Waikato Regional Council Technical Report 2013/54

Assessing erosion in the Waipa catchment using the New Zealand Empirical Erosion Model (NZeem®), Highly Erodible Land (HEL), and SedNetNZ models

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

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October 2013

Document #: 2920564

Approved for release by:
Patrick Whaley Date November 2013

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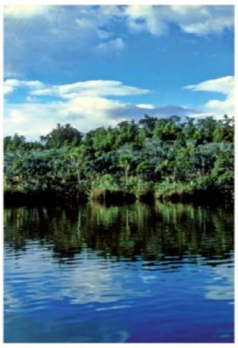

Landcare Research
Manaaki Whenua

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ISO 14001

Doc#: 2920564

Contents

Summary

Project and Client

Landcare Research was funded by Waikato Regional Council (WRC) to undertake an analysis of the Waipa catchment to identify high-risk areas of hillslope sediment generation, high-risk areas of stream bank erosion, and undertake an assessment of the work required to reduce suspended sediment loads in the river and stream network.

Objectives

- using the Highly Erodible Land (HEL) model, evaluate high risk areas of hillslope sediment generation
- using NZeem®, provide a quantitative analysis of where sediment in rivers is sourced
- assess stream bank erosion using the SedNetNZ model
- undertake simulation/scenario modelling to assess reductions in sediment loads through potential mitigation strategies.

Methods

The Highly Erodible Land (HEL) model was used to identify land at risk to landslide erosion (using slope thresholds defined by erosion terrain and vegetation cover) and whether the sediment is likely to be delivered to streams. It also identifies land at risk of earthflow erosion based on previous mapping of earthflows and distinguishes two classes (moderate earthflow risk, and severe earthflow risk).

To identify where fine sediments across the Waipa catchment are potentially coming from, we used the soil particle size (*PS* field) from the Fundamental Soil Layers, which provides an estimate of the dominant particle size class of the soil profile to c. 1 m. The classes were grouped in to clay-, silt-, and sand-dominated particle sizes. We also analysed a series sediment samples from floodplain of the main Waipa stem and all major tributaries.

The New Zealand Empirical Erosion Model (NZeem®) was used to provide estimates of spatial variation in sediment generation from rainfall, erosion terrain and vegetation cover. Under tall woody vegetation cover NZeem® assumes a reduction factor of 10 in erosion rates compared with herbaceous vegetation or bare ground. For the Waipa catchment woody vegetation cover was determined by using both the EcoSat (~2003) and the LCDB3 (~ 2008) layers.

NZeem® and AgriBase were intersected to estimate the potential of sediment reduction through adoption of soil conservation farm plans, assuming a 70% reduction in sediment where farm plans were fully implemented. This was used to calculate the potential reduction in sediment generation by focusing on farms that have the greatest area of HEL.

The SedNetNZ model was used to calculate bank erosion from bank height, mean annual flood, and bank migration rate. Bank erosion was summed across stream links to provide overall stream bank erosion. The potential reduction in bank erosion from riparian fencing

was also calculated assuming a reduction in stream bank erosion of 80% where adequate fencing was provided.

Waikato Regional Council provided information on the current status for stream bank fencing across the Waipa catchment. An analysis was undertaken to estimate stream bank erosion where no fencing was present, 25% (current situation), 50%, and 100% fenced on both sides of the river or stream.

To provide additional information around particle size characteristics, sediment samples were collected from selected tributaries and the Waipa River main stem immediately above selected tributaries. The rationale was to explore the likely sources of fine sediments (clay) associated with the Waipa River and its tributaries.

Results

Of the Waipa catchment, 3.2% was classed as Highly Erodible Land (HEL), with 3180 ha at risk of landsliding with potential of delivery to streams, and a further 2100 ha are classed as non-contributing. The HEL erosion mostly occurs along the western margins and in the upper reaches. Land with a moderate (4360 ha) and severe earthflow risk (185 ha) occurs in the northwest and southern Waipa catchment. Seven hundred and 8800 ha of HEL have a dominant clay- and silt-particle-size distribution respectively.

NZeem® provides a quantitative spatial picture of the source of sediment in rivers. The NZeem® analysis identifies the steeper terrain along the north-western and western margins and the south-west of the Waipa catchment as having the highest erosion rates. When data are converted to a sediment load basis (t yr^{-1} from each sub-catchment), the Mangapu, Moakurarua, and the Whatawhata/Ngaruawahia sub-catchments have the highest loads: 33 000, 30 000, and 21 000 t yr^{-1} respectively. Using NZeem® and AgriBase, a scenario model was developed to investigate on-farm sediment reduction through mitigation strategies (farm plans). The model focuses on farms in the Waipa catchment that have the greatest area of Highly Erodible Land (HEL), and thereby greatest potential to erosion risk. The model assumed a 70% reduction in sediment was achieved where farm plans were fully implemented. The model suggests that sediment loss prevented using NZeem® values ranges from 60 000 to 100 000 t yr^{-1} across 100–500 farms respectively.

The SedNetNZ model was used to undertake an assessment of stream bank erosion occurring within the Waipa catchment. The stream bank sediment yield (t m^{-1} yr^{-1}) was modelled with no management intervention, 25% fenced (current status), 50% fenced, and 100% fenced on both sides of rivers and streams. Estimates show a potential reduction in sediment load (total) of 488 000 t yr^{-1} was potentially possible from the current modelled status of 650 000 t yr^{-1} to 162 000 t yr^{-1} by fencing all rivers and streams of the Waipa catchment.

Sediment samples collected from selected tributaries and the Waipa River main stem immediately above the selected tributaries show that clay percentages are extremely low (< 5%) with a dominance in all samples of sand and silt. This is very low compared with what might have been expected from the clay content of soils in the catchment, especially those from old volcanic ash or weathered greywacke. The clay content measured in all samples is low and considering the low water clarity suggests more attention is needed to define the nature of the sediment load.

Conclusions

The area of highly erodible land (HEL) in the Waipa catchment is small (3% of the Waipa catchment area). HEL identifies that about half of the erosion area is at risk from landsliding and the remainder from earthflow erosion. The areas at risk from landslide erosion occur mostly in the steeper headwaters of the western and southern tributaries. Earthflow areas at risk of erosion are mostly found in the southern headwaters of the Waipa catchment.

A similar result is found using the NZeem® model. Sediment loads (t yr^{-1}) are highest in the Mangapu, Moakurarua, and the Whatawhata/Ngaruawahia sub-catchments with 33 000, 30 000, and 21 000 t yr^{-1}, respectively. Scenario modelling using NZeem® and AgriBase suggests an on farm sediment reduction through mitigation strategies (farm plans) from 60 000 to 100 000 t yr^{-1} for farms identified as having the greatest HEL area across 100–500 farms, respectively (based on AgriBase polygons) is possible. This approach enables a focus on farms identified by AgriBase and HEL and the application of potential mitigation strategies for targeted farm numbers.

SedNetNZ scenario modelling predicts that if all remaining stream banks be fenced, total stream bank erosion could be reduced from 650 000 t yr^{-1} (with 25% fencing on both sides of rivers and streams) to 162 000 t yr^{-1}.

Sediment samples collected from overbank floodplain deposits were found to have low clay percentages (generally <5%). The clay content measured in all samples along the Waipa River and its tributaries is relatively low and considering the low water clarity suggests more attention is needed to define the nature of the sediment load in the water column.

Considering the high turbidity of the lower reaches of the Waipa, the sediment yield measured at the Whatawhata site is low (60 t km^{-2} yr^{-1}). This suggests that to improve the clarity of the Waipa River we need a better understanding of the factors controlling clarity along with sediment load. This would require targeting areas that produce the finest sediment. The clarity of the Waipa River remains poor even at low flows, which implies that particles suspended in the water column are fine.

1 Introduction

A Waipa Catchment Plan is being developed by the Waikato Regional Council (WRC) to provide direction for the protection and restoration of the health and well-being of the Waipa catchment. An overview of the sub-catchments, and the rivers and streams associated with the Waipa catchment is shown in Figure 1. Landcare Research has been funded by WRC to undertake an analysis of the Waipa catchment to identify (1) high risk areas of hillslope sediment generation, (2) high risk areas of stream bank erosion, and (3) undertake an assessment of the work required to reduce suspended sediment loads in the stream and river network.

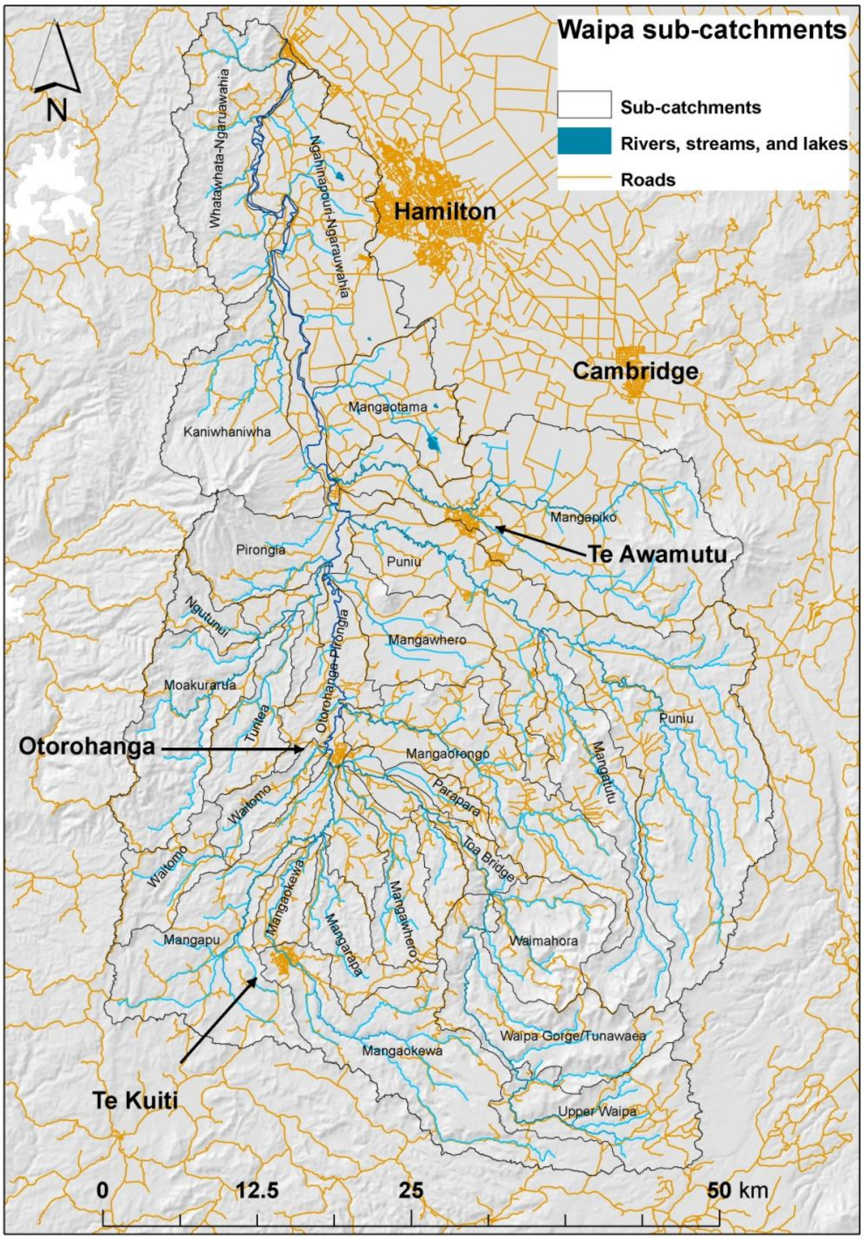

Figure 1 The sub-catchments of the Waipa River as defined by the Waikato Regional Council. Major cities, towns, and roads are provided for completeness.

2 Background

The Waipa River is the biggest sediment contributor to the Waikato River system, supplying 67% of the total load of the lower Waikato (Hicks et al. 2001; Hicks & Hill 2010). It has a dramatic effect in increasing turbidity of the main stem to the Waikato River at the Waipa confluence. Average water clarity in the Waipa at Whatawhata over the period 1989–2007 was only 0.6 m and it decreased over that period (Rutherford & Quinn 2010). The Waikato River Independent Scoping Study has set a target for water clarity of 1.6 m (Appendix 13 in Rutherford & Quinn 2010).

Identifying sediment sources is a key to reducing the load of the river. Hicks and Hill (2010) and Hill (2011) suggest mass movement and streambank erosion are major sources of sediment, and also point to a large landslide that occurred in the Tunawaea catchment in 1991 as a significant contributor. Suspended sediment yields measured at sites within the Waipa catchment (Hoyle et al. 2011) vary widely from 37 t km^{-2} yr^{-1} in the Mangatutu to 230 t km^{-2} yr^{-1} in the Waitomo (Table 1). The yield at the lowermost gauging site at Whatawhata is 60 t km^{-2} yr^{-1}.

Table 1 Suspended sediment yields in the Waipa catchment (Hoyle et al. 2012)

Catchment	Area (km^2)	SSY (t km^{-2} yr^{-1})	Load (t yr^{-1})
Waipa at Otewa	317.0	175.2	55 538
Waipa at Otorohanga	919.0	96.8	88 959
Mangatutu Stream at Walker Rd Bridge	123.0	37.3	4588
Mangapu River at SH3 bridge us Mangaokewa confluence	151.0	71.5	10 775
Mangaokewa at Te Kuiti Pumping Station	173.2	54.5	9439
Waitomo at Aranui Caves	20.5	229.9	4713
Waipa at Whatawhata	2826.0	59.6	168 430

Typically sediment is derived from only small parts of a landscape with these critical source areas tending to have spatially distinct zones of generation and transport that vary greatly according to management and land use. Predictive models can be used to target these critical source areas and predict the impact of erosion on water quality and quantity under current and future land management regimes (Elliott et al. 2006; Elliott & Basher 2011). There is also a need to evaluate contemporary sediment loads in relation to natural or background levels in order to set realistic targets for reducing sediment load.

The highly erodible land (HEL) model (Dymond et al. 2006) identifies land at risk of severe mass-movement erosion (landslide, earthflow, and gully), assesses the risk of sediment delivery to streams, but does not provide numerical estimates of erosion. HEL identifies land susceptible to landsliding using three main datasets: slope derived from a Digital Elevation Model (DEM), rock type derived from the New Zealand Land Resource Inventory (NZLRI, Newsome et al. 2000), and a land cover map (from satellite imagery (Landcare Research 2004). Land at risk of landslide erosion is defined by slope thresholds that are related to rock type and land cover (Dymond et al. 2006). Using a 15-m cell size resolution layer, slope can be examined to see if it exceeds the threshold set for each rock/regolith type. If a cell exceeds the slope threshold, and does not have protective woody vegetation (determined from land cover imagery) then the land is identified as susceptible to landsliding. Land at risk to landsliding is further classified as connected to a stream channel or not connected. The flow path downstream is traversed across a 15-m cell size resolution DEM using flow direction and accumulative flow algorithms, to determine whether a cell at that location can deliver sediment to a stream. If the modelled sediment flow path encounters more than two consecutive cells of low slope (i.e. <5 degrees), the cell is termed 'non-contributing', if not, the cell is determined as 'contributing'. Land susceptible to earthflow and gully erosion is derived from the erosion data in the New Zealand Land Resource Inventory.

Current empirical erosion models developed for New Zealand relate specific suspended sediment yield (t km^{-2} yr^{-1}) to mean annual rainfall and an 'erosion terrain' classification. Erosion terrains were developed from 1:50 000 NZLRI data. These empirical models are calibrated using long-term load estimates from ~200 rivers across New Zealand. The models include (1) Suspended Sediment Yield Estimator (Hicks & Shankar 2003; Hicks et al. 2011), (2) SPARROW (Elliot et al. 2008), and (3) NZeem® (Dymond et al. 2010). NZeem® and SPARROW both use the influence of land cover to modify sediment source contribution based on vegetation. The NZeem® model assumes that herbaceous land cover and bare ground erode at 10 times the rate of woody cover. Using the SPARROW model Elliott et al. (2008) found pasture had 4.5 times the erosion rate of the base land cover of trees and shrubs. In both models the vegetation source contribution modifier is applied uniformly across the landscape and ignores differences in the effect of inherent erosion susceptibility on responses to vegetation cover change. SPARROW further includes source modification terms for mean catchment slope, while NZeem® modifies sediment delivery dependent on slope-dependent connectivity between the hillslope and channel, as described for the HEL model. The SPARROW model is included as part of the NIWA CLUES water quality modelling system (Woods et al. 2006). None of these models provide information on the contribution of different erosion processes to sediment yield. The New Zealand landscape is characterised by a wide range of erosion processes, from overland flow erosion to shallow landslide and stream bank erosion and assessment of erosion process contribution would assist better targeting of erosion mitigation.

The sediment budget for river networks model (SedNet) modelling approach was developed in Australia (Wilkinson et al. 2004) to provide an improvement on lumped empirical erosion models, by incorporating some process information but with realistic calibration data requirements. It is currently being developed for application in New Zealand (De Rose & Basher 2011) by incorporating landslides, earthflows, large-scale gully erosion, and streambank erosion typical of parts of New Zealand (SedNetNZ).

This report is divided into three main parts:

- Part 1 uses the Highly Erodible Land (HEL) model to define spatially the land at greatest risk from landsliding, gully and earthflow erosion.
- Part 2 uses NZeem® to provide a quantitative spatial picture of where sediment in rivers is sourced.
- Part 3 identifies areas of high risk for stream bank erosion using SedNetNZ and undertakes an assessment of the work required to reduce suspended sediment loads across the Waipa catchment.

3 Objectives

- Assess high risk areas for hillslope sediment generation using the HEL model
- Provide a quantitative analysis of spatial variation in sediment generation using NZeem®
- Assess the areas at risk of stream bank erosion using SedNetNZ
- Undertake an assessment of the work required to reduce suspended sediment loads to the Waipa stream and river network.

4 Methods

4.1 Highly Erodible Land (HEL)

Highly erodible land is defined as land at risk of severe erosion (landslide, earthflow, and gully) if it does not have protective woody vegetation (i.e. shrubs or forest). To be at risk of landslide erosion, a slope threshold must be exceeded. If the land has protective woody vegetation (i.e. indigenous forest, exotic forest, or scrub) then it is considered not at risk to severe landslide erosion, earthflow or gully erosion. Particle-size variation within HEL is also examined.

4.1.1 The modelling approach used by HEL

The program Erdas Imagine was used to undertake the spatial modelling of highly erodible land. The modelling approach used to define the classes of highly erodible land uses a slope threshold defined for each erosion terrain (Table 2). All pixels in a 15-m cell size resolution DEM above the threshold defined by the cell's erosion terrain were assigned to "high landslide risk". All "high landslide risk" cells were examined to see if they were connected to a watercourse. Land was considered capable of delivering sediment if it was possible to traverse down a flowpath (streamline) until a watercourse was reached without encountering two consecutive cells of low slope (i.e. <5 degrees). If "high landslide risk" can deliver sediment to a watercourse then it is classified as "high landslide risk – delivery to stream". Otherwise it is classified as "high landslide risk – non-delivery to stream". Cells in moderate earthflow land were assigned to "moderate earthflow risk", whereas cells in severe earthflow land were assigned to "severe earthflow risk". Cells occurring in gully land were assigned to "gully risk".

Table 2 Waipa catchment erosion terrains and slope thresholds above which land is at risk of landsliding if there is no protective woody vegetation (modified from Dymond et al. 2008)

Erosion terrain	Description	Slope threshold in degrees
	Hill country (most slopes 16–25°)	
6.1.2	Young tephra (Waimihia or younger), usually over older tephra—shallow (0.3–1.0 m)	26
6.1.4	Mid-aged (late Pleistocene/early Holocene) tephra, or tephric loess	26
6.2.1	Relatively young basalt domes and cones	28
6.3.1	Weak to very weak Tertiary-aged mudstone	24
6.3.3	Crushed mudstone or argillite with severe earthflow-dominated erosion	24
6.4.1	Cohesive, generally weak to moderately strong Tertiary-aged sandstone	28
6.4.2	Non-cohesive Tertiary-aged sandstone	26
6.6.1	Unweathered to moderately weathered greywacke/argillite	28
6.7.4	Residual weathered to highly (often deeply) weathered greywacke/argillite	24
	Hilly steeplands (most slopes >25 °)	
7.1.1	Young tephra (Waimihia or younger), usually over older tephra—shallow (0.3–1.0 m) covers	26
7.1.3	Mid-aged (late Pleistocene/early Holocene) tephra	26
7.2.1	Fresh to slightly weathered welded rhyolitic rock, or bouldery, andesitic lahar deposits	28
7.4.1	Cohesive, generally weak to moderately strong Tertiary-aged sandstone	28
7.4.2	Non-cohesive Tertiary-aged sandstone, and younger sandy gravels and gravelly sands	26
7.6.1	Unweathered to moderately weathered greywacke/argillite	28
7.7.2	Residual weathered to highly (often deeply) weathered welded rhyolite	24
	Mountain steeplands	
9.1.1	Greywacke/argillite or younger sedimentary rocks of the main ranges prone to landslide erosion	45
9.2.1	Volcanic rocks in mountain terrains and upland hills	45

All highly erodible land was examined to determine if protective woody vegetation was present either according to the EcoSat woody layer or to LCDB3 layer, with imagery representing 2003 and 2008 respectively. If woody vegetation was present, then land was labelled as "woody vegetation". In other words, land is not highly erodible when there is protective woody vegetation. Two final models were developed: the first using EcoSat and the second using LCDB3 (see Table 3 for details).

The Highly Erodible Land algorithm produces 5 classes of highly erodible land:

1. High landslide risk – delivery to stream
2. High landslide risk – non-delivery to stream
3. Moderate earthflow risk
4. Severe earthflow risk
5. Gully risk (only occurs adjacent to the Waipa study area)

Table 3 Spatial surfaces developed in the Waipa study to assist with identifying the high-risk areas of hillslope sediment generation using the highly erodible land (HEL) model

File name	Description
Waipa_hel_08	Map of highly erodible land showing land at risk to landslide, earthflow, and gully erosion. Land with woody vegetation (2008 from LCDB3) is not at risk.
Waipa_hel_03	Map of highly erodible land showing land at risk to landslide, earthflow, and gully erosion. Land with woody vegetation (2003 from EcoSat with high spatial resolution) is not at risk.

4.1.2 Particle size analysis

Improving the water clarity of the Waipa River may require targeting land areas that produce the finest sediment rather than those areas that produce a higher load but of coarser particle sizes. In an attempt to identify these areas we extracted information on soil particle size class (*PS* field) from the Fundamental Soil Layers (Newsome et al. 2000). This provides an estimate of the dominant particle size class of the soil profile to c. 1 m. To simplify the map we amalgamated the *PS* classes clayey, loamy over clayey, and silty over clayey into clay-dominant particle sizes; loamy, loamy over sandy, silty, and silty over sandy into silt-dominant particle sizes; and sandy and sandy over silty into sand-dominant particle sizes. This distinguishes soils dominated by clay size particles from those dominated by silt and sand-size particles. The rationale for this analysis was to overlay risk of erosion identified from the highly erodible land (HEL) model onto particle size with the view to highlighting sub-catchments with not only high risk of erosion, but also with finer particle size characteristics that could potentially contribute long-term towards the poor clarity of the Waipa River and its tributaries.

4.2 New Zealand Empirical Erosion Model (NZeem®)

Dymond et al. (2010) developed the New Zealand Empirical Erosion Model (NZeem®) primarily as a means of assessing the long-term impacts of woody vegetation cover on erosion and sediment yield. NZeem® relates erosion rate to rainfall, erosion terrain and vegetation cover. Under woody vegetation cover NZeem® assumes a reduction factor of 10 in erosion rates compared with hebaceous vegetation or bare ground. Erosion is defined as:

$$E = aCR^2 \tag{1}$$

where E is the erosion rate (t km^{-2} yr^{-1}), a is the erosion terrain coefficient (Table 4), C is a value 1 where woody vegetation is present, and 10 where woody vegetation is absent, while R is mean annual rainfall (mm yr^{-1}). For application in the Waipa, woody vegetation cover was determined by using both the EcoSat layer and the LCDB3 layer. These are the same layers used in the Highly Erodible Land (HEL) analysis. Two final NZeem® models were developed for the Waipa catchment, the first using EcoSat and the second using LCDB3.

Table 4 Waipa erosion terrains and their erosion coefficients (t km^{-2} yr^{-1} mm^{-2}) (modified from Dymond et al. 2008)

Erosion terrain	Description	Erosion coefficient (by 10^6)
	Active flood plains	
1.1.1	Undifferentiated alluvium from modern overbank depositional events. Parts may be Peaty. Includes non-peaty wetlands	8.6
	Peatland	
3.1.1	Organic soils on deep peat	0.3
	Terraces, low fans, laharic aprons (most slopes <8°)	
4.1.2	Young tephra, mostly pumiceous (Waimihia and younger)	5.3
4.1.3	Basins infilled with Taupo tephra flow deposits—intensely gullied	9.2
4.1.4	Mid-aged (late Pleistocene/early Holocene) tephra, older tephra, or tephric loess	2.0
	Downland (most slopes 8–15o)	
5.1.2	Young tephra (Waimihia and younger), over older tephra	3.8
5.1.3	Mid-aged (late Pleistocene/early Holocene) tephra, older tephra, or tephric loess	2.3
5.3.1	Weathered sedimentary and non-tephric igneous rocks	3.3
	Hill country (most slopes 16–25o)	
6.1.2	Young tephra (Waimihia or younger), usually over older tephra—shallow (0.3–1.0 m)	15.9
6.1.3	Young tephra (Waimihia or younger), usually over older tephra—deep (>1.0 m)	5.8
6.1.4	Mid-aged (late Pleistocene/early Holocene) tephra, or tephric loess	6.5
6.2.1	Relatively young basalt domes and cones	3.5
6.3.1	Weak to very weak Tertiary-aged mudstone	40.3
6.3.2	Crushed Tertiary-aged mudstone, sandstone; argillite, or ancient volcanic rock (frequently, with tephra covers in the Northern Hawke's Bay–East Coast area) - with moderate earthflow-dominated erosion	254.0
6.3.3	Crushed mudstone or argillite with severe earthflow-dominated erosion	688.0
6.4.1	Cohesive, generally weak to moderately strong Tertiary-aged sandstone	37.9
6.4.2	Non-cohesive Tertiary-aged sandstone	97.3
6.6.1	Unweathered to moderately weathered greywacke/argillite	23.6
6.7.4	Residual weathered to highly (often deeply) weathered greywacke/argillite	22.8
	Hilly steeplands (most slopes >25 o)	
7.1.1	Young tephra (Waimihia or younger), usually over older tephra—shallow (0.3–1.0 m) covers	28.3
7.1.3	Mid-aged (late Pleistocene/early Holocene) tephra	4.5
7.2.1	Fresh to slightly weathered welded rhyolitic rock, or bouldery, andesitic lahar deposits	6.5
7.4.1	Cohesive, generally weak to moderately strong Tertiary-aged sandstone	68.7
7.4.2	Non-cohesive Tertiary-aged sandstone, and younger sandy gravels and gravelly sands	113.0
7.5.1	Limestone	39.9
7.6.1	Unweathered to moderately weathered greywacke/argillite	55.5
7.7.2	Residual weathered to highly (often deeply) weathered welded rhyolite	6.7
	Mountain steeplands	
9.1.1	Greywacke/argillite or younger sedimentary rocks of the main ranges prone to landslide erosion	47.3
9.2.1	Volcanic rocks in mountain terrains and upland hills	2.1

NZeem® sediment loads and measured sediment loads were also compared. Using data from Hoyle et al. (2012), areas above the suspended sediment sample locations were identified using the SedNetNZ stream link system (see Figs 2 and 12). Using the NZeem® sediment yield data, the up-slope area and the area weighted mean associated with each sample location were determined and multiplied for comparison with the measured sediment loads.

Further analysis was undertaken to investigate the potential reduction in sediment (NZeem®) for farms identified with the greatest areas of HEL across the Waipa catchment. To achieve this Waikato Regional Council (WRC) provided an adjusted version of AgriBase for the 2013 year (pastoral extent from LCDB3). Adjustments to AgriBase included the removal of double representation by different farm types within a single polygon providing corrected areas per polygon. Using raster-based zonal means, statistics were calculated for NZeem® sediment yields and areas of Highly Erodible Land (HEL) for each AgriBase farm type polygon identified across the Waipa Catchment. HEL area values and NZeem® sediment yields were attached to the original AgriBase geodatabase unique identifier to enabled sorting of polygons with the greatest area of HEL erosion. We assumed that if a farm plan was put in place to reduce sediment, potentially a reduction of 70% was possible. This approach allows the identification of farms with the greatest area of HEL and the calculation of sediment reduction (NZeem® sediment loss prevented) should a farm plan be applied, providing a mitigation planning tool.

4.3 SedNetNZ model

4.3.1 The SedNetNZ model description

SedNet is 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, accounting for losses in water bodies (reservoirs, lakes) and deposition on floodplains and in the channel. The basic element in this model is the stream link (Fig. 2), typically several kilometres or more in length. Each link has an internal catchment area (stream link) that drains overland flow and delivers sediment to that link.

The main outputs from the model are predictions of 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 possible to simulate river loads for natural conditions (pre-European) and examine the consequences of future land use scenarios. If discharge-sediment concentration flow rating curves are known, then mean annual suspended sediment concentrations for indicative discharge events can be back-calculated from predicted loads.

SedNetNZ has three main components (1) an erosion submodel, (2) a hydrological submodel, and (3) a sediment-routing submodel of which each submodel has their own model algorithms. SedNetNZ is a relatively straightforward model to execute and run; however, data preparation and getting the data into the required format before running the model can be time consuming. A brief description of the model development and parameterisation for the calculation of stream bank erosion follows.

4.3.2 Stream and stream link network

The SedNetNZ stream link network for the Waipa catchment used a 15-m cell size resolution Digital Elevation Model (DEM), derived from 20-m contours (Landcare Research 2004). The stream link network was derived using the ArcHydro extension for ArcGIS. A hydrologically correct DEM was developed by first taking into account natural sinks that flow outside of the Waipa catchment before executing the "fill" tool in ArcGIS to remove all unwanted depressions, sinks, and pits. The DEM was further conditioned to ensure hydrological flow across the stream network. For stream network derivation, a minimum catchment area was defined as 0.5 km^2 for each raster cell of the stream network, producing an average catchment size of approximately 1 km^2 for the Waipa catchment. This enables the identification of critical sediment source areas at a reasonably fine scale (Fig. 2).

Input data layers were:

- 15-m raster cell size resolution DEM
- Land Information New Zealand (LINZ) rivers and streams (vector lines) for:
  - Main Waipa channel
  - Waipa tributaries

Modelling parameters (default values):

- Drainage area threshold for each stream link pixel: 1 km^2
- DEM reconditioning (Main Waipa channel)
  - Cells for stream buffer: 3
  - Smooth drop in z units: 1000
  - Sharp drop in z units: 500
- DEM reconditioning (Waipa tributaries)
  - Cells for stream buffer: 3
  - Smooth drop in z units: 1
  - Sharp drop in z units: 2

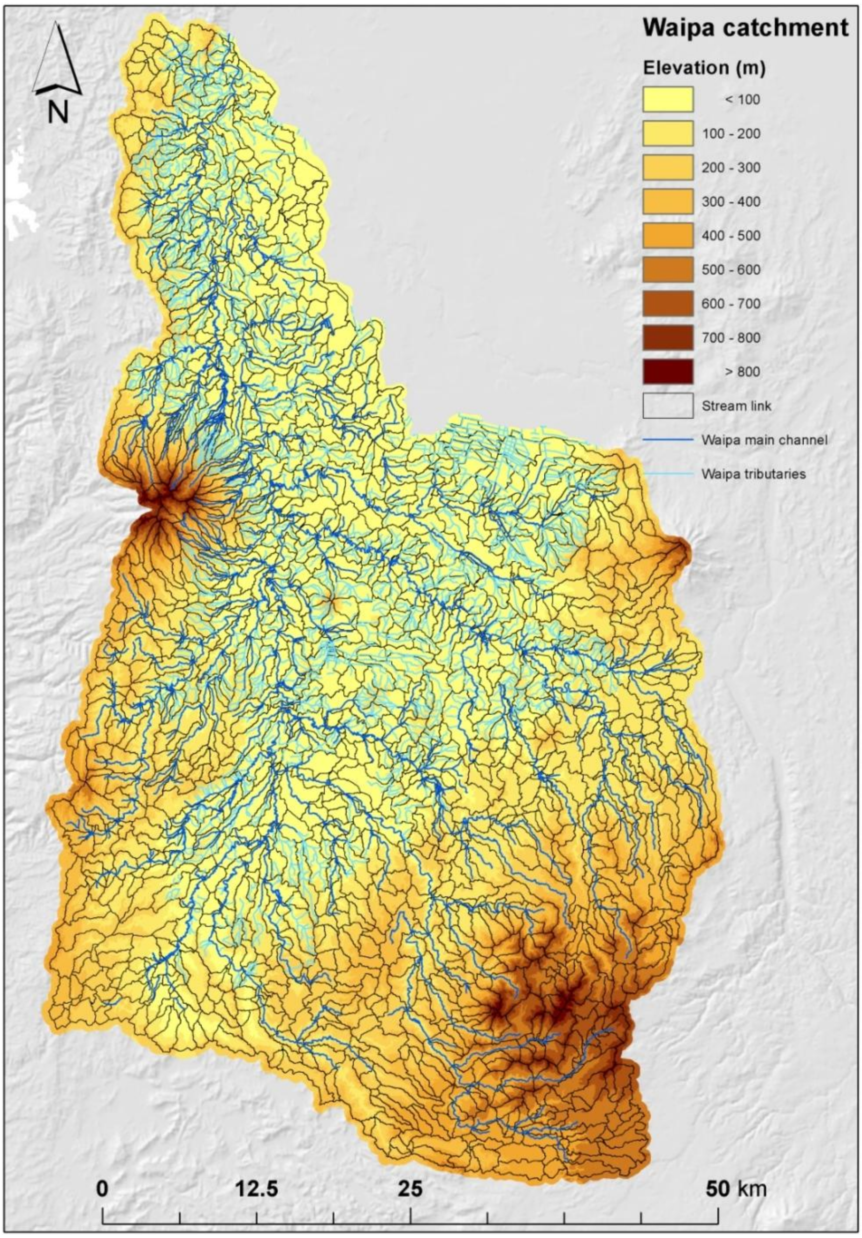

Figure 2 Graphic showing the Waipa catchment datasets used in the hydrological process including the main channel, tributaries, DEM, and stream link for the Waipa catchment as defined by parameter thresholds.

4.3.3 Stream bank erosion component

The volumetric rate of erosion per unit channel length (m^3 m^{-1} yr^{-1}) is given by the product of $M \times H$, where H is bank height, and M is the bank migration rate in m yr^{-1}. For conversion of volume erosion to mass erosion we assume a bulk density of unity. 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). The exponent in the regression model (0.469) is within the range of reported values elsewhere.

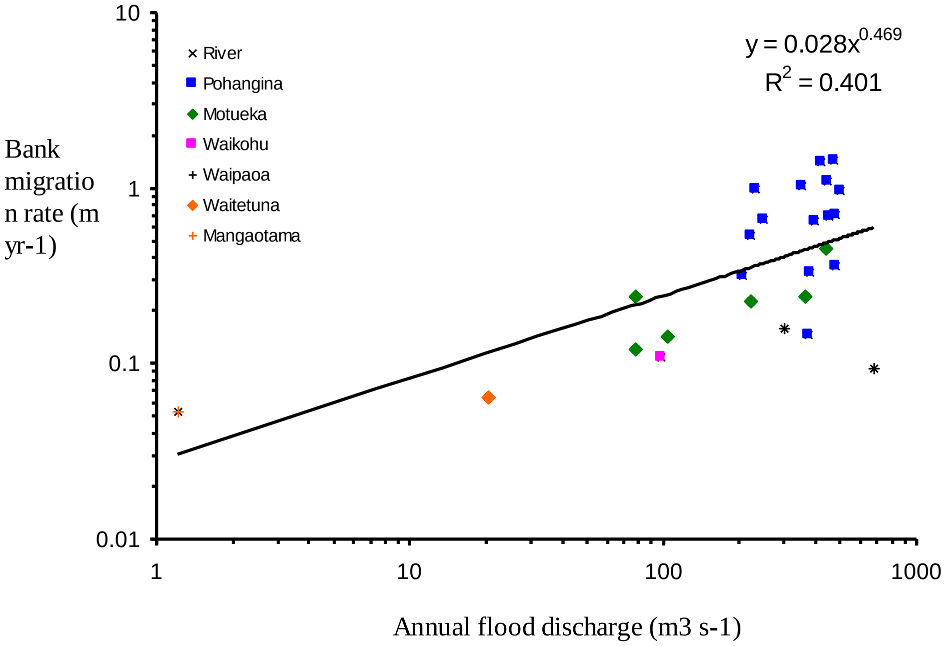

Figure 3 Average channel migration in relation to mean annual flood discharge (WRENZ-modelled) for New Zealand rivers.

The stream bank migration (B_m) for the Waipa was calculated using the equation:

$$B_m = 0.028\ F^{0.469} \qquad (2)$$

where, F is the mean annual flood.

4.3.4 Input data for stream bank erosion

The mean annual flood for each gauged subcatchment (Q_f) in the Waipa was related to the measured mean discharge ($\bar{q}$) using a second order polynomial:

$$Q_f = -0.0285q^2 + 7.1524q + 36.803 \qquad (3)$$

The mean discharge for each of the 1594 subcatchments in the Waipa SedNetNZ model was determined by first estimating the mean runoff in mm (estimated from the national Watyield model) and then multiplying by stream link area to determine the volume of runoff in a year. The SedNet accumulation routine was run to calculate the total mean discharge down the stream network. The mean annual flood was then estimated using Equation (3) for each stream link (Fig. 4).

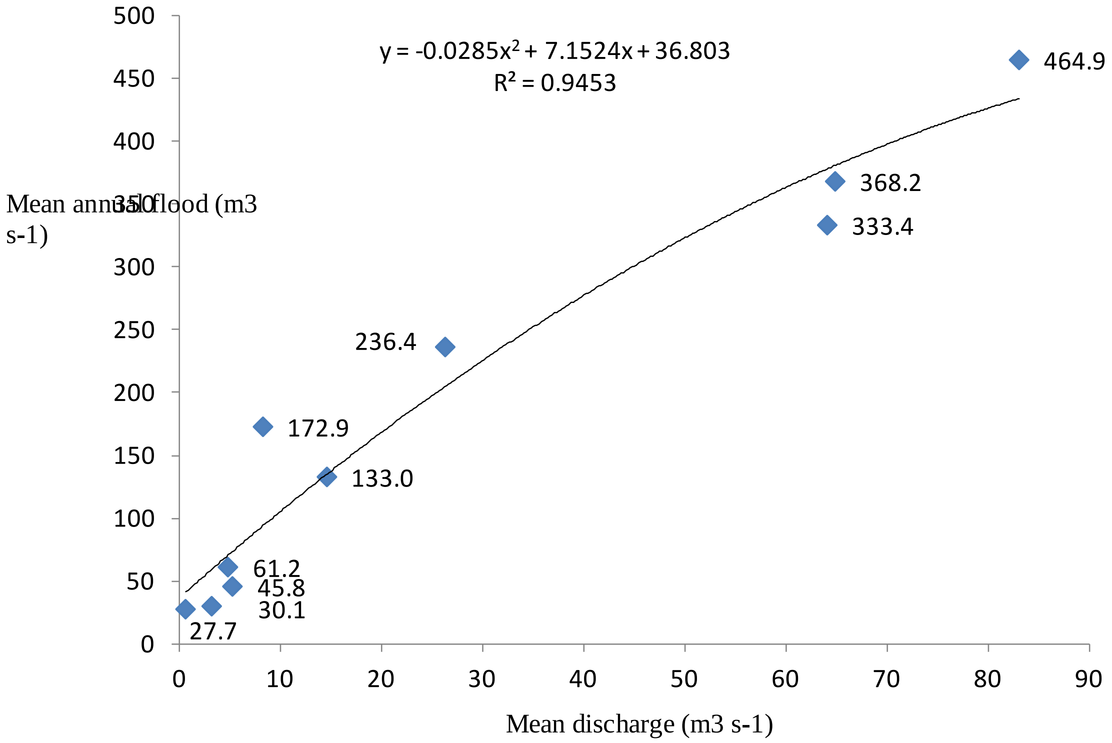

Figure 4 Relationship between mean annual flood and mean discharge for the main tributaries in the Waipa catchment.

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. Currently the riparian vegetation is assumed to be primarily grass.

In the summer of 2012/2013 the Waikato Regional Council undertook a riparian survey across the Waipa catchment in which they collected 221 observations of the height from the base of the river/stream channel to the top of the adjacent flood bank. These observations were used to develop the relationship between bank height and mean discharge. As a result, the bank height was estimated using a relationship of 2+2log10(mean discharge) for each stream link. Attempts were also made to develop relationships with bank height, stream/river gradient, stream sinuosity, and mean discharge with finer spatial resolution data. However, as weak correlations were found between these variables and the dependent variable, no further analysis was undertaken. The frequency of modelled bank heights across the Waipa stream links in metre classes can be seen in Figure 5.

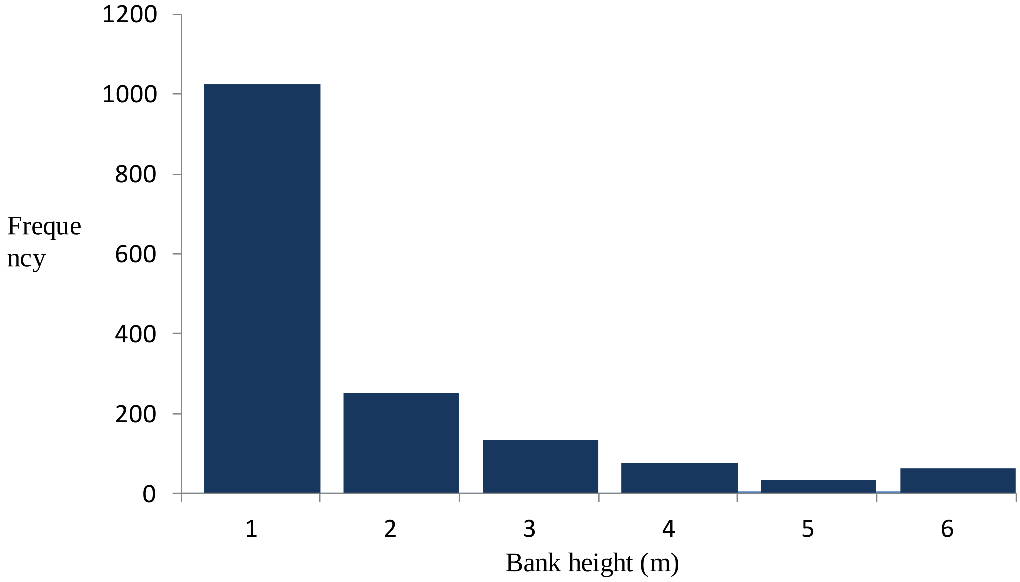

Figure 5 Frequency of modelled bank heights in metre classes.

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

4.4 Scenario modelling for stream bank erosion

Previous riparian studies undertaken by the Waikato Regional Council also provided some information on the stream bank fencing status across the Waipa catchment. Although we cannot identify locations of individual surveys for privacy reasons, the survey data provides the Waipa study with an estimation of the percentage of Waipa stream banks with adequate fencing required to withhold stock from riparian/stream edges. At present the survey estimates that 25% of streams in the Waipa catchment have fences on both sides in a condition that can withhold stock (Storey 2010). It is assumed that excluding stock from riparian margins will allow woody vegetation to fully colonise the banks and reduce the magnitude of bank erosion by 80%. A further analysis was undertaken to estimate stream bank erosion (*E*) where no fencing was present, where 25% (current situation), 50%, and 100% of streams are fenced on both sides. This was achieved by calculating a vegetation factor for each stream segment that is multiplied by the bank erosion to achieve the final bank erosion rate for the segment. The vegetation factor E_b is given by:

$$E_b = (1 – 0.8 * P_f)$$

where P_f is the percentage of stream bank fenced. The 0.8 value is a conservative value for the reduction in stream bank erosion set in the Australian SedNet model (Wilkinson et al. 2004) at 0.9.

4.5 Waipa River and tributaries sediment collection

Sediment samples were collected at locations along the Waipa River and selected Waipa tributary sites. Samples were collected within the floodplain by first removing surface vegetation before taking a spade width and breadth to a depth of 10-cm. One sample was taken from above the Waipa and selected tributary confluence and a second sample collected from the tributary. The rationale is that these paired sites will not only provide a general indication of the sand, silt, and clay percentage changes along the Waipa River, but also any variation in contribution from selected Waipa tributaries.

The University of Waikato analysed the Waipa sediment samples using the following protocol. Approximately 3 grams were subsampled from the original sample and 10 ml of 10% hydrogen peroxide was added to remove organic matter. Once the initial reaction decreased the sample was placed on a hot plate to induce the reaction. This process was repeated until the sample no longer showed effervescence with the addition of hydrogen, and no organic matter was visible. Ten percent calgon was added to the sample and left for approximately 12 hours to help disperse clays.

The Malvern 2000 (Malvern 1997) uses laser diffraction based on the principle that particles passing through a laser beam will scatter light at an angle that is directly related to their size. As the particle size decreases, the observed scattering angle increases logarithmically. The observed scattering intensity is also dependent on particle sizes and diminishes, to a good approximation, in relation to the particle's cross-sectional area. Large particles therefore scatter light at narrow angles with high intensity, whereas small particles scatter at wider angles but with low intensity. The Malvern 2000 was used to measure particle sizes between 0.06 microns and 2 mm in the Waipa samples.

5 Results and Discussion

5.1 Highly Erodible Land (HEL) model

The Highly Erodible Land (HEL) model was developed as two Imagine (.img) files that were converted to ESRI raster grids and masked to the Waipa catchment boundary. The rationale for providing two layers is that although the LCDB3 (2008) woody vegetation is a more recent dataset, EcoSat (2003) provides better resolution of detail (minimum mapping unit of 15 × 15 m compared with 100 × 100 m). Highly Erodible Land using the LCDB3 vegetation is similar to the EcoSat map at a coarse spatial extent; however there are subtle changes because of vegetation change over time (2003–2008) and because of better spatial representation. Figure 6 provides a close-up view of HEL; Figure 7 shows an overview of the entire Waipa catchment.

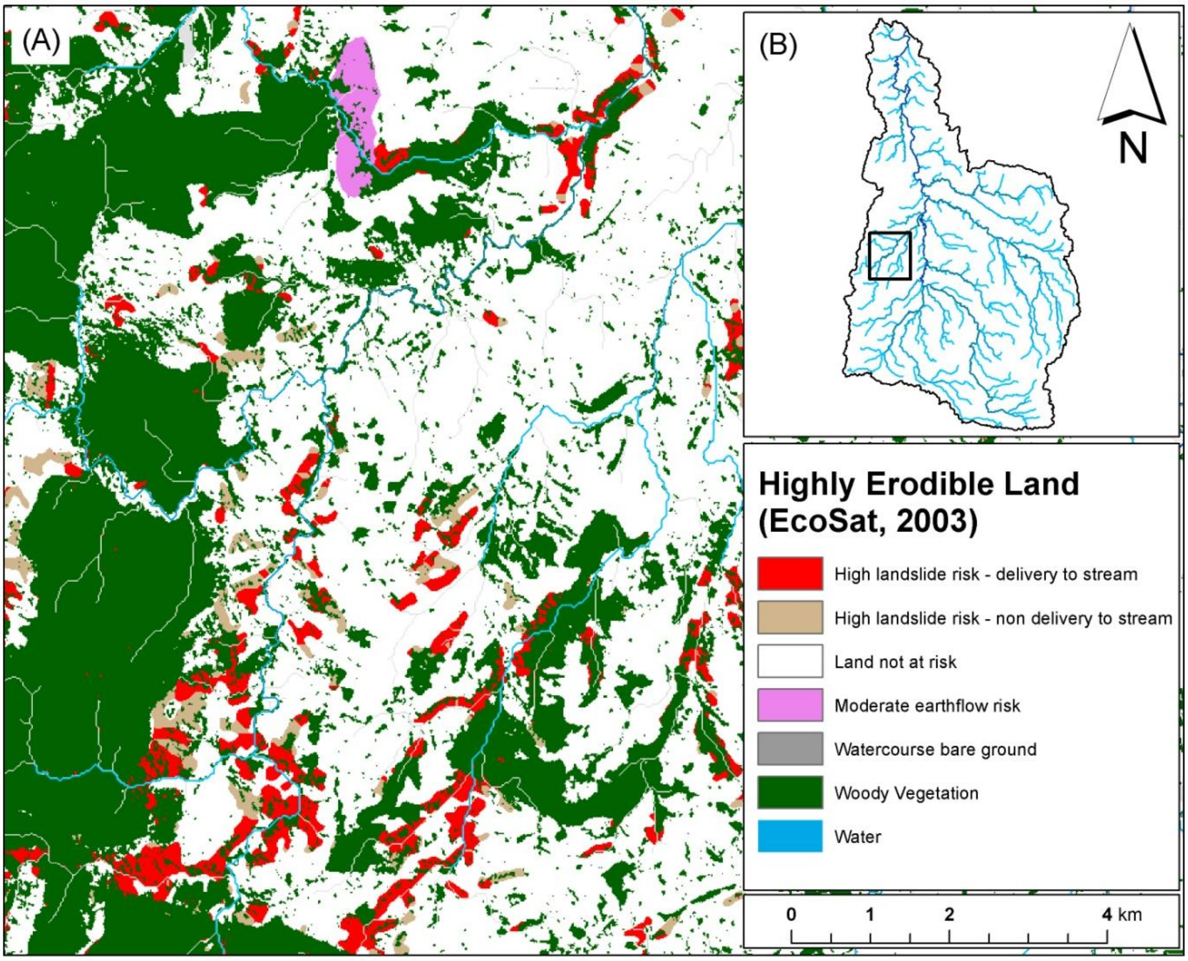

Figure 6 A clip of highly erodible land in the Waipa catchment (A) and its location within the stream network for the Waipa catchment (B).

Overall, a very small proportion of the catchment was classed as HEL (3.2%). The Highly Erodible Land (EcoSat, 2003: Fig. 7) model identified 3180 ha of land at risk of landsliding with potential of delivery to streams, and a further 2100 ha classed as not contributing to streams (see Table 5). HEL tends to occur along the western margins and upper reaches of the Waipa catchment. Land with a moderate (4,360 ha) and severe earthflow risk (185 ha) occurs in the northwest and southern parts of the Waipa catchment. It is worth noting that in the HEL model vegetation provides protection from erosion and, if cleared, the land is at increased erosion risk.

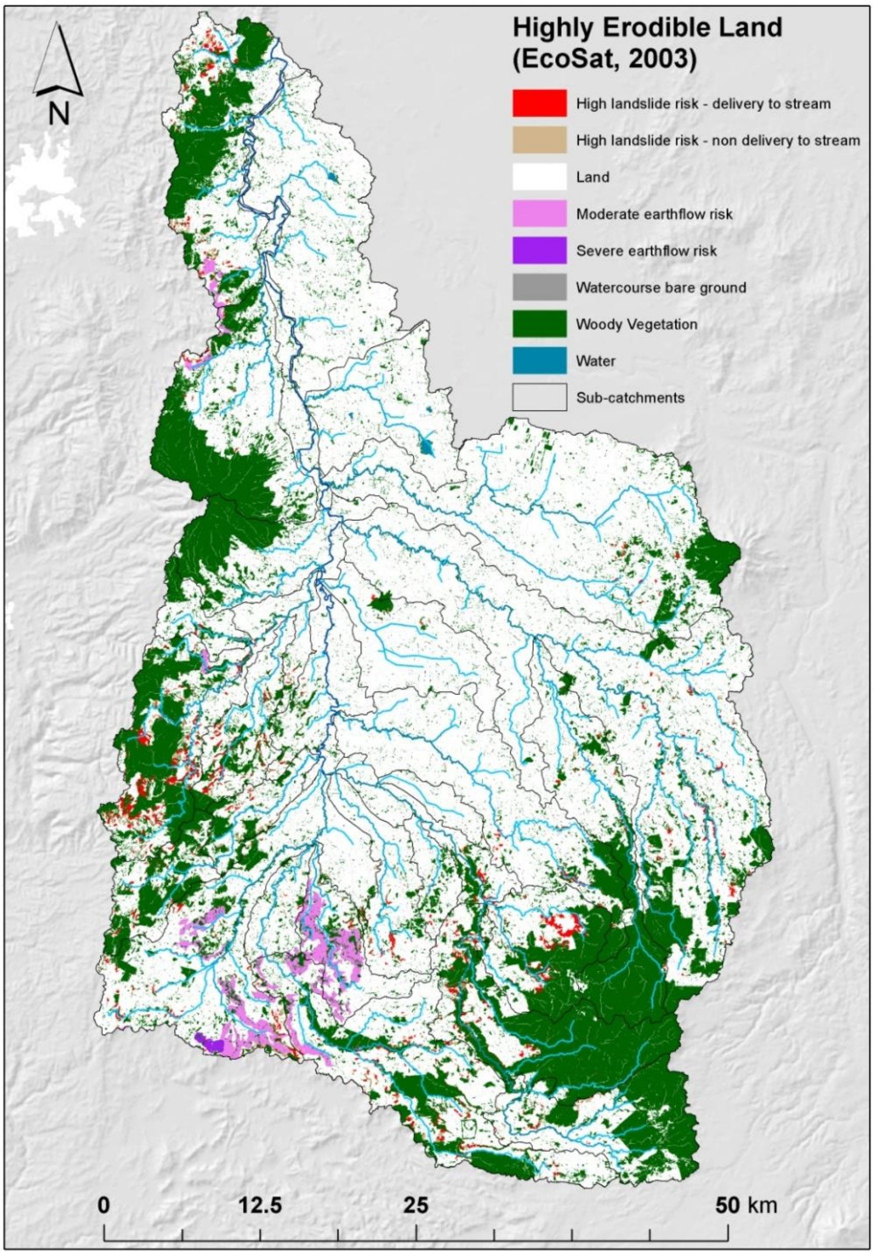

Figure 7 Highly Erodible Land across the Waipa catchment using EcoSat, 2003 to identify woody vegetation. Using the LCDB3 vegetation provides a similar map at this spatial extent.

Table 5 provides the area considered to be at risk of landslide and earthflow based on the HEL model.

Table 5 Area (ha) of Highly Erodible Land by erosion type and particle size (FSL overlay)

Erosion type	Clay	Silt	Sand	Total (ha)
High landslide risk - delivery to stream	320	2649	163	3183
High landslide risk - non delivery to stream	282	1710	84	2109
Moderate earthflow risk	98	4265	-	4365
Severe earthflow risk	-	185	-	185
Total	**700**	**8809**	**247**	**9841**

The percentage of sub-catchment erosion identified by HEL as having a high risk of erosion are the Mangarapa (31.2%), Mangapu (11.5%), Moakurarua (7.3%), and the Upper Mangaokewa (7.1%) (Table 6) in the south-west of the Waipa catchment (Fig. 1). Significant areas occur in the Waimahora (5.7%), Whatawhata–Ngaruawahia (4.6%), Turitea (4.5%), lower Waitomo (4.4%), and upper Waitomo catchments (3%). With the exceptions of the Mangaotama, Ngahinapouri to Ngarauwahia, and Waipa Pirongia – Ngaruawahia sub-catchments, the remaining sub-catchments are dominated by a high risk of landslide erosion, most of which is at high risk of being delivered to a stream.

The sub-catchments identified as having the highest percentage area of earthflow risk are the Mangarapa (30.2%), Mangapu (8.9%), and the upper Mangaokewa (3.7%) (Table 6). Earthflow erosion risk is important to consider because these areas are likely to be older landscape features that may have historically made relatively small contributions to sediment yields. Although earthflow movement may have increased post-deforestation, careful consideration should be given to these earthflow areas when assessing remediation. As landslides are known to produce high sediment yields, erosion mitigation activities should focus on those areas.

Table 6 Highly Erodible Land and woody vegetation as a percentage of area (%) summed by Waipa sub-catchments, and total Waipa catchment percentages

	High landslide risk		**Earthflow risk**			
Sub-catchment	Delivery to stream	Non delivery to stream	moderate	severe	Total area of erosion risk	Area of woody vegetation
Kaniwhaniwha	0.3	0.3	1.2	-	1.7	46.1
Lower Mangaokewa	0.3	1.2	1.4	-	2.9	6.4
Mangaorongo	0.6	0.2	-	-	0.8	12.1
Mangaotama	-	-	-	-	-	2.8
Mangapiko	0.2	0.1	-	-	0.2	9.1
Mangapohue	0.7	0.2	-	-	0.9	12.4
Mangapu	1.3	1.3	8.0	0.9	11.5	12.2
Mangarapa	0.3	0.6	30.2	-	31.2	11.8
Mangatutu	0.5	0.4	-	-	0.9	44.7
Mangawhero	0.8	0.4	-	-	1.2	4.8
Moakurarua	4.6	2.2	0.5	-	7.3	41.3
Ngahinapouri to Ngarauwahia	-	-	-	-	-	2.8
Ngutunui	0.5	0.1	-	-	0.6	34.7
Otorohanga to Pirongia	0.3	0.4	-	-	0.7	6.5
Parapara	0.1	-	-	-	0.1	2.0
Pirongia	0.1	0.0	-	-	0.1	46.4
Puniu	0.7	0.3	-	-	1.0	12.4
Toa Bridge to Otorohanga	1.7	0.5	-	-	2.2	12.5
Turitea	3.0	1.5	-	-	4.5	26.0
Upper Mangaokewa	1.8	1.6	3.7	-	7.1	26.1
Waimahora	4.5	1.2	-	-	5.7	44.7
Waipa Gorge/Tunawaea	1.7	0.8	-	-	2.5	67.5
Waipa Pirongia to Ngaruawahia	-	-	-	-	-	4.4
Waipa Valley Tributaries	0.3	0.6	-	-	1.0	55.0
Waitomo (Headwaters to Waitomo Caves)	1.8	1.2	-	-	3.0	51.1
Waitomo (Waitomo Caves to Otorohanga)	1.0	3.4	-	-	4.4	27.3
Whatawhata to Ngaruawahia	1.5	1.6	1.5	-	4.6	45.5
Waipa catchment (total)	1.0	0.7	1.4	0.1	3.2	23.7

The distribution of particle size in the top c. 1 m in the Waipa catchment from the Fundamental Soil Layer is shown in Figure 8. Those areas of HEL identified as being highly susceptible to erosion were intersected with the FSL *PS* field to identify the areas more likely to deliver clay- and silt-size material to the river. Overall, 700 ha (7%) of the HEL model has a dominant clay-particle-size distribution, while around 8800 ha (90%) were associated with silt-dominated particle sizes (Tables 5 and 7).

The analysis of the HEL model (Fig. 7) intersected with the FSL *PS* field (Fig. 8) showed that across the Waipa catchment the Mangapu (2272 ha), Mangarapa (1668 ha), upper Mangaokewa (1196 ha), and the Moakurarua (1093 ha) sub-catchments have the greatest areas of erosion dominated by clay and silt particles sizes (Table 7). When considering only the clay particle sizes, the Whatawhata–Ngaruawahia (429 ha), Kaniwhaniwha (174 ha), Moakurarua (62 ha), and Mangawhero (22 ha) have the greatest areas of clay soils across the erosion areas. Although spatial analysis of dominant particle size provides a picture of which sub-catchments are likely to have erosion types associated with finer sediments, it should be remembered that there is no way of assessing prediction certainty related to the original particle size spatial layer. Therefore it is recommended that this assessment be utilised only as a generalised particle size assessment of sub-catchment pattern.

Table 7 Area (ha) of Highly Erodible Land per with dominant particle size class within Waipa sub-catchments

Sub-catchment	Clay	Sand	Silt	Undefined	Total area (ha)
Kaniwhaniwha	174	-	84	-	258
Lower Mangaokewa	-	-	85	-	85
Mangaorongo	-	14	115	-	128
Mangapiko	-	-	74	-	74
Mangapohue	-	-	22	-	22
Mangapu	-	-	2,272	-	2,272
Mangarapa	-	-	1,668	-	1,668
Mangatutu	-	3	104	-	107
Mangawhero	22	-	144	-	165
Moakurarua	62	2	1,032	-	1,096
Ngutunui	7	2	8	-	17
Otorohanga to Pirongia	0	-	50	-	50
Parapara	-	-	2	-	2
Pirongia	4	-	3	-	8
Puniu	2	155	276	8	441
Toa Bridge to Otorohanga	-	-	89	-	89
Turitea	-	-	242	-	242
Upper Mangaokewa	-	-	1,196	77	1,273
Waimahora	-	35	413	-	448
Waipa Gorge/Tunawaea	-	-	327	-	327
Waipa Valley Tributaries	-	17	80	-	97
Waitomo (Headwaters to Waitomo Caves)	-	18	129	-	147
Waitomo (Waitomo Caves to Otorohanga	-	-	150	-	150
Whataahata to Ngaruawahia	429	-	247	-	676
Total	700	247	8,809	86	9,841

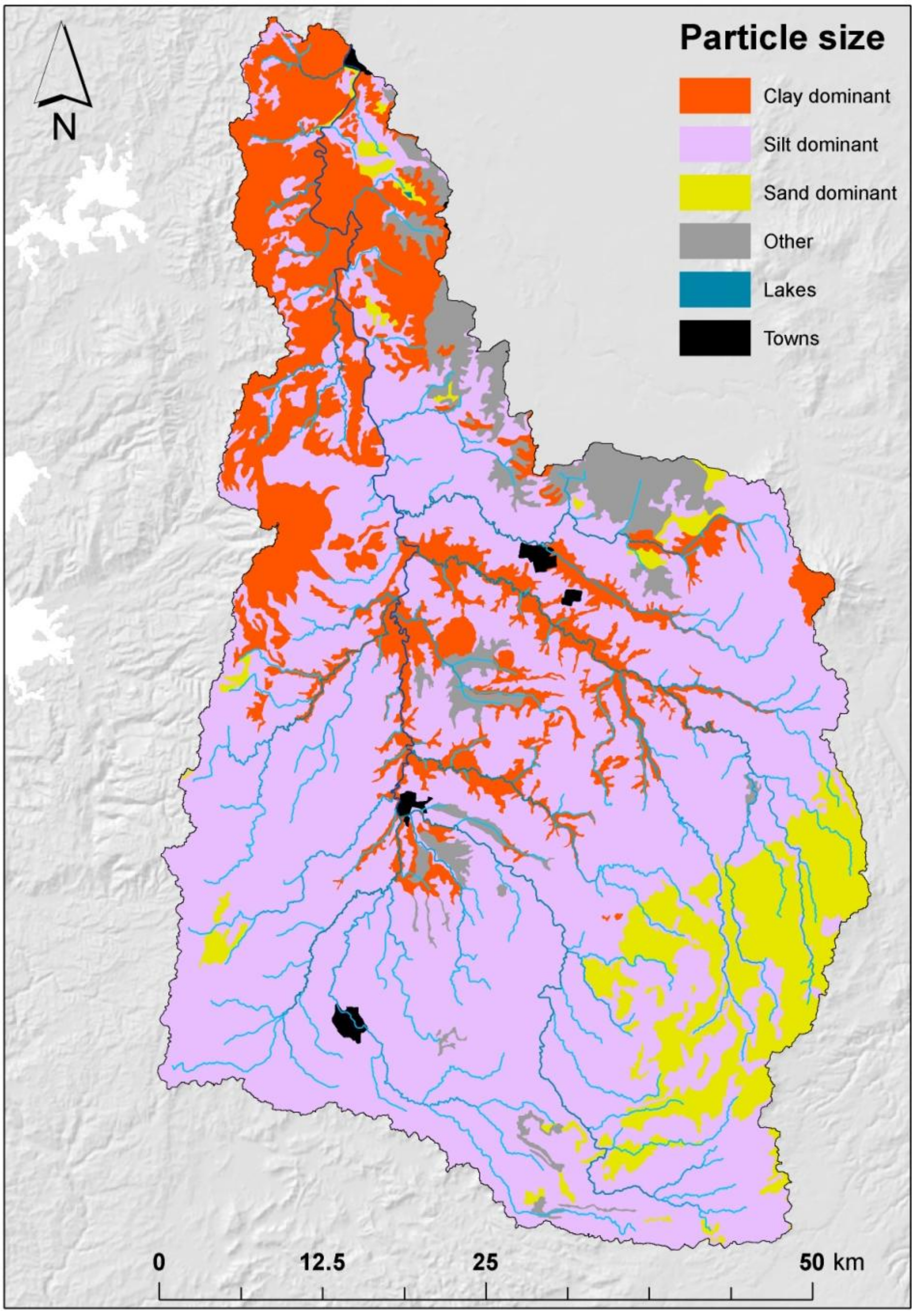

Figure 8 Dominant particle size across the Waipa catchment from the Fundamental Soil Layer (FSL).

5.2 New Zealand Empirical Erosion Model (NZeem®)

NZeem® provides a quantitative spatial analysis of where sediment in rivers is sourced. Figures 9 and 10 show an assessment of the long-term erosion and sediment yield modelled using vegetation cover, mean annual rainfall, and erosion terrain classification in terms of t km^{-2} yr^{-1}. The NZeem® analysis identifies the steeper terrain along the north-western and western margins and the south-west of the Waipa catchment as having the highest erosion rates. Figure 9 is a detailed view of a sub-catchment with erosion rates up to 2000 t km^{-2} yr^{-1}.

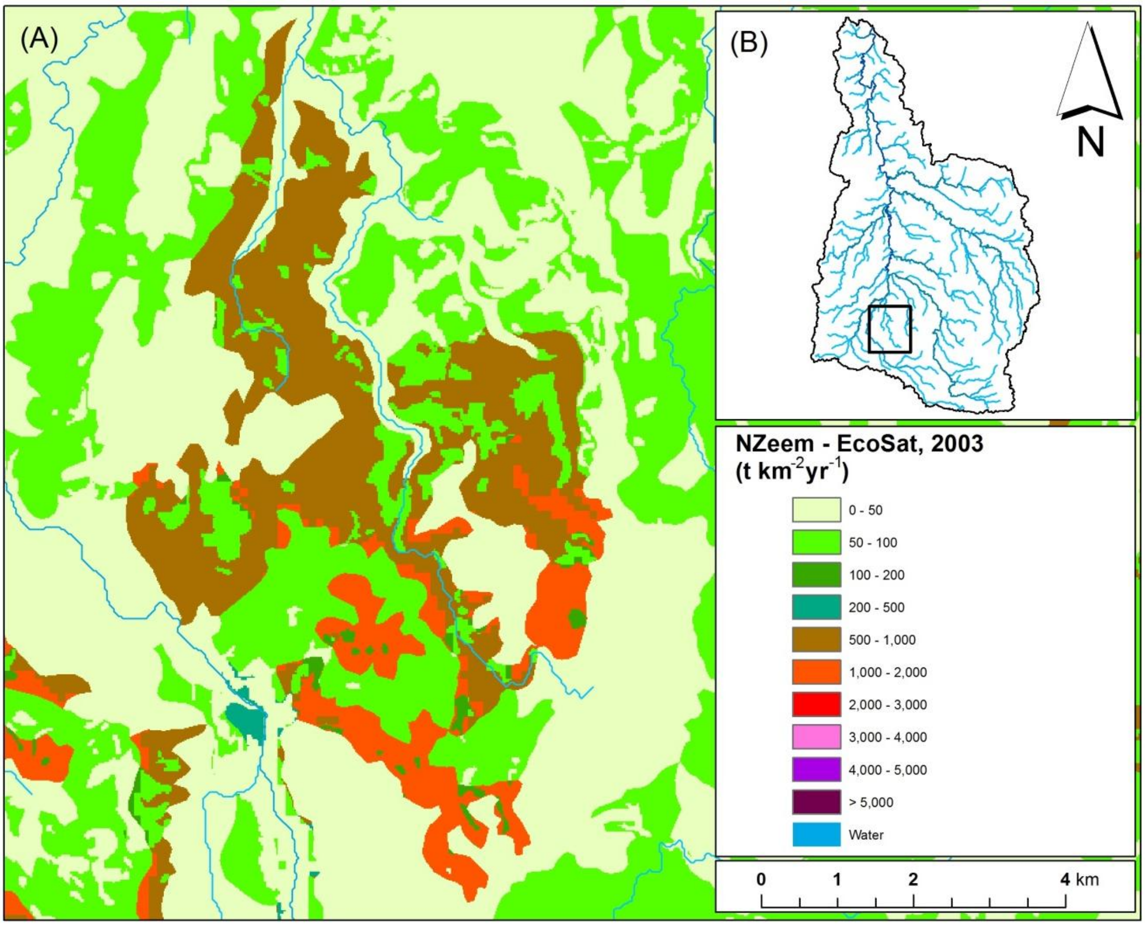

Figure 9 A clip of NZeem® for the Waipa catchment (A), and its location within the stream network for the Waipa catchment (B).

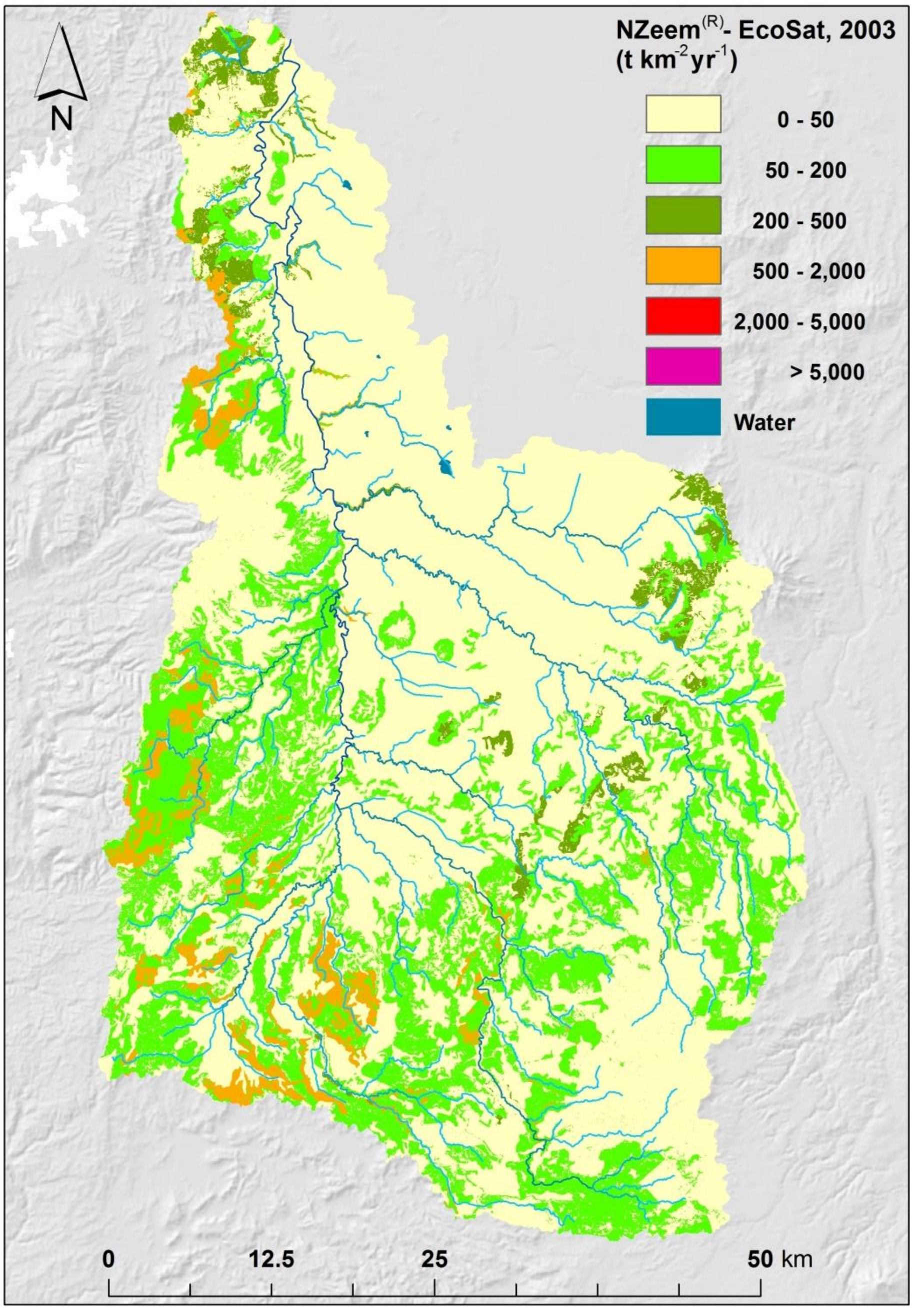

Figure 10 New Zealand Empirical Erosion model across the Waipa catchment.

Figure 11 uses the NZeem® mapped erosion and highlights the sediment yield on a sub-catchment basis (t yr^{-1} from each catchment). On an average-tonnes-per-year basis the Mangapu, Moakurarua, and the Whatawhata/Ngaruawahia sub-catchments have the highest sediment loads, with 33 000, 30 000, and 21 000 t yr^{-1}respectively. The Kaniwhaniwha, Mangarapa, Mangaokewa, and Puniu sub-catchments all have similar sediment loads of around 17 000 t yr^{-1}.

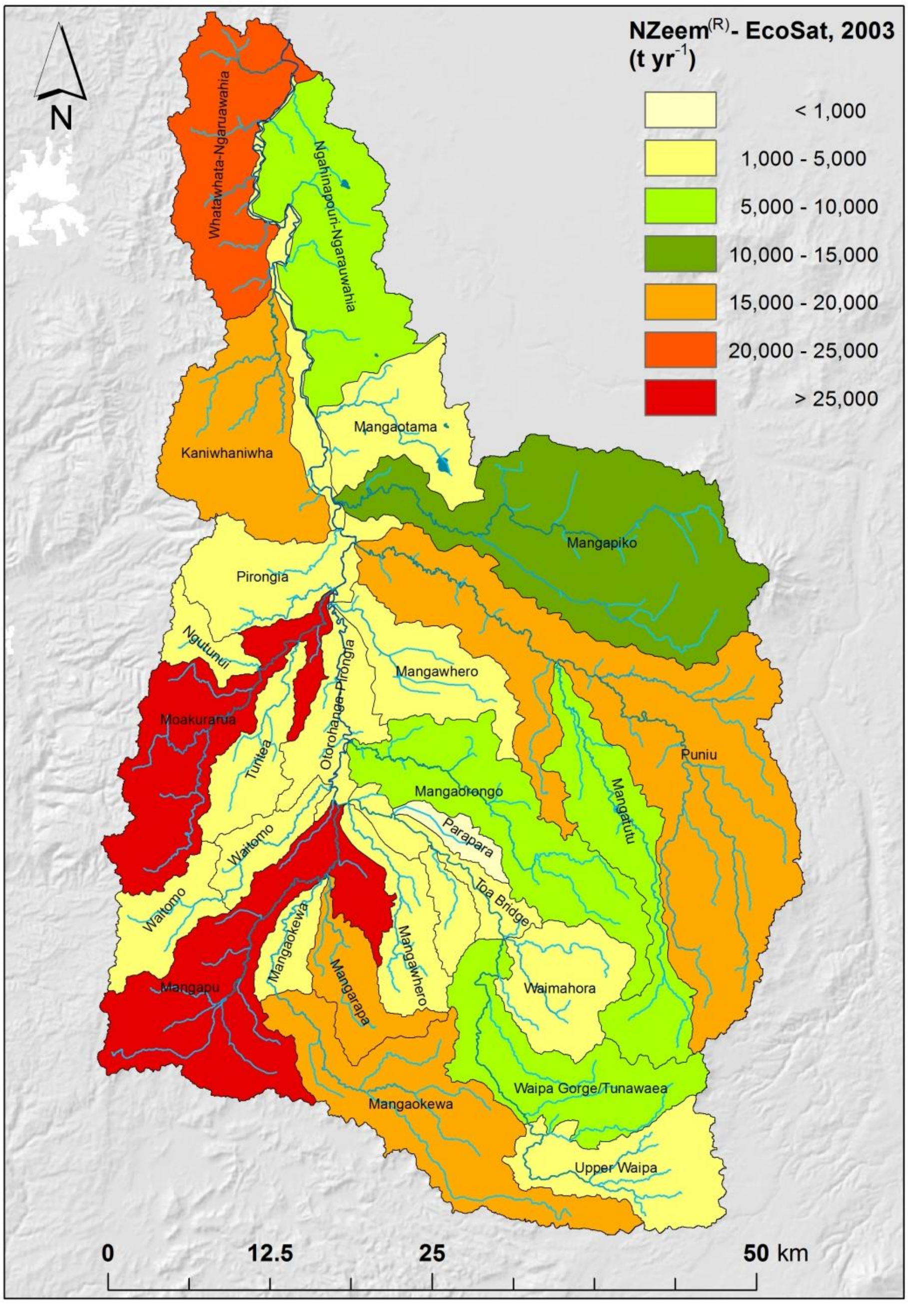

Figure 11 The Waipa catchment identifying the sediment load on a sub-catchment basis derived from NZeem®.

A comparison was made between NZeem® modelled erosion rate (Fig. 10) and the measured suspended sediment data across the Waipa catchment shown in Table 1. Considering that there would be major inconsistencies between the long-term modelled and relatively shorter-term measured sediment yield, and the calculated up-slope areas associated with each sample location, the correlation between measured and modelled is notable (Fig. 12).

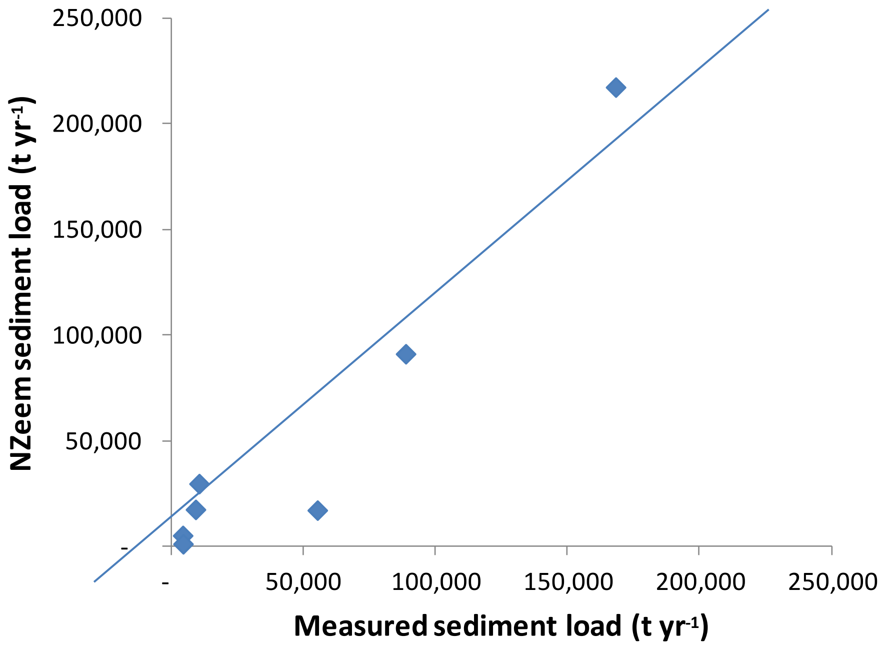

Figure 12 Plot of long-term sediment load estimated by NZeem® for Waipa tributaries compared with short-term measured sites shown in Table 1.

Using NZeem® and AgriBase data a scenario model was developed to estimate the on farm sediment reduction through mitigation strategies (farm plans). The rationale was to focus on farms in the Waipa catchment that have the greatest area of Highly Erodible Land (HEL), and thereby greatest potential to risk from landsliding and earthflow erosion. In the model we assumed a 70% reduction in sediment yield was achieved where farm plans were fully implemented. Table 8 illustrates the potential sediment loss reduction estimated using NZeem® for farms with the greatest area of HEL for up to 500 farms, ranging from 60 000 to 100 000 t yr^{-1}. This approach not only enables the focus on farms identified by AgriBase and the HEL model, but also provides an estimate of the outcomes from potential mitigation strategies for targeted farm numbers using NZeem® modelled values.

Table 8 Potential sediment reduction for farms identified with the greatest HEL areas across the Waipa catchment

No of farm plans	Sediment yield of Waipa (t yr^{-1})	Sediment loss prevented (t yr^{-1})	Farm plan areas (ha)
0	205 077	-	-
100	145 261	59 816	38 409
200	128 306	76 771	60 092
300	117 517	87 560	73 769
400	109 115	95 962	86 686
500	104 461	100 617	95 452

5.3 SedNetNZ and stream bank erosion

The SedNetNZ model was used to undertake an assessment of stream bank erosion occurring within the Waipa. Figure 13 shows the specific stream bank sediment yield (t m^{-1} yr^{-1}) modelled for (A) where no management intervention has taken place, (B) 25% fencing (current status), (C) 50% fencing, and (D) 100% fencing on both sides of rivers and streams within the Waipa catchment. The current fencing status was estimated from previous Waikato Regional Council (WRC) riparian surveys (Haydon Jones, WRC, pers. comm.) showing that on average 25% of the Waipa catchment currently has adequate fencing to withhold cattle from river or stream margins.

Using SedNetNZ bank erosion sediment yields for the entire Waipa catchment, a reduction of 488 000 t yr^{-1} is potentially possible from the current status of 65 000 t yr^{-1} (25% fencing on both sides of rivers and streams) to 162 000 t yr^{-1} by fully fencing rivers and streams of the Waipa catchment (Table 9). Soil eroded by bank erosion enters the river, but not all of this sediment exits the Waipa catchment. Some sediment will redeposit as bank accretion. There are currently insufficient data to quantify bank accretion.

Table 9 Scenario modelling using SedNetNZ to estimate the total stream bank erosion for the Waipa catchment where the impact of riparian management (% fencing both sides of the river and stream banks) is assessed for (A) no fencing management, (B) 25% fencing (estimated current status, Haydon Jones, WRC, pers. comm., Waikato Regional Council riparian survey), (C) 50% fencing, and (D) 100% fencing on both sides of rivers and streams

Management (fencing both sides)	SedNetNZ total stream bank erosion (t yr-1)	Percentage reduction (%)
No fences	810 000	
25% fencing (current status)	650 000	20
50% fencing	486 000	40
100% fencing	162 000	80

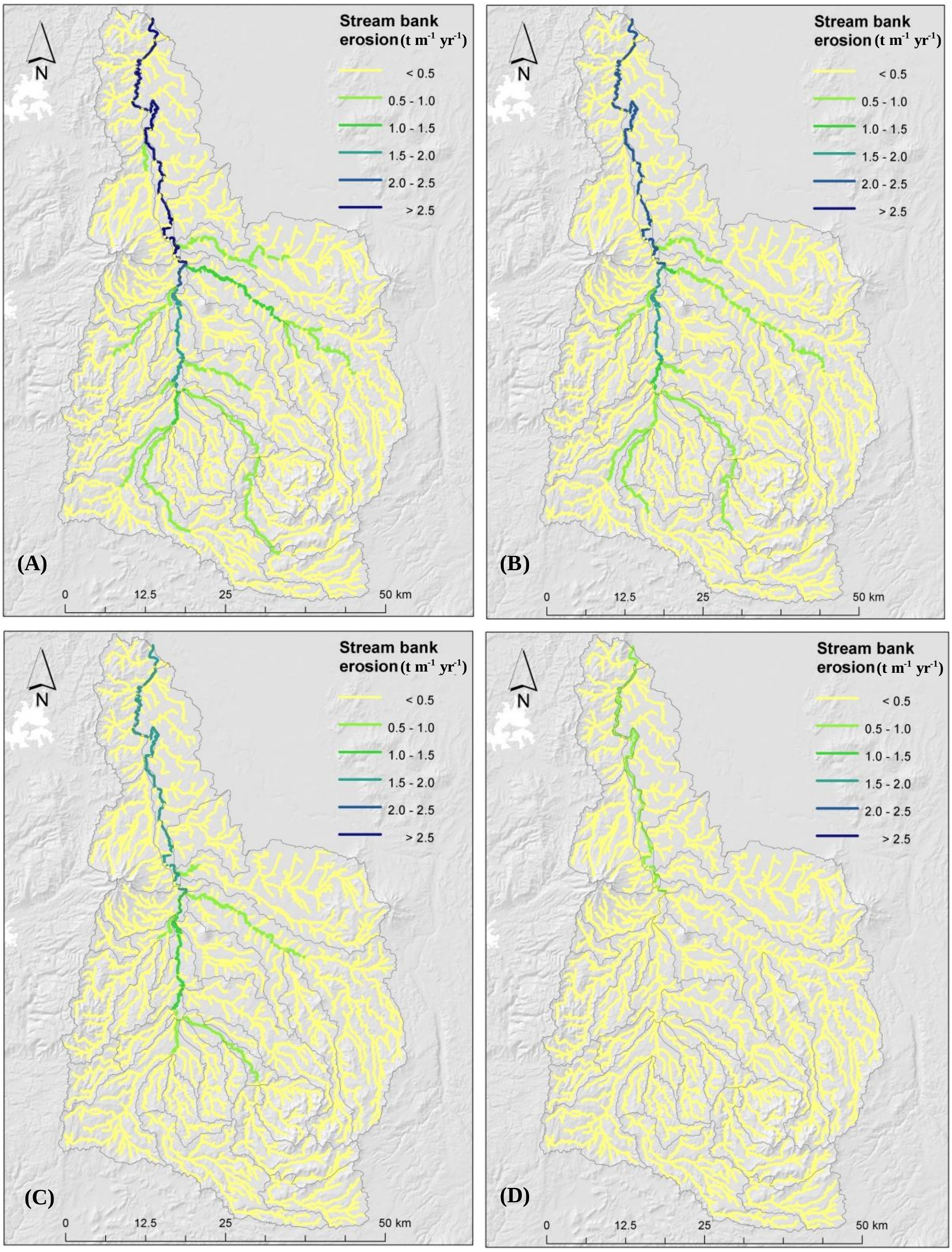

Figure 13 The Waipa catchment showing riverbank specific sediment yield (t m^{-1} yr^{-1}) across each stream link estimating the impact of riparian management where (A) no fencing, (B) 25% fencing (current status, 2012), (C) 50% fencing, and (D) 100% fencing on both sides of rivers and streams.

5.4 Waipa River and Waipa tributary sediment profile characteristics

To provide additional information about particle size characteristics, sediment samples were collected from selected tributaries and the Waipa River main stem immediately above the selected tributaries (Fig. 14). The rationale was to attempt to isolate the likely sources of fine sediments (clay) associated with the Waipa River. In general, the percentage of clay particles in the samples is extremely low (< 5% by volume) with a dominance in all samples of sand and silt. This is very low compared with what might have been expected from the clay content of the soils in the catchment, especially those from old volcanic ash or weathered greywacke (clay content typically >40%, Basher, unpublished data).

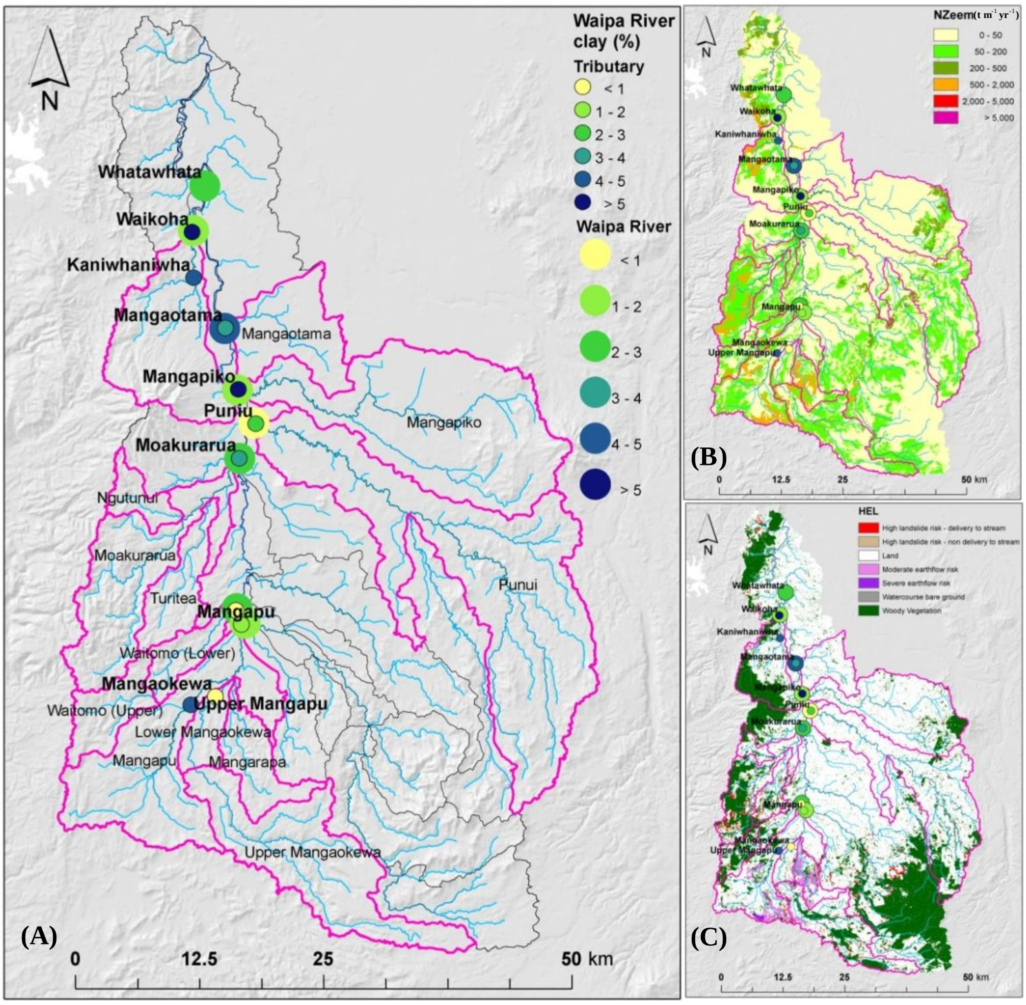

Figure 14 The percentage clay for samples collected from the Waipa River and selected tributaries at paired Waipa/tributary sites (A), New Zealand Empirical Erosion (B), and Highly Erodible Land associated with these sites (C). Bold text refers to the sample locations, while sub-catchments associated with sediment sample locations are given in red, with inserted captions.

Figures 14 and 15 suggest that the tributaries with the highest percentage of clay size particles are the Waikoha (6.9%) (Kaniwhaniwha sub-catchment), Mangapiko (6.1%), and the upper Mangapu (4.4%) tributaries. The other tributaries that have relatively high clay percentages are Kaniwhaniwha (4.2%), Mangaotama (4%), Puniu (3%), and the Moakurarua

(3.1%). Interestingly, on the day samples were collected from the Mangaokewa (0.1%), and the upper Mangapu (4.4%) a distinct difference in water colour could be seen at the confluence of these two rivers. It should also be noted that the Mangaokewa has the highest sand percentage and lowest clay and silt fractions of all the samples for the Waipa.

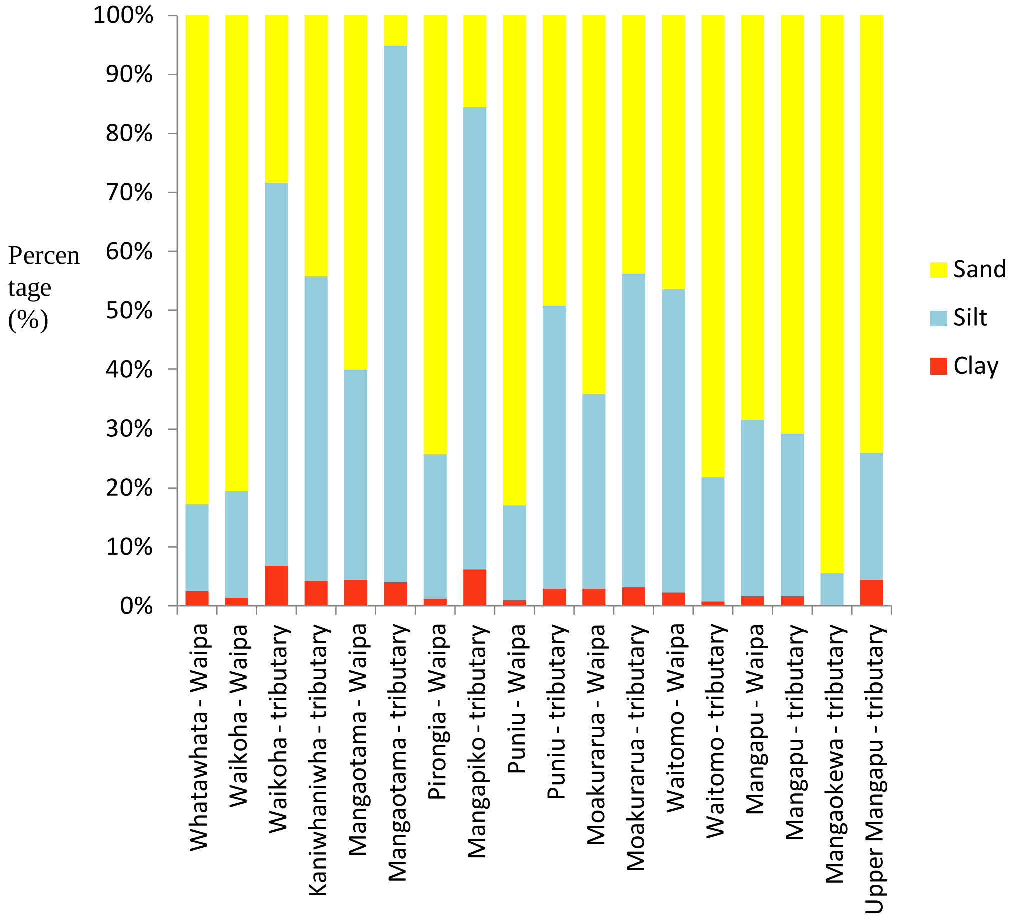

Figure 15 Particle size characteristics for the Waipa River and selected tributaries at paired Waipa/tributary sites.Sample sites are given in a north to south direction starting from Whatawhata to Mangapu. Note that the location is either a sample from the Waipa River or the tributary as stated with the place names, and that sample location names are given in bold lettering in Figure 14.

These results are consistent with observations in the adjacent Waitetuna catchment, which is also a very turbid stream draining similar topography and rock types. McKergow et al. (2010) found the suspended sediment load during a storm event was dominated by silt–size particles and had a low clay content (<5%). When disaggregated the clay content was much higher (c. 40%) and similar to values measured in the catchment soils (40–60% clay, Basher unpublished data). The clay content measured in all samples is relatively low and considering the low water clarity suggests more attention is needed to understand the nature of the sediment load.

Considering how turbid the lower reaches of the Waipa appear, the sediment yield at Whatawhata is low (60 t km^{-2} yr^{-1}). Other rivers of similar catchment size have much higher sediment yields (Hicks et al. 2011) but are considerably less turbid – for example, the Rangitikei at Mangaweka has a yield of 359 t km^{-2} yr^{-1}, and the Tukituiki at Red Bridge has a yield of 424 t km^{-2} yr^{-1}. Similarly other rivers considered highly turbid also have much higher suspended sediment yield (e.g. Manawatu at Teachers College 817 t km^{-2} yr^{-1}, and Waipaoa at Matawhero 7216 t km^{-2} yr^{-1}). This suggests that in order to focus on improving the clarity of the river a better understanding is needed of the factors controlling clarity as well as sediment load (Davies-Colley & Smith 2001; Julian et al. 2013). Measured clarity at base flow decreases downstream from about 1.6 m in the headwaters to 0.6 m in the lower reaches (Rutherford & Quinn 2010). The major factors controlling the optical character of suspended sediment are particle size, shape, and composition. In addition to suspended sediment there are other constituents in water that may affect clarity, including coloured dissolved organic matter, non-algal particulate organic matter, and phytoplankton (Julian et al. 2013; Ding & Richards 2009). Little is known of the suspended sediment characteristics of the Waipa River, other than its load. The Waikato River Independent Scoping Study has set a target for water clarity of 1.6 m, a substantial increase on the 0.60 m measured over the period 1989–2007.

6 Conclusion and future work

The area of highly erodible land within the Waipa catchment is relatively small (9825 ha or 3.2% of the catchment area). About half the HEL area is at risk from landsliding, and the other half is at risk from earthflow erosion. The areas at risk from landslide erosion are mostly in the steeper headwaters of the western and southern tributaries, whereas the areas at risk of earthflow erosion are mostly in the southern headwaters. The HEL model identified 3180 ha of Waipa land at risk of landsliding with potential of delivery to streams; a further 2100 ha are classed as not contributing to streams. Land with a moderate (4360 ha) and severe earthflow risk (185 ha) occurs in the northwest and southern parts of the Waipa catchment. Areas identified as being highly susceptible to erosion by the HEL map were intersected with the Fundamental Soil Layers (FSL) *PS* field in an effort to identify those areas of HEL more likely to deliver clay and silt size material to the river and stream network. Overall, 700 ha (7%) of HEL has a dominant clay particle size distribution, while around 8800 ha (90%) were associated with silt-dominated particle sizes.

Like the HEL model, the NZeem® model also indicates that the steeper terrain along the western margins and the south-west of the Waipa catchment as having the highest erosion rates. Sediment loads (t yr^{-1}) are highest in the Mangapu, Moakurarua, and the Whatawhata/Ngaruawahia sub-catchments respectively, with 33 000, 30 000, and 21 000 t yr^{-1}. Scenario modelling using NZeem® and AgriBase calculates an on-farm reduction in sediment through mitigation strategies (farm plans) of between 60 000 and 100 000 t yr^{-1} related to the worst HEL areas for 100–500 farms respectively, is possible (based on AgriBase polygons). This approach enables mitigation strategies to be applied on farms identified by AgriBase and HEL for targeted farms and mitigation strategies.

SedNetNZ predicts that if all remaining stream banks were fenced bank erosion could be reduced from 65 000 t yr^{-1} (with 25% fencing on both sides of rivers and streams) to 162 000 t yr^{-1}.

Sediment samples collected from overbank floodplain deposits had low clay percentage (generally <5%). The low clay content measured in all samples considering the low water clarity suggests more attention is needed in understanding the nature of the sediment load in the water column. Considering how turbid the lower reaches of the Waipa appear, the sediment yield at Whatawhata is relatively low (60 t km^{-2} yr^{-1}). This suggests that to improve the clarity of the river a better understanding is needed of the factors controlling both clarity and sediment load. Improving the clarity of the river may require targeting those areas that produce the finest sediment. The clarity of the Waipa remains poor even at low flows, implying the load comprises particles that persist suspended in the water column.

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