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Soil erosion and intertidal sedimentation in Lyttelton Harbour/Whakaraupō: The ongoing legacy of land use change assessed using the Revised Universal Soil Loss Equation (RUSLE).

Honours Dissertation

Melissa Shearer

Department of Geography, University of Canterbury

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1.0 INTRODUCTION

1.1 Background and significance of issue

The extensive mudflats within the inner area of Lyttelton Harbour/Whakaraupō are a predominant feature of the low tide environment. These mudflats cover an area of 11 square kilometres (km^2) at Mean Low Water Springs (MLWS)(Curtis 1985; Hart 2004; ECan 2007a) and their persistent growth has been attributed to land use change within the harbour catchment since European settlement approximately 170-180 years ago (Hart 2004; Goff 2005; Wilson 2009). Banks Peninsula was once covered in dense totara (*Podocarpus totara*) dominated mixed podocarp forest (Harding 2003, Harding et al. 2006) which was cleared by settlers to make way for agricultural developments and to supply timber to the growth of Christchurch and surrounding urban settlements. The level of forest cover was reduced by over 90 percent resulting in soils being destabilised and exposed to the erosive powers of wind and water (Harding 2003; Hart 2004; Harding et al. 2006; Campbell et al. 2008). Goff (2005) established that sedimentation rates within the harbour have in fact accelerated post European settlement and are currently accumulating at a rate of 35 millimetres (mm) per year. This history of enhanced sediment influx has resulted in the already shallow harbour significantly infilling with 47 metres of sediment (Curtis 1985; Hart 2004; ECan 2007a).

Erosion and sedimentation has a variety of on and off-site impacts in both the terrestrial and aquatic environments. Erosion is a key cause of land degradation worldwide (Valentin et al. 2005) and can result in a decline in soil fertility and productivity (Hartanto et al. 2003; Porto et al. 2009; Bartley et al. 2010a). Within the receiving aquatic environments, biological communities face habitat alteration or loss as fine sediments smother the bottom of the streams and the harbour (Uri and Lewis 1998; Harding 2003; Sidle et al. 2006; Jaffe et al. 2007) and water quality is degraded by the addition of excess sediment, nutrients and compounds such as heavy metals which may be associated with the soil particles (Nelson and Booth 2002; Goodwin et al. 2003; Hartanto et al. 2003; Valentin et al. 2005; Bartley et al. 2010a). From an economic perspective, dredging of an access channel is required to maintain viable operations at the Port of Lyttelton which is an ongoing and significant cost to the port company. The deforestation of Banks Peninsula has not only induced the augmented level of erosion in the harbour catchments, it has also resulted in the extinctions of endemic Banks Peninsula invertebrate and avian species and caused severe restrictions in the range of many of the surviving endemic species (Harding 2003, Harding et al. 2006).

In order to mitigate further sedimentation of the harbour and degradation of the terrestrial and aquatic environments, the catchments which are producing the largest quantities of sediment need to be identified and management strategies such as reforestation and soil conservation need to be developed and implemented to reduce sediment outputs from these key catchments.

1.2 Study Site

Lyttelton Harbour is situated on the east coast of the South Island within the northern part of Banks Peninsula (Fig. 1). The harbour is ringed by steep, hilly catchments incised by numerous permanent and ephemeral streams. The lithology and soil type is spatially varied around the harbour with volcanics making up the main rock types (Curtis 1985, ECan 2007b). Aeolian loess transported from the Canterbury Plains during the late Pleistocene is the main component of Lyttelton Harbour soils (Fig. 2), and deposits of this fine material are reported to be 10-20 m in depth in many locations (Curtis 1985, Hart 2004). The predominant soils found around Lyttelton Harbour are classified as: Takahe/Pawson, Stewart, Evans-Kiwi, Bossu, Motukarara and Barry (NZ Soil Bureau 1968a; 1968b; Griffiths 1974; Molloy 1993; Hewitt 1998). With the exception of Motukarara which is a sandy loam (65% sand, 25% silt, 10% clay), all soils are silt loams (20% sand, 65% silt, 15% clay).

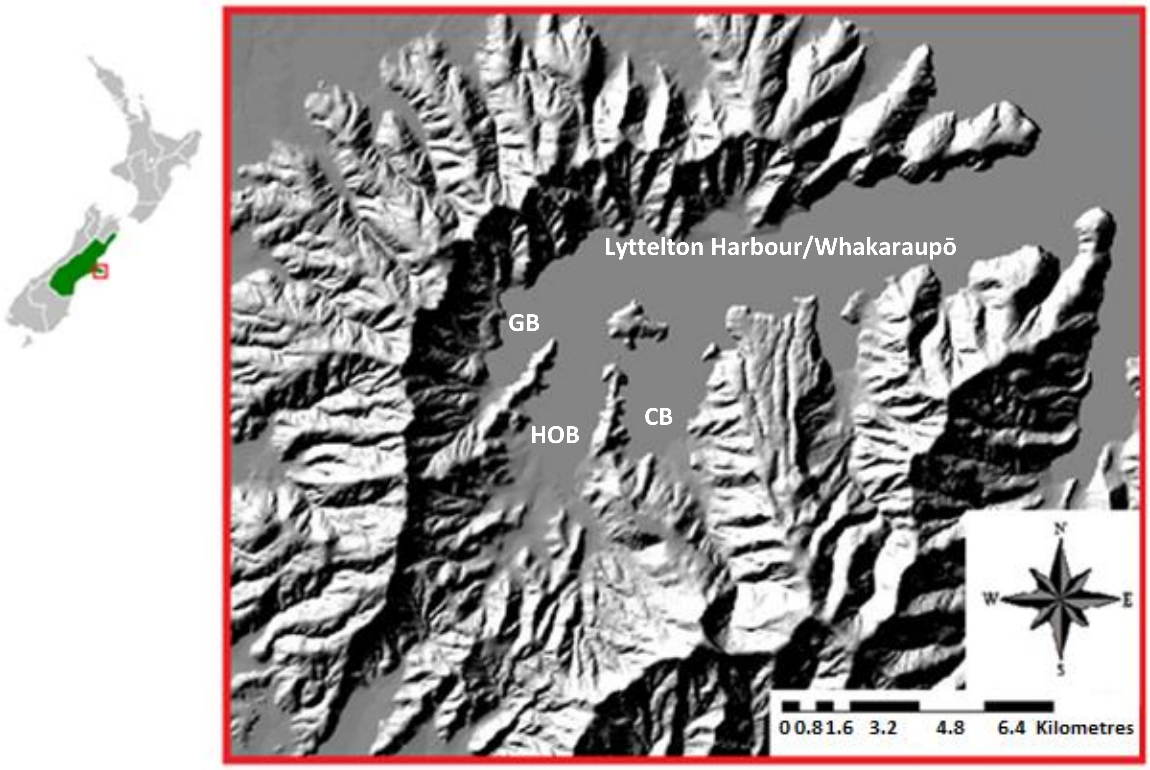


Figure 1. Lyttelton Harbour and the three main bays of the inner harbour area, Governors Bay (GB), Head of the Bay (HOB) and Charteris Bay (CB) situated within Banks Peninsula on the east coast of the South Island.

The inner harbour consists of three main bays; Governors Bay, Head of the Bay and Charteris Bay. The mudflats are contained within these bays and are the entry points to the harbour for the majority of the relatively minor fluvial inputs (Curtis 1985, Hart 2004).

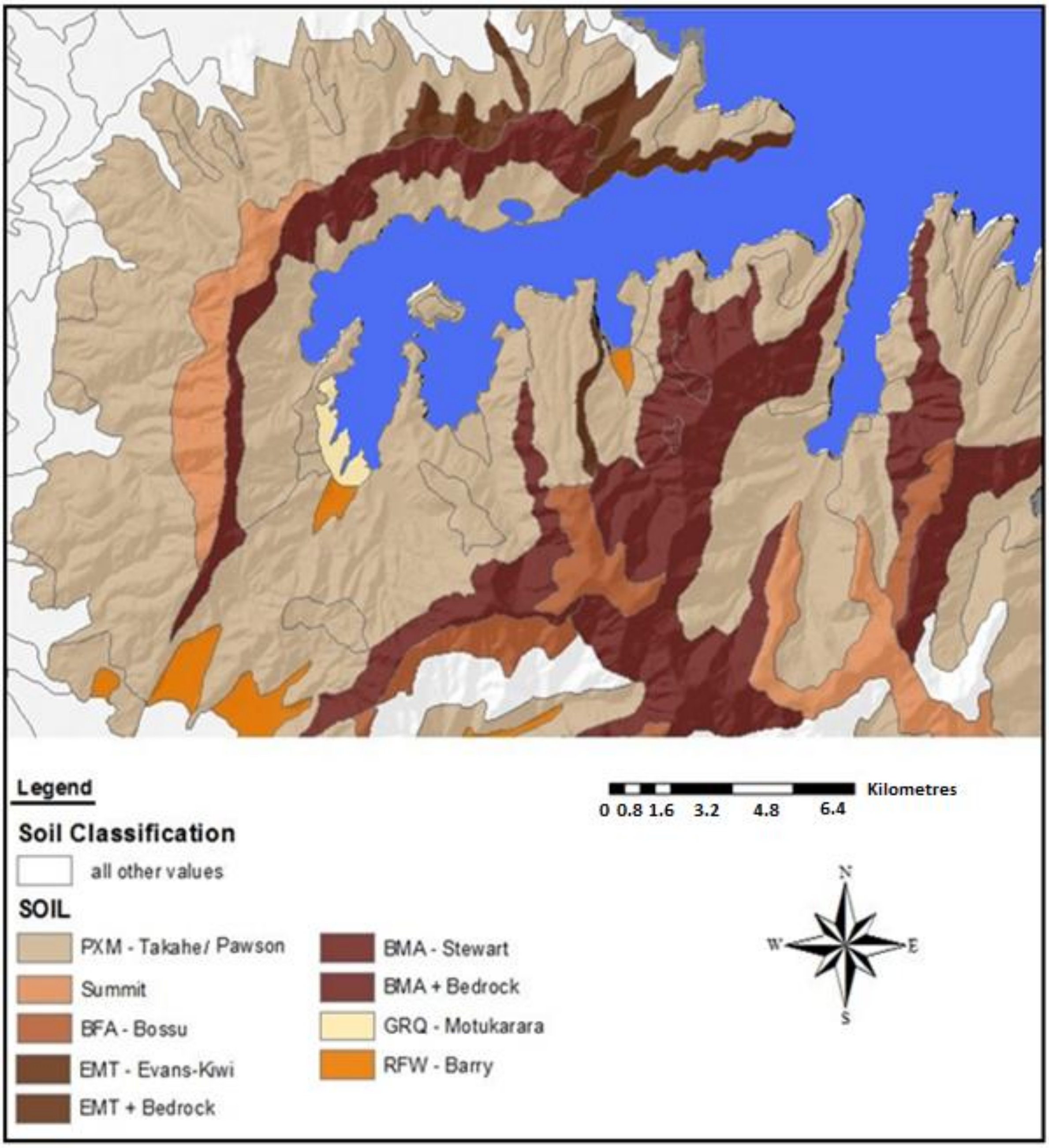


Figure 2. Type and distribution of soil groups around Lyttelton Harbour indicating the spatial variability of soil types and the predominance of greywacke loess (PXM). Source: Landcare Research 2011

A variety of land uses are found within the harbour catchments including low-intensity pastoral agriculture, horticulture, plantation forestry and native forest blocks, small urban settlements and quarrying (Fig. 3).

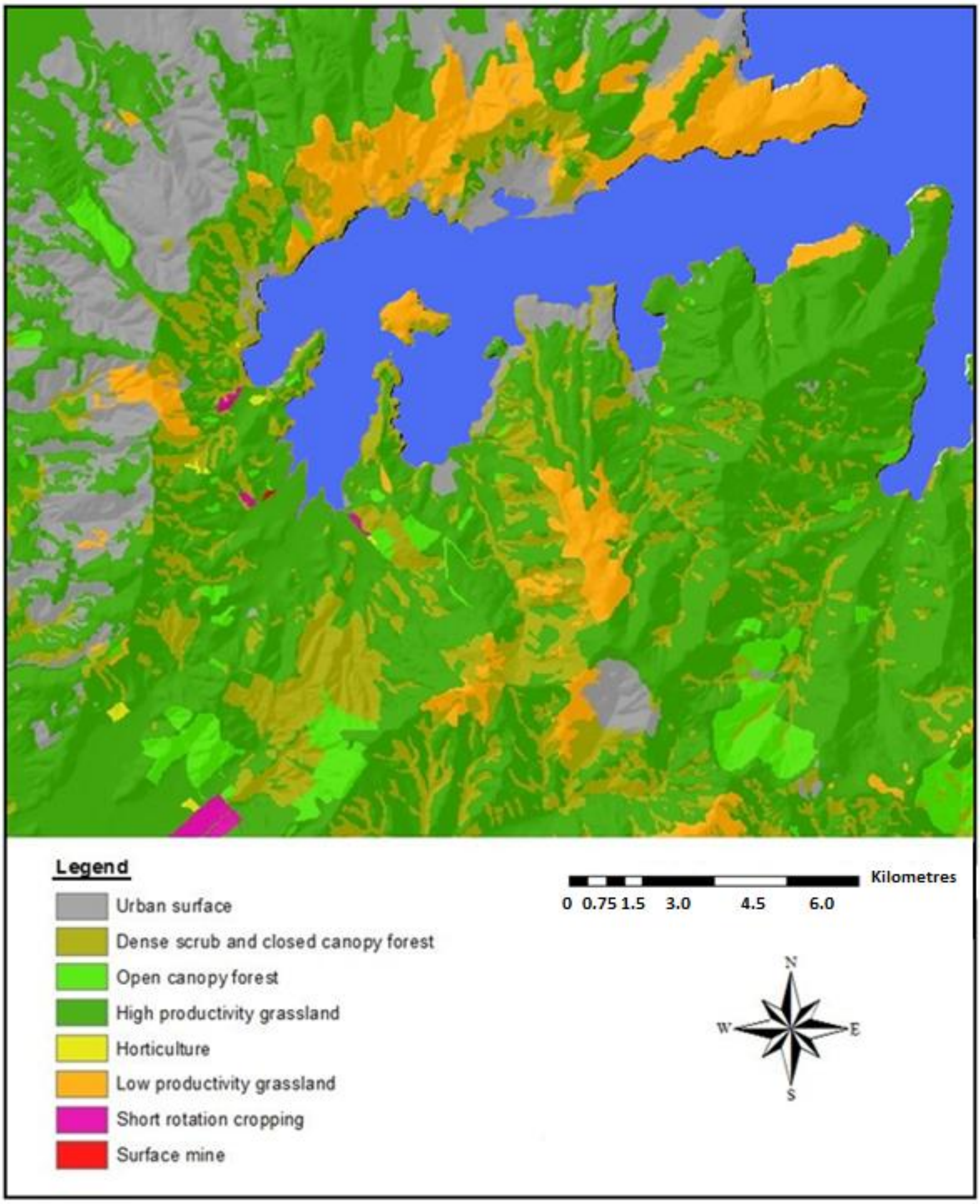


Figure 3. Distribution of land uses and vegetation types around Lyttelton Harbour. Source: Ministry for the Environment (2011)

There is significant spatial variability in the climate experienced over the harbour due to the effects of topography and aspect of the bays (Molloy 1993, NIWA Climate Database 2011). Overall, the northern side of the harbour is drier than the southern side with average rainfalls of >500 - < 800 mm yr^{-1} and >800 - > 1200 mm yr^{-1} respectively (NIWA 2007).

1.3 Aims and objectives of study

This study has been guided by the overarching aim of ascertaining which catchments within Lyttelton Harbour are contributing the most sediment into the marine environment. It is recognised that in order to effectively and efficiently implement a management strategy for reducing soil loss, identifying the key areas for the focus of management is vital (Valentin et al. 2005; Vahabi and Nikkami 2008; Dymond et al. 2010; Nigel and Rughooputh 2010). Once these key catchments have been determined, an additional objective of this study is to provide practical information on ways in which sediment losses can be mitigated. A further aim of this study is to provide for a more complete understanding of the sedimentation issue for Lyttelton Harbour, as presently there are no studies focusing on catchment sediment losses. Finally, this study also has the objective of testing whether or not the use of the Revised Universal Soil Loss Equation (RUSLE) is appropriate within New Zealand contexts and this shall be determined by comparing the similarities of results obtained here to that of existing sediment yield models for New Zealand.

A number of research questions have been formulated in order to meet the aims and objectives of this study:

1. Which catchments contribute the largest amounts of sediment into Lyttelton Harbour as estimated by erosion rates?
2. What are the characteristics of these catchments which lead to high amounts of erosion?
3. What can be done in these catchments to reduce soil losses?
4. How does the model used in this research compare to other models used to determine sediment yields in New Zealand?

1.4 Report structure

This report shall commence by placing this current research in the context of the already established knowledge about sedimentation within Lyttelton Harbour. This is followed by examination of the Revised Universal Soil Loss Equation and the limitations of this model. The methodological approach shall then be discussed and key results are outlined including which catchments are the most significant contributors of sediment to the harbour and the characteristics of these catchments which may be attributed to their high rate of erosion. A detailed discussion of erosional processes occurring within the catchments of Lyttelton Harbour and how the different characteristics of the physical environment are influencing the level of soil loss shall ensue. The report shall then be concluded with an analysis of the limitations of this study and suggestions for future research. Appendices included provide addition information on policy implications of soil erosion in Canterbury, the adverse effects of sedimentation and erosion on the harbour environment and ways in which soil loss may be mitigated in the future.

2.0 LITERATURE REVIEW

2.1 Current knowledge of issue

The existing knowledge on sedimentation within Lyttelton Harbour comes from a limited body of work completed by university students and research conducted for the regional council (such as Curtis 1985; Hart 2004; de Vries 2007; Hart et al. 2008). This existing knowledge is primarily focused on the processes occurring within the marine environment of the harbour such as mud flat dynamics, bathymetric studies and biological surveys. Only a single estimate has been made for sediment erosion from all catchments combined, with no analysis of spatial variation in catchment outputs. Environment Canterbury have however conducted a study aimed at identifying the key sources of suspended sediment to the harbour, which included areas such as urban developments, road cuttings, quarrying and storm water systems (ECan 2007a). Curtis (1985) determined that an annual average loss of sediment over the harbour as a whole was approximately 44,300 tonnes, estimated from foreshore changes and erosion from road cuttings. There are two main sources of sediment for the harbour. Curtis (1985) ascertained that re-circulated spoil material from dredging operations of the Lyttelton Port Company was the main internal sediment source, while catchment erosion is well recognised to be the main external source of sediment to the harbour and the source of sediment to the mudflats (Curtis 1985; Hart 2004; Goff 2005; Hart et al. 2008). It has been established that sediment from the dredging activity and areas external to Lyttelton Harbour such as Pegasus Bay does not contribute to the growth of the mudflats because of the wave and tide environment within the harbour (Curtis 1985; Hart 2004; de Vries 2007). Goff (2005) provided some useful insight to the accumulation of sediment in the inner harbour through a series of sediment core analyses. Through signals in the sediment core, the date of European arrival was ascertained and was found to be coupled with an increase in the sediment accumulation rate within the harbour, with a peak rate of 85 mm per year in 1868-1900. Goff also found a shift in grain size from coarser sediments to a predominance of fine silts as the loess soils were exposed to erosive forces.

It is important to recognise that infilling of sheltered inlets such as Lyttelton Harbour is a natural process. The flat plains at the bottoms of the valleys around the harbour indicate accretion of eroded sediment is a longstanding process (Hart 2004). However it is clear that the rate of sedimentation within the harbour has accelerated post European settlement (Goff 2005) as a result of forest removal and conversion to pasture (Fig. 4). More contemporary sediment fluxes are considered to be the result of a growing amount of urban developments on the hill slopes of Lyttelton Harbour (Hart et al. 2008).

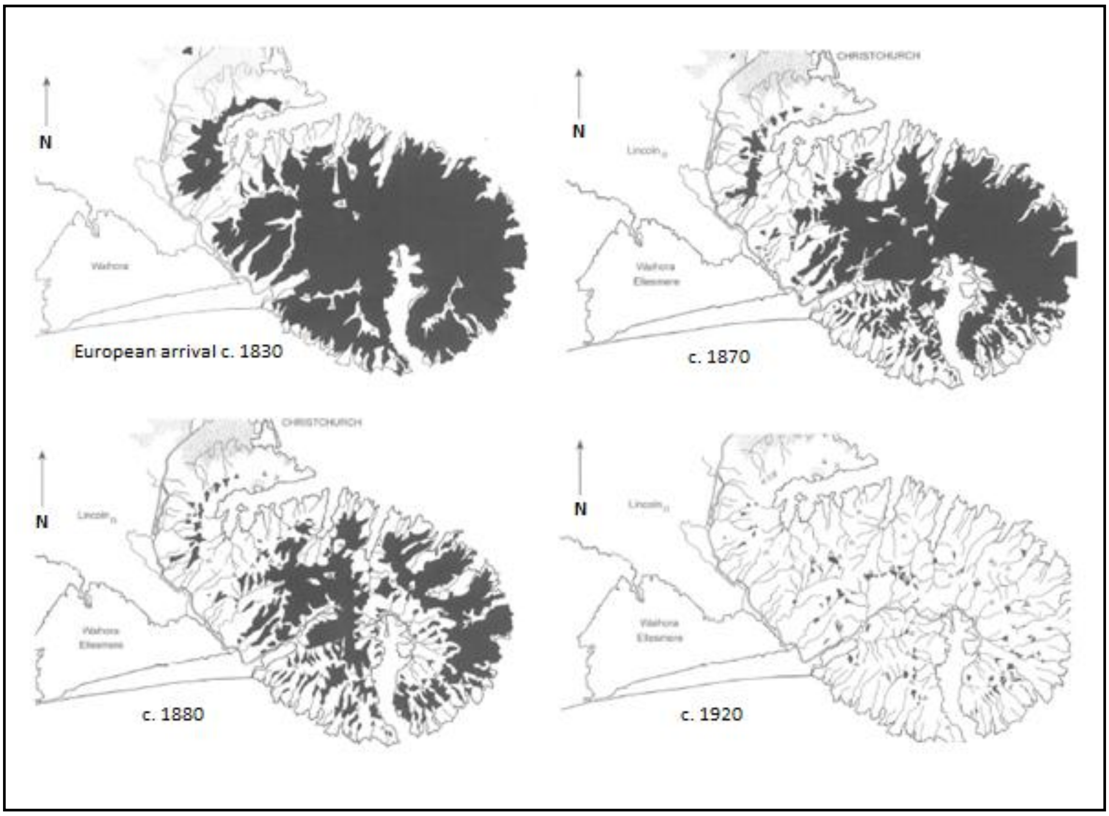


Figure 4. The significant (>90%) reductions in the extent of forest cover on Banks Peninsula and Lyttelton Harbour since European settlement which has been attributed to accelerating the rate of sediment accumulation within Lyttelton Harbour. Adapted from Boffa Miskell (2007), pg. 27.

Several factors have contributed to the catchments of Lyttelton Harbour being so prone to soil erosion including the steep topography and loess type soils which inherently provide for high sediment erosion, especially where there is a lack of substantial vegetation cover (ECan 2007a).

Indicators of erosion are evident in the inner harbour area such as visible riling in paddocks and mass wasting from road cuttings (Fig. 5).

Figure 5. Evidence of soil erosion in paddocks in the Rapaki Catchment and mass wasting from a typical road cutting. Photos taken 10/9/11 by M. Shearer.

There are several comparable studies to the present one which have been completed both within New Zealand and internationally. Increased sedimentation rates within Wellington Harbour (Goff 1997) and Whangape Harbour (Glade 2003) could be attributed to deforestation which occurred in the catchments of both of these harbours after European settlement in New Zealand. Similar studies on an international level include that by Jaffe et al. (2007) in San Pablo Bay, California and Wallbrink (2004) in Moreton Bay, Southeast Queensland. There appears to be no other studies within New Zealand which have made use of the Revised Universal Soil Loss Equation (RUSLE) to determine sediment losses, so the appropriateness of using RUSLE in New Zealand has not been illustrated.

2.2 Erosion

Soil erosion is defined as the process of detachment, transport and deposition of soil particles by the erosive agents of wind and water (Morgan 1995, Valmis et al. 2005). World wide, soil erosion is recognised as a leading cause of land degradation, loss of soil fertility and productivity and a major cause of poor water quality (Uri and Lewis 1998; Li et al. 2004; Valentin et al. 2005; Hartanto et al. 2003; Porto et al. 2009; Bartley et al. 2010a). The severity of soil erosion depends on a number of factors such as rainfall, land use, slope, soil texture, soil moisture, permeability, shear strength, and most importantly soil aggregate stability (Bryan 2000; Misra and Teixeira 2001; Cotler and Ortega-Larrocea 2006; Sidle et al. 2006; Vahabi and Nikkami 2008). These properties affect how the soil responds to the impact of rainfall, how this water moves through the soil matrix and the resistance of particles to entrainment by water (Bryan 2000).

According to the Soil Erosion Type and Severity Map from Landcare (Fig. 6), the predominant erosional processes occurring within the catchments of Lyttelton Harbour are sheet, soil slip, gullying and tunnel gullying which can be broadly classified as rill or interrill processes. Interrill erosion is a form of erosion where entrainment of soil particles is principally caused by rainsplash energy and overland flow not concentrated in a defined channel (Morgan 1995, Bryan 2000). Conversely rill erosion is when the main cause of particle entrainment is surface runoff confined in small temporary channels known as rills, or in more permanent gullies and streams (Morgan 1995, Bryan 2000).

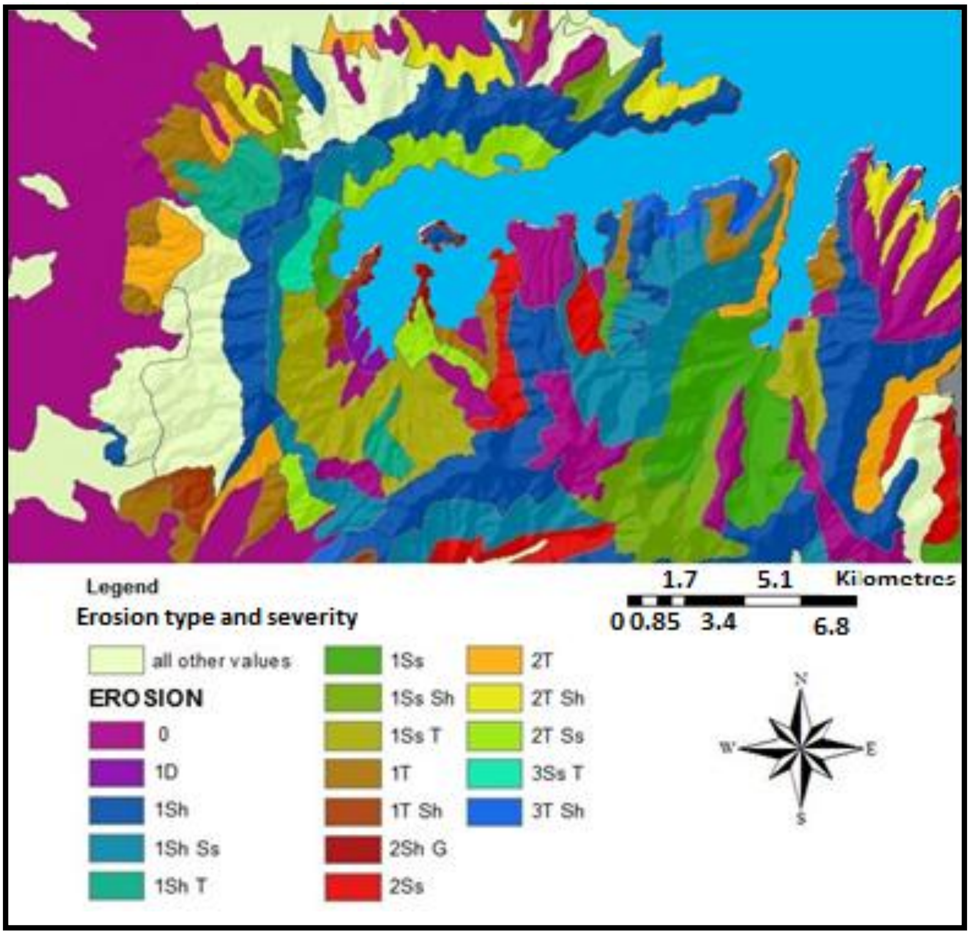


Figure 6. Erosion type and severity where D= G= Sh= Ss= T= and 1=Minor, 2=Moderate, 3=Severe. Source: Landcare Research 2011

2.2.1 Soil erosion and conservation policy in New Zealand

In the 1930s the realisation occurred that there was a need for soil conservation in New Zealand (Clough and Hicks 1992) which led to the development of early soil conservation legislation such as the Soil Conservation and Rivers Control Act 1941 and the Water and Soil Conservation Act 1967. The Resource Management Act 1991 (RMA) is the current overarching legislation for resource management and sustainability in New Zealand. The requirements of the Act are implemented in Lyttelton Harbour through policy developed by Environment Canterbury. The Canterbury Natural Resources Regional Plan (NRRP) sets out objectives for a variety of environmental outcomes, including the conservation of soil, which makes up Chapter 8 of the NRRP. The aims and requirements of the NRRP feed into the Canterbury Regional Policy Statement (RPS) where Chapter 15 of the RPS focuses on soils and provides a clear statement of objectives and policies which must be implemented to conserve and protect the soils of Canterbury (Appendix A).

2.3 Land use change

2.3.1 Deforestation

Significant amounts of forest have been removed from the Americas, Australia, South-East Asia and New Zealand (Garcia-Ruiz 2010). In New Zealand, the extensive deforestation has lead to increased rates of soil erosion and subsequently sedimentation of aquatic environments like Lyttelton Harbour (Glade 2003, Dymond et al. 2010). Forest removal has also had significant impacts on stream habitats and invertebrate communities adapted to forested ecosystems (Quinn et al. 2004, Harding et al. 2006). The destruction of forest causes an increase in the sediment yield from that land because the soil is exposed and now more vulnerable to water erosion. The canopy trees in combination with a ground story of ferns, shrubs and herbaceous plants form a dense protective cover against rainsplash erosion (Glade 2003). Removing the forest flora also results in a decrease in organic matter of the soil which weakens the soil further increasing the susceptibility to erosion (Valentin et al. 2005). Mohammad and Adam (2010) state that soil seals are a common feature after vegetative covers have been removed, this induces greater runoff and erosion. In addition to this, it is reported that the conversion to pasture from indigenous forest in New Zealand has increased the amount of mass movements such as landslides (Fahey and Marden 2000; Glade 2003; Kasai et al. 2005). These processes would likely have occurred within Lyttelton Harbour post deforestation thus contributing to the accelerated rate of soil erosion and sedimentation within the harbour.

The harvesting of commercial forest plantations is also well recognized to increase catchment sediment yields. As there are a number of plantation forestry blocks around Lyttelton Harbour, their removal will potentially cause a large influx of sediment into the harbour, especially those located on the small peninsulas around the inner harbour area. However, many of the adverse effects from mechanical harvesting can be avoided by prohibiting or limiting harvesting in the riparian area by maintaining a buffer zone, as discussed in Appendix B

2.3.2 Agriculture

Farming practises can further enhance sediment losses. There are numerous examples of situations in both New Zealand (Goff 1997; Fahey and Marden 2000; Fahey et al. 2003; Dymond et al. 2010) and internationally (Wallbrink 2004; McKergow et al. 2005; Jaffe et al. 2007; Bartley et al. 2010a) in which agriculture has induced increased rates of erosion and sedimentation. Disturbance to the soil from farming activities like ploughing and compaction results in a depletion of organic matter and disruption to the soil structure and stability which reduces the soils resistance to erosion (Stocking 1994; Bryan 2000; Valentin et al. 2005). As the majority of farms within Lyttelton Harbour are pastoral with low stocking rates and only three paddocks under short rotation cropping (Fig. 3) the current agricultural use of the land is not expected to provide significant fluxes of sediment into the harbour when compared to land which is actively cultivated and cropped (Rodriguez-Blanco et al. 2010).

2.3.3 Other land uses within Lyttelton Harbour

Other land uses within Lyttelton Harbour which have the potential to contribute fine sediments into the harbour include urban development, storm water infrastructure and quarrying (ECan 2007a). There are numerous small settlements already established within the harbour with more small subdivisions underway (Fig. 7). Urbanization of the watershed changes the hydrology and surface characteristics of the catchment (Corbett et al. 1997). However, overall it is the initial construction phase which is the period of highest sediment delivery (Roberts and Pierce 1974; Nelson and Booth 2002; Chin 2006). Wotling and Bouvier (2002) found that compared to a natural basin, urban catchments produced two times more sediment while an actively urbanizing catchment produced 12 times more. Therefore stringent controls need to be put in place and enforced as part of the resource consent process to ensure that the earthworks associated with subdivision are not contributing excess sediment into the streams and contractors should consult ECan's (2007c) report on *Erosion and Sediment Control Guidelines.*

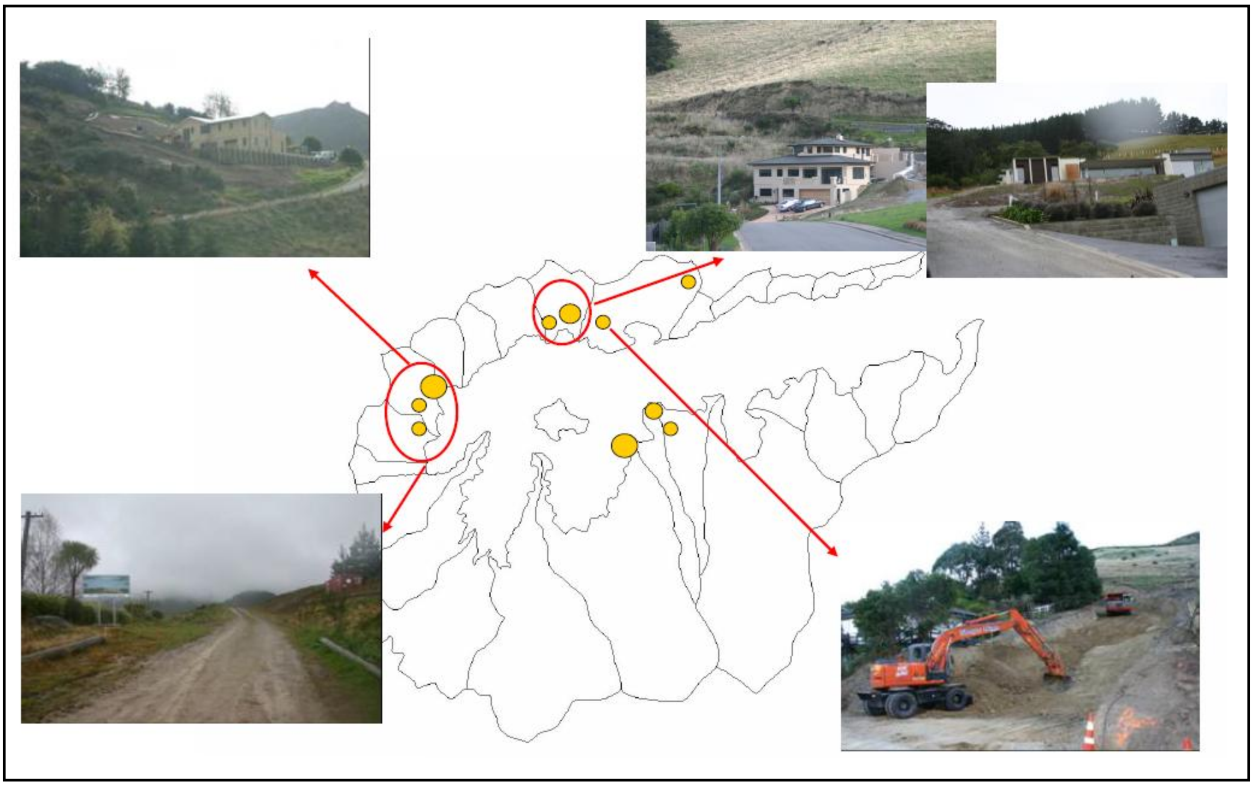


Figure 7. Locations and images of the major subdivision developments around Lyttelton Harbour. Source: ECan (2007a, pg. 13).

A small scale aggregate quarry is located adjacent to Foleys Stream in the Head of the Bay. The effects of this quarry on the near by stream are apparent (Fig. 8) and should be the focus of future work as it has the potential to supply significant amounts of fine sediment into the harbour due to the large surface area of exposed soil and sediment and the close proximity of the quarry to both Foleys Stream and the harbour itself. Environment Canterbury has also recognised the potential for this quarry to supply sediments to the harbour in their 2007 study (ECan 2007a).

Figure 8. A) The quarry adjacent to Foleys Stream in the Head of the Bay, B) a reach of the stream upstream of the quarry, C) and D) illustrate how the morphology of the channel and flow velocity has changed due to an increase in fine sediments forming a thick layer of mud on the banks and bed. Photos taken 26/8/2010 by M. Shearer.

2.4 Adverse effects of erosion and sedimentation

Soil erosion results in a number of on site and off site adverse effects. Space does not permit the discussion of this here, but an overview of the effects of land degradation and sedimentation from soil erosion can be found in Appendix C. This overview provides some evidence for why the mitigation of induced soil erosion in Lyttelton Harbour is important and necessary to avoid the adverse effects in the terrestrial and aquatic environments of the harbour.

2.5 The Revised Universal Soil Loss Equation (RUSLE)

The RUSLE developed by Renard et al. (1997) is an advance on the Universal Soil Loss Equation (USLE) model originally developed by Wischmeier and Smith (1978) (Zhang et al. 1996; Angima et al. 2003; Croke and Nethery 2006; Kinnell 2010). The enhancement of this empirically based model has meant the RUSLE is able to be used under conditions not originally present during the development of the USLE (Croke and Nethery 2006, Kinnell 2008). A detailed summary of the changes made in the RUSLE can be found in Croke and Nethery (2006). The original purpose for the development of the USLE was to predict soil losses from agricultural lands for soil conservation and management policy for farmland (Kinnell 2010).

The RUSLE predicts the average annual rate of soil erosion for hillslopes by multiplying a number of factors together, typically given as the following:

$$A = R \times K \times LS \times C \times P \qquad \text{(eq. 1)}$$

Where *A* is average soil loss due to water erosion (t/ha /a), *R* is the rainfall erosivity factor (MJ mm ha/h/a), *K* is the soil erodibility factor (t/ h/ MJ/ mm), *L* is the slope length (m), *S* is the steepness factor (%), *C* is the cover management factor and *P* is the support practise factor. The values for these factors were derived from 10,000 plot years of data from runoff and soil loss plots over 37 states in USA (Croke and Nethery 2006; Kinnell 2008; Terranova et al. 2009). The rainfall erosivity factor *R* accounts for the impact of raindrops and the level of runoff associated with rainfall on a storm by storm basis over an annual timescale (Angima et al. 2003). McIntosh and Laffan (2005, pg. 132) define soil erodibility as *"the inherent susceptibility of a soil to the detachment and transport of soil particles or aggregates by erosive agents"*; *K* therefore identifies the ease of soil particle detachment and transport by rainsplash or by surface flow (Morgan 1995, Anigma et al. 2003). This factor is influenced by rainfall, runoff and infiltration and describes how the properties of the soil (such as organic matter content, size of void spaces and particle structure) can determine the level of erosion during a rainfall event (Morgan 1995; Angima et al. 2003; Park et al. 2011). The *L* and *S* factors are typically combined to provide an index of soil loss illustrating the influence of slope length and steepness on erosion (Morgan 1995; Anigma et al. 2003; Park et al. 2011). *C* accounts for the effects of different vegetative land covers and land management practices. The value of *C* varies depending on vegetation type and size, plant root size, surface roughness and disturbances to the soil such as tillage and can be an order of magnitude different. *P* is the ratio of soil loss with a certain support practice compared to soil loss with up and down slope tillage (Morgan 1995; Angima et al. 2003; Park et al. 2011). This factor accounts for management practices put in place such as contouring, terracing, hedge rows and subsoil drainage networks (Morgan 1995, Park et al. 2011). Where no support practice is in place, *P* takes on a value of 1.0 (Morgan 1995).

2.6 Limitations of the Revised Universal Soil Loss Equation

The broad use of the RUSLE in a variety of contexts has faced great criticism and the results derived from these studies need to be considered with caution. The wide use of the USLE/RUSLE is considered to be the result of the relative ease of use and minimal data inputs required to operate the model, not because of its applicability to a wide range of environments (Kinnell 2005). Many ague that the USLE family of models are not 'Universal' at all, and should not be used outside the context for which they were developed as they have not been tested and validated and because of the empirical nature of the model (Zhang et al. 1996, Evans 2002, Nigel and Rughooputh 2010). Another major limitation for the RUSLE is that erosional processes included in the model are limited to sheet and rill erosion (Kinnell 2010) while processes such as gully and channel erosion and mass movements are excluded (Zhang et al. 1996; Evans 2002; Glade 2003; Croke and Nethery 2006; Terranova et al. 2009). The absence of these processes in the model is a limiting factor as mass movements are considered by some (for example DeRose et al. 1998, Glade 2003) to be the major contributor to fine sediment loads, where as chronic erosion such as gullies are considered to be the greatest contributor by others (Croke and Nethery 2006, Terranova et al. 2009). Deposition of sediment or the sediment delivery ratio are also not considered in RUSLE which is also considered as a flaw as these two processes are a fundamental part of assessing sediment yields (Morgan 1995, Croke and Nethery 2006).

Despite these limitations, the RUSLE can still be useful for highlighting areas most prone to hillslope erosion, if the limitations of the model are taken into consideration and the results are interpreted appropriately.

3.0 METHODOLOGY

A modelling based methodology has been considered to be the best approach for this research due to the limited time frame available to complete the research and because modelling is a very useful tool for predicting soil loss in un-gauged catchments where data is scarce as is the case in Lyttelton

Harbour (Angima et al. 2003; Croke and Nethery 2006; Terranova et al. 2009). In addition to this, modelling helps to overcome the issue of the high spatial and temporal variability of soil erosion rendering field measurements over a short time period and limited spatial extent unrepresentative (Lufafa et al. 2003). Due to the limitations of the RUSLE outlined above, this modelling approach is only being used comparatively and the results are not intended to be considered in absolute terms as is suggested by Terranova et al. (2009) for using the model outside the context for which it was developed.

A Geographic Information System (GIS) is computer based software system used to capture, manipulate and display spatial information. The integration of GIS and RUSLE has allowed for easy storage and manipulation of the topography, land use and soil type data and therefore the *K* and *C* factors of the RUSLE (Desmet and Govers 1996; Lufafa et al. 2003; Park et al. 2011). The use of Digital Elevation Models (DEM) in a GIS framework provides for the topographical factors of slope length (L) and slope steepness (*S*), so allows for the inclusion the complex nature of the landscape in the model (Desmet and Govers 1996; Zhang et al. 1996; Winchell et al. 2008). As most erosion models involve many factors with great spatial and temporal variation, the use of GIS allows for feasible soil erosion estimation and the spatial representation of this possible over whole watershed areas which may otherwise be restrictively costly (Terranova et al. 2009, Park et al. 2011).

3.1 Methods

3.1.1 Sources of data

Data for soil classification, land cover and topography were obtained from Landcare's Land Resources Information Services (LRIS) portal and the Ministry for the Environment's Environment Land Cover Data Base version 2 (LCDB2). Data for annual average rainfall for Lyttelton Harbour was obtained from NIWAs national climate database and data for hourly rainfall totals was obtained from the Department of Geography at Canterbury University over the last ten years.

3.1.2 Calculation of RUSLE factors

The following flow chart and series of map layers illustrates the process which was undertaken to determine the values for each of the factors within the RUSLE equation (eq. 1) and how the model was executed using ArcMap in ArcGIS 10.

K

Soil types were assigned appropriate *K* values as determined by following the procedure for the nomograph (Fig. 9) using information sourced from New Zealand Soil Bureau publications (Table 1).

C

Land uses and types of vegetative covers were grouped by similarities in their morphological characteristics and *C* values were assigned to each group. These values were assigned based on the values used in the RUSLE for vegetation types in the USA which were deemed comparable to what was present in Lyttelton Harbour (found in Morgan 1995, pg. 67).

LS

The *LS* factor was calculated within the 25m DEM using the following:

$$LS = (a/22.13)^{0.4} . (\tan ß/0.896)^{1.3} \qquad \text{(eq. 2)}$$

where a is the upslope area per unit width ($m^2\ m^{-1}$), ß is the local slope angle and the constants 22.13 and 0.0986 normalize the data to the standardized RUSLE plot dimensions. Calculation of the components of eq. 2 was performed in the raster calculator by implementing hydrology and surface tools from the geospatial analysis tool box.

R

R was calculated as the kinetic energy of rainfall (eq. 3) and average maximum 30 minute storm intensity, given together as the EI_{30} index.

$$KE = 0.29\ (1-0.72\ e^{-0.082.I}) \qquad \text{(eq. 3)}$$

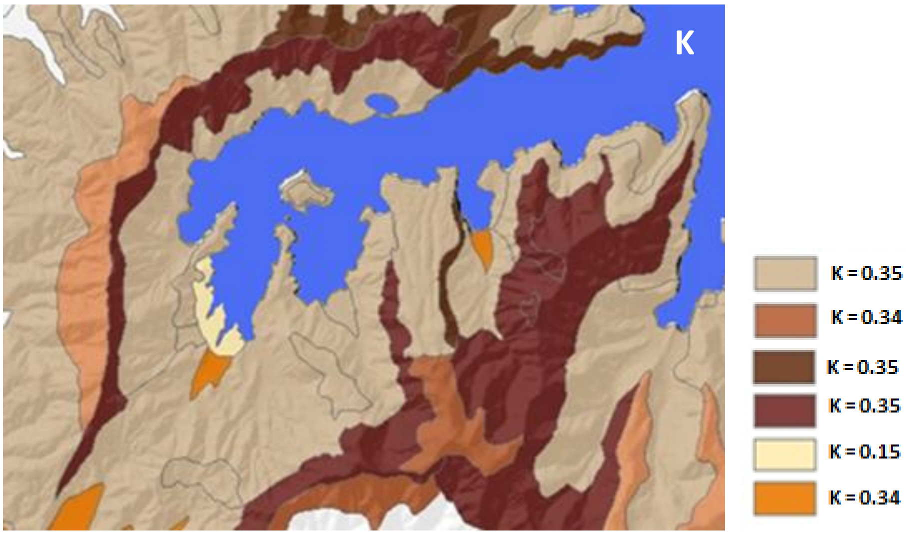
The I_{30} component was determined on a storm by storm basis then averaged over an annual timescale for rainfall data for Christchurch over the last ten years. *R* was then determined by summing the EI_{30} of individual storms averaged over a year then divided by 173.6 to convert to American units as per the procedure followed in Brasington (2007). An individual storm event was classified as having a minimum of 0.4mm rainfall, lasting at least one hour and having at least a six hour period between each event.

P

As there are no apparent soil conservation measurements in place in the catchments of Lyttelton Harbour, the value of *P* was assigned as 1.0 across the entire spatial extent of the area under study.

A

The average annual rate of soil erosion (*A*) was calculated in ArcMap using the raster calculator in the map algebra function by multiplying the layers for each of the RUSLE factors together as per eq. 1. All polygon files were converted to raster files using the polygon to raster conversion tool in the geospatial analysis tool box. Cell sizes were corrected to be set at 25 metres to conform to the resolution of the 25 metre DEM for the South Island.


K
K = 0.35
K = 0.34
K = 0.35
K = 0.35
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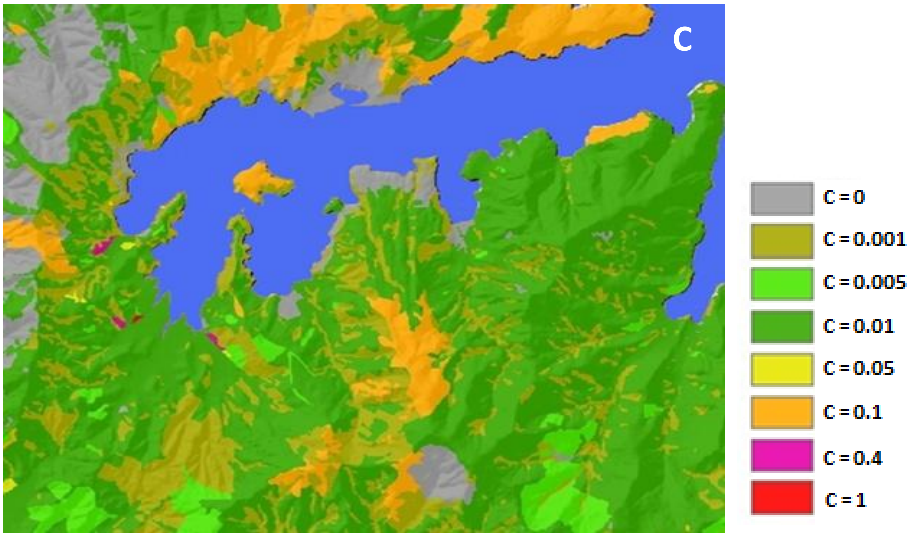
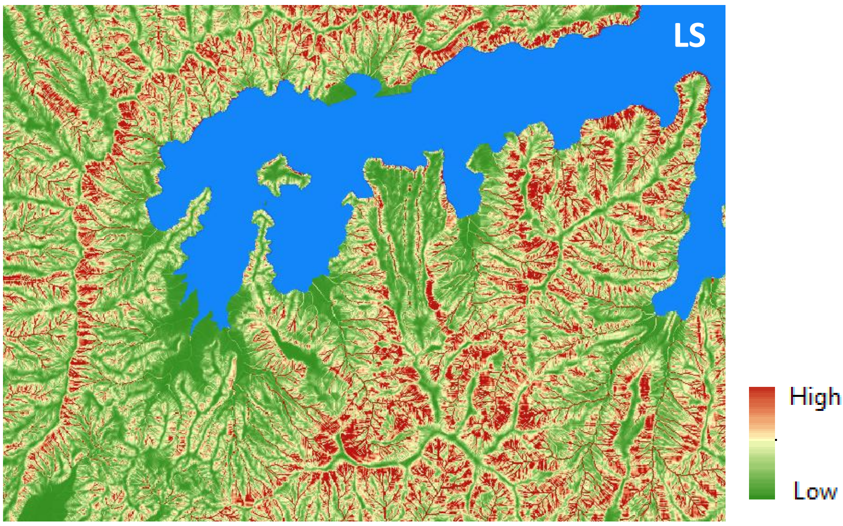
K = 0.34

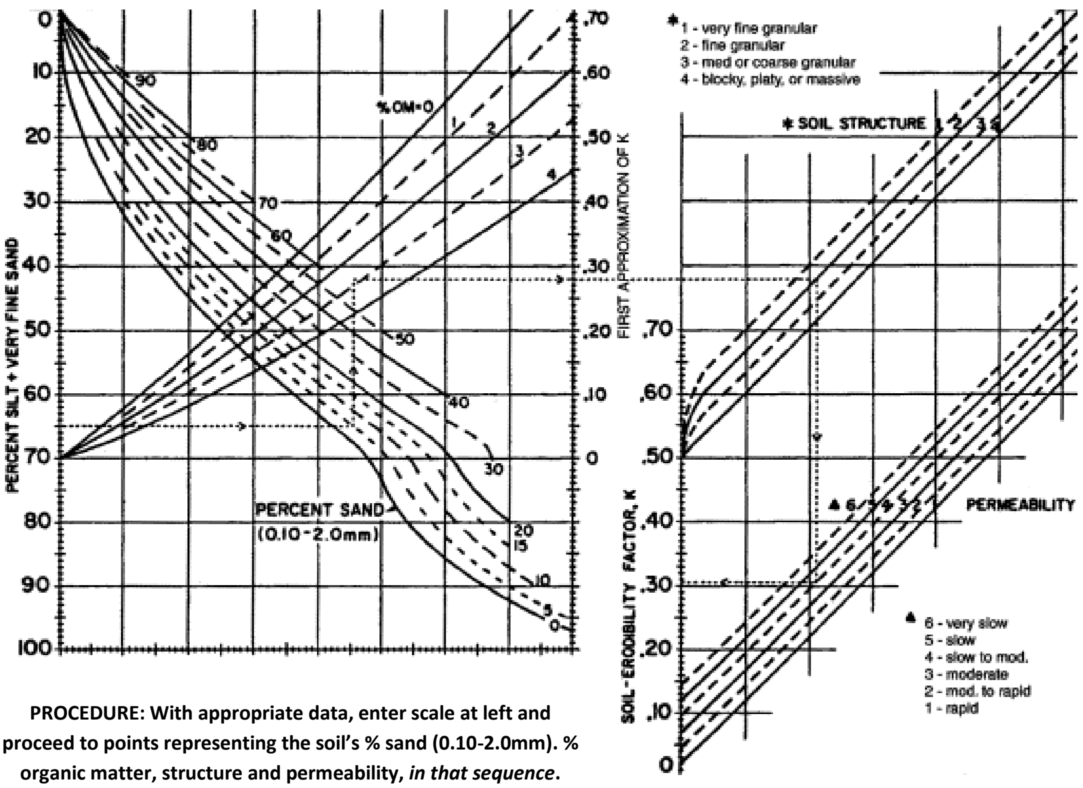

C
C = 0
C = 0.001
C = 0.005
C = 0.01
C = 0.05
C = 0.1
C = 0.4
C = 1


LS
High
Low

R = 158

P = 1

Average individual catchment soil losses were obtained by first identifying the points of greatest accumulation and generating the catchment from these points using the watershed tool in the hydrology toolbox. These delineated catchments were used as individual masks to extract the pixel values from the average annual soil erosion layer, from which the average erosion value for the catchment was obtained.



PROCEDURE: With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10-2.0mm). % organic matter, structure and permeability, *in that sequence*. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: st+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K=0.31

Figure 9. The standard nomograph which is used widely to determine the value of *K* for different soils by following the procedure outlined. Source: Morgan (1995), pg. 33

Table 1. Soil types found within Lyttelton Harbour, their characteristics which are included in the calculation of *K* and the *K* values. Silt loam contains 65% Silt, 15% Clay and 20% Sand, and Sandy loam contains 25% Silt, 10% Clay and 65% Sand. Source: NZ Soil Bureau 1968b, Griffiths 1974, Webb and Wilson 1995, Landcare Research 2011).

Soil series	Genetic Classification	NZSC code	Permeability	Textural Classification	OM content %	K
Takahe/Pawson	PXM	15gH/28eH	Moderate over slow	Silt loam	9.61	0.35
Stewart	BMA	77a	Moderate over slow	Silt loam	12.24	0.35
Evans-Kiwi	EMT	77	Moderate over slow	Silt loam	5.95	0.35
Bossu	BFA	54H, 54aH	Moderate	Silt loam	6.97	0.34
Motukarara	GRQ	92	Moderate	Sandy loam	4.93	0.15
Barry	RFW	98e	Moderate	Silt loam	6.12	0.34

4.0 RESULTS

4.1 Highest contributing catchments

There is a high degree of spatial variation in the level of soil loss across the catchments of Lyttelton Harbour (Fig. 10a; 10b). The Purau Bay catchment is the site of the highest point value of 36.74 t/

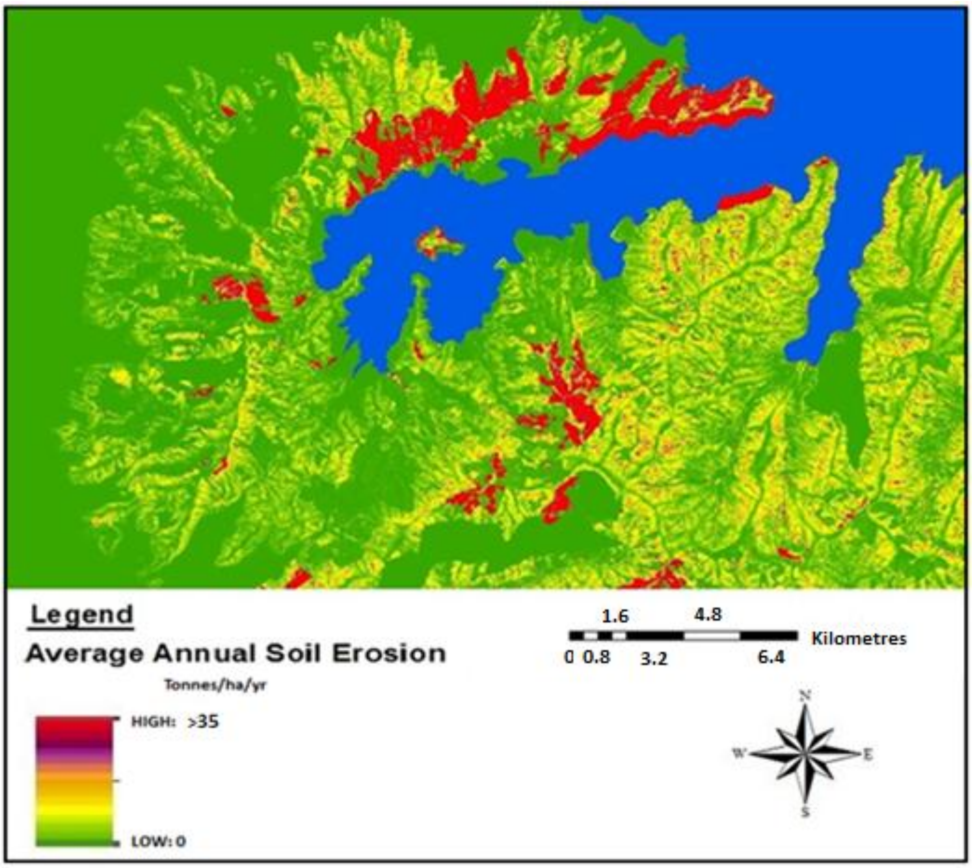
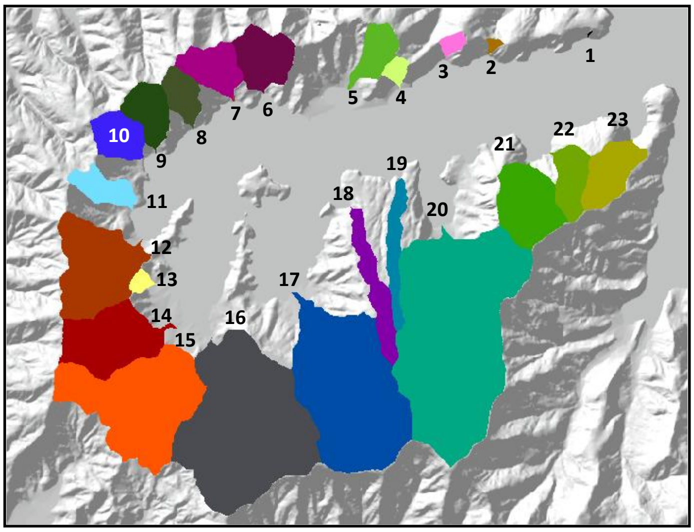


Figure 10a. Average annual soil loss estimated by the RUSLE given in tonnes per hectare per year. Areas in red indicate a large amount of erosion where as green areas indicate a low level of erosion.

ha/a, however the low values in the rest of the catchment have meant that this catchment is not one of the highest contributors. Overall, the catchments in order of highest soil loss in are 1) Gollans Bay, 2) Mechanics Bay, 3) Livingstone Bay, 4) Cass Bay, 5) Rapaki Bay.



	Catchment	Mean	Min	Max	Std Dev.
1	Mechanics Bay	4.16	1.69	8.25	2.2
2	Livingstone Bay	4.06	0.41	20.11	2.9
3	Gollans Bay 1	5.51	0	18.68	3.93
4	Gollans Bay 2	2.67	0	20.71	3.82
5	Lyttelton	0.94	0	11.59	1.88
6	Cass Bay	3.63	0	31.31	2.88
7	Rapaki Bay 1	3.56	0	17.09	2.93
8	Error in Data				
9	Dyers Pass	0.27	0	5.66	0.4
10	Governors Bay	0.23	0	2.85	0.34
11	Allandale	0.15	0	1.69	0.21
12	Allandale - HOB	0.95	0	18.05	2.12
13	Foleys Stream	0.19	0	0.61	0.13
14	Teddington	0.26	0	29.92	0.83
15	Gebbies Pass	0.17	0	2.94	0.19
16	Waieke Stream	0.2	0	17.67	0.5
17	Te Wharau Stream	0.62	0	19.09	1.66
18	Church Gully	0.8	0	14.64	1.3
19	Diamond Harbour	0.62	0	19.09	1.66
20	Purau Bay	0.68	0	36.74	1.52
21	Camp Bay 1	0.5	0	6.95	0.43
22	Camp Bay 2	0.49	0	3.87	0.39
23	Little Port Cooper	0.38	0	5.37	0.36

Figure 10b. Location and erosion statistics for catchments around Lyttelton Harbour (in t/ha/a) with the red figures highlighting the highest contributing catchments were maximum and minimum values are for individual cells while standard deviation and mean are for the whole catchment. Green figures = lowest contributing catchments, red = highest contributing catchments.

These highest contributing catchments are all found on the northern side of the harbour (Fig. 11) and have several similarities in their characteristics (Table 2).

Table 2. Characteristics of the catchments which have been illustrated as having the highest annual average sediment loss including soil type, vegetation cover, topographical characteristics, approximate rainfall, aspect and the main processes of erosion which are occurring.

Catchment	Soil	Vegetation	Catchment Topography	Rainfall (approx.)	Aspect	Main erosional process
Gollans Bay	EMT + BRock	Low prod grassland	Steep, short	636mm/yr	S	1Sh
Mechanics Bay	EMT + BRock	Low prod grassland	Steep, short	636mm/yr	S	1Sh
Livingstone Bay	EMT + BRock	Low prod grassland	Steep, short catchment	636mm/yr	S	1Sh
Cass Bay	PXM upper, BMA lower	Low prod grassland	Moderately steep, short	675mm/yr	SE	1 Sh upper, 2T Ss lower
Rapaki Bay	PXM upper, BMA lower	Low prod grassland	Moderately steep, short	714mm/yr	SE	1 Sh upper, 2T Ss lower

The catchments showing the lowest level soil loss are found on south western side of the harbour (Fig. 11) with the catchment around Bush Road in Governors Bay contributing overall smallest amount of sediment with an average soil loss value of 0.15 t/ha/a.

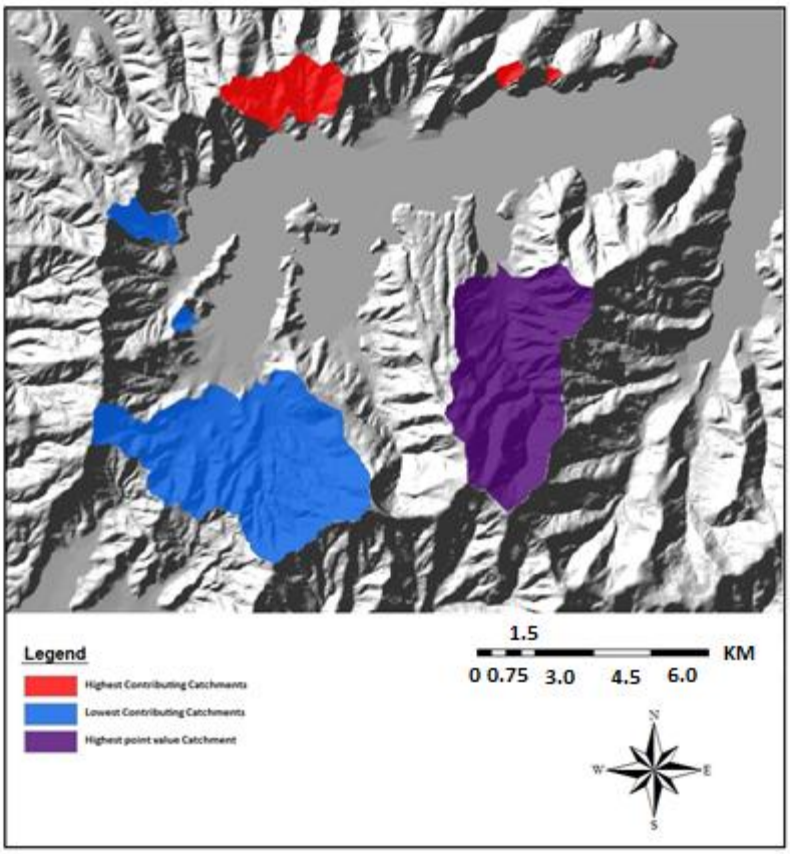


Figure 11. Locations of the catchments which are contributing on average the most sediment (in red), the lowest amount of sediment (in blue) and Purau Bay catchment (in purple) which contains the site of the highest level of erosion. Catchments on the northern side of the harbour are contributing the most sediment, while catchments on the southern side contribute the lowest levels of sediment into the aquatic environments of Lyttelton Harbour.

4.2 Comparison with other models

4.2.1 NIWA – Water Resource Explorer NZ (WRENZ)

The Water Resources New Zealand (WRENZ) online model developed by NIWA produced sediment yields for Lyttelton Harbour catchments in the range of zero to 3500 t/ha/a (Table 3 and Appendix D)

Table 3. The sediment yields for catchments around Lyttelton Harbour predicted by NIWAs online WRENZ model. Stream names allocated here are based on their physical location, not necessarily their actual name as many streams are too small to be named. Source: NIWA 2007

		Sediment Yield (t/km²/yr)			
Catchment Group	Stream	Upper	Middle	Lower	**Total (t/yr)**
Mechanics, Breezes and Livingstone	Mechanics	No data			
Mechanics, Breezes and Livingstone	Breezes	No data			
Mechanics, Breezes and Livingstone	Livingstone	No data			
A Gollans, Port of Lyttelton and Corsair	Gollans	<50	<50	<50	0
B Gollans, Port of Lyttelton and Corsair	Lyttelton	<50	~	<200	200
C Gollans, Port of Lyttelton and Corsair	Corsair	<200	<200	<200	0
D Cass and Rapaki	Cass	<50	~	<200	100
E Cass and Rapaki	Rapaki	<50		<200	100
F Governors	Zephyre	<200	<50	<200	200
G Governors	Allandale	<200	<200	<200	600
H Head of the Bay	Foleys	<500	~	<200	700
I Head of the Bay	Teddington	<500	~	<200	1800
J Head of the Bay	Waieke	<500	<500	<500	3500
K Charteris, Quail Is., Diamond	Te Wharau	<200	<500	<200	2400
L Charteris, Quail Is., Diamond	Church	<200	~	<50	200
M Charteris, Quail Is., Diamond	Diamond	<50	<50	<50	0
N Purau, Pile, Deep Gully	Purau	<200	<500	<200	2600
O Purau, Pile, Deep Gully	Pile	<50	<50	<50	0
P Camp, Little Port Cooper	Camp	<50	~	<200	100
Q Camp, Little Port Cooper	LPC	<50	~	<200	100

The values obtained here from the WRENZ cannot be directly compared with the work done in this research as these are values for catchment sediment yield where as the values obtained in the current work are simply measures of annual soil loss. Sediment yields for Lyttelton Harbour catchments were not calculated here but should be done in future work to have an appropriate comparison between WRENZ and the RUSLE. However, it can be determined that there are some dissimilarity between the values from the WRENZ and the RUSLE. Most obviously, the areas identified by the RUSLE as having the lowest values of erosion are identified by the RUSLE as having the highest sediment yields.

5.0 DISUCSSION

5.1 Characteristics of the highest contributing catchments

The spatial variability of soil loss around Lyttelton Harbour can be attributed to a number of different factors operating at different scales. On a broad scale, it is evident that land cover is the main driver of high levels of soil loss, in particular areas of low productivity grass land. Comparisons between the annual average soil loss map (Fig 10.) and the land cover map (Fig. 3) show that the areas of low productivity grassland correlate with the highest amounts of soil loss. In addition to the low productivity grassland, the quarry and short rotation cropping land uses have induced a higher rate of soil loss when compared to the other land uses within Lyttelton Harbour. This is due to the enhanced vulnerability to soil erosion created by relative lack of resistance to erosion by rainfall under these land uses. The quarry (Fig 8.) represents a large area of exposed sediment making it highly susceptible to soil loss and therefore a high level of erosion. Rotation cropping consist of cyclic alternations of bare soil then crop cover, the exposure of this bare soil enhances soil loss and tillage practices associated with the cultivation of crops is also known to further enhance soil loss (Stocking 1994; Bryan 2000; Valentin et al. 2005). The type of land cover present is not only determining the areas of highest soil loss, but also controls areas yielding the lowest levels of soil loss. These areas tend to be under land covers consisting of more substantial vegetation such as shrubland and forest. Urban areas also indicate low levels of erosion as typically erosion levels are minimal from urban areas, unless there are active earthworks for land development and construction underway. As indicated, there are a number of active subdivision developments within Lyttelton Harbour, these were however not included in this modelling work as it was not included in the existing data used for land use, a flaw which should be corrected in any future work on this subject.

On a finer scale, it is evident that the role of topography becomes more significant in determining the level of erosion occurring. Areas of highest soil loss tend to be found in the upper reaches of the catchments where steeper slope gradients provide for higher energy water flow. The large areas of higher levels of soil loss are predominantly found on the northern side of the harbour, a pattern which could be accounted for by the role of topography as the catchments on this side of the harbour area all relatively short and steep. Areas of a flatter relief produce lower kinetic energies and therefore tend to be more depositional, a pattern evident around the harbour (Fig. 10).

Soil type can influence which erosional processes are operating at a particular location. The effectiveness of a raindrop to detach and displace a particle of soil depends on the kinetic energy of the raindrop, the grading of the soil particles and soil shear strength. For example, coarse sands would be resistant to detachment because of their large mass, while silt loams and loams are most vulnerable because of their fine texture and small particle size (Morgan 1995, Bryan 2000). The shear strength of the loess soils of Banks Peninsula was studied by Hughes (2002). Typically, detachment decreases with greater shear strength, and as Hughes (2002) found the Banks Peninsula loess to have low shear strength (depending on moisture content), this soil would easily be detached. Another example of this is how tunnel gullies are typically restricted to saturated clays, loess and organic soils (Bryan 2000) and as loess is the predominant soil constituent in Lyttelton Harbour, this accounts for the presence of tunnel gullies in the many of the catchments with the highest levels of soil loss (Fig. 6). Severe tunnel gulling in the Camp Bay to Little Port Cooper area is resulting in the high amount of soil loss occurring in the lower part of those catchments. A further example is the susceptibility of loam type soils to seal formation (Morgan 1995). As the soils within Lyttelton Harbour are either Silt Loam or Sandy Loam, surface seal formations should be a regularly occurring feature resulting in large amounts of surface runoff, which may be contributing to the ubiquity of sheet erosion in Lyttelton Harbour (Fig. 6).

In addition to land cover, topography and soil type, the climate of Lyttelton Harbour plays an important role in determining the level of soil loss occurring in the different catchments. However as there is a scarcity in rain gauging in Lyttelton Harbour for collecting data at the required temporal scale for this analysis this factor could not be accounted for in this study. As there is known to be spatial variation in the amount of rainfall received among the different catchments (Molloy 1993, NIWA Climate Database 2011), under certain conditions, areas of higher rainfall would tend to have a greater level of soil loss (Mitchell and Bubenzer 1980, Morgan 1995)

5.2 Mitigating soil loss in highest contributing catchments

Various techniques may be employed within Lyttelton Harbour to combat further expansion of the intertidal mudflats and continued land degradation. Appendix B provides a greater depth of information than space permits here on three mitigation strategies which may be implemented including soil conservation policies, riparian buffer zones and reforestation.

5.3 Is using the RUSLE appropriate in New Zealand?

The comparisons made between the WRENZ and the RUSLE used in this research have illustrated that the use of the RUSLE in New Zealand environments may not a suitable modelling methodology to ascertain soil erosion here, as the WRENZ and the RUSLE appear to be obtaining opposing values for soil loss. However as the WRENZ is modelling sediment yield based on stream exports it is not accounting for erosion occurring within the smaller catchments on the northern side of the harbour which do not have permanently flowing streams. In addition to this, the variation in rainfall over the spatial extent of the harbour is accounted for in the WRENZ (Hicks et al. 2011); where as previously mentioned it is not in the RUSLE here. This could be the reason for catchments on the southern side of the harbour showing a greater sediment yield as they have larger annual rainfalls. However most importantly, a sediment delivery ratio analysis needs to be completed so that the results from the two models are comparable.

A comparison made between the New Zealand Empirical Erosion Model (NZEEM) by Landcare and the RUSLE would have been a more appropriate analysis as the NZEEM and the RUSLE use a similar methodology (Dymond et al. 2010). Both contain soil erodibility, rainfall erosivity and land use factors, while topographical factors are not considered to the same extent (Dymond et al. 2011). However difficulties obtaining the data required for this have meant that this was also not able to be completed in the time frame available.

Therefore further validation is required by either comparing results gathered from work with the RUSLE and the NZEEM or by a detailed observational study to determine the similarities between modelled and real world sediment losses before the use of the RUSLE in New Zealand can be completely discounted or accepted.

6.0 CONCLUSIONS

To conclude, this study has assessed the level of soil erosion occurring in stream catchments of Lyttelton Harbour in Banks Peninsula using the RUSLE. The fine sediments which are sourced from the terrestrial environment of the harbour have been recognised as the cause of the growing extent of the intertidal mudflats within Governors Bay, Head of the Bay and Charteris Bay induced by acceleration in the rate of erosion post European settlement. Identifying the present day sources of these fine sediments is vital for efficient and cost effective management. The study has found that there are several areas contributing large amounts of sediment into the harbour including catchments in the Breezes, Mechanics and Livingstone Bay area, in Cass, Corsair and Rapaki Bay area, in upper parts of Governors Bay, Diamond Harbour and Purau Bay and finally in the lower area of Camp Bay and Little Port Cooper. More specifically, the Gollans Bay catchment was recognised as contributing the largest of sediment to the harbour. Land cover could be attributed to providing for the largest rates of soil loss on a large scale, while at smaller scales topography was a substantial controlling factor on soil outputs. A comparison between the results obtained from the RUSLE model used here and the model developed by NIWA indicated that the use of the RUSLE in New Zealand may not be appropriate in New Zealand as indicated by the disparity in the results obtained by these different approaches. There are various policies in place nationally and regionally such as the Water and Soil Conservation Act 1967, the Canterbury Natural Resources Regional Plan and the Canterbury Regional Policy Statement which serve to avoid, remedy or mitigate accelerated erosion induced by anthropogenic land use change. These policies promote measures such as soil conservation, riparian buffer zones and reforestation to combat induced erosion. These measures are suggested for implementation in the catchments identified as having a high suspended sediment outputs and can be effective at reducing erosion, sediment exports and further sedimentation of Lyttelton Harbour.

7.0 LIMITATIONS

- Limited time frame for completing research due to the repeated interruptions to the study year from earthquakes in Christchurch. This also includes the closure of the campus and the geography building for an extended period of time at the beginning of the year.
- Using a model outside of the context for which it was developed with the limitations this imposed as discussed.
- Data – different scales of detail, for example climate and rainfall does vary substantially from bay to bay, but no data is collected there to provide for are more detailed analysis of climate. There is for Christchurch city, which is why it was used. Yet detailed vegetation and soil data was used.

- Sensitivity of factors to total sediment loss rate could result in inaccurate predictions of sediment losses in Lyttelton Harbour if the assigned values for the RUSLE factors were incorrect.

8.0 FUTURE RESEARCH

- Calculating catchment sediment delivery ratios in Lyttelton Harbour.
- Developing a soil erosion model specific to both Lyttelton and Akaroa Harbours
- A biological survey to determine if the streams in the catchments which are producing and exporting the greatest amount of sediment are of poorer health in terms of biological diversity and taxa richness. This should be assessed using a Macroinvertebrate Community Index (MCI) methodology.
- Running this model under a range of rainfall regimes and under different levels of forest cover to see how changes in these variables affect the sediment yields. Could provide inferences into the future in terms of climate change and reforestation, plus also a look into the past and how sediment yields changed over the period of deforestation.

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APPENDICES

APPENDIX A – Soil erosion in the Resource Managment Act 1991, the Canterbury Natural Resources Regional Pland and the Regional Policy Statement.

RMA 1991

The purpose of the RMA from Section 5 of the Act is:

"(1) The purpose of this Act is to promote the sustainable management of natural and physical resources.

(2) In this Act, sustainable management means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural wellbeing and for their health and safety while—

> *(a) Sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and*
>
> *(b) Safeguarding the life-supporting capacity of air, water,* ***soil****, and ecosystems; and*
>
> *(c) Avoiding, remedying, or mitigating any adverse effects of activities on the environment."*

Regional Policy Statement – Chapter 15: SOILS (proposed)

Issue 15.1.2 – Induced soil erosion

Induced soil erosion as a result of land-uses can limit the productive capability of the land, and can have adverse effects on other values. Explanation As well as the loss of the soil itself, induced soil erosion can lead to dust problems and contamination, including the contamination of water bodies with excessive nutrients and sediment. Avoiding soil erosion promotes the sustainable management of the soil resource and its associated ecosystems, its productivity, and the social, cultural, environmental and economic values that depend on good soil. Soil erosion can put wāhi tapu and wāhi taonga at risk through the unearthing of kōiwi tangata and wāhi taonga (artefacts).

Factors contributing to induced soil erosion include:
(1) Loss of vegetative cover on sloping land, particularly in hill and high country areas, caused by clearance of vegetation

(2) Loss of vegetative cover on sloping land, particularly in hill and high country areas, by over-grazing by stock and/or pest animals, especially where drought conditions limit available grazing

(3) Cultivation, where it is badly managed, especially where a fine tilth is developed and/or sloping land is tilled. Creation of a fine tilth increases the risk of wind erosion. This is of particular concern on the plains and downs, and especially in cropping areas where a high proportion of the land is cultivated each year

(4) Earthworks that reduce slope stability, for example, the inappropriate or indiscriminate cutting of tracks on hill country.

Objective 5.2.2 – Prevention of Soil Erosion: Prevention of significant induced soil erosion.

Policy 15.3.2 implements this objective:

Policy 15.3.2 – Avoid and remedy significant induced soil erosion

To avoid significant induced soil erosion resulting from the use of land and remedy or mitigate significant induced soil erosion where it has occurred. Particular focus is to be given to the desirability of maintaining vegetative cover on non-arable land.

Methods
The Canterbury Regional Council:
Will:
(1) Set out objectives, policies or methods in regional plans to control the use of land to avoid the significant loss or erosion of soil, and to remedy or mitigate significant induced soil erosion where it has occurred.
Should:
(2) Identify soil erosion issues and risks associated with land development on the basis of land types throughout the region.

This identification should assist in prioritising efforts to address erosion by identifying:
(a) the degree to which erosion is occurring at a rate greater than it would under natural vegetation, and
(b) the source areas of sediment that adversely impacts downstream or downslope environments

Local authorities:
Should:
(3) Promote land-use practices that avoid soil erosion by supporting programmes of education, planting and use of soil for local food production, information and assistance for land-users and by working with research, farming and other organisations. Particular attention should be given to the need to maintain vegetative cover where soil is vulnerable to erosion.

(4) Take actions to prevent land-uses from causing soil erosion and to remedy or mitigate soil erosion where it has occurred, in undertaking their own operations and activities.
(a) the degree to which erosion is occurring at a rate greater than it would under natural vegetation, and
(b) the source areas of sediment that adversely impacts downstream or downslope environments
(5) Identify Ngāi Tahu cultural values in relation to soil, through engagement with Ngāi Tahu, and through relevant iwi management plans.
(6) Cooperate to develop methods including protocols to manage earthworks and sediment generation, including the delineation of responsibilities on a district by district basis.

ANTICIPATED ENVIRONMENTAL RESULTS

(1) The quality and life-supporting capacity/mauri of Canterbury's soils and their health and capability of providing for the social, cultural, environmental and economic well-being of Canterbury's people and communities will be maintained or improved.

(2) Significant induced soil erosion will be avoided or reduced.

Natural Resources Regional Plan – Chapter 8: SOIL CONSERVATION (operative)

Policy SCN4: Stabilisation of hill country slopes subject to deep-seated erosion

(1) On loess-mantled hill slopes and soft rock hill country where soils are susceptible to, or show evidence of, deep-seated forms of erosion (see Figures SCN2.1 and SCN2.2), encourage the retention or establishment of a deep-rooted vegetation cover that will contribute to long-term stabilisation of the land.

(2) Landholders will be encouraged to adopt the following practices:

- *(a) maintain existing areas of tree or shrub cover, improving, where appropriate, the effectiveness of that cover for stabilising the land;*
- *(b) on slopes where the existing vegetation cover is inadequate to provide slope stability, plant fast growing species at spacing's that are effective in rapidly stabilising slopes;*
- *(c) once slopes are stabilised, encourage the replacement of original trees with long lived species where this is necessary to provide long-term stabilisation. Preference should be given to the use of indigenous species where these will provide effective long-term stability. Where a permanent forest cover is required to stabilise the slopes, encourage natural succession or planting to restore indigenous forest cover; and*
- *(d) manage areas planted with trees for harvesting to provide and maintain long term stabilisation through all stages of production.*

(3) Plantings to achieve (1) and (2) should:

- *(a) avoid the spread of any plant pest species;*
- *(b) avoid significant adverse effects on any outstanding natural features and landscapes or amenity values for the area, or the loss of indigenous biodiversity;*
- *(c) avoid adverse effects on important cultural values for the area including sites of significance to Ngāi Tahu and mahinga kai values; and*
- *(d) minimise adverse effects on stream flows, in particular the minimum flow requirements for flow-sensitive catchments identified in Chapter 5 Appendix WQN3.*

(4) Priority areas for stabilisation will include land that is:

- *(a) actively eroding; or*
- *(b) at a high risk of erosion; or*
- *(c) where off-site effects of erosion could result in adverse effects on important natural, cultural or amenity values.*

(5) The target for implementing this policy will be to have 10 percent of the priority areas identified in (4) planted with a stabilising vegetation cover within three years of the NRRP becoming operative, and to reach 50 percent of priority areas planted within 25 years.

(6) In flow-sensitive catchments with deep-seated slope stability problems, where afforestation may affect water yield, the preference is to use wide-spaced tree planting where this will achieve effective stabilisation of the slopes and meet the requirements for Policy WQN6 in Chapter 5: Water Quantity.

Policy SCN5: Earthworks and vegetation clearance activities

(1) Wherever any earthworks or vegetation clearance activity is carried out that increases the risk of soil erosion, the use of best management practices for reducing the amount of erosion likely to occur as a result of that activity should be adopted.

(2) Earthworks and vegetation clearance activities that have the potential, regardless of the method adopted, to result in significant induced soil erosion, or to lead to significant off-site effects, should not be undertaken unless effective measures are in place to:

(a) minimise the risk of induced erosion occurring;
(b) contain the movement of sediment transported in runoff generated from the activity site;
(c) undertake land rehabilitation necessary to stabilise the site, and to restore an intact vegetation cover wherever practicable; and
(d) avoid any significant adverse effects of erosion or sediment deposition on:
(i) water bodies, including their aquatic habitat and beds, associated wetlands and their flood carrying capacity;
(ii) areas important for the protection of indigenous biodiversity, including indigenous flora, and the habitats of indigenous fauna;
(iii) sites of significance to Ngāi Tahu, including wāhi tapu;
(iv) sources of mahinga kai;
(v) outstanding natural features and landscapes or amenity values for the area; and
(vi) property or built assets including network utilities.

(3) Priority areas for the management of activities in (2) will focus on:
(a) all land above 900 metres altitude;
(b) all land with a slope greater than 25 degrees; and
(c) all soft rock and loess-mantled hill slopes greater than 20 degrees

Full explanations and rationales for the necessity of the above policies are given in the RPS and NRRP documents which can be obtained from *www.ecan.govt.nz*.

APPENDIX B - Mitigating soil loss in highest contributing catchments

Soil conservation

As stated in Morgan (1995, pg 96), *"the aim of soil conservation is to obtain the maximum sustained level of production from a given area of land whilst maintaining soil loss below a threshold level which, theoretically, permits the natural rate of soil formation to keep pace with the rate of erosion".* In New Zealand under the RMA 1991 this means that present users of the land must maintain the soil for use by future generations and to limit the extent of offsite impacts of soil erosion (Braden 1991). Soil conservation strategies generally fall into three categories; agronomic, soil management and mechanical or physical management but all have the ultimate goals of protecting the soil from the impact of rain and to improve soil condition to increase infiltration and aggregate stability (Morgan 1995). Past techniques used for soil conservation throughout New Zealand have drawn from all three categories and include: land or riparian zone retirement, surface and subsoil drainage structures, engineering and tree plantings to control gully erosion and restrictions on vegetation clearance (Clough and Hicks 1992). Other conservation strategies include policies on education, technical and financial assistance and regulation or taxes to inhibit undesirable activities and to promote preferred activities (Uri and Lewis 1998). Subsidies from the New Zealand government for the agriculture sector has played an important role in soil conservation in the past (Braden 1991) but such subsidies were abolished in the late 1980's (Clough and Hicks 1992). A simple soil conservation strategy which could be put in place on Lyttelton Harbour farms could be better grazing land management (GLM). GLM is considered to be an economically favourable option has land is not required to be forfeited or investments into technology and structures aren't required. Instead better management of the pasture by having rest periods to allow grass regeneration between stocking and reduced stocking rates can mean the grass has a better overall condition ultimately leading to lower levels of rill and interrill erosion (Morgan 1995, Bartley et al. 2010a; 2010b).

Riparian buffers

Riparian zones are areas of macrophyte and terrestrial vegetation immediately adjacent to a stream and the allocation of this area to a stream buffer zone serves to restrict activities from stream to protect it from surrounding land uses (Bren 1995, McKergow et al. 2003). Riparian buffers filter sediment and nutrients from overland flow, provide habitat corridors, protect streams from bank damage and attempt to maintain natural forested conditions which stream ecosystems are adapted to (Bren 1995, Quinn et al. 2004, Harding et al. 2006).The use of riparian buffers within in commercial forests is well recognised to reduce the impacts of logging on stream morphology and ecosystems as machinery is excluded from the buffer zone and sediments in runoff generated by forestry operations is intercepted within the buffer zone (Graynoth 1979, Quinn et al. 2004, McIntosh and Laffan 2005). They are also effective at minimising the impacts on a stream from agricultural land use (McKergow et al. 2003). However the effectiveness of the riparian buffer depends on a number of characteristics such as the type of vegetation and buffer width (Carling et al. 2001, McIntosh and Laffan 2005). These characteristics must be determined on a case by case basis, as a 'one size fits all' philosophy has found to be insufficient (Carling et al. 2001). Graynoth (1979) determined that a buffer width of at least 30 metres was sufficient in New Zealand to limit the impact of logging on a forest stream, a figure also reported for Australian streams by McIntosh and Laffan (2005). However, buffers need to be continuous along the entire length of the stream to provide ecosystem benefits and to be truly effective (Quinn et al. 2004, Harding et al. 2006).

Not only do riparian buffers zones exclude logging activity and provide a filtering mechanism for nutrients and sediment, if they are fenced off stock may also be excluded from the stream channel which has been proven to decrease suspended sediment yields (McKergow et al. 2003, Bartley et al. 2010a). Stock, such as cattle trample stream banks and consume riparian vegetation which induces stream bank erosion causing a high export of sediment. Cattle have had access to Te Wharau Stream in Orton Bradley park which may have contributed to the high suspended sediment concentrations found in that stream in the past (pers. obs.). Therefore, riparian buffers should be implemented where possible in Cass Bay and Rapaki Bay along the entire stretch of these streams to reduce amount of suspended sediment entering the streams, to improve water quality and to restore habitat values lost during deforestation of Lyttelton Harbour.

Reforestation

The re-establishment of native forest within the catchments identified as providing the greatest amount of sediment is a more radical approach to mitigating further sedimentation of Lyttelton Harbour compared to soil conservation or riparian buffer zones, however this may be a more effective measure as it reverses the fundamental cause of accelerated erosion within Lyttelton Harbour catchments, deforestation. Reforestation can reduce erosion by providing a protective buffer for the soil from erosive agents (Morgan 1995, Mohammad and Adam 2010). The canopy layer of forest provides a certain degree of protection for the soil by intercepting falling rain; however it is the provision of woody debris and leaf litter on the forest floor which generates the greatest protection against erosion as almost all kinetic energy is expended upon the debris and litter (Hartanto et al. 2003). Reforestation has been illustrated to reduce the level of gully erosion in several degraded catchments within New Zealand (DeRose et al. 1998, Valentin et al. 2005). However, reforestation of the entire catchment may not be necessary. A discussion with a resident of Corsair Bay who have Corsair Stream running through their property has noticed that after a small block of pine trees had been planted within the stream catchment, the stream was noticeably less turbid. This suggests that planting trees in the areas with most obvious signs of erosion may have a positive effect on reducing soil erosion in Lyttelton Harbour catchments. In addition to this, reforestation is the preferred option under the NRRP for Canterbury as indicated by policy SCN4 (Appendix A).

A combination of the above three mitigation strategies implemented within the catchments identified by this research as contributing the most sediment to the harbour (Gollans Bay, Mechanics Bay, Breeze Bay, Cass Bay and Rapaki Bay) would decrease the rate of soil erosion thus slowing further growth of the intertidal mudflats and prevent continued land degradation.

APPENDIX C - Adverse effects of soil erosion and sedimentation.

Land degradation

Soil erosion ultimately leads to land degradation, decreased soil productivity (Hartanto et al. 2003) and crop yield (Cerdan et al. 2010) because of the loss of nutrient rich topsoil (Morgan 1995). The loss of a forest vegetative cover causes a decline in the organic component and nutrients in a soil. Forest cover provides organic matter which is incorporated into the soil by microbial activity which creates a soil with a better structure and therefore resistance to erosion (Stocking 1994). In addition to loss of productivity in eroding landscapes, surface lowering as a result of soil loss may uncover historic deposits of toxic compounds or areas of contaminated land (Brasington 2007, Jaffe et al. 2007). Historic sheep dip bath sites are a widespread source of land contamination throughout New Zealand as the chemicals used in old dip technology are hazardous to the environment. As sheep have been farmed on Banks Peninsula and Lyttelton Harbour there is the potential for these to be present and soil contaminated with substances such as arsenic, dieldrin, lindane and DDT to be uncovered by soil erosion and redistributed into the aquatic environment (ECan 2003).

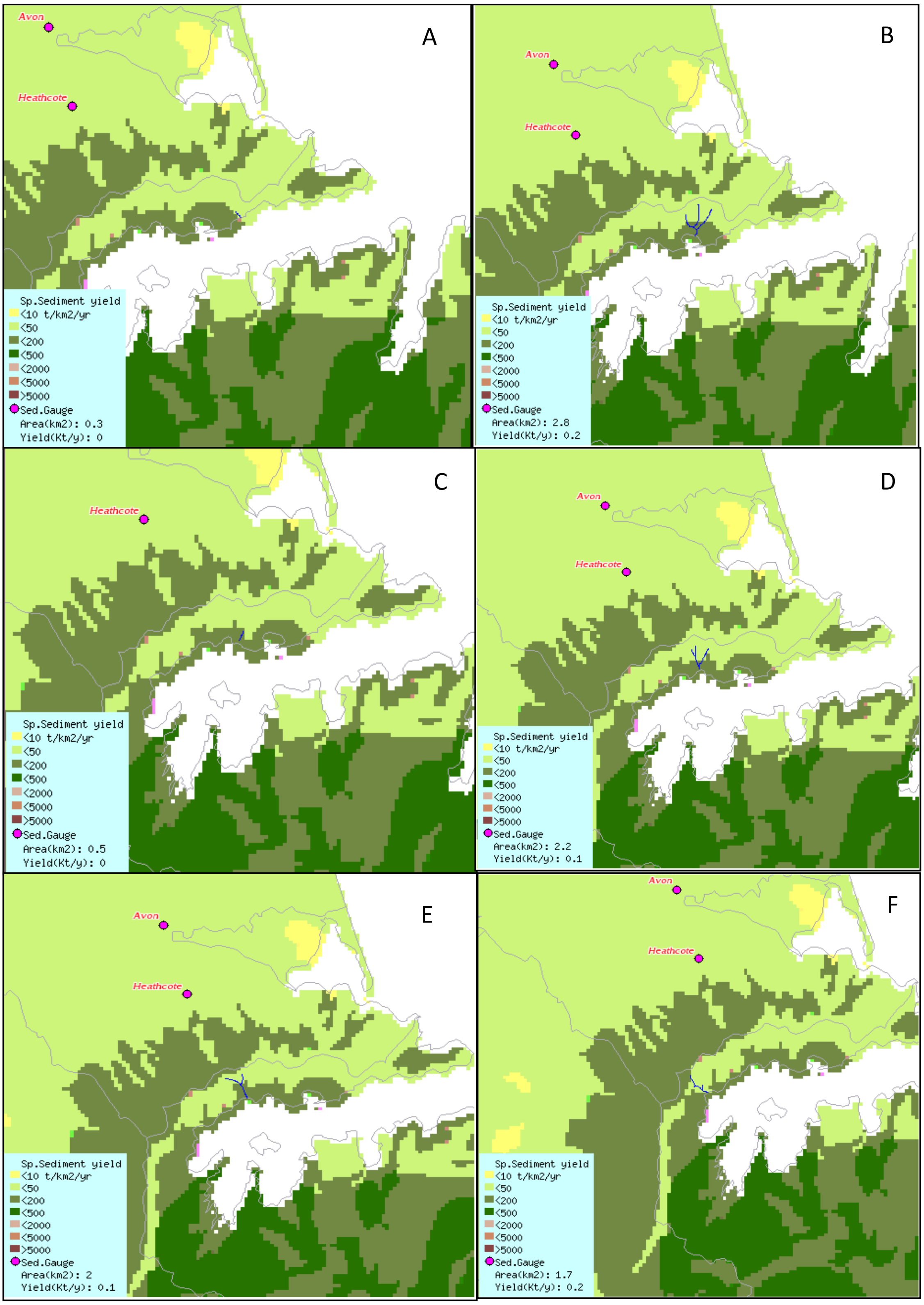
Ecological

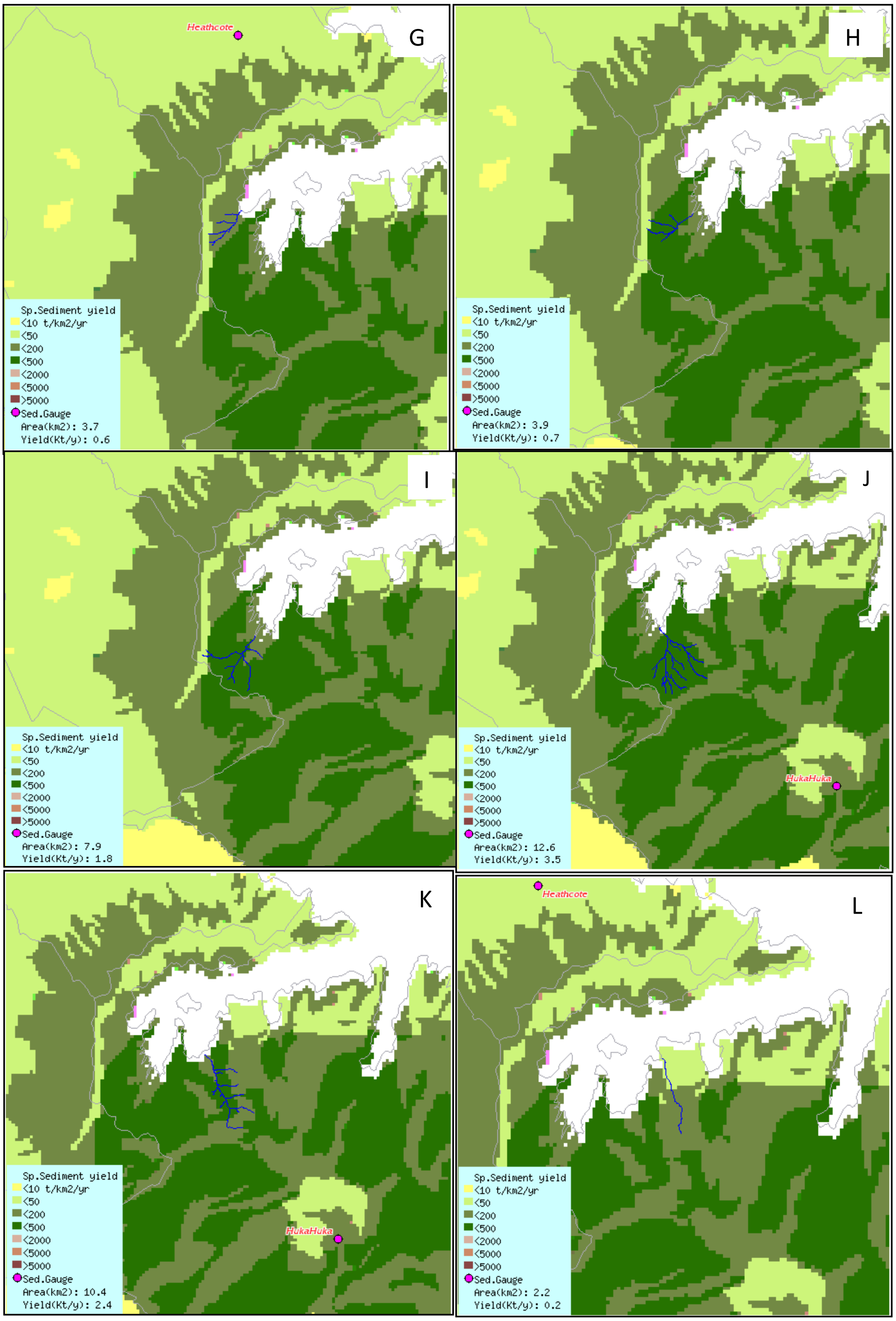
The initial effect of erosion on aquatic environments, both freshwater and marine, is a decrease in water quality because of the increase in suspended sediment, nutrients and heavy metals or other chemical compounds associated with the eroded soil (Uri and Lewis 1998, Goodwin et al. 2003, Hartanto et al. 2003, Valentin et al. 2005, Sidle et al. 2006, Bartley et al. 2010a). The higher suspended sediment content is usually presented as an increase in turbidity. This has been illustrated to decrease the transmission of sunlight through the water column, which can affect both the benthic and pelagic flora and fauna (Uri and Lewis 1998). When these suspended sediments and other compounds within the water column settle down to the bottom of the streams or the harbour they can smother benthic communities and can result in a major alteration of the existing range of habitats or completely destroy habitat and cover food gathering and oviposition sites (Uri and Lewis 1998, Sidle et al. 2006). Within Lyttelton Harbour, the extension of the mudflats poses a threat to the shell fish beds and other marine life found within the harbour (Hart et al. 2008). In addition to this, extensions of the mudflats can mean a change in bathymetry which can alter current patterns within the harbour which as found by Jaffe et al. (2007) can cause a change in the transport of nutrients, sediment and the dispersing larval stage of aquatic organisms.

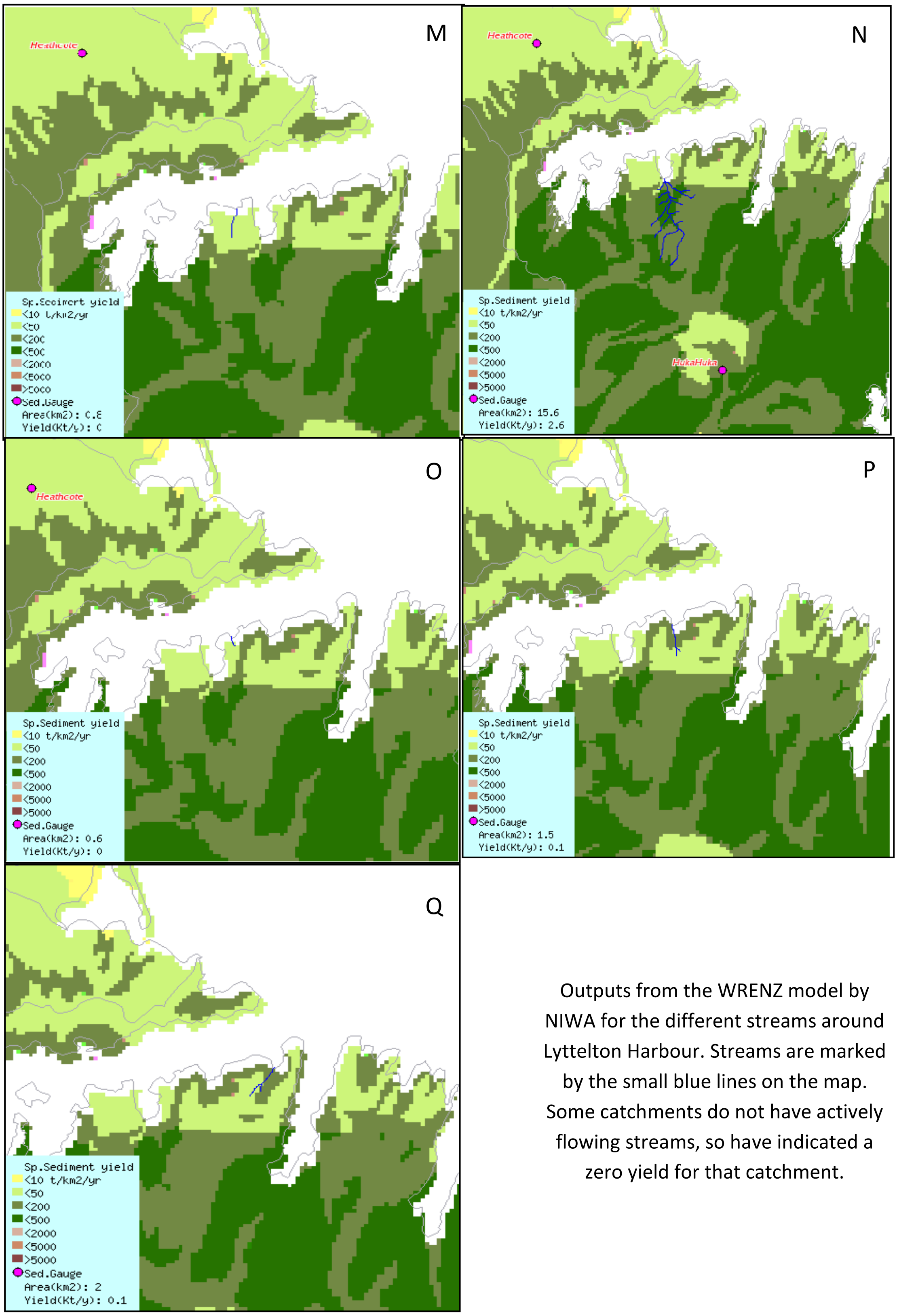
Associated with urban runoff are sediments contaminated with various chemical compounds which wash from the paved surfaces (Corbett et al. 1997, Walker et al. 1999, Goodwin et al. 2003). These can accumulate in the aquatic environments which receive urban runoff which can be toxic to the biota within these environments (Corbett et al. 1997) and can contribute to eutrophication or a build up of toxicity in shell fish which may be harvested for consumption by humans (Morgan 1995, Nelson and Booth 2002).

In addition to the adverse effects within the harbour, the streams which convey the sediment from the surrounding hills are also exhibiting signs of sedimentation, degrading these environments for freshwater aquatic organisms (Harding 2003). Changes in flow, stream morphology and sediment regime associated with the removal of forest adversely effects species adapted to originally forested stream habitats. Banks Peninsula was once a place of rich taxonomic diversity and a high degree of endeminism in its aquatic and avian species, many of which have been lost or had sever range restrictions post deforestation (Harding 2003, Harding et al. 2006). This includes the extinction of at least 12 bird species which were only found within Banks Peninsula forests and the absence of Banks Peninsula endemic macroinvertebrates such as *Costachorema peninsulae* and *Edpercivalia banksiensis* in agricultural streams (Harding 2003). If time had permitted it, a biological survey of streams within Lyttelton Harbour would have been conducted to ascertain the health of stream communities.

APPENDIX D – Graphical output from the Water Resources Explorer New Zealand online model.




G
Heathcote
Sp.Sediment yield
<10 t/km2/yr
<50
<200
<500
<2000
<5000
>5000
Sed.Gauge
Area(km2): 3.7
Yield(Kt/y): 0.6
H
Sp.Sediment yield
<10 t/km2/yr
<50
<200
<500
<2000
<5000
>5000
Sed.Gauge
Area(km2): 3.9
Yield(Kt/y): 0.7
I
Sp.Sediment yield
<10 t/km2/yr
<50
<200
<500
<2000
<5000
>5000
Sed.Gauge
Area(km2): 7.9
Yield(Kt/y): 1.8
J
HukaHuka
Sp.Sediment yield
<10 t/km2/yr
<50
<200
<500
<2000
<5000
>5000
Sed.Gauge
Area(km2): 12.6
Yield(Kt/y): 3.5
K
HukaHuka
Sp.Sediment yield
<10 t/km2/yr
<50
<200
<500
<2000
<5000
>5000
Sed.Gauge
Area(km2): 10.4
Yield(Kt/y): 2.4
L
Heathcote
Sp.Sediment yield
<10 t/km2/yr
<50
<200
<500
<2000
<5000
>5000
Sed.Gauge
Area(km2): 2.2
Yield(Kt/y): 0.2



Outputs from the WRENZ model by NIWA for the different streams around Lyttelton Harbour. Streams are marked by the small blue lines on the map. Some catchments do not have actively flowing streams, so have indicated a zero yield for that catchment.