Manaaki Whenua
Landcare Research

Application of a revised SedNetNZ model to the Oreti and Aparima catchments, Southland

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Application of a revised SedNetNZ model to the Oreti and Aparima catchments, Southland

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Summary

Project and Client

- Manaaki Whenua – Landcare Research committed to revising and applying the SedNetNZ model to a case study catchment in Southland as part of the Our Land and Water (OLW) National Science Challenge 'Sources and Flows' programme
- Following discussion with OLW and Environment Southland it was agreed that a revised version of the SedNetNZ model would be applied to both the Oreti and Aparima river catchments.

Objectives

- Revise the surface and channel bank erosion components of SedNetNZ in recognition of the likely importance of these erosion processes to catchment fine sediment budgets in Southland.
- Apply the revised version of the SedNetNZ model to the Oreti and Aparima catchments.
- Compare the results with the current version of SedNetNZ to assess the effect of changes to model components.

Methods

- The original surficial and bank erosion components of SedNetNZ (referred to as the CLASSIC model configuration) were compared with the following model configurations based on 1) improved spatial representation of surface runoff contributing areas combined with a revised bank erosion component (REVISED configuration), and 2) the revised contributing areas and bank erosion components combined with replacement of the single, uniform sediment delivery ratio (SDR) previously applied in SedNetNZ with a topographically based, spatially varying SDR between the land surface and channel network (REVISED-HSDR configuration).
- The revised bank erosion model component used in the REVISED and REVISED-HSDR SedNetNZ model configurations was implemented based on the stream power of the mean annual flood for each REC2 reach and includes spatial representation of the effects of riparian woody vegetation, channel sinuosity, bank erodibility, valley confinement, and erosion control works on bank migration rates.
- The original and revised SedNetNZ model configurations were applied to the Oreti and Aparima catchments using available spatial data for topography, land cover, precipitation, and soils.
- Model outputs are reported at the REC2 reach-scale.

Results

- Predicted suspended sediment loads amounted to 253 and 67 kt y^{-1}, respectively, for the Oreti and Aparima catchments draining to the coast, using the REVISED model configuration.
- Predicted suspended sediment contributions from surface and bank erosion were significantly lower using the other model configurations compared to the CLASSIC configuration.
- The REVISED model configuration produced proportional surface and bank erosion contributions to the mean annual catchment suspended sediment load of 74% and 26%, respectively, for the Oreti catchment. Relative surface and bank erosion contributions were estimated at 56% and 44%, respectively, for the Aparima.
- The performance of the SedNetNZ model configurations could not be evaluated directly in the absence of longer-term suspended sediment load data for the catchments.

Conclusions and recommendations

- Predictions using the REVISED model configuration were closest to previous estimates of suspended sediment load from Hicks et al. (2011) based on the sum of absolute relative differences (28%) between the REVISED configuration and the Hicks et al. (2011) estimated sediment loads for the Oreti and Aparima catchments. The CLASSIC configuration produced the largest absolute relative difference summed across both catchments (96%). However, this comparison must be treated with caution, given that the Hicks et al. (2011) values were also estimates based on an empirical model.
- Continuing development of the SedNetNZ model aims to produce improvements in predictive performance. The absence of longer-term suspended sediment load data is a limitation for evaluation of model performance in this study.
- Additional work is required to more fully evaluate model performance with collection of new data on erosion processes, sediment sources, and catchment suspended sediment loads along with improvements to model representation of erosion and sediment delivery processes. This includes addressing model parameterisation related to the impact of land cover (including riparian cover) on erosion rates, soil erodibility (for both surficial and bank erosion), bank height and further work on the SDR.

1 Introduction

Rivers have experienced a decline in water quality associated with intensification of agricultural land use practices in the Southland region (Hamill & McBride 2003; McDowell et al. 2009). This trend in water quality has been linked to increased dairying in Southland, which corresponds with reduced dissolved oxygen and increased levels of dissolved reactive phosphorus (Hamill & McBride 2003). Dairying is also linked to elevated nitrate losses, which exceed those from sheep or deer grazed pastures (Monaghan et al. 2010). Simulations of water quality in the Oreti catchment suggest that significant reductions in nitrogen and phosphorus could be achieved with specific management interventions such as use of herd shelters and stock exclusion from selected LUC units (Monaghan et al. 2010).

In contrast to nitrogen and phosphorus, there has been comparatively little investigation of suspended sediment and the link between catchment erosion sources and downstream sediment loads in Southland. Previous paddock-scale work in South Otago has shown that winter grazing of dairy cattle and deer on croplands exacerbate loss of sediment from land to streams (McDowell 2006; McDowell et al. 2005; McDowell & Stevens 2008). Moreover, field measurements of pastoral land grazed by dairy cows in Southland indicate that most sediment and phosphorus is transferred with surface runoff, in contrast to losses of nitrogen that occur largely via subsurface mole-pipe drains (Monaghan et al. 2016). At the catchment scale, suspended sediment yields have been estimated across New Zealand using annual precipitation and erosion terrain classification as factors in an empirical model (Hicks et al. 2011). This analysis indicates that rivers draining to the south coast of the South Island deliver approximately 2.1 Mt y^{-1} of suspended sediment, which is low compared with other regions (Hicks et al. 2011).

To better link patterns and processes of soil erosion to catchment suspended sediment output, we require a model based approach. This recognises the considerable challenge and cost of measuring erosion and suspended sediment delivery processes across large areas. The SedNetNZ model has been developed to address this challenge. This conceptual, steady-state sediment budget model is 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). While the SedNetNZ model has been applied to several regions in the North Island (Palmer et al. 2015; Mueller & Dymond 2015; Dymond et al. 2016), it has not previously been applied to catchments in Southland. This is significant because the Southland landscape differs from the landscape in which SedNetNZ was initially developed, which included extensive areas of highly erodible, soft rock hill country in the North Island.

Large river catchments in Southland such as the Oreti are characterised by extensive areas of flat to rolling terrain subject to intense dairy or sheep/beef grazing and associated cropping with winter grazing. Moreover, hill country areas tend to be formed of less erodible rocks compared to the North Island, and little evidence of shallow landsliding was observed in these parts of the Oreti catchment during field reconnaissance in 2018. Localised areas affected by gullying occur in the steep mountainous headwaters of the Oreti but in many cases these gullies are not connected to the drainage network. Instead, field reconnaissance suggested that surface and channel bank erosion are likely to be dominant sediment sources in the catchment.

In this report, we present an application of the SedNetNZ model to two catchments in the Southland region as part of the Our Land and Water (OLW) National Science Challenge 'Sources and Flows' programme. The total area of the Oreti and Aparima river catchments draining to the coast are 3,527 and 1,570 km^2, respectively. We report model outputs for these total catchments areas to enable comparison with previous studies. We also report outputs for the smaller catchment areas (Oreti: 2,149 km^2; Aparima 1,243 km^2) targeted by the Sources and Flows programme for modelling across four contaminants (sediment, N, P and *E. Coli*).

Both the Oreti and Aparima catchments are characterised by predominantly intensive agricultural land use on flat to rolling slopes, while headwaters are dominated by steep mountainous terrain. Given the apparent dominance of surface and channel bank erosion as sediment sources in the region, we focus on developing a revised approach to the representation of these erosion processes in the SedNetNZ model. In the absence of long-term suspended sediment load data, we cannot presently directly calibrate or fully evaluate performance of the revised model for either catchment. Instead, the revised modelling approach aims to provide a conceptual development on the representation of these erosion processes by better utilising nationally available spatial datasets. In this way, the revised approach is also relevant to applications of SedNetNZ in other regions across New Zealand.

2 Methods

The methods section comprises 1) a description of the revised surficial erosion and channel bank erosion model components, and 2) an outline of the application of the revised model to the Oreti and Aparima catchments. We do not include representation of shallow landslide and gully erosion in the revised model based on the observations from field reconnaissance indicating little evidence of shallow landslides and only localised areas of gullying that are in many cases disconnected from the channel network. Moreover, evidence from sediment tracing suggests that surface erosion made the largest contribution to sediment delivered to the New River Estuary from the Oreti and Waihopai Rivers in recent decades (Brown 2018).

2.1 Revised SedNetNZ model description

2.1.1 Surficial erosion

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

$$ES = a\,P^2 KLSC \qquad (1)$$

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 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 report, we use a revised representation of surficial erosion processes as part of the SedNetNZ model. This includes replacing the uniform slope length (L) factor 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):

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

where:

- L : slope length factor for a given raster cell (pixel)
- A : upstream catchment area (m^2) at the cell inlet
- D : raster cell width (m)
- m : slope length exponent
- x : sin a + cos a
- α: 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 and alluvium):

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

$$m = \frac{\beta}{1+\beta} \quad (4)$$

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

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

2.1.2 Hillslope sediment delivery ratio

To represent spatially-varying delivery of detached sediment to streams, we apply the connectivity index (IC, Eq. 6) introduced by Borselli et al. (2008). This replaces the single, spatially uniform sediment delivery ratio used in previous SedNetNZ applications (Dymond et al. 2016). The GIS-based approach expresses the effect of topography and land cover on the potential of sediment being delivered to a sink (i.e. a river or lake). It considers each point (i.e. raster cell) in the catchment lying on a flow path from a source to a sink and describes its upstream and downstream characteristics. Thereby, the area upstream of a point is characterised according to its potential to deliver sediment to this point, represented as function of contributing area (A), average slope of the upslope contributing area (S), and land cover (W) (Eq. 6, numerator). The downstream component is characterised according to its potential to transport sediment from the given point to a sink and is expressed as a function of the distance (d) to the sink, the slope (S), and the land cover (W) of each individual point on the downstream flow path (Eq. 6, denominator) (Borselli et al. 2008):

$$IC_k = log_{10}\left(\frac{\overline{W}_k\overline{S}_k\sqrt{A_k}}{\sum_{i=k,n_k}\frac{d_i}{W_iS_i}}\right) \quad (6)$$

with:

IC: Index of connectivity (-)

$\overline{W}$: average weighting factor (-) for the upstream contributing area, expressing the impact of land cover on sediment transport

$\overline{S}$: average slope gradient (m/m) of upstream contributing area

A: upstream contributing area (m^2)

W: land cover weighting factor (-) for a point on the downstream flow path

S: slope gradient (m/m) of a point on the downstream flow path

d: distance from a point on the downstream flow path to the sink (m)

k, i: index of an individual point (i.e. raster cell)

Since the domain of the connectivity index (IC) ranges from $-\infty$ to $+\infty$, its values need be scaled to the range [0,1] for use as a sediment delivery ratio. Here, we use a functional approach described by Vigiak et al. (2012). It assumes the hillslope sediment delivery ratio ($HSDR$) can be described as a function of the connectivity index (IC) using a Boltzmann-type sigmoid function (following Vigiak et al. 2012):

$$HSDR_k = HSDR_{max,k}\left(1 + \exp\left(\frac{\psi_0 - \psi_k}{u}\right)\right)^{-1} \quad (7)$$

with:

$HSDR_k$: sediment delivery ratio for hillslope erosion of raster cell k

$HSDR_{max}$: maximum attainable sediment delivery ratio within range [0,1] (here $HSDR_{max}$ = 1 for all configurations)

ψ_0: connectivity index (IC) value representing a sediment delivery ratio of 0.5

ψ_k: connectivity index value of raster cell k

u: calibration factor to control the shape of the sigmoid curve (here u =1 for all scenarios)

2.1.3 Bank erosion

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

$$B_j = \rho M_j H_j L_j \quad (8)$$

where B_j is the total eroded mass for the jth stream link (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 jth stream link.

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

Previously, the bank migration rate (equation 9) was estimated using an empirical relationship with mean annual flood (*MAF*, ranging 1–500 m^3 s^{-1}) based on measurements of bank migration rates from six rivers in New Zealand:

$$M_j = 0.028\, MAF_j^{\,0.47} \qquad (9)$$

Bank height is derived from a regional relationship with mean annual discharge (Dymond et al. 2016).

The riverbank erosion component of SedNetNZ has since been revised to better represent spatial variability in the factors influencing riverbank migration rates (Smith et al. 2019). The revised version retains the estimated net bank erosion contribution as one-fifth of gross bank erosion and uses the same approach for estimating bank height as the original model outlined by Dymond et al. (2016). The new approach represents the mean annual bank migration rate as a function of six factors as follows:

$$M_j = SP_j Sn_j T_j V_j \left(1 - PR_j\right)(1 - PW_j) \qquad (10)$$

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

Stream power (SP_j) for the mean annual flood (MAF_j, m^3 s^{-1}) is estimated for each stream link 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}), as per Dymond et al. (2016), using data from long-term river flow gauging within the catchment or region of interest:

$$SP_j = MAF_j S_j = a{q_j}^b S_j \qquad (11)$$

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

$$Sn_j = \frac{1}{(Sinu_j - 1)\sigma\sqrt{2\pi}} e^{\left(-\frac{(ln\,(Sinu_j - 1) - \mu)^2}{2\,\sigma^2}\right)} \quad (12)$$

where $Sinu_j$ is sinuosity of the *j*th stream link of the 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 migration rates.

The texture of bank material influences bank migration rates (Hickin & Nanson 1984; Julian & Torres 2006; Wynn & Mostaghini 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 (Fig. 1b):

$$\tau_c = 0.1 + 0.1779SC + 0.0028SC^2 - 0.0000234SC^3 \quad (13)$$

SC is obtained from spatial data on soil textural classes. The soil texture data is compiled from the Fundamental Soil Layers (FSL) (Newsome et al. 2008), which provides 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 (Fig. 1c) for the *j*th stream link:

$$T_j = c\tau_{c,j}^{\ -d} \quad (14)$$

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 approach to estimate a valley confinement factor (V_j) by using the mean slope (SB_j) in degrees of a buffer zone either side of the *j*th stream link:

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

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 & Collinson, 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 link (equation 10). Stream links with complete riparian woody vegetation cover are assumed to erode at 0.05 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, groynes, tied tree works) as well as stopbanks employed for flood protection, where such data are available. 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 link. PEC_j is computed as the length of erosion control measures within a stream link relative to the total length of that link. 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 link relative to 2 x link length.

2.2 Application to the Oreti and Aparima catchments

2.2.1 Surficial erosion and sediment delivery ratio

Spatial input data used to apply the revised surficial erosion component comprise the national 15 m DEM for the calculation of the L and S factors of the NZUSLE, alongside the Land Cover Database (LCDB) v4.1 and a national rainfall layer with 15-m resolution to assign C factor values and calculate the R factor of the NZUSLE, respectively. Individual sub-catchments of the River Environment Classification (REC2) were used to summarise pixel-based modelling results. The estimation of the spatially varying sediment delivery ratio for hillslope erosion was based on the 15-m DEM.

To assess the impact of changes to the model components on SedNetNZ-based sediment load estimates, we applied the surficial and bank erosion components in different configurations, as follows:

1 For the baseline configuration (termed CLASSIC), we ran the original surficial and bank erosion components of the SedNetNZ model (Dymond et al. 2016) as applied previously in other areas of New Zealand.

2 The effect of the revised calculation of the L and S factors (Section 2.1.1) for surficial erosion combined with the revised bank erosion model component on the estimated suspended sediment load is represented by the REVISED model configuration.

3 To examine the effect of the spatially-variable sediment delivery ratio (Section 2.1.2), we ran two additional configurations, i.e. REVISED-HSDR and REVISED-HSDR2, both in

combination with the revised calculation of the L and S factors, and the revised bank erosion model component. The difference between REVISED-HSDR and REVISED-HSDR2 configurations lies in the selection of ψ_0 (Eq. 7), i.e. the connectivity value (IC) that represents the sediment delivery ratio of 0.5.

Figure 1 shows the distribution of connectivity index (IC) values based on the combined Oreti and Aparima catchments. Apart from noticeable spikes at $IC \approx 3$ and $IC \approx -1.1$, the connectivity values show a bell-shaped distribution around $IC \approx -4.5$. Pixel values of $IC \approx 3$ indicate areas that were classified as streams based on REC2 river lines and flow accumulation values >= 22.5 ha. Pixel values of $IC \approx -1.1$ indicate essentially flat areas with very low slope gradients and flow accumulation (i.e. influx from neighbouring cells).

For the REVISED-HSDR configuration, we selected $\psi_0 = -4.5$, i.e. approximating the median of the bell-shaped distribution. This is intended to match on average the current sediment delivery ratio of 0.5 that is applied uniformly across a catchment, but adds spatial variability according to topographic attributes, as summarised by the connectivity index (Borselli et al. 2008). For comparison, we selected ψ_0=-3 for the REVISED-HSDR2 configuration to associate the sediment delivery ratio of 0.5 with the mean value of the observed range ([-9,3]) of connectivity index values (Fig. 1).

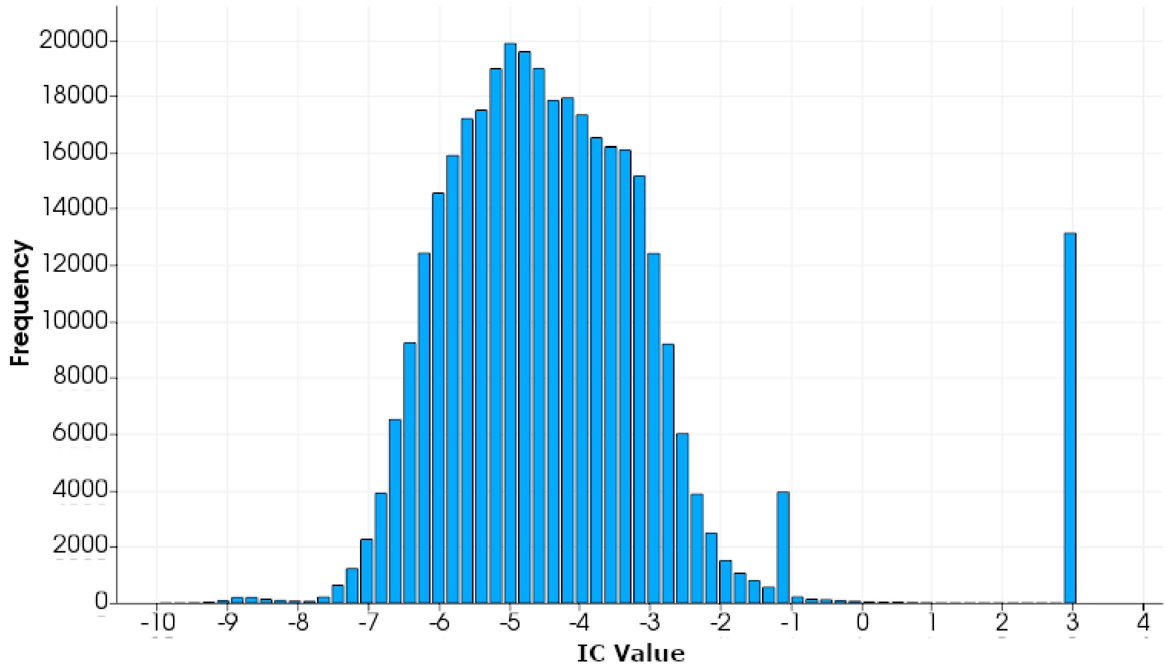

Figure 1. Distribution of connectivity index values (IC) for the combined Oreti and Aparima catchments.

2.2.2 Bank erosion

Inputs to the bank erosion model component were obtained from national-scale spatial datasets comprising the REC2 and LINZ stream networks, 15 m DEM to calculate channel slope, FSL for soil data, and EcoSat Woody for 2002 woody vegetation cover. The 2012 New Zealand Land Cover Database (LCDB) was not used despite being more recent because it has a minimum mapping unit of 10,000 m^2 versus 225 m^2 for EcoSat. This makes LCDB less suitable for characterising narrow corridors of woody vegetation often found along channel banks. Data on riparian plantings or channel protection works were unavailable for the two Southland catchments. Spatial data on stopbank locations are available and have been included in model simulations.

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 to fit a relationship between mean annual discharge and mean annual flood (Fig. 2) for use in calculating stream power (equation 11).

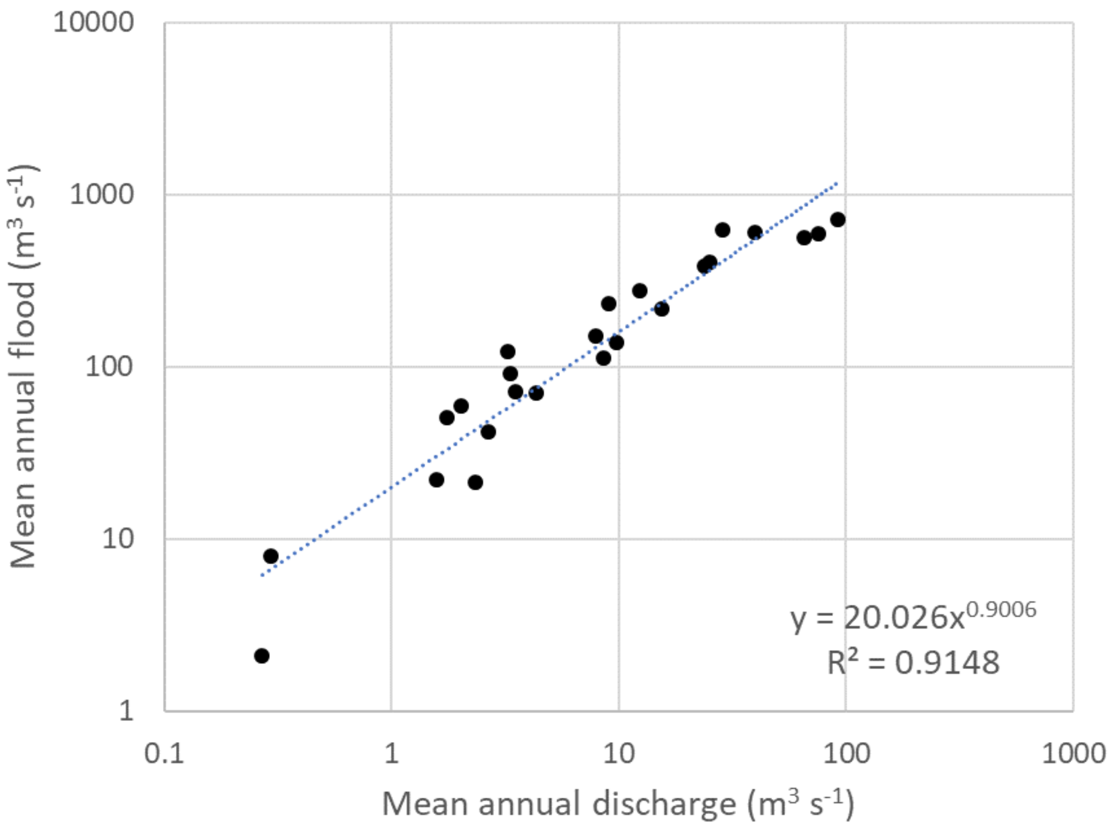

Figure 2. Fitted power relationship between mean annual discharge and mean annual flood (MAF) based on data from 24 gauging stations across Southland (catchment area range: 21–5,109 km^2).

Calibration of the riverbank 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 the absence of mapped reach-scale channel changes for the Oreti and Aparima catchments, we used a combined dataset comprising measured bank migration rates from the Manawatu and Kaipara catchments to calibrate the model (Fig. 3; Spiekermann et al. 2017; Smith et al. 2019).

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 riverbank migration model was found to significantly improve prediction, once calibrated, compared to the original SedNetNZ bank migration model using data for the Manawatu and Kaipara catchments (Smith et al. 2019; Fig. 3).

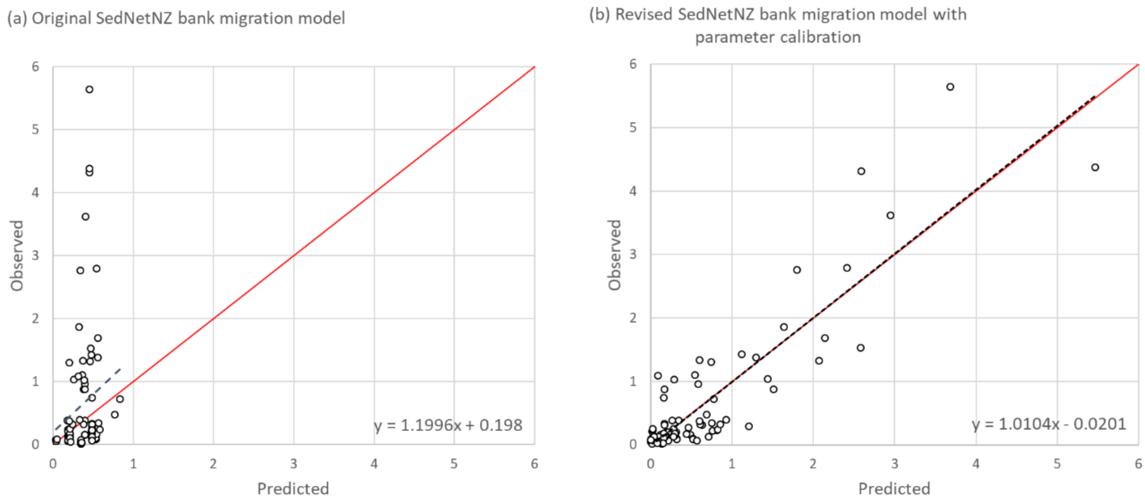

Figure 3. Comparison of predicted versus observed bank migration rates (m y^{-1}) for (a) original and (b) revised SedNetNZ bank migration models. Red line indicates the 1:1 line.

3 Results

3.1 Catchment-to-coast SedNetNZ sediment load predictions

Predictions based on the REVISED configuration of the SedNetNZ model, using a spatially uniform hillslope sediment delivery ratio of 0.5, indicate suspended sediment contributions of 196 and 66 kt y^{-1} from surficial and channel bank erosion, respectively, for the Oreti catchment draining to the coast (Table 1). For the Aparima, suspended sediment contributions from surface and bank erosion were 40 and 30 kt y^{-1}, respectively. The surficial and bank erosion estimates by the REVISED configuration of the SedNetNZ model are significantly lower than predictions made using the CLASSIC configuration of the SedNetNZ model (Dymond et al. 2016; Table 1).

Table 1. Predicted suspended sediment load contributions (kt y^{-1}) from surficial and riverbank erosion to the channel network for the CLASSIC and REVISED model configurations

Catchment	CLASSIC		REVISED	
	Surficial erosion	Bank erosion	Surficial erosion	Bank erosion
Oreti	340	129	196	66
Aparima	66	48	40	30

The predicted mean annual suspended sediment load according to the REVISED configuration of the SedNetNZ model amounted to 253 and 67 kt y^{-1} for the Oreti and Aparima catchments, respectively (Table 2). Note that the surficial and bank erosion sediment loads do not sum to the catchment suspended sediment load due to losses of sediment with overbank floodplain deposition (Dymond et al. 2016). These loads are significantly less than the mean annual suspended sediment loads predicted by the CLASSIC configuration of SedNetNZ (Table 2). The predicted catchment sediment loads for both the REVISED and CLASSIC configurations are based on a spatially-uniform hillslope sediment delivery ratio of 0.5. The predicted spatial pattern in mean annual surficial erosion and in REC2 reach-scale mean annual riverbank migration rates are shown in Figures 4 and 5, respectively. Figure 4 shows that the highest surficial erosion rates are modelled for steep areas with high mean annual rainfall, whereas areas with low slope and less mean annual rainfall show significantly less surficial erosion.

Table 2. Predicted suspended sediment loads for the Oreti and Aprima catchments (kt y^{-1}) for the CLASSIC and REVISED model configurations

Catchment	CLASSIC	REVISED	Hicks et al. (2011)
Oreti	452	253	260
Aparima	110	67	90

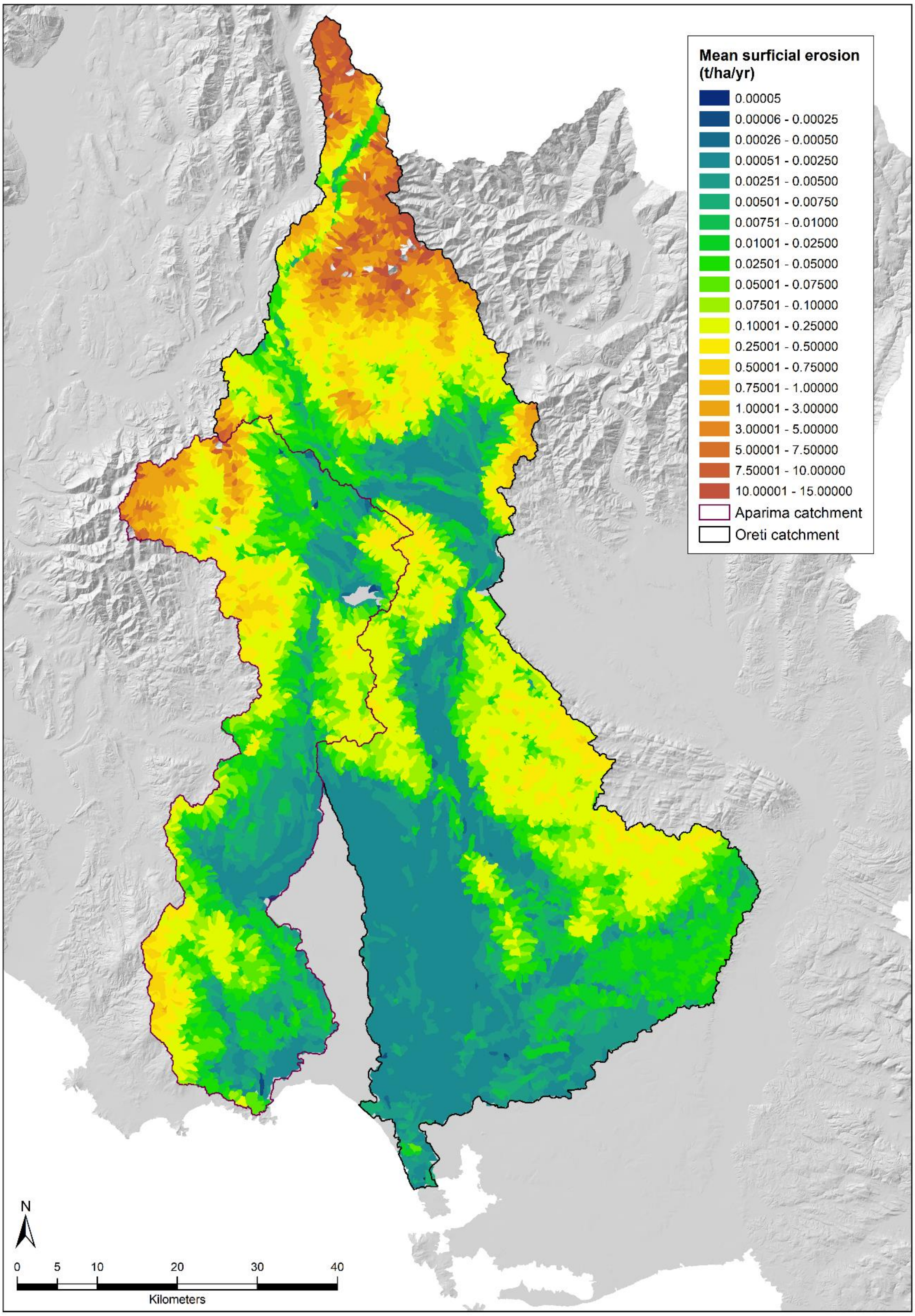

Figure 4. Spatial pattern in surficial erosion averaged across REC2 sub-watersheds for the Oreti and Aparima catchments using the REVISED configuration of the SedNetNZ model.

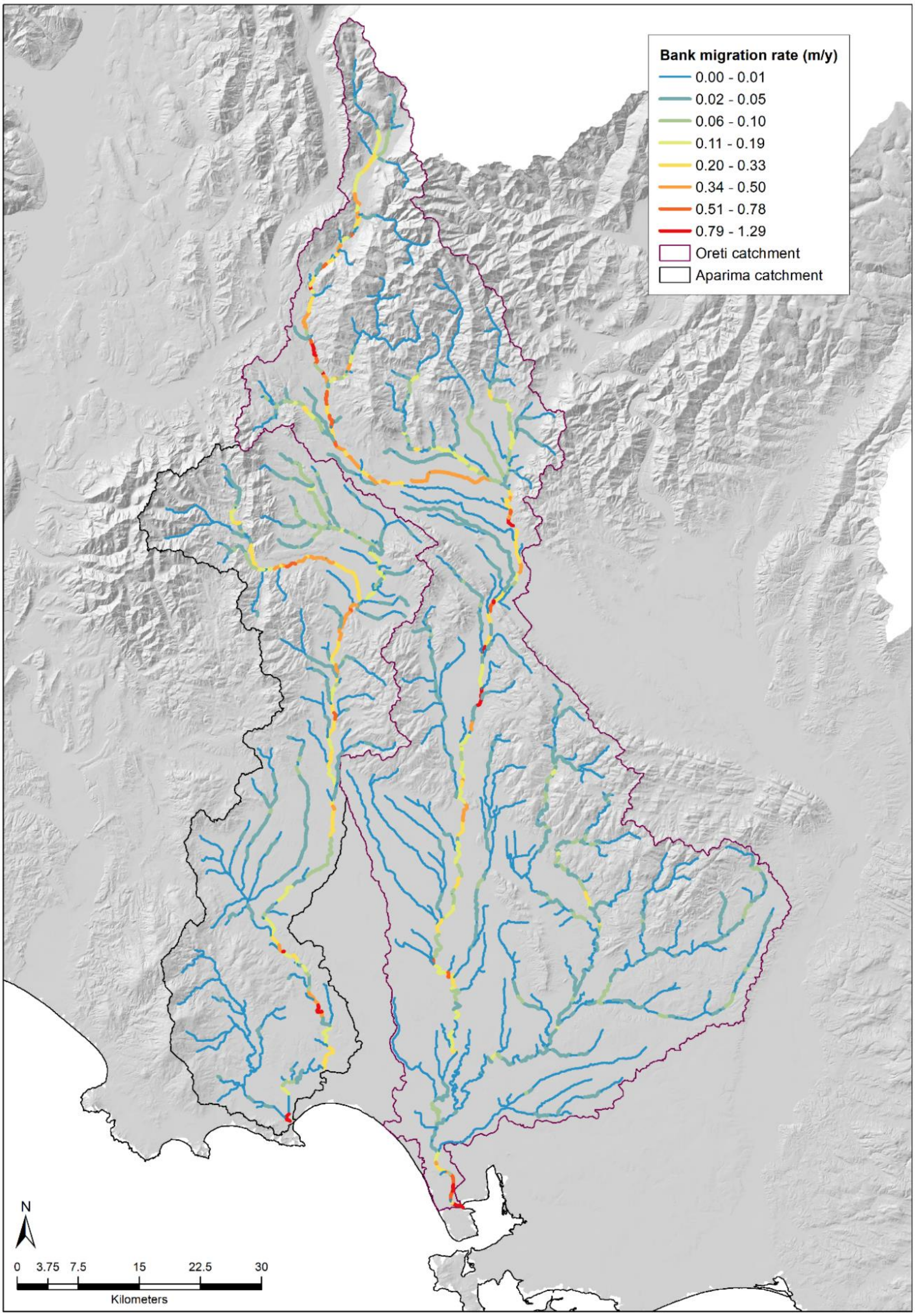

Figure 5. Spatial pattern in riverbank migration rate (m y^{-1}) for the REC2 stream network (3rd order and above) for the Oreti and Aparima catchments using the REVISED configuration of the SedNetNZ model.

Estimates of surficial erosion and catchment suspended sediment loads for the trialled REVISED-HSDR and REVISED-HSDR2 configurations of SedNetNZ for the Oreti and Aparima are given in Table 3. Introducing a spatially variable SDR has a significant influence on predicted sediment loads. In comparison with the REVISED configuration, estimates of surficial erosion based on the REVISED-HSDR configuration of SedNetNZ show an increase of 46 and 45% for the Oreti and Aparima catchments, respectively. These translate to increases in suspended sediment load estimates of 34 and 27% for the Oreti and Aparima catchments, respectively. In contrast, estimates of surficial erosion based on the REVISED-HSDR2 configuration of SedNetNZ show a decrease relative to the REVISED configuration of –12 and –13% for the Oreti and Aparima catchments, respectively. Catchment suspended sediment load estimates based on the REVISED-HSDR2 configuration show a decrease of –9 and –8 % for the Oreti and Aparima catchments, respectively.

Table 3. Estimated surficial erosion and catchment suspended sediment loads (kt y^{-1}) for the trialled REVISED-HSDR and REVISED-HSDR2 model configurations of SedNetNZ for the Oreti and Aparima catchments

Catchment	Surficial erosion		Catchment sediment load	
	REVISED-HSDR	REVISED-HSDR2	REVISED-HSDR	REVISED-HSDR2
Oreti	287	173	339	229
Aparima	58	34	85	62

Figure 6a and 6b shows the spatially varying sediment delivery ratios (SDR) for the REVISED-HSDR and REVISED-HSDR2 configurations of the SedNetNZ model, respectively. The maps show a similar pattern overall, i.e. the sediment delivery ratio increases with the steepness of the terrain and with the proximity to streams. Consequently, the stream network shows the maximum possible delivery ratio of 1. However, while the general spatial pattern of the two configurations is similar, the overall magnitude of SDR values differs significantly.

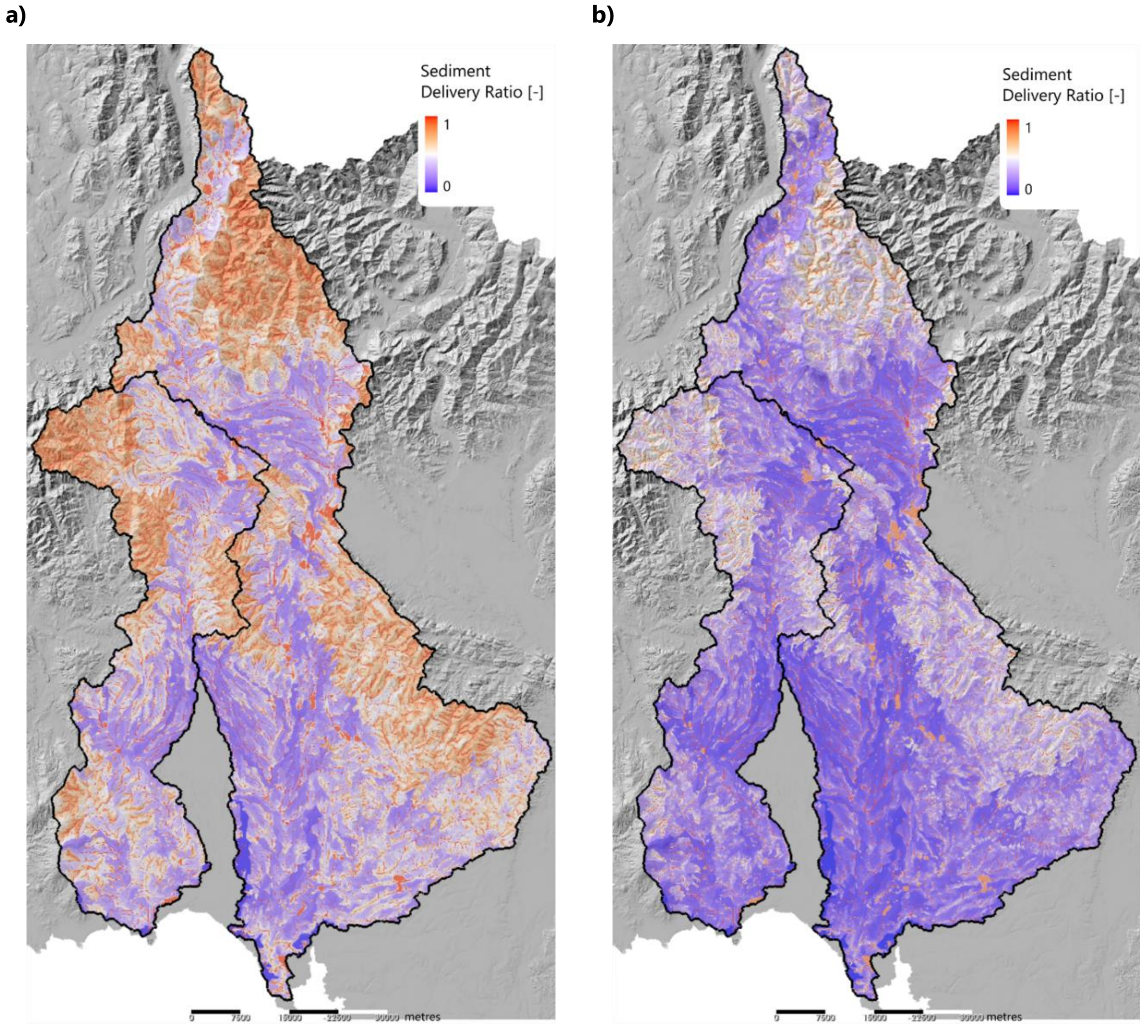

Figure 6. Spatially-varying sediment delivery ratio based on (a) REVISED-HSDR configuration and (b) REVISED-HSDR2 configuration (cf. Section 2.1.2) for the Oreti and Aparima catchments.

3.2 Target catchment SedNetNZ sediment load predictions

We also report SedNetNZ outputs from the REVISED model configuration for the target catchment areas selected by the 'Sources and Flows' programme (Table 4). These target catchments do not cover the complete catchment areas draining to the coast (Fig. 7) and for this reason are not used when comparing model results with previous studies at this scale (see section 4.1). However, the model outputs for these target catchment areas are supplied for use alongside modelling outputs for the other contaminants (N, P and *E. coli*) investigated within the OLW 'Sources and Flows' programme.

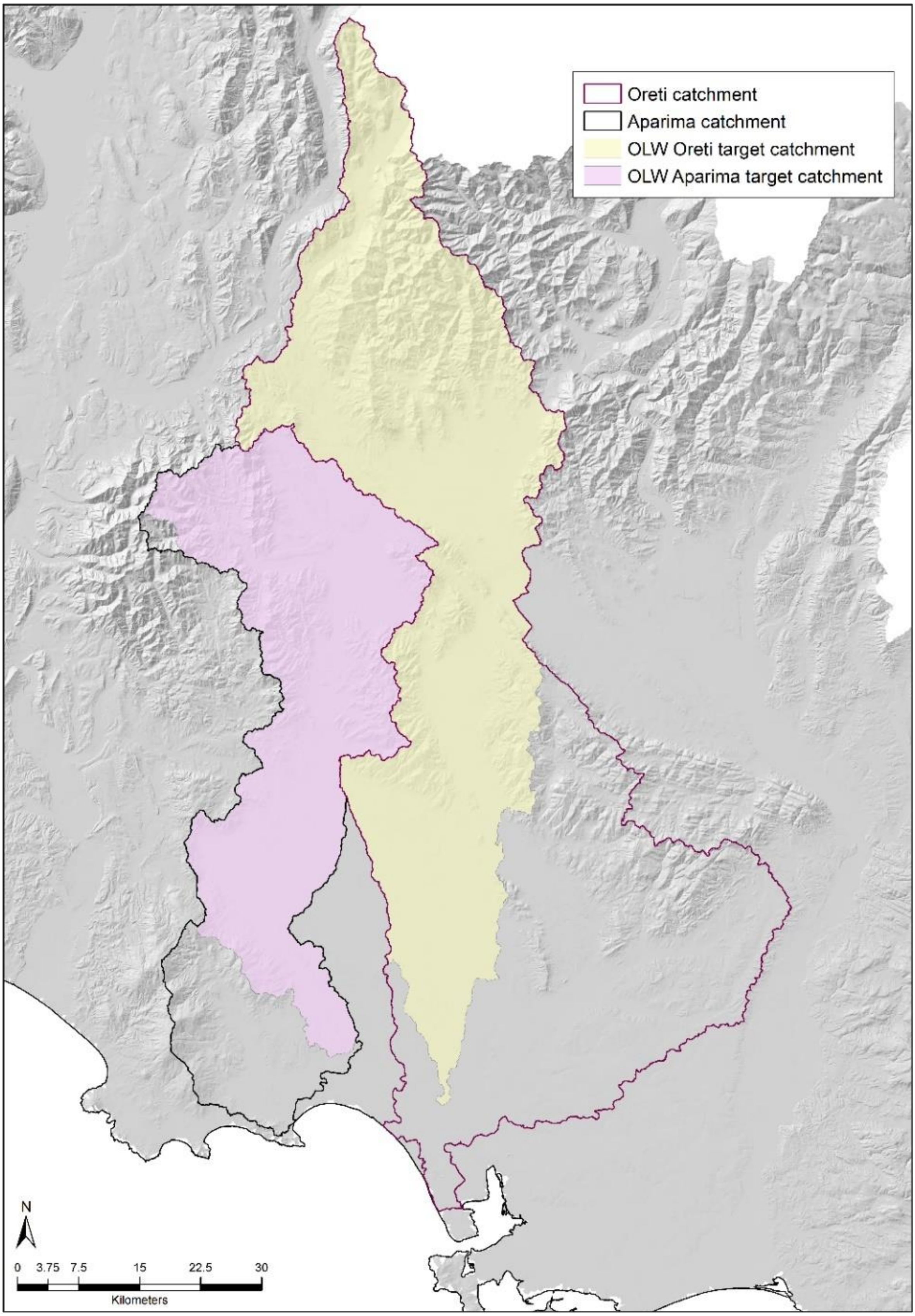

Figure 7. Comparison of catchment areas for the Oreti and Aparima catchments draining to the coast (results summarised in Tables 1–3) versus the OLW target catchment areas (results summarised in Table 4).

Table 4. Predicted surficial and bank erosion contributions and the catchment-scale suspended sediment loads (kt y^{-1}) for the OLW 'Sources and Flows' Oreti and Aparima target catchment areas using the REVISED model configuration

Catchment	Area (km^2)	Surficial Erosion	Bank erosion	Catchment suspended sediment load[1]
Oreti	2149	188	54	236
Aparima	1243	36	27	61

[1]Note that the surficial and bank erosion sediment loads do not sum to the catchment suspended sediment load due to losses of sediment with overbank floodplain deposition (Dymond et al. 2016).

4 Model evaluation and limitations

4.1 Model evaluation

SedNetNZ is designed to predict spatial patterns in erosion and suspended sediment loads on a mean annual basis for periods spanning several decades. Long-term suspended sediment yield data are unavailable for the entire Oreti and Aparima catchments, or for sites within the catchments. Therefore, we are unable to directly assess performance of the revised model in these two catchments. Instead, we compare our revised model predictions with other available information.

Suspended sediment loads at the outlet of both the Oreti and Aparima catchments have previously been reported as 260 and 90 kt y^{-1}, respectively, estimated from an empirical model based on precipitation and erosion terrain classification (Hicks et al. 2011 – see Table 2). The CLASSIC SedNetNZ configuration (110 and 452 kt y^{-1}) exceeds the suspended sediment load values reported by Hicks et al. (2011) for the Aparima and Oreti catchments by 22% and 74%, respectively. By contrast, in comparison with the Hicks et al. (2011) estimates, the REVISED SedNetNZ configuration with spatially uniform SDR is lower than the suspended sediment load for the Aparima catchment (–25%), but predicts a similar load for the Oreti catchment (–3% deviation).

Recent work has examined historic changes in sedimentation rates and sources of sediment supplied to the New River Estuary by the Oreti and Waihopai Rivers (Brown 2018). This study concluded that there has been a shift in sediment contributions from subsoil to surface sources dominating in recent decades. This trend also corresponds to an increasing sedimentation rate and change from marine to terrestrial dominated sediment sources after 1975–1986. The findings of the estuary sedimentation study are consistent with the relative contributions from surficial (74%) and bank (26%) erosion sources predicted by the REVISED model configuration for the Oreti catchment.

The difference in predictions between the CLASSIC and REVISED configurations of SedNetNZ reflects changes made to both the surficial and bank erosion model components, as described in section 2.1. For surficial erosion, the key changes include replacement of the slope length term with a surface runoff contributing area term. For bank erosion, we replaced the empirical relationship between bank migration rate and mean annual flood (Dymond et al. 2016) with an approach based on stream power of the mean annual flood and spatial representation of other factors that influence variability in bank migration rates (Smith et al. 2019).

The effect of the implementation of a spatially-varying sediment delivery ratio (SDR) (cf. Section 2.1.2) depends on the scaling of the DEM-dependant connectivity index values (IC, Borselli et al. 2008) to the SDR value domain of [0,1], which is represented in the REVISED-HSDR and REVISED-HSDR2 configurations (Section 2.1.2) of the SedNetNZ model. While the REVISED-HSDR configuration increases the total sediment load in comparison to the REVISED configuration (Table 3, Fig. 6a), the REVISED-HSDR2 configuration reduces the total sediment load compared with the REVISED configuration (Table 3, Fig. 6b) for both catchments. This can be explained by the different spatial distribution of the SDR across the three configurations.

The REVISED configuration applies a uniformly distributed SDR of 0.5 across each catchment that evenly reduces the gross sediment yield regardless of the topographic context of individual erosion source areas as modelled by the NZUSLE (c.f. Fig. 4). This is typically the way SDR is applied in previous modelling applications such as for the SedNet model in Australia (Wilkinson et al. 2009) and SedNetNZ (Dymond et al. 2016), although more recent catchment sediment load modelling has moved towards using a spatially-varying SDR (Vigiak et al. 2012; Wilkinson et al. 2014). While the distribution of SDRs based on the REVISED-HSDR configuration in the present study was designed to match an average SDR of 0.5 (Fig. 8a), its spatial distribution (Fig. 6a) increases effective sediment yield from areas with high gross sediment yield (cf. Fig. 4), which correspond to areas with high slope, compared with the REVISED configuration. The REVISED-HSDR2 configuration (Fig. 8b) has the opposite effect. Its spatial distribution (Fig. 6b) decreases the effective sediment yield for areas with high sediment yield compared with the REVISED configuration.

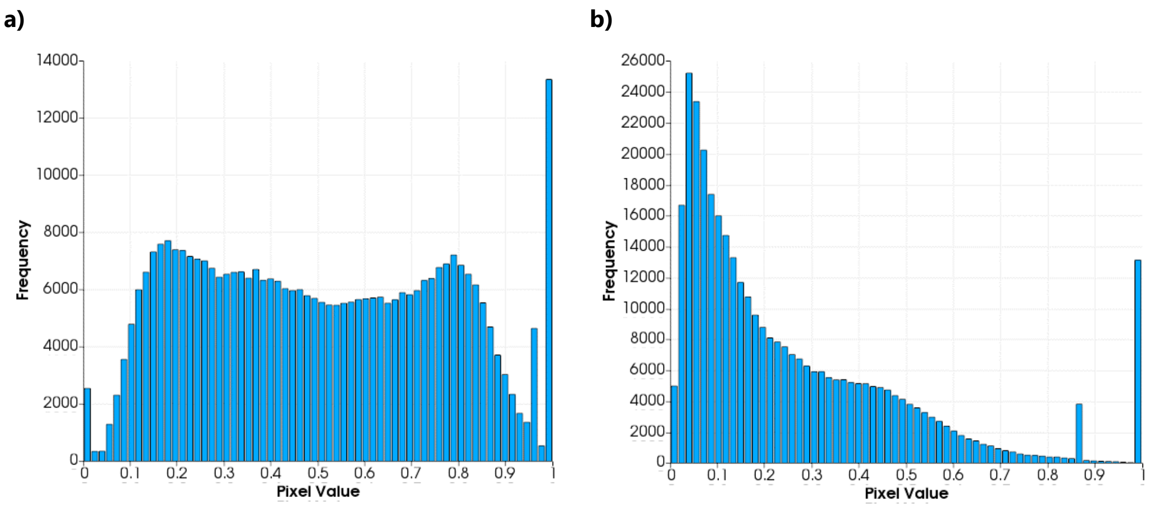

Figure 8. Distribution of sediment delivery ratios (Pixel Value [0,1]) for (a) the REVISED-HSDR and (b) REVISED-HSDR2 configurations of SedNetNZ (Section 2.1.2).

4.2 Model limitations

There are a range of limitations in our SedNetNZ modelling and the available input and calibration datasets. Here, we consider these limitations in relation to both the surficial and bank erosion model components. Model outputs should be interpreted in the context of these limitations.

4.2.1 Surficial erosion

Key limitations for the surficial erosion component relate to implementations of the NZUSLE land cover C factor and soil erodibility K factor, and the availability of suitable input data. Developing a spatially explicit representation of the sediment delivery ratio also represents an important challenge.

The impact of land cover on surficial erosion is currently represented by three different C-factor values (Dymond 2010, 2016): 1.0 for bare ground, 0.01 for pasture, and 0.005 for woody vegetation (i.e. scrub and forest cover). While this may be sufficient to represent the dominant land-use types in NZ for most parts of the country, it does not represent well those land-use types or land management practices that are particularly prone to surficial erosion, such as cropping or winter grazing of fodder crops. In fact, the NZUSLE represents long-term annual average soil losses and is conceptually not well suited to account for the impact of seasonal management practices like winter grazing. In addition, it is difficult to source up-to-date land-cover information required for mapping C factor values and to average them over several decades for use in SedNetNZ.

The soil erodibility factor K of the CLASSIC configuration of SedNetNZ has applied a single value, i.e. 0.25 for loam soils, uniformly across all soil types in an investigation area (e.g. Dymond et al. 2016). This may lead to an overestimation of fine sediment supply from steep slopes with soils characterised by coarser material. Incorporating spatial heterogeneity in soil erodibility, as used by Dymond (2010), is an area for future model development that could make better use of soil spatial data.

A further limitation of the present surficial erosion component of SedNetNZ is the lack of a spatially varying sediment delivery ratio. In this study, we trialled two experimental configurations to address this limitation of the model. However, to demonstrate improvement in the spatial representation of SDR requires field measurements for calibration and validation, and presents a challenge that requires further attention as part of the ongoing development of SedNetNZ.

4.2.2 Bank erosion

There are several limitations related to the revised bank erosion component that require consideration. The revised model representation of riverbank migration rates requires spatial data on riparian woody vegetation. Presently, this is only available for 2002 using EcoSat Woody (Dymond & Shepherd 2004). As noted previously, LCDB is less suitable for representing narrow strips of riparian woody vegetation due to its comparatively coarse resolution compared to EcoSat. Therefore, model predictions of spatial patterns in bank migration rates based on riparian woody vegetation in 2002 (Fig. 5) may differ from rates under contemporary riparian vegetation cover in locations where significant vegetation change has occurred. A further challenge results from channel planform change reducing the spatial correspondence between the mapped channel position and riparian woody vegetation. An important future data need is an updated version of EcoSat to provide more recent, higher-resolution information on the spatial extent of woody vegetation. Moreover, future availability of catchment-wide LiDAR data would enable improved spatial representation of riparian woody vegetation.

The effect of livestock tramping is not represented in the revised model. It is challenging to represent the effect of livestock trampling on bank stability given the localised and variable nature of livestock access to banks. However, Williamson et al. (1992) reported that livestock grazing showed no effect on channel form for wider, higher-order streams compared with narrow (<2 m), low-order streams under intensive grazing in Southland.

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 (Fig. 3). We recognise that this potentially introduces additional and unquantified error into model predictions for the Oreti and Aparima 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. 2019). One important point of difference is the absence of braided channel reaches from this calibration dataset, whereas braiding is present in the middle reaches of the Oreti River. This points to the need to develop a calibration dataset for this channel form.

We were unable to include representation of channel works designed to reduce bank erosion. While such works have been undertaken in the Oreti and Aparima catchments, digital spatial information was not available for inclusion in model representation of bank erosion. Therefore, it is likely that our prediction of bank erosion rates and net bank-derived suspended sediment loads are over-estimated for some reaches where erosion mitigation works have been applied. We did include spatial representation of stopbanks. The inclusion of stopbanks in the model assumes that either erosion mitigation works have been applied to protect stopbanks or that such measures will be applied over the longer-term to ensure eroding channels do not threaten the integrity of stopbanks. However, we observed bank erosion occurring on floodplains inside stopbanks in the lower reaches of the Oreti (Fig. 9) so the treatment of stopbanks requires a better understanding of their influence on bank erosion rates.

Figure 9. Bank erosion in the lower reaches of the Oreti River, June 2018. Note the stopbank in the front of the trees.

The prediction of bank erosion for the lowermost reaches of the Oreti and Aparima rivers does not account for possible tidal effects on erosion rates (Fagherazzi et al. 2004). The high bank migration rates predicted for these reaches may also reflect under-estimated riparian woody vegetation as well as the absence in the model of the effect of any channel bank stabilisation works.

Finally, it is important to recognise the wider limit on insights available from catchment models. Models such as SedNetNZ, which represent erosion processes and sediment loads on a mean annual basis for a period typically approximating several decades, do not capture the catchment history and broader socio-economic drivers of accelerated erosion, including stream bank erosion (Ellis et al. 2018). This is relevant in terms of understanding the effectiveness of erosion mitigation measures given the influence of factors such as past catchment vegetation change (increasing runoff/stream flow) and channel modification (straightening, drainage) on bank erosion rates.

5 Conclusion

This report presents an application of a revised version of the SedNetNZ sediment budget model to the Oreti and Aparima catchments in Southland. We focused on modifying the surface and bank erosion components of the SedNetNZ model. This reflects observations from field reconnaissance, and previous research, that these widespread erosion processes are likely to dominate suspended sediment loads.

The main model developments include modifications to the surficial erosion component to incorporate an improved spatial representation of surface runoff contributing areas and trialling of spatially varying sediment delivery between surface erosion sources and the channel network. The bank erosion component was revised to include additional factors that influence bank migration rates, namely riparian woody vegetation, soil texture, channel sinuosity, valley confinement, and erosion mitigation works.

Predicted suspended sediment contributions from surface and bank erosion were significantly lower using the other model configurations compared with the CLASSIC configuration. The REVISED model configuration predictions were closest to previous estimates of suspended sediment load from Hicks et al. (2011) based on the sum of absolute relative differences (28%) between the REVISED configuration and the Hicks et al. (2011) estimated sediment loads for the Oreti and Aparima catchments. The CLASSIC configuration produced the largest absolute relative difference across both catchments (96%). However, this comparison must be treated with caution, given that the Hicks et al. (2011) values were also estimates based on an empirical model.

The continuing development of SedNetNZ aims to produce improvements in model predictive performance. The absence of longer-term suspended sediment load data at whole catchment and subcatchment scales was a limitation for evaluating model performance in this study. Moreover, information on sediment source contributions using sediment fingerprinting could provide independent data against which to compare model predictions. Additional work is required to more fully evaluate performance with collection of new data on erosion processes and suspended sediment loads. As part of the model application in the present study, we identified limitations associated with both model input datasets and process representation for consideration alongside model predictions.

6 Acknowledgements

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