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SedNetNZ modelling of soil erosion in Northland

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Markus U. Mueller and John R. Dymond

Landcare Research

Prepared for:

Northland Regional Council (NRC)

36 Water St, Whāngārei
Private Bag 9021
Whāngārei Mail Centre
Whāngārei 0148

December 2015

Landcare Research, Gate 10 Silverdale Road, University of Waikato Campus, Private Bag 3127, Hamilton 3240, New Zealand, Ph +64 7 859 3700, Fax +64 7 859 3701, www.landcareresearch.co.nz

Reviewed by:	*Approved for release by:*
David Palmer Researcher, Soils and Landscapes Landcare Research	Chris Phillips Portfolio Leader – Managing Land & Water Landcare Research

Landcare Research Contract Report: LC2424

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Contents

Summary

This report was undertaken to allow Northland Regional Council (NRC) prioritisation of erosion reduction measures for Northland region. Hillslope erosion was modelled for the whole region using SedNetNZ, including all four major erosion processes surface erosion, landsliding, gully and earthflow erosion. Resulting sediment yield values were summed and zonal statistics calculated for all farms (based on AgriBase farm polygons). Farm plan scenarios for the reduction in erosion were calculated when implementing farm plans for different percentages of the overall number of farms in the priority catchments defined by NRC.

An additional module utilised a dataset of river bank erosion and sedimentation for the Kaipara Harbour created in a previous project. The dataset was clipped to one of the NRC priority catchments (Greater Kaipara). Protection from stock and stabilisation from vegetation scenarios were also calculated using the percentage of river fenced to estimate likely reductions in stream bank erosion.

The final spatial data were provided to NRC to enable interrogation, and scenario modelling and adjustment for their erosion mitigation planning requirements.

1 Introduction

Northland Regional Council (NRC) is interested in understanding the severity and spatial pattern of the major erosion processes. In order to reduce soil erosion it is necessary to estimate both sediment loads at the farm level and sediment delivery from stream bank erosion under different management scenarios.

2 Background to SedNet

SedNet is a GIS model designed as a spatially distributed, time-averaged (decadal to century) model that routes sediment through the river network, based on a relatively simple physical representation of hillslope and channel processes at the reach scale. SedNet accounts for losses in water bodies (reservoirs, lakes) and deposition on floodplains and in the channel. It is often thought of as a ‘reduced complexity’ or hybrid empirical/physical model. SedNet was first developed by CSIRO for the National Land and Water Audit of Australia (Prosser et al. 2001), but has increasingly been used at regional scales by incorporating higher resolution datasets (McKergow et al. 2005; Wilkinson et al. 2009) and is gaining wider acceptance for use outside Australia (Ding & Richards 2009).

The basic element in the model is the stream link, typically several kilometres or more in length. Each link has an internal catchment area (watershed) that drains overland flow and delivers sediment to that link. For each link, an annual mass budget and sediment yield are calculated by taking the difference between: (1) the sum of sediment supplied from the internal catchment area and upstream tributaries; and (2) the loss of sediment in the channel, on floodplains and in any reservoirs and lakes. Sediment supply is the sum of sediment delivered from hillslope, gully, and riverbank erosion processes. The original model did not include mass movement erosion processes (landslides, earthflows) as source terms or the type of gully erosion that is prevalent in many North Island east coast river basins, nor does it consider the channel environment (via bed degradation and incision) as a potential source of sediment. De Rose and Basher (2011) describe the modifications made to SedNet for application to New Zealand. SedNet models suspended load (silt and clay) and conserves mass in these fractions.

The main outputs from the model are mean annual suspended sediment loads in each stream link throughout the river network. Because source erosion is spatially linked to sediment loads, it is also possible to examine the proportionate contribution that specific areas of land make to downstream export of sediment. By adjusting input data and model parameters it is also possible to simulate river loads for natural conditions (pre-European) and examine the consequences of future land-use scenarios. If the rating curves of discharge-sediment concentration flow are known, then mean annual suspended sediment concentrations for indicative discharge events can be back calculated from predicted loads (Ausseil & Dymond 2008).

3 Objectives

1. Create a layer of sediment delivery by hillslope erosion using the four hillslope erosion sub-models of SedNetNZ (surficial, landslide, earthflow, gully) for the Northland region.

2. Create a spatial dataset of sediment delivery by hillslope erosion at the farm level using the AgriBase dataset to delineate farm boundaries. The AgriBase enables the examination of different scenarios for farm plan implementation.

3. Examine the impact stream bank fencing potentially has on sediment loads using an existing layer of river bank erosion for the Kaipara Harbour catchment.

4 SedNetNZ model components and data requirements

As in the original SedNet model, there are three main components of SedNetNZ: erosion, hydrology, and sediment routing submodels, each with their own suite of model algorithms. As a rule, most time spent during application of SedNetNZ involves data preparation, rather than code execution, since the model takes minutes to run on a typical desktop computer. If the erosion data layers (i.e. spatial maps of erosion processes) are not available, then a considerable amount of time will be required to derive this information. The model components are summarised below together with the required input data, variables, and parameters.

4.1 Overland flow erosion (New Zealand Universal Soil Loss Equation, NZUSLE)

A version of the USLE has been developed to estimate erosion rates from sheetwash, rill, and inter-rill processes at broad scales across New Zealand (Dymond 2010). It has the same factors as the USLE except that the rainfall factor is a function of mean annual rainfall only. NZUSLE gives the annual erosion rate (HE, t km^{-2} yr^{-1}) as a product of five factors:

$$HE = \alpha \times P^2 \times K \times L \times S \times C \tag{1}$$

where: α is a constant calibrated with published surficial erosion rates; P is mean annual rainfall (mm) squared; K is the soil erodibility factor (sand 0.05; silt 0.35; clay 0.20; loam 0.25); L is slope length factor ($(\lambda/22)^{0.5}$ where λ is slope length in metres); C is a vegetation cover factor (bare ground 1.0, pasture 0.01, scrub 0.005, forest 0.005); and S is the slope factor given by Equation 2:

$$S = 0.065 + 4.56\frac{dz}{dx} + 65.41\left(\frac{dz}{dx}\right)^2 \tag{2}$$

where $\frac{dz}{dx}$ is the slope gradient.

The NZUSLE was calibrated against published data from c. 50 studies within New Zealand where surface erosion was considered the dominant contributing process, including some from plantation and indigenous forest catchments (Fig. 2). The majority of measurements were made over short periods (years rather than decades) and represent yields from small plots and catchments (up to several km^2). They are considered to represent broad, background rates of surficial erosion in the absence of mass movement processes.

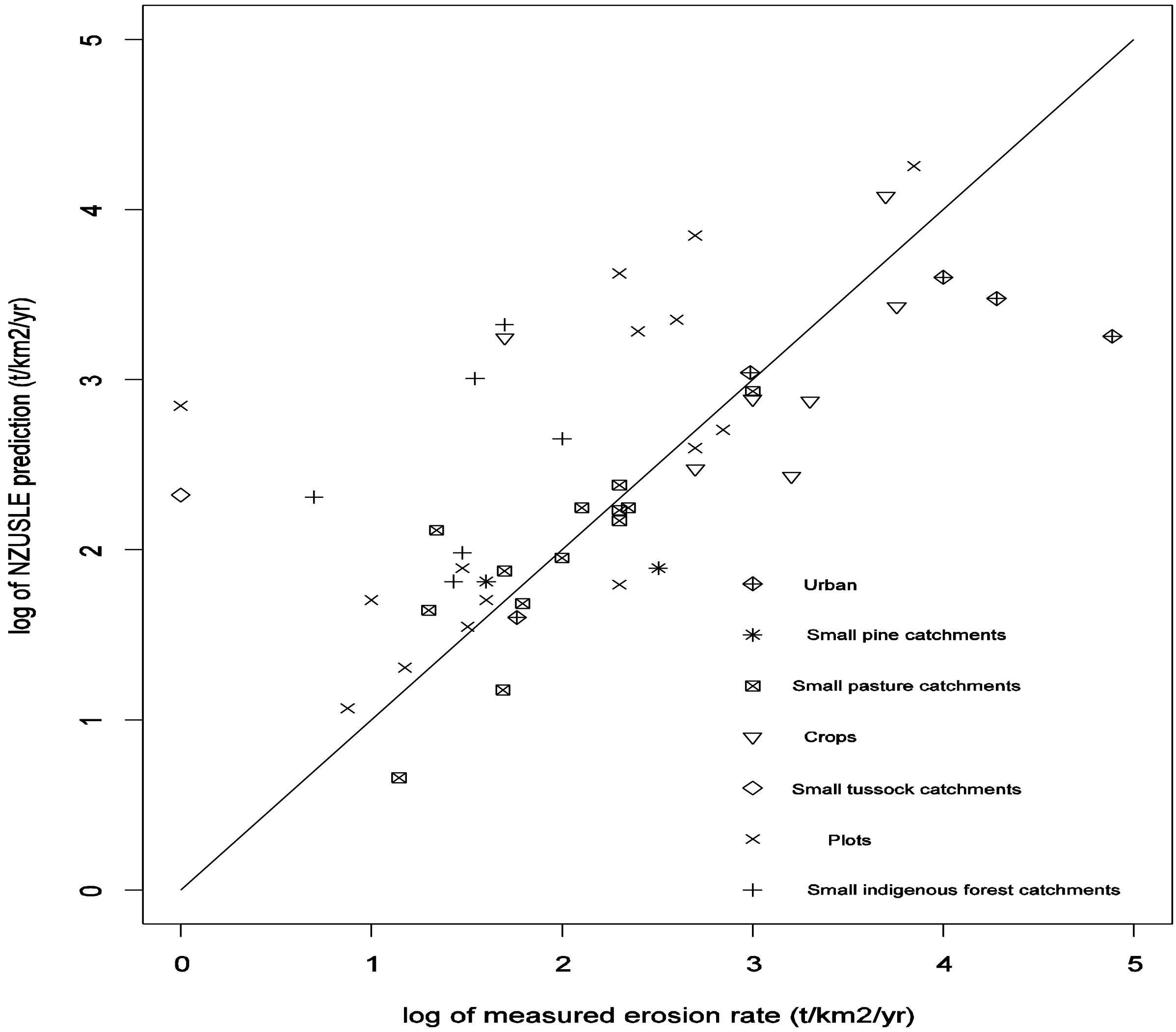

Figure 1 NZUSLE predictions with the published measurements (from Dymond 2010).

4.1.1 Input data for NZUSLE

Input data are estimated for each 15-m resolution grid cell

$\alpha = 1.2\times10^{-5}$

P is mean annual rainfall (mm) and comes from the LENZ climate data layer (Leathwick et al. 2003)

K = 0.25 everywhere (i.e. soil is assumed to be loam everywhere)

$\lambda = 200$ m for stream density < 2000 m km^{-2}, and for stream density > 2000 m km^{-2} there is an exponential decay of λ so that it is 100 m when stream density = 4000 m km^{-2}. Stream densities are defined per subcatchment in the subcatchment file.

$\frac{dz}{dx}$ is the slope gradient derived from a 15-m cell size resolution DEM.

C is read from a land cover raster. C is 0.1 for bare ground, 0.01 for pasture, 0.005 for scrub and forest, and 0.005 for urban.

4.2 Shallow landslide erosion

Landslides are the most common form of erosion in New Zealand hill country. These are typically shallow failures, rarely greater than 2-m depth, and individually of small areal extent (20–500 m^2). They commonly have a debris tail of deposited sediment below them and only part of the eroded sediment is delivered to a stream channel. They tend to occur as clusters during individual infrequent high intensity or prolonged rainfall events. Most studies (e.g. De Rose 1995, 1996, 2012; Dymond et al. 2006) show that shallow landslides are confined to the steeper slopes (> 28°), though they can occur on slopes down to 15°, but rarely less. The debris tails from landslides frequently extend onto gentler slopes.

The main input for landslide erosion is a raster giving the probability of landslides (LD). The total area of landslides in a watershed is calculated by summing in all cells the product of landslide probability with the cell area (A, m^2). The product is multiplied by the average depth of failure below the ground surface ($\overline{D}$), soil bulk density (ρ_{ls}), and divided by the period of landslide activity (T), to derive the mass of sediment eroded from hillslopes per year. Not all sediment reaches the channel and a sediment delivery ratio (SDR_{L}) is used to account for losses along the landslide runout path. SDR_{L} is used to determine the amount of eroded sediment (LE, t yr^{-1}) that finally reaches the stream link:

$$LE = SDR_L \times \frac{\overline{D} \times \rho_{ls} \times A \sum_{j=1}^{n} LD_j}{T} \tag{3}$$

Depth of landslide failure is assumed to be 1.0 m. There are insufficient published data to indicate whether landslide depths are spatially predictable (e.g. by geology or soil type).

4.2.1 Landslide probability – slope relationships

The first step in modelling landslide erosion is the mapping of landslide probabilities, which gives the proportion of land at any locality that has experienced landsliding. There are surprisingly few published data, the only known example being from Taranaki consolidated sandstone hill country (De Rose 1995, 1996). Dymond et al. (2006) similarly examined the probability of landsliding versus slope angle for a single storm event in the Manawatu using slope derived from a 15-m-cell-size resolution DEM. An important outcome of the study was to show that underlying lithology and vegetation has an important influence on governing spatial variation in landslide probability densities, confirming previous studies (e.g. Glade 1998; Reid & Page 2003).

Figure 2 shows the probability–slope relationships derived from measurements from aerial photographs of landsliding occurring over the last 70 years in the Manawatu catchment. The measurements showed evidence of

- an effect of underlying geology on the probability density–slope relationships,
- event resistance whereby very steep slopes (> 30 degrees) showed lower probability of landsliding, possibly due to them having already failed in previous events.

As we do not wish to account for event resistance here, we set probability of failure to a constant for high slopes (Table 1).

Figure 2 Estimated probability–slope relationships for landslide-prone grassland hillslopes in Northland hill country over a 70-year time period. The y-axis shows the percentage (i.e. probability times 100) of land at the corresponding slope angle which has experienced a landslide in the last 70 years. The x-axis shows slope angle in degrees.

4.2.2 Sediment delivery ratio

Not all sediment eroded from landslides is delivered to the channel; a debris tail, representing deposited sediment, usually forms on the intervening slope between the landslide scar and stream line. The sediment delivery ratio (SDR) is highly variable and a function of hillslope topography, physical characteristics, runout distances of landslide debris tails, and any subsequent storm runoff that may remove sediment, before revegetation of the debris tail. Short steep slopes that connect directly to the channel are much more likely to deliver eroded sediment (*SDR* ~80–100%) than the long gentler slopes (*SDR* ~20–80%). Where there are intervening very low angle slopes in the flow path between the landslide site and channel, such as terraces, there is a lower probability that sediment will reach the channel (*SDR* < 20%).

In the sediment budget of the Tutira catchment following Cyclone Bola in 1988, Page et al. (1994) showed that of the sediment generated from hillslopes, 57% entered or passed through the lake, with the remainder being deposited equally on hillslopes and valley floors. Landslide erosion was the dominant (89%) sediment source. Similarly, Reid and Page (2003) found landslide sediment delivery ratios varied from 0.4 to 0.6 (40–60%) in the Te Arai Land System. A number of other studies, however, indicate that a smaller percentage of sediment from landslides from individual storm events will reach stream channels. For example, Preston (2008) examined 220 landslides in the Muriwai Hills and found that ~26% of soil material was delivered to the fluvial system. Similarly, a study of landslide runout following the February 2004 storm in the Mangawhero catchment (Wright 2005) found that 33% of material from fluvially coupled and 14% of non-coupled landslides reached the fluvial system, showing that event coupling increases the likelihood of sediment delivery from hillslopes.

Sediment delivery ratios have been assigned to each erosion terrain based on the field data collection and published literature.

Table 1 Currently assigned SDRs

Erosion terrain description	Erosion terrain code	SDR
Hill country with loess	611	0.5
Hill country with tephra	614	0.5
Hill country on mudstone	631	0.5
Hill country on crushed mudstone/argillite with moderate earthflow erosion	632	0.5
Hill country on crushed mudstone/argillite with severe earthflow erosion	633	0.5
Hill country on cohesive sandstone	641	0.5
Hill country on non-cohesive sandstone	642	0.5
Hill country on limestone	651	0.5
Hill country on moderately weathered greywacke/argillite	661	0.5
Hill country on slightly weathered white argillite	662	0.5
Hilly steeplands on mudstone	731	0.5
Hilly steeplands on sandstone	741	0.5
Hilly steeplands on non-cohesive sandstone	742	0.5
Hilly steeplands on sandstone/limestone	751	0.5
Hilly steeplands on greywacke/argillite	761	0.5
Hilly steeplands on white argillite	762	0.5
Mountain land on greywacke/argillite/younger sedimentary rocks	911	0.1
Mountain land/steepland with sheet/wind/scree erosion	912	0.1

4.3 Gullies

The primary input for gully erosion is a gully density raster representing the lineal extent of gullies per unit area (km km^{-2}), which is combined with average gully area, and soil density to calculate the mass of soil delivered by gullies. One hundred percent sediment delivery is assumed. Sediment delivery to the channel within an internal watershed area (*GME*, t km^{-2} yr^{-1}) is given as

$$GME = \frac{\rho \overline{A_g}\ \overline{GD}}{T} \tag{4}$$

where $\overline{A_g}$ is the mean cross sectional area of gullies, ρ is soil bulk density and $\overline{GD}$ is the gully density in square kilometres and T is the time since gully initiation (= 100 years). Gully density and cross sectional area have been established by air photo analysis and field characterisation. Spatial extrapolation of gully data is based on mapping of those erosion terrains in which gully erosion occur. This is limited to hill country and hilly steeplands on non-cohesive sandstone (erosion terrains 642 and 742).

4.3.1 Input data for mass-movement gully complexes

Input data are estimated for each 15-m resolution cell in a gully erosion terrain:

ρ = 1.5 t m^{-3}

$\overline{A_g}$ = 900 m^2 (estimated from field data)

$\overline{GD}$ = 0.22 for erosion terrains 742 and 642

4.4 Earthflow erosion

Slow-moving earthflows are common in some areas, particularly those underlain by crushed mudstone and argillite lithologies. Their morphology has a central conveyer system that delivers sediment from hillslopes to the valley bottom. Sediment is ultimately delivered to streams as a result of channel erosion at the toe of the earthflow.

Sediment delivery from earthflows (*EE*, t km^{-2} yr^{-1}) is estimated similarly to gully erosion as a function of areal density of earthflows, average movement rate, and the depth and bulk density of earthflow materials:

$$EE = \rho \overline{M_e}\,\overline{D_e}\,\overline{ED} \tag{5}$$

$\overline{M_e}$ is the mean speed of earthflows (m yr^{-1}),

$\overline{D_e}$ is the mean depth of earthflows (m),

$\overline{ED}$ is the density of earthflows in m km^{-2}, and ρ is the bulk density.

The primary inputs for earthflow erosion were derived for a representative window in earthflow erosion terrain and spatially applied using the mapped distribution of earthflow-prone erosion terrains. Movement rates and earthflow depths were estimated from previous studies (Pearce et al. 1987; Marden et al. 1992, 2008; Zhang et al. 1993) and by expert opinion based on extensive field experience (Chris Phillips and Mike Marden, pers. comms). Spatial extrapolation of earthflow data is based on mapping of erosion terrains in which earthflow erosion occurs. This is limited to hill country on crushed mudstone/argillite (erosion terrain codes 632 and 633).

4.4.1 Input data for earthflow erosion

Input data is estimated for each of 15-m resolution grid cells:

ρ = 1.5 t m^{-3}

$\overline{M_e}$ = 0.1 m yr^{-1}

$\overline{D_e}$ = 3.0 (m)

$\overline{ED}$ = 1024 m km^{-2}

4.5 Stream and watershed network

The SedNetNZ stream link and watershed network for Kaipara Harbour was derived from NIWA's reference stream network – River Environment Classification (REC2).

4.6 Riverbank erosion

The volumetric rate of erosion per unit channel length (BE, m^3 m^{-1} yr^{-1}) is given by

$$BE = M \times H \tag{6}$$

where H is bank height (m) and M is bank migration rate in m yr^{-1}. A preliminary dataset of bank migration rate in (m yr^{-1}) on 26 New Zealand river reaches has been compiled and these are positively correlated with the Water Resources Explorer New Zealand (WRENZ) (NIWA 2007) modelled annual flood discharge (Fig. 3) allowing bank migration rate to be predicted from annual flood discharge. The exponent in the regression model (0.469) is within the range of values reported elsewhere.

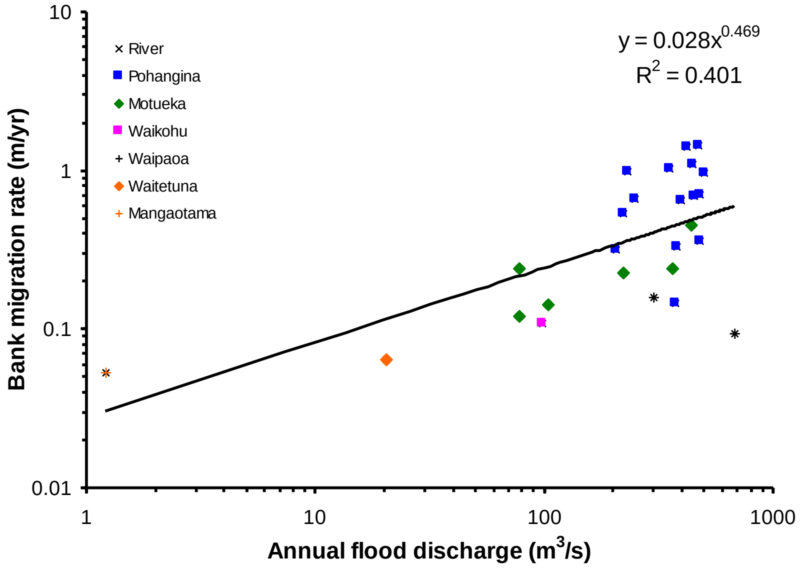

Figure 3 Average channel migration in relation to mean annual flood discharge (WRENZ-modelled) for New Zealand rivers.

4.6.1 Input data for bank erosion

The mean annual flood for each gauged subcatchment (Q_f) in the Kaipara harbour catchment was related to the measured mean discharge ($\bar{q}$) using equation 7:

$$Q_f = a\bar{q}^b \qquad (7)$$

where a = 30 and b = 1.0 (see Fig. 3.)

The mean discharge for the subcatchments in the Kaipara SedNetNZ model was determined by first estimating the mean runoff in mm (estimated from the national WATYIELD model (Fahey et al., 2010)) and multiplying by subcatchment area to determine the volume of runoff per year. The SedNetNZ hydrological accumulation routine was executed to determine the total mean discharge down the stream network. The mean annual flood was estimated using equation (7) for each subcatchment.

The bank migration rate for each subcatchment was estimated using the relationship between the mean annual flood and bank migration rate shown in Figure 3. Riparian vegetation is assumed to be primarily grass.

Bank height was estimated using a regional relationship between bank height and mean discharge (Q_{mean}):

$$H = 2 + \log_{10} Q_{mean} \qquad (8)$$

The final bank erosion rate was derived from the product of bank migration rate, bank height, and stream length and stored as the total for each subcatchment.

Floodplain deposition

Floodplain deposition rates are estimated separately for Wairoa, Kaipara, and Hoteo rivers. Other rivers are assumed to have similar deposition rates and without flood-control stopbanks. For each tributary the proportion, p, of the total sediment load that overtops the banks, i.e. the sediment load carried in discharges exceeding bank-full discharge (defined as the discharge with return period of 1.5 years) is estimated. The total sediment deposited on floodplains for each tributary is then estimated by the product of p and the total sediment load in the tributary. The annual rate of floodplain deposition for a tributary is then estimated by dividing the total deposited sediment by the area of flood plain in the tributary catchment (from erosion terrains). If the tributary is controlled by flood-control banks then the deposition rate is modified by multiplying by a flood-control factor (presently set to 0).

5 Modelling effect of farm plan and river bank fencing scenarios

5.1 Farm plan scenarios

Based on AgriBase, the total sediment delivery from hillslope erosion for each farm was calculated and the results summed up for each of the priority catchments defined by NRC. A 70% erosion reduction was assumed for farms with farm plans implemented (Dymond et al. 2010). AgriBase cannot be considered complete in regard to its inclusion of individual farms. AgriBase contains gaps or missing polygons in the data covered by farms. These data gaps have to be considered when interpreting the results of the scenario modelling.

5.2 River bank fencing scenarios

The rationale for scenario modelling of river bank fencing is the protection from stock trampling and stabilisation by vegetation to reduce stream bank erosion. Erosion reduction was estimated by applying percentage reduction of sediment loads when a fencing scenario was applied. These scenarios were applied to river fencing of the most erosion-prone subcatchments for the Greater Kaipara catchment (one of the priority catchments defined by NRC). It was assumed that river fencing reduces net riverbank erosion by 80%.

6 Results

6.1 Comparison of modelled with measured sediment yields

Table 2 shows measured sediment loads for water level recorder sites in the Kaipara Harbour Catchment where sediment loads have been measured (Curran-Cournane et al. 2013). Modelled loads by SedNetNZ compare favourably with measurements.

Table 2 Comparison of measured sediment loads with modelled sediment loads

	Measured			*Modelled*	
Site	Area (km^2)	sediment yield ($t/km^2/yr$)	sediment load (t/yr)	SedNetNZ yield ($t/km^2/yr$)	SedNetNZ load (t/yr)
Kaipara at Waimauku	163	32	5216	62	10065
Kaukapakapa at Taylors	62	76	4712	60	3719
Hoteo at Gubbs	268	74	19832	125	33366

6.2 Predicted erosion reduction

The individual datasets for the 11 priority catchments defined by NRC can be found in Appendix 1, Table 3–13. The tables show the reduction in sediment load that can be achieved when implementing farm plans for different percentages of the overall number of farms in the priority catchments. The farms are ordered according to their total sediment delivery by hillslope erosion. Percentages were calculated when comparing the achievable reduction with the overall sediment delivery of all farms identified by Agribase and with the overall sediment delivery in the priority catchment.

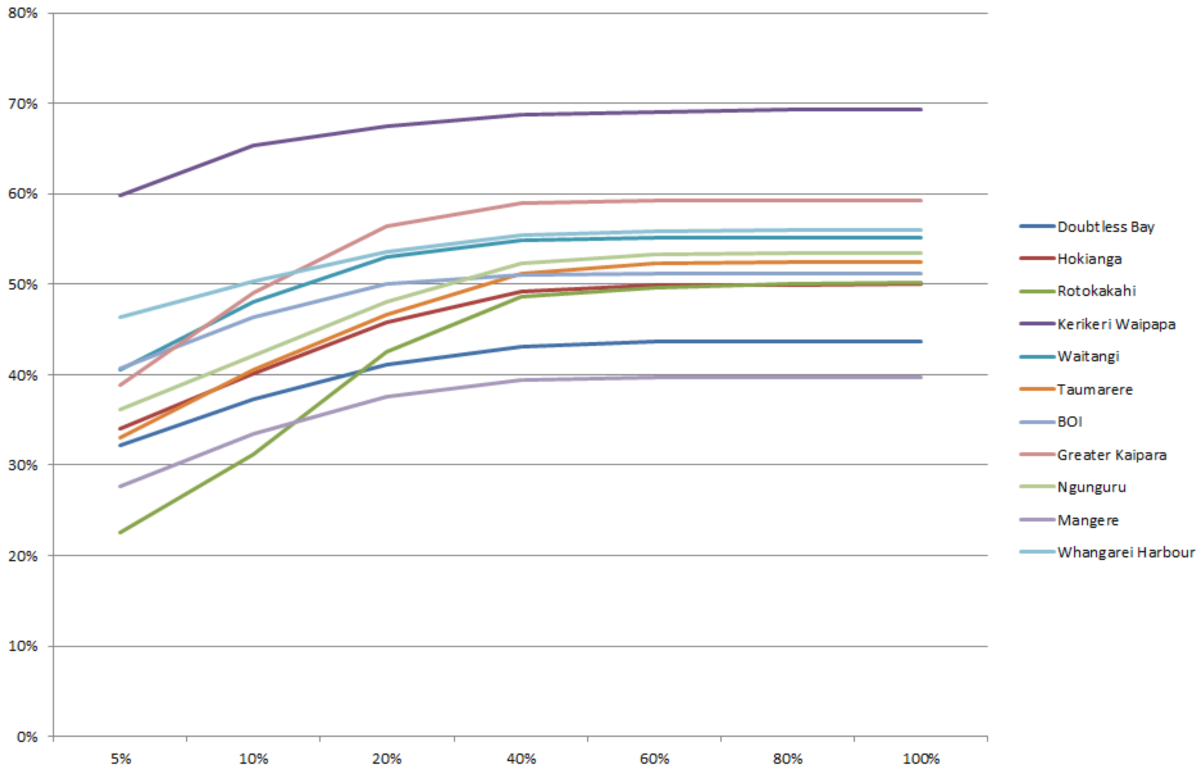

Figure 4 Comparison of predicted erosion reduction between priority catchments. The X-axis denotes the percentage of farms with implemented farm plans, ordered by erosion severity. The Y-axis shows the reduction in sediment by the priority catchment.

Figure 4 shows the predicted erosion reductions when different percentages of farm plans are implemented when comparing between the priority catchments.

Results for predicted erosion reduction by river fencing can be found in Appendix 1, Table 14. Similar to the farm plan scenarios, the catchments are ordered by their sediment load.

7 Discussion

In all priority catchments we found that the best erosion reduction can be achieved when farm plans are implemented in the 5% of farms with highest sediment loads with the reductions becoming marginal for the lower 60 %. It has to be taken into account that high sediment loads are a result of both farm size as well as erosion severity. A similar trend can be overserved in the river fencing scenarios.

The maximum hillslope erosion reduction that can be achieved by farm plans differs between the priority catchments. This is a result of different land use patterns: in some of the priority catchments a high percentage of the overall area is covered by farms, while in others this number is lower and larger areas are under forest.

8 Conclusions

- The implementation of farm plans could be focused on farms identified as having the highest total erosion rates; the priority catchments show a similar trend in this regard, but the erosion reduction differs.
- Gaps in the AgriBase dataset create uncertainty about the margins that can be reached.
- Ratio of sediment coming out of farm and other areas differs quite strongly between priority catchments.

9 References

Ausseil A-GE, Dymond JR 2008. Estimating the spatial distribution of sediment concentration in the Manawatu River, New Zealand, under different land-use scenarios. IAHS Publication 325: 502–509.

CurranCournane F, Holwerda N, Mitchell F 2013. Quantifying catchment sediment yields in Auckland. Auckland Council technical report TR2013/042.

De Rose RC 1995. Slope limitations to sustainable land use in hill country prone to landslide erosion. New Zealand Association of Resource Managers Broadsheet, November 1995. Pp. 117–133.

De Rose RC 1996. Relationships between slope morphology, regolith depth, and the incidence of shallow landslides in eastern Taranaki hill country. Zeitschrift für Geomorphologie NF Supp.-Bd. 105: 49–60.

De Rose RC 2012. Slope control on the frequency distribution of shallow landslides and associated soil properties, North Island, New Zealand. Earth Surface Processes and Landforms 38: 356–371.

De Rose RC, Basher LR 2011. Strategy for the development of a New Zealand SedNet. Landcare Research Contract Report LC226 for AgResearch and Ministry of Science and Innovation. 60 p.

Ding J, Richards K 2009. Preliminary modelling of sediment production and delivery in the Xihanshui River basin, Gansu, China. Catena 79: 277–287.

Dymond JR 2010. Soil erosion in New Zealand is a net sink of CO_2. Earth Surface Processes and Landforms 35: 1763–1772.

Dymond J, Shepherd J 2006. Highly erodible land in the Manawatu/Wanganui region. Landcare Research Contract Report LC0607/027 for Horizons Regional Council.

Dymond JR, Ausseil A-G, Shepherd JD, Buettner L 2006. Validation of a region-wide model of landslide susceptibility in the Manawatu–Wanganui region of New Zealand. Geomorphology 74: 70–79.

Dymond JR, Betts H, Schierlitz CS 2010. An erosion model for evaluating regional land-use scenarios in New Zealand. Environmental Modelling and Software 25: 289–298.

Dymond J, Herzig A, Betts H, Marden M, Phillips C, Basher L 2013. Application of SedNetNZ for assessment of critical source areas for the Manawatu catchment. Landcare Research Contract Report.

Dymond JR, Shepherd J, Page M 2008. Roll out of erosion models for regional councils. Landcare Research Contract Report LC0708/094 for Ministry of Agriculture and Forestry. 50 p.

Elliott AH, Basher LR 2011. Modelling sediment flux: a review of New Zealand catchment-scale approaches. Journal of Hydrology (NZ) 50: 143–160.

Elliott AH, Oehler F, Schmidt J, Ekanayake JC 2012. Sediment modelling with fine temporal and spatial resolution for a hilly catchment. Hydrological Processes 26: 3645–3660.

Elliott AH, Shankar U, Hicks DM, Woods RA, Dymond JR 2008. SPARROW regional regression for sediment yields in New Zealand rivers. In: Sediment Dynamics in Changing Environments, Proceedings of a symposium held in Christchurch, New Zealand, December 2008. International Association of Hydrological Sciences Publication 325: 242–249.

Fahey B, Ekanayake J, Jackson R, Fenemor A, Davie T, Rowe L 2010. Using the WATYIELD water balance model to predict catchment water yields and low flows. Journal of Hydrology (NZ) 49: 35–58.

Glade T 1998. Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. Environmental Geology 35: 160–174.

Hicks DM, Hill J, Shankar U 1996. Variation of suspended sediment yields around New Zealand: the relative importance of rainfall and geology. IAHS Publication 236: 149–156.

Hicks DM, Shankar U 2003. Sediment from New Zealand rivers. NIWA Chart, Misc. Series no. 79. Wellington, National Institute of Atmospheric and Water Research.

Hicks M, Quinn J, Trustrum 2004. Stream sediment load and organic matter. In: Harding JS, Mosley MP, Pearson CP, Sorrell BK eds Freshwaters of New Zealand. Christchurch, New Zealand Hydrological Society and New Zealand Limnological Society. Pp. 12.1–12.16.

Hicks DM, Shankar U, McKerchar AI, Basher L, Jessen M, Lynn I, Page M 2011. Suspended sediment yields from New Zealand rivers. Journal of Hydrology (NZ) 50: 81–142.

Hicks M, Hoyle, J 2012. Analysis of suspended sediment yields from the rivers in the Horizons sediment monitoring program. NIWA Client Report No. CHC2012-107.

Leathwick J, Wilson G, et al. 2003. Land environments of New Zealand. David Bateman, Auckland.

Marden M, Rowan D 1993. Protective value of vegetation on tertiary terrain before and during cyclone Bola, East Coast, North Island, New Zealand. New Zealand Journal of Forestry Science 23: 255–263.

Marden M, Phillips CJ, Jackson RJ, Zhang XB, Ekanayake J 1992. A decade of earthflow research and interrelated studies in the North Island of New Zealand. In: Proceedings of International Symposium on erosion, debris flows and environment in mountain regions. Chengdu, China, July 1992. IAHS Publication 209: 263–271.

Marden M, Phillips, C, Rowan D 2008. Recurrent displacement of a forested earthflow and implications for forest management, East Coast Region, New Zealand. In: Sediment dynamics in changing Environments (Proceedings of a symposium held in Christchurch, NZ December, 2008). IAHS Publ. 325: 491–501.

McKergow LA, Prosser IP, Hughes AO, Brodie J 2005. Sources of sediment to the Great Barrier Reef World Heritage Area. Marine Pollution Bulletin 51: 200–211.

NIWA 2007. Water Resources Explorer New Zealand (WRENZ). http://wrenz.niwa.co.nz/webmodel/.O'Loughlin CL, Pearce AJ 1976. Influence of Cenozoic geology on mass movements and sediment yield response to forest removal, North Westland New Zealand. Bulletin of the International Association of Engineering Geology 14: 41–46.

Page MJ, Trustrum NA, Dymond JR 1994. Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. Geomorphology 9: 169–188.

Parkner T, Page M, Marden M, Marutani T 2007. Gully systems under undisturbed indigenous forest, East Coast Region, New Zealand. Geomorphology 84: 241–253.

Pain CF, Stephens PR 1990. Storm damage assessment using digitised aerial photographs: Eltham, New Zealand, 24–25 February 1986. New Zealand Geographer 46: 12–25.

Pearce AJ, O'Loughlin CL, Jackson RJ, Zhang XB 1987. Reforestation: on-site effects on hydrology and erosion, eastern Raukumara Range, New Zealand. Forest Hydrology and Watershed Management, Proceedings of the Vancouver Symposium, August 1987. IASH Publication 167: 489–497.

Phillips JD, Gomez B 2007. Controls on sediment export from the Waipaoa River basin, New Zealand. Basin Research 19: 241–252.

Preston NJ 2008. Off-slope sediment delivery from landsliding during a storm, Muriwai Hills, North Island. In: New Zealand sediment dynamics in changing environments. IAHS Publication 325: 237–241.

Prosser IP, Young B, Rustomji P, Moran C, Hughes AO 2001. Constructing river basin sediment budgets for the National Land and Water Resources Audit. CSIRO Tech. Rep. 15/01, Canberra, Australia, CSIRO Land and Water.

Reid L, Page MJ 2003. Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology 49: 71– 88.

Roygard J 2011. Cleaning up the Manawatu River. http://www.ipenz.org.nz/riversgroup/events-documents/presentations/06%20John%20Roygard%20'Cleaning%20up%20the%20Manawatu_%20River'.pdf

Schmidt J, Turek G, Clark MP, Uddstrom M, Dymond JR 2008. Probabilistic forecasting of shallow, rainfall-triggered landslides using real-time numerical weather predictions. Natural Hazards and Earth System Sciences 8: 349–357.

Wilkinson S, Henderson A, Chen Y, Sherman B 2004. SedNet user guide. Client Report, Canberra, CSIRO Land and Water. 96 p. (www.toolkit.net.au/sednet)

Wilkinson SN, Prosser IP, Rustomji P, Read AM 2009. Modelling and testing spatially distributed sediment budgets to relate erosion processes to sediment yields. Environmental Modelling & Software 24: 489–501.

Woods R, Elliott S, Shankar U, Bidwell V, Harris S, Wheeler D, Clothier B, Green S, Hewitt A, Gibb R, Parfitt R, Wheeler D 2006. The CLUES Project: predicting the effects of land-use on water quality – Stage II. NIWA Client Report HAM2006-096.

Wright KC 2005. The landslide event of February 2004 in geomorphic perspective. Unpublished MSc thesis, Victoria University of Wellington, New Zealand.

Zhang X, Phillips C, Marden M 1993. A comparison of earthflow movement mechanisms on forested and grassed slopes, Raukumara Peninsula, North Island, New Zealand. Geomorphology 6: 175–187.

Appendix 1 - Scenarios

Table 3 Farm plan scenarios for Doubtless Bay priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	74543.70	159.52	51.58	32.21
10	86273.48	228.04	59.70	37.27
20	95123.30	308.89	65.82	41.10
40	99890.33	400.11	69.12	43.16
60	100992.98	437.14	69.88	43.63
80	101148.02	458.34	69.99	43.70
100	101162.14	464.48	70.00	43.71

Table 4 Farm plan scenarios for Hokianga priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	117908.98	376.77	47.70	34.06
10	138792.99	502.90	56.15	40.09
20	158492.25	673.13	64.12	45.79
40	170350.90	823.41	68.92	49.21
60	172603.95	881.77	69.83	49.86
80	172985.89	912.69	69.99	49.97
100	173016.62	921.79	70.00	49.98

Table 5 Farm plan scenarios for Rotokakahi priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	11213.18	26.53	31.57	22.61
10	15505.65	50.18	43.66	31.26
20	21071.07	71.12	59.33	42.48
40	24098.56	92.99	67.86	48.58
60	24630.34	100.00	69.35	49.66
80	24829.76	103.42	69.91	50.06
100	24860.06	104.56	70.00	50.12

Table 6 Farm plan scenarios for Kerikeri Waipapa priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	3398.28	59.26	60.50	59.89
10	3706.13	74.27	65.98	65.31
20	3828.38	85.52	68.15	67.47
40	3898.04	94.26	69.39	68.69
60	3920.84	98.30	69.80	69.10
80	3929.70	101.46	69.96	69.25
100	3932.14	102.80	70.00	69.29

Table 7 Farm plan scenarios for Waitangi priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	10912.64	74.72	51.42	40.56
10	12931.61	118.70	60.94	48.06
20	14267.87	174.90	67.23	53.03
40	14746.14	211.08	69.49	54.81
60	14826.58	222.85	69.87	55.11
80	14849.91	227.35	69.98	55.19
100	14854.85	228.94	70.00	55.21

Table 8 Farm plan scenarios for Taumarere priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	51833.45	107.33	44.05	32.99
10	63614.68	153.67	54.06	40.48
20	73194.61	199.33	62.20	46.58
40	80344.01	272.16	68.27	51.13
60	82106.72	303.83	69.77	52.25
80	82367.31	312.44	69.99	52.42
100	82377.45	314.48	70.00	52.42

Table 9 Farm plan scenarios for Bay of Islands priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	88090.56	329.88	55.76	40.75
10	100249.73	467.24	63.46	46.37
20	108087.24	632.72	68.42	50.00
40	110283.29	740.05	69.81	51.01
60	110509.68	767.07	69.96	51.12
80	110566.98	779.12	69.99	51.15
100	110579.61	784.76	70.00	51.15

Table 10 Farm plan scenarios for Greater Kaipara priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	247918.41	1439.59	45.97	38.92
10	312279.63	1971.19	57.91	49.02
20	359105.64	2622.98	66.59	56.37
40	375504.31	3290.36	69.63	58.94
60	377223.25	3514.62	69.95	59.21
80	377453.41	3580.26	69.99	59.25
100	377488.61	3596.77	70.00	59.26

Table 11 Farm plan scenarios for Ngunguru priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	4681.73	41.66	47.35	36.19
10	5444.41	45.68	55.06	42.09
20	6210.61	54.41	62.81	48.02
40	6771.77	61.41	68.48	52.35
60	6897.81	63.57	69.76	53.33
80	6919.71	64.37	69.98	53.50
100	6921.74	64.66	70.00	53.51

Table 12 Farm plan scenarios for Mangere priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	2800.90	23.74	48.56	27.58
10	3395.07	35.12	58.86	33.43
20	3811.63	50.08	66.08	37.53
40	4006.23	58.51	69.46	39.45
60	4028.99	61.14	69.85	39.67
80	4036.01	62.79	69.97	39.74
100	4037.46	63.37	70.00	39.76

Table 13 Farm plan scenarios for Whangarei harbour priority catchment

% of farms (AgriBase) with farm plans	Overall reduction (T/yr)	Area (sqkm)	% reduction achieved (Agribase farms)	% reduction achieved (total)
5	18538.11	89.24	57.96	46.40
10	20129.84	111.36	62.93	50.38
20	21390.77	135.46	66.88	53.53
40	22129.58	153.51	69.19	55.38
60	22327.55	172.46	69.80	55.88
80	22379.45	180.58	69.97	56.01
100	22390.18	184.92	70.00	56.04

Table 14 River fencing scenarios

% of subcatchments fenced	Overall reduction (T/yr)	Area (sqkm)	% reduction
5	174915.94	252.81	60.84
10	198198.25	491.56	68.94
20	215224.54	1054.81	74.86
40	226026.69	2095.57	78.62
60	228815.74	3059.14	79.59
80	229709.51	3829.73	79.90
100	229988.94	4343.87	80.00