	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**
Hill	0	0	4	2	7	30,000
Lake Fed	0	0	5	2	7	8,000
Lowland Hard Bed	0	0	4	0	7	30,000
Lowland Soft Bed	0	0	5	0	7	11,000
Mountain	0	0	1	2	5	1,000
Spring Fed	0	0	4	0	7	13,000

Table 31. Summary of uncertainties for proportional (reported as percentage points) and absolute load reductions required across REC2 segments to achieve objectives for visual clarity by reporting zone

	Minimum		Median		Maximum	
Reporing Zone	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**
Aparima & Pourakino Catchment	<1	<1	5	<1	7	800
Bluff Zone	<1	<1	7	<1	7	5
Catlins Zone	<1	<1	5	<1	5	10
Matāura Catchments	<1	<1	5	<1	7	24,000
Orepuki Coastal Zone	<1	<1	5	<1	7	40
Ōreti & Invercargill Catchments	<1	<1	5	<1	7	18,000
Te Waewae Bay Western Coastal Zone	<1	<1	3	<1	7	2
Tokanui Coastal Zone	<1	<1	5	<1	7	200
Waiau Catchment	<1	<1	4	<1	7	27,000
Waikawa Catchment	<1	<1	6	1	7	500
Waimatuku & Taunamau Catchments	<1	<1	5	<1	7	20
Waituna Catchments	4	<1	6	<1	7	20

Table 32. Summary of uncertainties for proportional (reported as percentage points) and absolute load reductions required across REC2 segments to achieve objectives for suspended fine sediment by reporting zone

	Minimum		Median		Maximum	
Reporing Zone	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**	**Percentage points**	**Load (t/yr)**
Aparima & Pourakino Catchment	<1	<1	5	<1	7	2,500
Bluff Zone	<1	<1	6	<1	7	2
Catlins Zone	<1	<1	<1	<1	<1	<1
Matāura Catchments	<1	<1	3	<1	7	30,000
Orepuki Coastal Zone	<1	<1	7	<1	7	10
Ōreti & Invercargill Catchments	<1	<1	5	<1	7	14,000
Te Waewae Bay Western Coastal Zone	<1	<1	6	<1	7	1
Tokanui Coastal Zone	<1	<1	2	<1	7	100
Waiau Catchment	<1	<1	5	<1	7	8,000
Waikawa Catchment	<1	<1	2	<1	7	200
Waimatuku & Taunamau Catchments	2	<1	5	<1	6	10
Waituna Catchments	1	<1	6	<1	7	4

Appendix 2 – Reporting Zone Areas

Reporting Zone	**Zone area (km^2)**
Aparima & Pourakino Catchment	1,568
Bluff Zone	82
Catlins Zone	40
Fiordland	1,415
Fiordland Southern Catchments	1,376
Mataura Catchments	5,844
Orepuki Coastal Zone	241
Oreti & Invercargill Catchments	3,793
Te Waewae Bay Western Coastal Zone	306
Tokanui Coastal Zone	219
Waiau Catchment	8,304
Waikawa Catchment	238
Waimatuku & Taunamau Catchments	253
Waituna Catchments	213