Best practice phosphorus losses from agricultural land

Roger Parfitt[1], John Dymond[1], Anne-Gaelle Ausseil[1], Brent Clothier[2], Markus Deurer[2], Allan Gillingham[3], Ross Gray[4], David Houlbrooke[4], Alec Mackay[4], Richard McDowell[4]

[1]Landcare Research
Private Bag 11052
Palmerston North
New Zealand

[2]HortResearch Palmerston North

[3]Research Consultant, Palmerston North

[4]AgResearch Palmerston North and Invermay

Landcare Research Contract Report: LC0708/012

PREPARED FOR:
Horizons Regional Council
Private Bag 11025
Palmerston North

DATE: September 2007

ISO 14001

Reviewed by:	Approved for release by:
John Scott Scientist Landcare Research	Alison Collins Science Leader Soils & Landscapes

Contents

Executive Summary 5
1. Introduction 11
2. Objective 13
3. Farm Types and the Potential Impact on Water Quality in Upper Manawatu Water Management Zones (UMWMZ) 15
4. What is the best practice acceptable DRP loss from a farm that Horizons should endorse in UMWMZ? 18
5. What is the best practice acceptable total-P loss from a farm that Horizons should endorse in UMWMZ? 24
6. How can Overseer® be used to estimate changes in P loss from farms in the UMWMZ catchment? 28
7. BMPs for UMWMZ 29
8. Conclusions 32
9. Acknowledgements 33
10. Glossary 33
11. References 34
12. Appendices 37

Executive Summary

Horizons Region Council is implementing both the sustainable land-use initiative (SLUI) to address erosion issues on farms and issues of sediment in rivers, and the Farmer Applied Resource Management strategy (FARM strategy) to target reductions in nitrogen and phosphorus leakage from intensive land uses in priority catchments.

Horizons Regional Council have asked Landcare Research and SLURI – New Zealand's multi-CRI Sustainable Land Use Research Initiative – to develop a method to determine the potential for water quality improvement through these combined initiatives in relation to phosphorus in water ways, and also provide an indication as to whether erosion control or nutrient management should be the priority management target in that catchment.

For the first time in New Zealand, SLURI estimated both the total and dissolved phosphorus losses for a large catchment (Upper Manawatu Water Management Zones above Hopelands) by using the Overseer® and NZEEM models together. Using these models for this catchment (126669 ha), that has 77% sheep and beef, 16% dairy and 6% forest, and data for the catchment above Weber Rd, we were able to assess the likely sources of these losses.

Most phosphorus comes down the rivers in particles of eroded sediment from steeper land during major floods – about 511 tonnes of phosphorus per year goes under the bridge at Hopelands attached to particles of sediment.

90% of the erosion occurs under pastures on steep land and 10% under forest.

These phosphorus particle losses could be reduced from 511 to 280 tonnes by targeted planting of trees on Highly Erodible Land (Figure A).

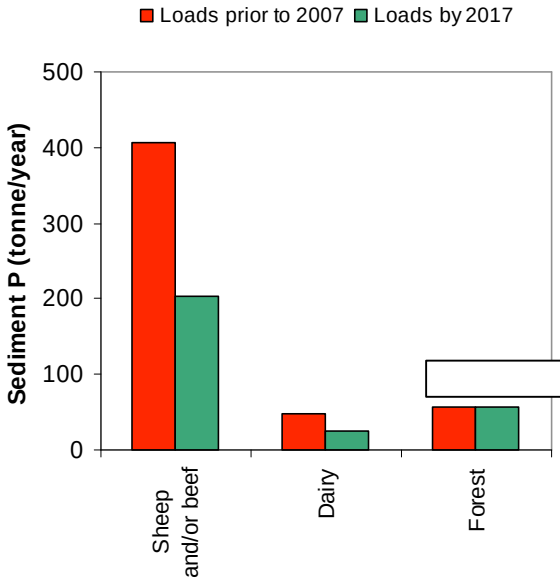
During low flows sediment particles on the bed of the river release about 4 tonnes of dissolved phosphorus per year. This could be halved by reducing erosion.

Dissolved phosphorus causes blooms of periphyton in summer. Most dissolved phosphorus, however, comes from pastures. For sheep and beef farms this could be reduced from 14 tonnes per year down to 10 tonnes per year with targeted planting of trees and riparian zones. For dairy farms it could be reduced from 9 tonnes down to 5 tonnes per year with changes to management of effluent, excluding cows from streams and limiting soil P fertility to the optimum agronomic range (Figure B).

Dissolved phosphorus from point sources at Dannevirke and Oringi could be reduced from 7 down to 2 tonnes per year with changes to management of effluent.

Based on the finding of this, we recommend the two pronged approach offered by SLUI to reduce total P loadings to the river and the FARM strategy to reduce DRP during low flow, to improve the water quality by reducing P contamination in the UMWMZ.

Monitoring of phosphorus concentrations in the Manawatu River should be carried out on a regular basis to define a more precise base line, and to monitor improvements to water quality as SLUI and the FARM strategy programmes progress.



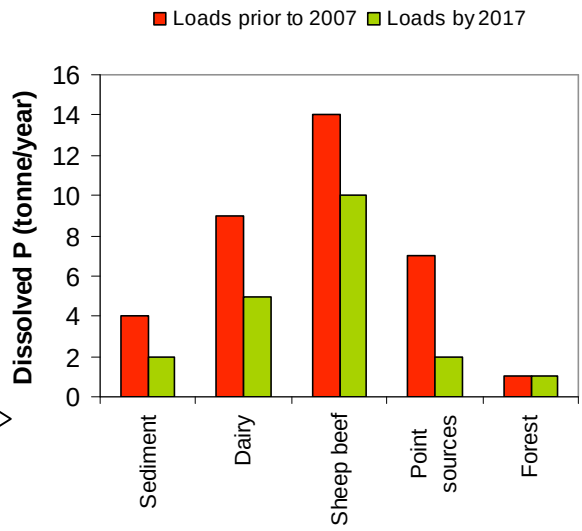


Figure A. Estimates of sources of particulate phosphorus in the Manawatu River at Hopelands in 2007, and loads achievable by 2017 if recommendations are implemented (tonnes phosphorus per year)

Figure B. Estimates of sources of dissolved phosphorus in the Manawatu River at Hopelands in 2007, and loads achievable by 2017 if recommendations are implemented (tonnes P per year). Note: Some of the 511 tonnes of particulate phosphorus remains on the bed of the river and generates about 4 tonnes of dissolved phosphorus per year

Summary

Background

Horizons is implementing the sustainable land use initiative (SLUI) to address both erosion issues on farms and issues of sediment in rivers. A further Horizons initiative, the Farmer Applied Resource Management strategy (FARM strategy) will target reductions in nutrient loss (mainly nitrogen and phosphorus) from intensive land uses in priority catchments. Both these initiatives are a part of Horizons recently notified One Plan. The proposed One Plan, a combined regional policy statement, regional plan and coastal plan, emphasises integrated catchment management. Horizons Regional Council have asked SLURI – New Zealand's multi-CRI Sustainable Land Use Research Initiative incorporating best fit teams from Landcare Research, AgResearch, HortResearch and Crop & Food – to develop a method to determine the potential for water quality improvement through these combined initiatives in relation to phosphorus (P) in water ways.

Using data for the Upper Manawatu catchment above Hopelands (126669 ha; 77% sheep and beef, 16% dairy, 6% forest) and data for the catchment above Weber Rd, we were able to assess the P losses from land to waters for different land uses. We have estimated the current average P losses from farms above Hopelands, as well as the water quality outcome that results from introducing best practice on all farms. The project has implications for integrated catchment management in other hill country locations. The results from this study give numerical estimates for the P sourced from both non-point sources and point sources. They have implications for future resource consent decisions regarding P inputs into the river, and managing P to achieve a water quality target, and provide a framework for the management of other catchments.

Objective

This project reports on the loads of P lost from non-point sources and point sources for current management practices, and provides a better understanding of the P sources in the Upper Manawatu Water Management Zones (UMWMZ) above Hopelands. This project seeks to quantify the impact of implementing best practice on the water quality of those catchments, and thus better targeted approaches to P management. It also provides some further indication as to whether erosion control or nutrient management should be the priority management target in that catchment.

Objectives to be addressed are:

- Estimate current P loadings in the Manawatu River at Hopelands
- Estimate relative contributions of P from sediment, nutrients on farms, point sources and other sources
- Identify best practice P losses in relation to erosion control
- Determine what the implementation of best practice for erosion control would achieve in terms of a water quality outcome
- Identify best practice P losses in relation to nutrient management on sheep and beef, and dairy farms
- Determine what the implementation of best practice for nutrient management control would achieve in terms of a water quality outcome
- Determine the combined effect of implementing best management for both erosion control and nutrient management

Conclusions

For the first time in New Zealand we have estimated both the total and dissolved P losses and the likely sources of P for a large catchment, by using the Overseer® and NZEEM models together.

P is lost in three forms: P in suspended sediment particles (PP), dissolved reactive P (DRP), and dissolved organic P (DOP) with the first of these dominant (60–90%). DRP is readily available to periphyton; DOP is less available and requires biological energy (enzymes) to access this P and then mineralise the DOP into DRP. Sediment on the river bed releases about 2% of its P as DRP by mineralisation, desorption and/or reducing conditions. Periphyton appear to strip both DRP and nitrate from the Manawatu River in summer.

Within the Manawatu Catchment we investigated the P losses above Hopelands that occur in low flows, in all flows except the highest 10%, in "background" years when there are no major storms, and the long-term average that includes major storms.

At the Hopelands bridge, DRP losses at low flows (e.g. summer) are 8 t P yr^{-1}, of which 3.5 t P yr^{-1} arises from point sources and industrial sites (Dannevirke, PPCS Oringi freezing works, etc.). The remainder is from non-point sources (i.e. pastures and forests).

At all flows except the largest 10% of flows, DRP losses are 12 t P yr^{-1}, of which approximately 5.3 t P yr^{-1} arise from point sources, 4 t P yr^{-1} arise from sheep and beef land, 2.5 t P yr^{-1} from dairy land, and 0.4 t P yr^{-1} from forest.

"Background" annual P loss largely involves surface and sub-surface run-off, and this is modelled by Overseer®, and includes DRP, DOP and some PP. For "background" years total-P losses are estimated at 76 t P yr^{-1}, of which approximately 7 t P yr^{-1} arise from point sources, 4 t P yr^{-1} from forest 51 t P yr^{-1} from sheep and beef land, and 14 t P yr^{-1} from dairy land. Losses of DRP+DOP are estimated at 14 t P yr^{-1} from sheep and beef land and 9 t P yr^{-1} from dairy land. In terms of kg P ha^{-1} yr^{-1} these losses translate into average losses of 0.7 kg P ha^{-1} yr^{-1} for sheep and beef land and 0.9 kg P ha^{-1} yr^{-1} from dairy land.

A significant proportion of the total P loss occurs during single-storm events that cause erosion. Huge amounts of P are lost to the oceans as PP during these events. The long-term average losses, which include the major storms, yield total-P losses of 546 t P yr^{-1}, of which approximately 406 t P yr^{-1} arise from soil erosion in sheep and beef pastures, 48 t P yr^{-1} from erosion in dairy land, and 57 t P yr^{-1} from erosion in forests. The remaining 35 t P yr^{-1} from background losses of dissolved-P.

Mitigation measures that would improve water quality during times of low flow include reducing losses from point sources and industrial sites, removing animals from water ways, and better management of effluent. Decreasing the sediment load to the river will also improve water quality during times of low flow since less P will be released from the sediment in the river bed.

The greatest gains can be made from managing erodible land under pasture. Loss of PP at Hopelands is 511 t P yr^{-1} (for the long-term average), with 454 t P yr^{-1} from eroding land on farms. Most of this will occur in major storm events. Target planting of trees could reduce the losses to about 280 t P yr^{-1} by implementing whole farm plans on approximately 10 % of farms with the highest proportion of Highly Erodible Land. By reducing the introduction of

fresh sediment into the bed of the Manawatu River there would also be reductions in P released from the river bed that is available to periphyton.

Gains can be made from better managing point sources which add 3.5 t P yr^{-1} as DRP to the Manawatu River above Hopelands at low flows; this is 44% of the load at low flows. The load at of DRP at all flows is approximately 21 t P yr^{-1}; and 5 t P yr^{-1} is from point sources. The DOP loads are estimated to be 10 t P yr^{-1}, with 2 t P yr^{-1} from point sources. The loads from point sources could be reduced considerably with improved management of effluent using engineering and chemical technologies.

For dairy farms, dairy cows in water ways contribute about 0.5 kg P ha^{-1} yr^{-1} to rivers. Gains can be made from removing animal stock from these water ways. If this applies to 10% of the dairy farms, this could reduce the load in the Manawatu River at Hopelands by 1 t P yr^{-1}. Planting trees on steeper slopes, and riparian fencing and planting on rivers and larger streams on sheep and beef farms could reduce the DRP load by another 4 t P yr^{-1}. This would be a valuable mitigation for P during periods of low flow.

Gains can be made through moving tracks that link to streams. For dairy farms this could reduce the losses by 0.1 kg P ha^{-1} yr^{-1}. If this applies to half of the dairy farms, this could reduce the load in the Manawatu River at Hopelands by 1 t P yr^{-1}.

Gains can be made from irrigating farm dairy effluent according to deferred irrigation criteria where applications are only made to soil that has a sufficient soil water deficit to store applied volumes. Furthermore, when soil infiltration limitations exist or preferential flow of applied effluent is likely; further gains can be made using low rate irrigation technology. For dairy farms this could reduce the losses by 1 kg P ha^{-1} yr^{-1} on at least 10% of the milking platforms. If this applies to all dairy farms, this could reduce the load in the Manawatu River at Hopelands by 2 t P yr^{-1}. The consented effluent loads directly discharged to water at Hopelands have been reduced from a peak of about 3.0 tonnes DRP yr^{-1} in 1998 to 0.5 tonnes DRP yr^{-1} by 2006.

Gains can be made from using reactive phosphate rock (RPR) rather than more soluble P fertilisers on pastures, since fertilisers can fall within streams and soluble fertilisers can rapidly move short distances to streams (Alan Gillingham, unpublished data from Waipawa). The gains depend on weather conditions (such as storms shortly after applying fertiliser, and the amount of fertiliser that falls directly into waterways). Assuming the loss from soluble P fertilisers during a large storm is 1 kg P ha^{-1}, the loss over 1000 ha would be 1 t P. Assuming the loss from RPR fertiliser is 0.5 kg P ha^{-1}, the loss over 1000 ha would be 0.5 t P.

The sum of all these gains could reduce the average DRP + DOP (dissolved-P) load at Hopelands from 35 to 19 tonnes P yr^{-1}. The SLUI plan could reduce the sediment P losses from pasture land from 511 to 280 tonnes P yr^{-1} with targeted planting of the Highly Erodible Land. Since it takes several years for tree roots to bind the soil, the achievement of these gains may take about 10 years. Targeting the SLUI whole farm plans to the highest priority farms is the best way to achieve gains in the shortest time.

The ANZECC (2000) recommended guideline for slightly disturbed lowland ecosystems for DRP has been set at 0.010 g P m^{-3}. Current concentrations at Hopelands are usually > 0.010 g P m^{-3}, except when periphyton are actively stripping DRP in summer. It should be possible to reduce current DRP concentrations down towards the guideline concentration with these

mitigation measures. Since the geology of the Upper Manawatu catchment has some P rich materials it may not be possible to lower the DRP concentrations further than the guideline concentration.

Recommendations

Based on the finding of this, we recommend the two pronged approach offered by SLUI to reduce total P loadings to the river and FARM strategy to reduce DRP during low flow, to improve the water quality by reducing P contamination in the UMWMZ.

We also recommend:
Attention to point sources, since rapid gains may be possible.
Attention to animals in rivers, since rapid gains may be possible.
Attention to effluent disposal, since rapid gains may be possible.
Riparian fencing and planting, managing stream crossings, and other recommendations in the Clean Streams Accord should be implemented.
SLUI Farm Plans should be targeted on high priority farms.
Both nitrogen and phosphorus should be managed year round.
Overseer® nutrient budgets on farms should be implemented to provide more precise numbers about nutrients under different management and for the different soils.
Monitoring of phosphorus (DRP, DOP, PP) in the Manawatu River should be carried out on a regular basis to give more precise numbers, to provide a base line, and to monitor improvements to water quality.

1. Introduction

Horizons have recently notified the One Plan. The proposed One Plan includes a rule making intensive farms, in catchments with identified degraded water quality, a controlled activity requiring a resource consent. The resource consent requires a nutrient budget and a management plan via a farmer applied resource management strategy (FARM strategy) to demonstrate the operations are within the nutrient loss limit set for the water management zone.

Following the February 2004 storm event in the Manawatu-Wanganui Region, Horizons and a range of key stakeholders have initiated the sustainable land-use initiative (SLUI). SLUI is a “mountains to sea” approach to the problem of accelerated erosion in highly erodable land. A variety of tools have been developed to implement SLUI with the development of whole farm business plans being the primary tool.

Horizons Regional Council have asked SLURI – the multi-CRI Sustainable Land Use Research Initiative, to provide a better understanding of the phosphorus (P) sources in the catchment, and better targeted approaches to P management, that will lead to reduced impacts of P in the waterways of the catchments. The total losses of P in waterways in the Horizons region are estimated at 3500 tonnes P yr^{-1} (Parfitt et al. 2008). P is lost in three forms: P in suspended sediment particles (PP); dissolved reactive P (DRP); and dissolved organic P (DOP) with PP dominant. DRP is readily available to periphyton (Wilcock et al. 2007a). DOP is less available to aquatic organisms than DRP since biological energy (enzymes) is required to access DOP and mineralise it into DRP (Turner et al. 2003; Ellwood & Whitton 2007). Periphyton appear to strip 90% of both DRP and nitrate from the Manawatu River in summer (Parfitt 2006), and since the nitrate concentrations are well above the MFE guideline concentration of 0.10 mgN/l, the periphyton appear to take up excess N, and probably have the energy needed to use some DOP as well as DRP. Algae can also use P from sediment on the river bed (Hedley 1978). Both the surface-bound organic-P and inorganic-P are readily taken up by algae that are in contact with sediment. In some circumstances, sediment on the river bed may also release a small fraction of PP into the river water as DRP by mineralisation, desorption and/or reducing conditions. P in stream bank material is less available to algae than P in sediment from farm runoff (Hedley 1978).

A significant proportion of the P loss occurs during single-storm events involving soil erosion. Major erosion events cause losses of huge amounts of sediment and P to the oceans. “Background” annual P loss largely involves surface and sub-surface run-off, and this is modelled by Overseer®, and includes DRP, DOP and some PP. Leaching to aquifers can also occur on lighter soils that have by-pass flow.

P losses arising from erosion are being addressed by the Sustainable Land Use Initiative (SLUI). SLUI is targeting hill country erosion in the Manawatu-Wanganui region and is a major investment on behalf of the regional council. The overall plan of this initiative is to complete at least 1500 whole farm plans over the next 10 years. Whole farm plans (WFP) are detailed assessments of the economic and environmental aspects of a farm (Appendix 1), that also cover nutrient management considerations in the farming operation. This project, looking at best practices for land management, has the potential to influence the works programmes of 1500 whole farm plans for erosion control in the next ten years. The project results also have the potential to influence the FARM strategy consent conditions for

management of P on farms. The One Plan proposes the FARM strategy will be rolled out by water management zones from 2009.

This project sets out to develop a method to determine the potential for water quality improvement through reduced P contamination from these combined initiatives in the UMWMZ. We investigated the P losses above Hopelands that occur in low flows, in all flows except the highest 10%, in “background” years when there are no major storms, and the long-term average that includes major storms. Current average P losses from farms in the catchment will also be calculated, as well as the water quality outcome that would result from introducing best practice on all farms. The results from this project (studying and providing numerical estimates for the P sourced for non point sources) have implications for future resource consent decisions regarding non-point source P inputs into the river. The project also has the potential to inform resource consent decisions regarding point source P inputs to water ways from the time the project is complete.

At the request of Horizons Regional Council the framework has been developed with the view to developing best management practices for management of P on farms in the whole of the Manawatu-Wanganui region. This project will be useful to decision makers in relation to consents, policy, whole farm plan developers, FARM strategy developers, farmers implementing works programmes on their farm and potentially point source dischargers. The project may also lead to further work in other catchments to reach numerical estimates and similar types of positive environmental outcomes through implementation of best practice on farms.

2. Objective

This project reports on the estimated loads of P lost from non-point sources and point sources for current management practices, and gives a quantitative understanding of the P sources in the Upper Manawatu Water Management Zones above Hopelands (Figure 1). This project seeks to quantify the impact of implementing best practice on the water quality of those catchments, and thus better targeted approaches to P management. It also provides some further indication as to whether erosion control or nutrient management should be the priority management target in that catchment.

Objectives to be addressed are:

- Estimate current P loadings in the Upper Manawatu Water Management Zones (UMWMZ) above Hopelands
- Estimate relative contributions from erosion, nutrients on farms, point sources and other sources
- Identify best practice P losses in relation to erosion control
- Determine what the implementation of best practice for erosion control would achieve in terms of a water quality outcome
- Identify best practice P losses in relation to nutrient management on sheep and/or beef farms and dairy farms
- Determine what the implementation of best practice for nutrient management control would achieve in terms of a water quality outcome
- Determine the combined effect of implementing best management for both erosion control and nutrient management

The project will provide input into decision making on works programmes for WFP for P management, and determine the level of effort in these WFPs that is put into P management, i.e. identifying hotspots and addressing them through the works programme. It will also feed into a test farms project.

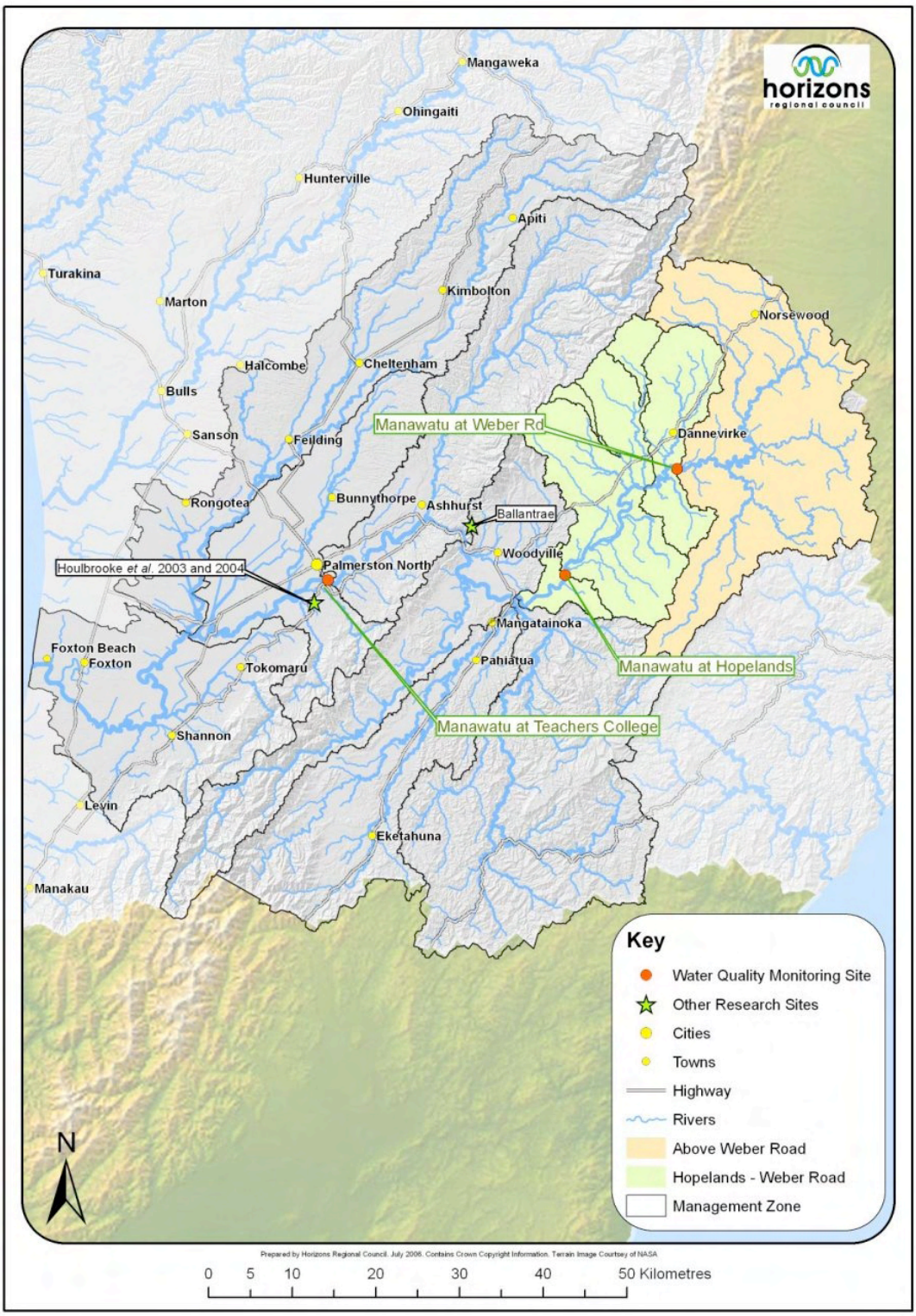


Figure 1. The Upper Manawatu Water Management Zones, monitoring locations and research sites, above Weber Road (in yellow) and above Hopelands (in green).

3. Farm Types and the Potential Impact on Water Quality in Upper Manawatu Water Management Zones (UMWMZ)

Horizons Regional Council has identified dairying, irrigated sheep and beef, market gardening, and cropping as four intensive forms of farming. Based on the paper by Menneer et al. (2004), these were ranked in our SLURI report "Farm Strategies for Contaminant Management" (Clothier et al. 2007) for P as:

Table 1. Likely losses of P from farms with intensive forms of farming (Menneer et al. 2004)

Total-P Loss (kg P ha^{-1} yr^{-1})
Market Gardening
Cropping
Dairying
0.2–1.0
Sheep and beef
0.1–1.6

There are no data for P losses from market gardening and cropping, and since these are a very small area (493 ha) in the Upper Manawatu, these land uses are not considered further in this report. The land areas for dairying are 20534 ha (16%), for sheep and beef are 97622 ha (77%) and forest are 7672 ha (6%) (Figure 2).

The catchment above Weber Road is dominated by sheep and beef farming: land areas for sheep and beef are 64101 ha (89%), dairying are 5825 ha (8%), and forest are 1987 ha (3%).

The catchment area between Weber Road and Hopelands has 33521 ha (62%) of sheep and beef, 14709 ha (27%) of dairying, and 5685 ha (10%) of forest.

Dairy Farms

Recent studies of five dairy catchments (Wilcock et al. 2007b) give *total-P* losses, arising from both DRP and PP, of 0.3–1.2 kg P ha^{-1} yr^{-1} (excluding one catchment on the West Coast that had 5 m of rain). The losses of DRP ranged from 0.15 to 0.68 kg P ha^{-1} yr^{-1}. The P content of the particles was generally 4000 mg P kg^{-1}, which is extremely high.

Houlbrooke et al. (2003) measured P concentrations in drainage water collected from mole and tile drainage at a dairy farm on poorly drained soils in Manawatu (Figure 1). The loss of total-P was 0.34 kg P ha^{-1} yr^{-1} and DRP was 0.13 kg P ha^{-1} yr^{-1}, but, with effluent applied losses of total-P were 0.86 kg P ha^{-1} yr^{-1} and DRP were 0.51 kg P ha^{-1} yr^{-1}; the differences between total-P and DRP probably arise from organic-P. Unpublished data from Houlbrooke for same site for the following season showed a 1 kg P/ha difference in P loss between the same effluent and non-effluent treatments. The P load from blocks where effluent is spread onto land is greater than for other parts of the farm. P losses for different blocks on a dairy farm can be estimated using the Overseer® model.

When cows have direct access to streams and rivers they add a considerable amount of dung

to the rivers. This adds to the P load in the rivers, and is estimated to be 0.5 kg P ha^{-1} yr^{-1} (McDowell 2006). This will obviously depend on the number of cows and the frequency of access to waterways.

Sheep farms

P losses from sheep farms in hill country have been studied near Waipawa and at Ballantrae (near Woodville) (Figure 1). Lambert et al. (1985) reported that total annual P losses at Ballantrae were 0.7–1.5 kg P ha^{-1} yr^{-1}, and just 15% of this was DRP. Losses at Waipawa have been less than 0.7 kg P ha^{-1} yr^{-1} in the last 5 years (R. McDowell, unpublished). However, earlier data from Gillingham and Gray (2006) showed larger losses occurred during some storm events. They found that during 2001 two large storms caused 1.2 kg P ha^{-1} to move as sediment from land (with Olsen-P = 26) to streams (See Glossary). There were also losses during 15 other smaller events that year, with 0.7 kg P ha^{-1} yr^{-1} moving as PP from dung, sheep tracks and other areas of exposed soil. They reported *total-P* losses of 1.8 kg P ha^{-1} yr^{-1} where the Olsen-P value was 6, and 4.1 kg P ha^{-1} yr^{-1} where the Olsen-P was 26. The DRP *concentrations* were 0.019 and 0.037 g m^{-3}, DOP values were 0.018 and 0.019 g m^{-3}, and PP were 0.024 and 0.053 g m^{-3} respectively (Gillingham & Gray 2006).

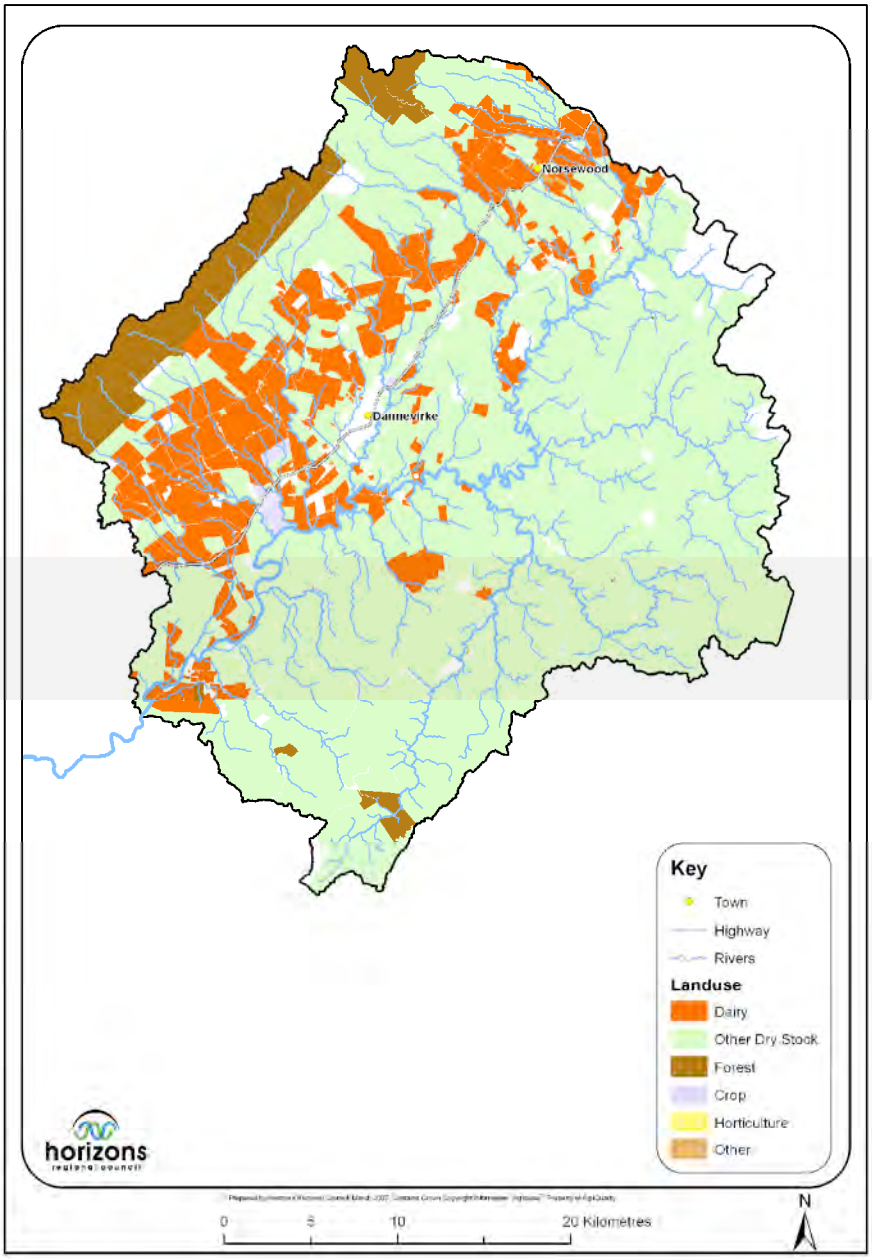


Figure 2. Major land use categories in UMWMZ

The concentration of DRP in seepage water parallels soil Olsen-P levels. The water in springs at Ballantrae in winter 2006 had an average DRP concentration of 0.10 g m^{-3} for a paddock with Olsen-P = 48 (High-P farmlet), compared with a DRP concentration of 0.017 g m^{-3} at a paddock that had not received P fertiliser for the past 25 years and where Olsen-P = 9 (No-P farmlet) (Parfitt et al. 2007).

Intense rain can flush out additional DRP from topsoils, and in a storm on 6 July 2006 (50 mm in 20 hours) when the soil was saturated, the water-table was at the surface, overland flow occurred, and the DRP concentration was 1.1 g m^{-3} for the fertilised paddock, and 0.02 g m^{-3} for the unfertilised paddock. The DRP lost by overland flow in this event (which may occur one year out of two) for the High-P farmlet, was estimated at 0.33 kg P ha^{-1}, whereas the DRP lost in all the rain events by subsurface flow was 0.68 kg P ha^{-1} yr^{-1}. The total annual loss of DRP in 2006 was 1.0 kg P ha^{-1}. For the No-P farmlet in 2006, the loss was 0.1 kg P

ha^{-1} yr^{-1} in subsurface flow and 0.01 kg P ha^{-1} yr^{-1} in overland flow.

Since there are more data for DRP than for PP in the Upper Manawatu, we will consider DRP separately in the next section. PP in the Upper Manawatu will be considered in section 5.

4. What is the best practice acceptable DRP loss from a farm that Horizons should endorse in UMWMZ?

We wish to establish what the target best management practices (BMP) are for sheep and beef and dairy farms to ensure that water quality in Horizons Water Management Zones approaches guideline criteria (McArthur et al. 2007). For DRP the recommended guideline for slightly disturbed lowland ecosystems has been set at 0.010 g P m^{-3} (ANZECC 2000). To establish BMPs that would meet such guideline water-quality targets, we first needed to link what we consider is happening on the farm, with what is observed in the river.

On farms, P loss to waters is directly related to soil properties such as Olsen-P and P-retention (more commonly known as Anion Storage Capacity). The Olsen-P concentration is related to inputs of P onto a farm block as fertiliser, effluent and imported feed. P-retention is related to long term soil weathering processes. McDowell and Condron (2004) developed laboratory tests to estimate potential subsurface loss of DRP in runoff for 44 soils in New Zealand. To calculate P leaching potential below topsoils (to 30 cm soil depth), they derived the formula DRP (g m^{-3}) = 0.069 x P_{Olsen}/P_{Ret} + 0.007 based on Olsen-P and P-retention of soils. Outputs from the model are given in Table 2.

Table 2. Model results showing concentration of DRP (g m^{-3}) below the top-soil for different combinations of P-retention and soil Olsen-P level within the top-soil (upper 7.5 cm)

P-retn.	Olsen-P value (mg kg^{-1})				
(%)	10	20	30	40	60
10	0.08	0.15	0.21	0.28	0.42
30	0.03	0.05	0.08	0.10	0.15
50	0.02	0.03	0.05	0.06	0.09
70	0.02	0.03	0.04	0.05	0.07
90	0.01	0.03	0.04	0.05	0.05

It is clear that soil Olsen-P status is a major factor influencing P concentration in seepage waters, and the DRP concentrations increase exponentially at Olsen-P concentrations greater than about 50 (McDowell et al. 2001). For a soil with a P-retention of 50% the P concentration increases from 0.02 to 0.09 g m^{-3} as Olsen-P increases from 10 to 60 mg kg^{-1} (Table 2). All these DRP concentrations are above the recommended guideline for slightly disturbed lowland ecosystems of 0.010 g P m^{-3} (ANZECC 2000). If the Olsen-P of a topsoil is 20, then the P concentration in seepage waters will decrease from 0.15 g m^{-3} to 0.03 g m^{-3} as the P-retention properties of soils change from 10 to 90. This occurs as the soils in the landscape change from sandy raw soils to weathered volcanic (Allophanic) soils; P-retentions in “Manawatu Soils” (alluvial soils) are 30 and in Dannevirke Soils (Allophanic) they can be as high as 90. P-retention generally increases with increase in rainfall above 1200 mm on terraces in UMWMZ. If the annual subsurface drainage is 500 mm (i.e. as at Ballantrae; Parfitt et al. 2007), then 0.15 g m^{-3} gives a loss of DRP of 0.75 kg P ha^{-1} yr^{-1}; 0.03 g m^{-3} gives a loss of DRP of 0.15 kg P ha^{-1} yr^{-1}.

Olsen-P concentrations under various land uses in New Zealand have been determined in the '500 Soils' project undertaken by Landcare Research between 1995 and 2002. The dataset comprises measurements for 0 to 10 cm soil depth from nearly 600 sites (Table 3; Figure 3).

Table 3. Concentrations for Olsen-P tests measured under different land uses in New Zealand (Data taken from Landcare Research Soil Horizons: Issue 10)

Land use	No of sites	Olsen-P (mg kg^{-1})	
		Mean	Std Dev.
Indigenous forest	62	12	14
Plantation forest	69	10	12
Sheep-beef pasture	154	21	19
Dairy pasture	139	46	32
Horticulture	48	57	42
Mixed cropping	25	54	44
Arable cropping	54	53	47

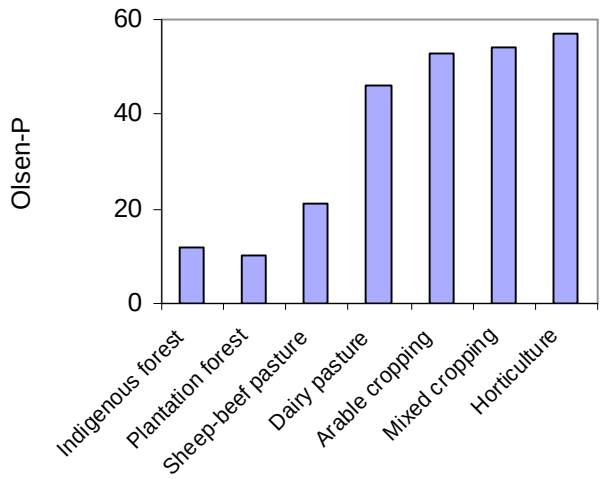


Figure 3. Concentrations for Olsen-P measured under different land uses in New Zealand (Data taken from Landcare Research Soil Horizons Issue 10)

DRP in Upper Manawatu Water Management Zone

To estimate transmission factors, we first carried out analysis for DRP in UMWMZ. DRP data for all flows except the highest 10% are the most reliable data available for UMWMZ, since data at the highest 10% of flows have some extreme values. We then used the equations of McDowell and Condron (2004) to predict the DRP losses from farms. By linking observations of nutrient loadings in the river to these DRP losses at the farm, we have a tool to link farm practices to water quality, through which we may be able to suggest how BMPs will contribute to achieving water quality targets for DRP to be met.

We used the contrasting patterns of land use in two monitored sub-catchments of the UMWMZ to explore the farm-to-river transmission link for the key land uses of dairying, and sheep and beef. Above the monitoring station at Weber Road, the catchment is dominated by sheep and beef farms, whereas the area upstream of monitoring at Hopelands has a greater relative proportion of dairy farms (Figures 1 and 2).

Linking River Observations to Land Practices: A Framework

To establish the link between the land and receiving waters, we will use a simple transfer-function approach (McDowell & Condron 2004) to estimate the loss rate of P from farms in the UMWMZ. Initially, we will use McDowell and Condron (2004) to predict what the loss rates are from current practices:

$$O(L=q^*_d) = \text{f [Olsen, P-retention]} \qquad [1]$$

$$O(L=q^*_{sb}) = \text{f [Olsen, P-retention]} \qquad [2]$$

where $O(L=q^*_d)$ is the McDowell and Condron (2004) calculation of the P loss, L being the value of the annual flux of P, (q^* is kg P ha^{-1} yr^{-1}) at 30 cm in the soil. The subscript d and sb refer to dairying and sheep and beef. The loss will be, inter alia, a function of Olsen-P and P-retention.

We adopt an inverse functional notation of O^{-1} for the McDowell and Condron (2004) calculation of the P flux q^* as

$$q^* = O^{-1}(L_f) \qquad [3]$$

We use this notation to indicate that the flux q^* is estimated from McDowell and Condron (2004) calculation of loss for a specific farm scenario L_f.

This predicted loss q^* will be attenuated in the farm-groundwater-river system, so that from the perspective of the river, a back-calculation based on observations in the river would suggest that farms only "seem" to be losing the flux, q (kg P ha^{-1} yr^{-1}).

We can therefore estimate transmission factors $\Re$ for both dairy and sheep and beef as:

$$\Re_d = \frac{q_d}{q^*_d} \quad \& \quad \Re_{sb} = \frac{q_{sb}}{q^*_{sb}}. \qquad [4]$$

Here we have chosen to use a transmission factor, $\Re$; however, we could have alternatively written this as its complement, an attenuation factor, which would be 1-$\Re$.

Using this simple, transfer-function approach, from annual average data we can predict the denominators from McDowell and Condron (2004) and we use the Manawatu River in UMWMZ to assess the numerators.

There are two river monitoring stations in the UMWMZ: one at Weber Road, the other at Hopelands (Figures 1 and 2). Because these two catchments, designated *W* and *H*, have differing proportions of dairying and sheep and beef farms (Table 4), we can set up simultaneous equations to find both $\Re_d$ and $\Re_{sb}$, by first calculating the loss values 'seen' by the river: q_d and q_{sb}. The area of each farm-type in each catchment is *A* (ha), appropriately subscripted. We also need to consider the contribution from the small areas of forest, both native and exotic, and from cropping, designated by subscripts *f* and *c*. The point-source discharges around Dannevirke, *D*, (kg-N yr^{-1}) also need to be accounted for. This *D* includes point sources discharges at Norsewood, Ormondville, and PPCS Oringi, plus Dannevirke itself. Horizons have provided us with the annual river loadings of DRP at Weber Road and Hopelands, viz. Q_W and Q_H (kg P ha^{-1} yr^{-1}), calculated by summing the loadings across the percentile classes of flows to arrive at the annual average required by our approach.

Mass Balance Equations
So, on an annual average basis, [5]

$$Q_W = q_d\, A_d(W) + q_{sb}\, A_{sb}(W) + q_f\, A_f(W) + q_c\, A_c(W)$$

$$Q_H - Q_W = q_d\, A_d(H-W) + q_{sb}\, A_{sb}(H-W) + q_f\, A_f(H-W) + q_c\, A_c(H-W) + D$$

GIS data from Horizons were used to determine the areas on dairying (A_d), sheep and beef (A_{sb}), cropping (A_c) and forestry (A_f) in the Weber (*W*) and the Hopelands less Weber (*H-W*) catchments. The town area of Dannevirke area (462 ha) was removed from *H-W*. These areas are given in Table 4.

Table 4. Areas of land-use types in the two sub-catchments

Land-Use Type	Weber (*W*) – ha	Hopelands (*H-W*) – ha
Dairying (A_d)	5825	14 709
Sheep and beef (A_{sb})	64 101	33 521
Cropping (A_c)	34	459
Forestry (A_f)	1987	5685

The contrast in the respective areas, and downstream trends, of dairying and sheep and beef between the two sub-catchments enables us to solve Eq. [5] simultaneously for q_d and q_{sb}, if we assume *q* values for cropping and forestry. These assumptions will have only a limited effect on our solution for $\Re$ as their respective areas are not great, especially for cropping; or their fluxes *q* are known not to be large, as for both exotic and native forests. For DRP we assume q_c = 0.1 kg P ha^{-1} yr^{-1} from this very small area, and that q_f = 0.05 kg P ha^{-1} yr^{-1} applies for forestry (Walker & Syers 1976; Parfitt et al. 2007). Next, we assumed a value for the point-source discharges from around Dannevirke (Horizons have advised us to consider that *D* contributes 5.3 t P yr^{-1} (Ledein et al. 2007)). Horizons annual-average river data on P loading (t P yr^{-1}) are given in Table 5.

Table 5. Average DRP loadings in the two sub-catchments

	Weber (*W*)	Hopelands (*H-W*)
P loading (t P yr^{-1})	3.3	12.0

Solving Eq. [5], using these values, enables us to calculate q_d and q_{sb}. We can then compare these with the McDowell and Condron (2004) calculations of q^*_d and q^*_{sb}, from which we can then estimate the transmissions $\Re_d$ and $\Re_{sb}$. The analysis assumes there is no lag effect, but rather a direct link between DRP losses at the farm scale and the DRP loadings in the river at mid-flow.

Uncertainties and Variability

There will of course be uncertainty in the derived values from Eq. [5]. In the absence of information, we cannot consider measurement errors in the flow and concentration observations, or the error in the loading calculation of summing the percentile classes to arrive at the annual figure. There is considerable variation in the DRP concentration with flow (Figure 4), since DRP depends on the rain events in the various sub-catchments, and on time lags as the P moves through the streams and rivers. Some events in some sub-catchments will produce more P than others due to processes such as overland flow from fertile pastures (Parfitt et al. 2007). DRP concentrations appear to be diluted in very large storm events (Figure 4b), but the total load during these events is high. The variation in weather between years is another large source of variation in the 'leakiness' performance of farming enterprises, and this will be discussed later in the section on PP.

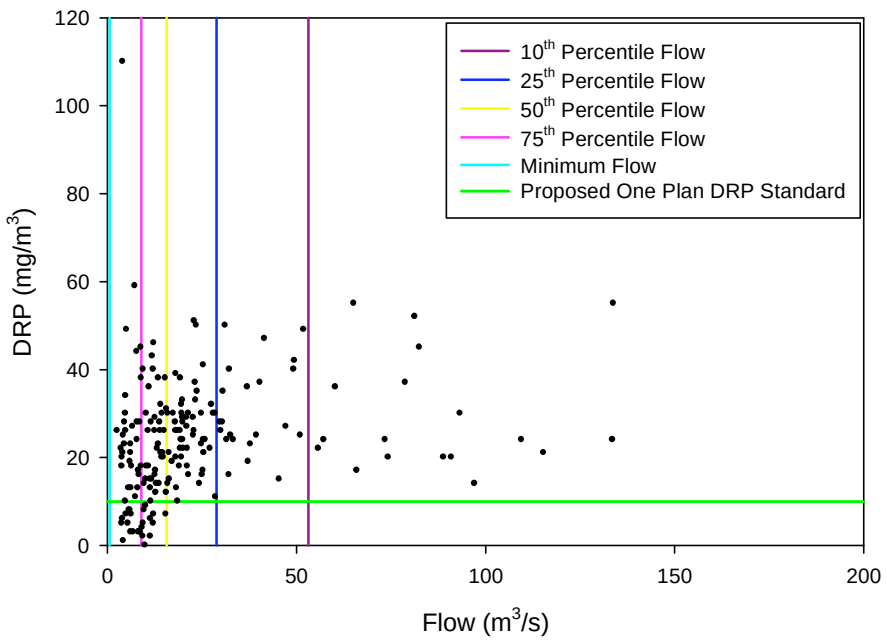


Figure 4a. DRP concentrations of samples collected at various flows in Manawatu River at Hopelands flow recorder from 1989 to 2005. Flow percentiles demonstrate the percentage of time that a particular flow is exceeded at the site. Maximum flow for Manawatu at Hopelands is 1670 $m^3 s^{-1}$. Flow Statistics are derived from Henderson and Diettrich (2007)

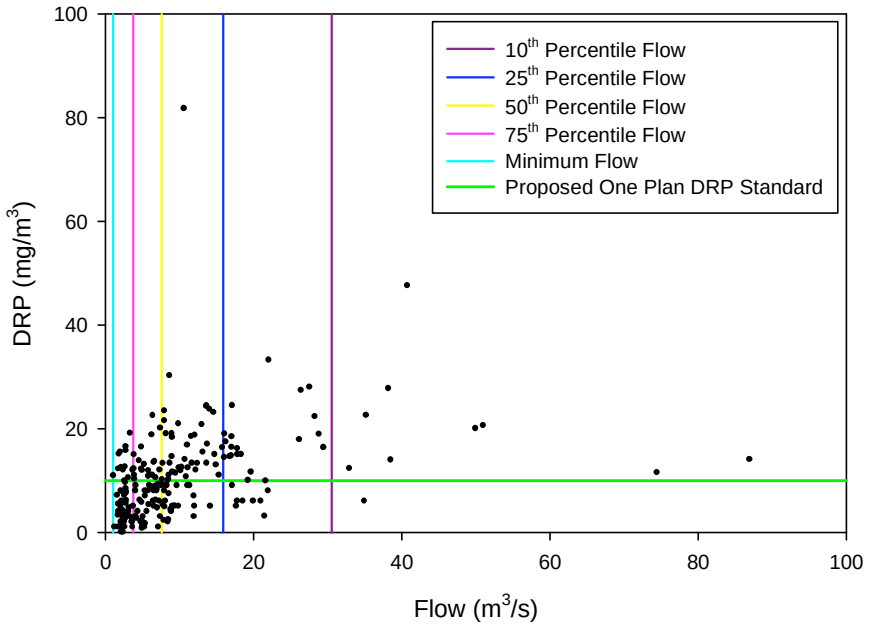


Figure 4b. DRP concentrations of samples collected at various flows in Manawatu River at Weber Road flow recorder from 1989 to 2005 (NIWA). Flow percentiles demonstrate the percentage of time that a particular flow is exceeded at the site. Maximum flow for Manawatu at Weber Road is 1417 $m^3 s^{-1}$. Flow statistics are derived from Henderson and Diettrich (2007)

Diagnostics and Results

General results are given in Table 6 for the range of McDowell and Condron (2004) calculations in kg P ha^{-1} yr^{-1}. The median Olsen-P value for sheep and beef is 14 and for dairy is 30 (Clothier et al. 2007). Based on the National Soils Database, the P-retention values of topsoils in the region for sheep and beef are estimated at 30, and for dairy at 50. This, however, can vary from 15 in the eastern hills to 90 on Dannevirke soils.

Table 6. Model results showing loss of DRP (kg P ha^{-1} yr^{-1}) below the top-soil for combinations of P-retention and Olsen-P, and for 500 mm of drainage loss

	P-retn.	Olsen-P concentration (mg kg^{-1})					
	(%)	10	14	20	30	40	60
Sheep & Beef	20	0.21	0.28	0.4			
Sheep & Beef	30	0.15	0.20	0.3			
Sheep & Beef	50	0.10	0.13	0.2			
Dairy	30			0.3	0.38	0.5	0.7
Dairy	50			0.2	0.24	0.3	0.4
Dairy	90			0.1	0.15	0.2	0.3

Table 7 gives q (in the river) for dairying as 0.12 kg P ha^{-1} yr^{-1} and for sheep and beef as 0.03 kg P ha^{-1} yr^{-1} at these "low" flows.

Table 7 gives q^* (from land) for dairying is 0.24 kg P ha^{-1} yr^{-1} and for sheep and beef as 0.20 kg P ha^{-1} yr^{-1}. These loads in the river from pastures represent 53% of the DRP; point sources represent 44%.

These loads may be compared with DRP loads in the Manawatu River at Teachers College of 0.2 kg P ha^{-1} yr^{-1} for 2004 – a year with many flood events (Parfitt unpublished).

$\Re$ (the transmission factor from land to river) for dairying is 0.5 and for sheep and beef is 0.2. Since many of the head water streams on sheep and beef farms flow through grasses, there is more opportunity for attenuation of P by uptake into plants and organisms, and by sorption processes.

Table 7. The "low-flow" river-based farm DRP fluxes q, the assumed q^* (and range) of McDowell and Condron (2004) calculations (Table 6), and derived transmission estimates for dairying and sheep and beef

	q (Eq5) kg P ha^{-1} yr^{-1}	q^* (Eq3) kg P ha^{-1} yr^{-1}	$\Re$
Dairying	0.12	0.24 (0.1–0.7)	≈ 0.5
Sheep and beef	0.04	0.20 (0.1–0.4)	≈ 0.2

The greatest gains in removing DRP from rivers at low flows could be made from managing point sources and applying BMP on farms – see below.

5. What is the best practice acceptable total-P loss from a farm that Horizons should endorse in UMWMZ?

Overseer® calculations give "background" losses of P to headwater streams in years when there is no major erosion event.

Overseer® calculations of "background" losses of P can be used to estimate a total-P loss (q^*) from farms in kg P ha^{-1} yr^{-1}. Overseer® gives an estimate of the losses of DRP plus DOP plus background-PP losses that come from dung, sheep tracks and other areas of exposed soil. The outputs from all the Overseer® model runs are given in Clothier et al. (2007).

On dairy farms, estimated losses range from 0.4 kg P ha^{-1} yr^{-1} on farms with allophanic soils to 1.3 kg P ha^{-1} yr^{-1} on fertile non-allophanic soils. On blocks irrigated with effluent, the losses range from 0.8 to 1.8 kg P ha^{-1} yr^{-1}.

On sheep and beef farms the estimated losses are 0.6 kg P ha^{-1} yr^{-1} in easy hill country and 0.8 kg P ha^{-1} yr^{-1} in steep hill country. The results (q^*) for the "typical" dairy farm are

estimated at 0.9 kg P ha^{-1} yr^{-1} and for sheep and beef are 0.7 kg P ha^{-1} yr^{-1} (Table 8). Long-term data from NIWA give an annual total-P load in the Manawatu River at Opiki of 1.2 kg P ha^{-1} yr^{-1} (Sandy Elliott pers. comm.). The Overseer® data for losses at the farm are less than the loads found in the river because the Overseer® model does not allow for major erosion events or for erosion of stream bed and bank sediment in waterways larger than 2nd order. NIWA data, however, may not include the largest (one in 40 year) erosion events, that are included in the NZEEM model for sediment given below.

Table 8: The river-based farm fluxes *q*, (from PP and DRP (Table 6)), and q^* from Overseer® calculations for dairying and sheep and beef. No transmission estimates could be made since Overseer® does not account for P losses in large storm events

	q (Eq5) kg P ha^{-1} yr^{-1}	q^* (Eq3) kg P ha^{-1} yr^{-1}	$\Re$
Dairying	Not available	0.9	not available
Sheep and beef	Not available	0.7	not available

If the P losses from soil profiles (q^*) enter the Manawatu River (excluding "annual" large storm events), the total-P load at Hopelands would be 89 t P yr^{-1}, of which 68.5 t P yr^{-1} are from sheep and beef, 18.5 t P yr^{-1} from dairy, 7 t P yr^{-1} from point sources, and 4 t P yr^{-1} from forests. There is, however, likely attenuation of P between farms and rivers. Assuming this to be low (about 25%), since most P moves in large storms (transmission of 75%) when wet areas on farms are connected to streams and rivers, the total-P load at Hopelands would be 76 t P yr^{-1}, of which 51 t P yr^{-1} are from sheep and beef land and 14 t P yr^{-1} from dairy land. The loss per ha is slightly greater for dairy land than for sheep and beef land (Table 8).

Other losses are possible from dairy farms in UMWMZ (R. McDowell pers. comm.). These are:

Cows in streams = ~ 0.5 kg P ha^{-1} yr^{-1}
Milking platform losses = ~ 1 kg P ha^{-1} yr^{-1}

Gains can therefore be made from removing cows from streams, and from containing all milking platform P losses in effluent ponds.

Calculations for losses of total-P in years including major erosion events
The NZEEM (Dymond & Betts 2007: Appendix 2) was used to estimate the suspended sediment in the Manawatu River at Weber Road (641 000 t yr^{-1}) and at Hopelands (930 000 t yr^{-1}). This is a long-term average over about the last 40 years and includes major flood events but excludes the extreme 2004 flood event. The *total-P* content of dry particles in the Manawatu River one day after flood peaks was about 550 mg kg^{-1} (Parfitt & Hill, 2004). Assuming this is the concentration of P in suspended sediment in UMWMZ this gives 353 t P yr^{-1} as PP in the Manawatu River at Weber Road, and 511 t P yr^{-1} at Hopelands. This is consistent with the Horizons estimate (that does include the aftermath of the very large 2004 flood) of 903 t P yr^{-1} at Weber Rd. The average loss is 4.9 kg P ha^{-1} yr^{-1} from all land above Weber Road and 4.0 kg P ha^{-1} yr^{-1} from all land above Hopelands. This may be compared with the loss of 1.5 kg P ha^{-1} in just 12 hours in the flood of 16 February 2004 for the whole catchment above Teachers College (Parfitt & Hill 2004).

The losses from different land uses above Hopelands have been estimated using the shape files from Horizons. The losses of P from sheep and beef land are estimated at 406 t P yr^{-1} (4.8 kg P ha^{-1} yr^{-1}), losses from dairy land at 48 t P yr^{-1} (2.3 kg P ha^{-1} yr^{-1}), and losses from other land (mainly forest on very steep slopes) at 57 t P yr^{-1} (2.7 kg P ha^{-1} yr^{-1}) (Figure 5).

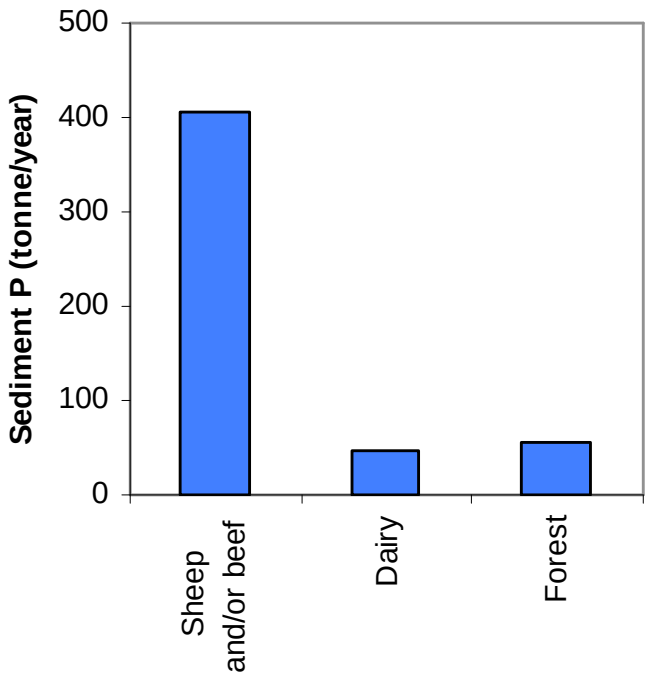


Figure 5. Estimates of sources of sediment derived P (Particulate P) in Manawatu River at Hopelands in 2007 based on the long-term average over about the last 40 years and includes major flood events but excludes the extreme 2004 flood event (tonnes P per year).

Assuming the area of sediment in the bed of the Manawatu River above Hopelands occupies 250 ha, and the bulk density on the river bed is 1.6 t m^{-3}, and if the surface 100 mm of sediment (500 mg P kg^{-1}) releases 2% of the P each year (Hedley 1978; McDowell & Wilcock 2007) the river bed contributes 4 t P yr^{-1}.

The DRP and DOP losses must be added to the erosion PP (511 t P yr^{-1}) to obtain the total-P losses in the Manawatu River at Hopelands (Table 9). The DRP losses are 21 t P (Maree Clark pers. comm.) and there is some evidence that DOP losses in the Manawatu are about 50% of DRP losses (Parfitt & Mackay 2007), giving dissolved-P in the river at Hopelands of 35 t P yr^{-1}. The 35 t P yr^{-1} is apportioned to sheep and beef = 14 t P yr^{-1} (0.1 kg P ha^{-1} yr^{-1}), dairy = 9 t P yr^{-1} (0.4 kg P ha^{-1} yr^{-1}), forest = 1 t P yr^{-1} (0.1 kg P ha^{-1} yr^{-1}), dissolving sediment = 4 t P yr^{-1}, and point sources = 7 t P yr^{-1} (Figure 6). The total losses are then the sum of 511 t P yr^{-1} and 35 t P yr^{-1}.

Table 9. P loads at Hopelands in **tonnes P per year** under different flows – most SSP rapidly goes to the ocean

	P fraction	Sheep and/or beef	Dairy	Pasture	Forest	"Point sources"	Release from SS in bed of river	Total	Reference
Low flow 2003 <90 percentile (15 yrs)	DRP			4.2	0.2	3.5		8	Ledein 2007 Maree Clark 2007 Overseer 5.2.6.0
	DRP	3.8	2.5	6.3	0.4	5.3		12	
Background annual	Total-P	51	14	65	4	7		76	
Erosion storms (long-term average)	SSP	406	48	454	57			511	NZEEM 2007
Annual average	DRP	9	6	16	0.5	5		21	Maree Clark 2007 50% of DRP
Annual average	DOP	5	3	8	0.5	2		10	
Release from sediment	DRP						4	4	Our estimate
Dissolved P	DRP+DOP	14	9	23	1	7	4	35	Our estimate
Dissolved P (kg/ha)	DRP+DOP	0.14	0.44	0.19	0.13				Our estimate
Hectares		97622	20534		7672				

The greatest gains in reducing total export of P from land to rivers at high flows could be made from applying BMP on erodible land.

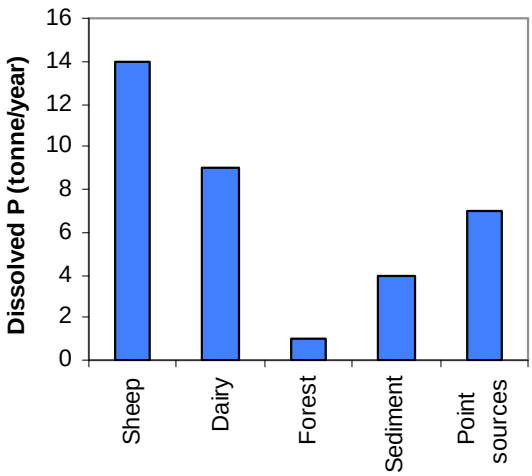


Figure 6. Estimates of sources of dissolved P in Manawatu River at Hopelands in 2007 (tonnes P per year)

6. How can Overseer® be used to estimate changes in P loss from farms in the UMWMZ catchment?

In the absence of any visible soil erosion P loss is largely in surface and sub-surface run-off; leaching to aquifers can also occur on lighter soils that have by-pass flow. P is lost in two forms: sediment-bound (PP) and dissolved P. A significant proportion of annual P loss can occur during single-storm events.

The mitigation options for reducing the "background" losses of P from pastoral systems are listed in Appendix 3. A number of these, including the role and impact of riparian strips and wetlands, will be incorporated into Overseer® in the next 12 months. Lack of a tool for assessing the mitigation options for reducing soil erosion is an obvious gap. A current Envirolink project for Horizons developing an on-farm monitoring protocol for estimating the effectiveness of soil conservations practices for reducing soil (and P) loss by erosion will provide in the short- to medium-term an option for assessing the effectiveness of options adopted for reducing P loss associated with soil erosion processes. In combination with running the Overseer® model and using the different management options an insight into the gains that can be made on that farm will be available to individual land owners.

Limiting P fertiliser use to maintaining inputs and holding soil Olsen levels in the optimum agronomic range offers a very cost-effective mitigation option for limiting farm P losses. Monaghan et al. (2007a) found targeting fertiliser inputs to maintain Olsen values in the optimum agronomic range offered the greatest saving and a predicted reduction in P losses by 30–37% in two dairy catchments. In situations where soil P levels are close to the agronomic optimum, the opportunity for cost savings and environmental gains are going to be much

smaller. This highlights the danger of prioritising or generalising about the suite of mitigations potential available to a producer. Most farms include more than one soil type. Soils differ in their stage of development, chemistry and physics, which influence the annual pasture production and annual P requirements. Therefore, good soil test information will be required, along with production levels for each major land unit on the farm if optimum use is to be made of P fertiliser inputs and by default the impact of added P on the environment is to be minimised.

Shifting from a pond system for effluent treatment to an effective land-based effluent disposal system that includes ensuring the effluent block is of sufficient size, application rates do not exceed the soils matrix infiltration rate and there is sufficient pond storage capacity to hold effluent when soils are wet, offers enormous scope for reducing farm P losses (Houlbrooke et al. 2004; Monaghan & Smith 2004; Monaghan et al. 2007b). This mitigation option, along with those listed in Appendix 3 will all come at some cost to the farm business.

7. BMPs for UMWMZ

Gains can be made from managing erodible land under pasture. Loss of PP at Hopelands is 511 t P yr^{-1} (long-term average), with 454 t P yr^{-1} from steeper land on farms. Most of this will occur in major storm events. Target planting of trees could reduce the losses to about 280 t P yr^{-1} by implementing whole farm plans on approximately 10 % of farms with the highest proportion of Highly Erodible Land (Dymond & Shepherd 2006; Schierlitz et al. 2006). Losses from forests are estimated to remain at 57 t P yr^{-1} (Figure 7). Gains can be made from decreasing the sediment load "sitting" in the bed of the Manawatu River since the surface of the sediment will release DRP that is available to periphyton (Figure 8).

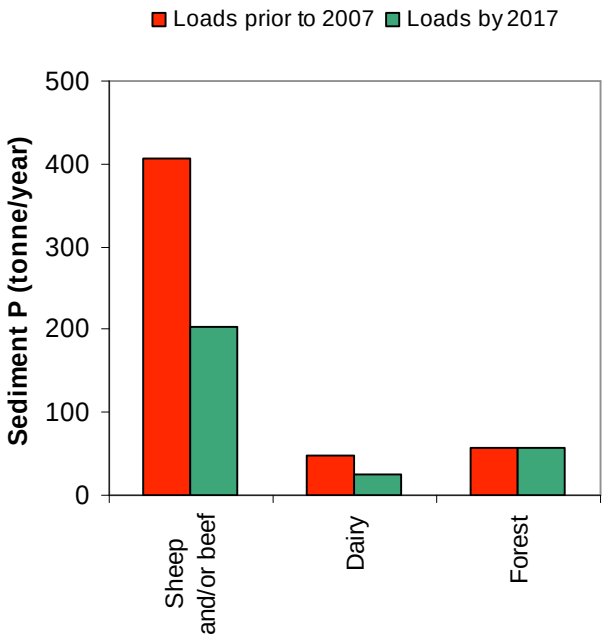


Figure 7. Estimates of sources of sediment P (particulate P) in Manawatu River at Hopelands in 2007, and loads achievable by 2017 and 2027 if recommendations are implemented on all effected land on day 1 (tonnes P yr^{-1})

Most gains during low flow can be made from management of dissolved P. Gains can be made from better managing point sources that add 3.5 t P yr^{-1} as DRP to the Manawatu River above Hopelands at low flows; this is 44% of the load at low flows (Ledein et al. 2007). The load of DRP at all flows is approximately 21 t P yr^{-1}; and 5 t P yr^{-1} is from point sources. The DOP loads are estimated to be 10 t P yr^{-1}, with 2 t P yr^{-1} from point sources. With improved management of waste using engineering and chemical technologies, the loads from point sources could be reduced. If they can be reduced by 5 t P yr^{-1} this would be 14% of the load (35 t P yr^{-1}).

Planting trees on steeper slopes, and riparian fencing and planting on rivers and larger streams on sheep and beef farms may reduce the DRP load by about 4 t P yr^{-1}. This estimate has large uncertainty and requires further study.

For dairy farms, cows in waterways contribute about 0.5 kg P ha^{-1} yr^{-1} to rivers. Gains can be made from removing animal stock from these water ways. If this applies to 10% of the dairy farms, this could reduce the load in the Manawatu River at Hopelands by 1 t P yr^{-1}.

Gains can be made from irrigating farm dairy effluent according to deferred irrigation criteria where applications are only made to soil that has a sufficient soil water deficit to store applied volumes (Houlbrooke et al. 2004; Monaghan & Smith 2004). Furthermore, when soil infiltration limitations exist or preferential flow of applied effluent is likely, further gains can be made using low rate irrigation technology (Houlbrooke et al. 2006). For dairy farms this could reduce the losses by 1 kg P ha^{-1} yr^{-1} on at least 10% of the milking platforms. If this applies to all dairy farms, this could reduce the load in the Manawatu River at Hopelands by 2 t P yr^{-1}. The consented effluent loads at Hopelands have been reduced from a peak of about 3.0 tonnes DRP yr^{-1} in 1998 to 0.5 tonnes DRP yr^{-1} by 2006 (Roygard & McArthur 2007).

Gains can be made from moving tracks that link to streams. For dairy farms this could reduce the losses by 0.1 kg P ha^{-1} yr^{-1}. If this applies to half of the dairy farms, this could reduce the load in the Manawatu River at Hopelands by 1 t P yr^{-1}.

Parfitt et al. (2008) estimated that P stored in soils was increasing by 20 000 tonnes P yr^{-1} in the Horizons region as a result of inputs of 33 000 tonnes P yr^{-1}; much of this will be labile P and generally Olsen-P levels are increasing, particularly on dairy farms (Wheeler et al. 2004). Gains can be made from limiting P fertiliser inputs to maintaining the soil Olsen P in the agronomic optimum range. When too much P fertiliser is used, the P losses increase exponentially, therefore P use (and losses) should be reduced. On the other hand, if fertiliser use is increased on less fertile land, P losses will increase. We assume these increases and reductions in P loss will cancel each other in the catchment budget, but there is uncertainty in this assumption. If farmers use Overseer® to assess nutrient budgets there will be more certainty in these numbers.

Gains can be made from using RPR rather than more soluble P fertilisers on pastures (Mackay et al. 1987; Hart et al. 2004; Parfitt & Mackay 2007), since fertilisers can fall within streams and soluble fertilisers can rapidly move short distances to streams (Allan Gillingham, unpublished data from Waipawa). The gains depend on weather conditions (such as storms shortly after applying fertiliser, and the amount of fertiliser that falls directly into waterways). Assuming that the loss from soluble P fertilisers during a large storm is an average of 1 kg P ha^{-1} then the loss over 1000 ha would be 1 t P. Assuming the loss from RPR is 0.5 kg P ha^{-1} then the loss over 1000 ha would be 0.5 t P. Most fertiliser P, however, is retained in soils.

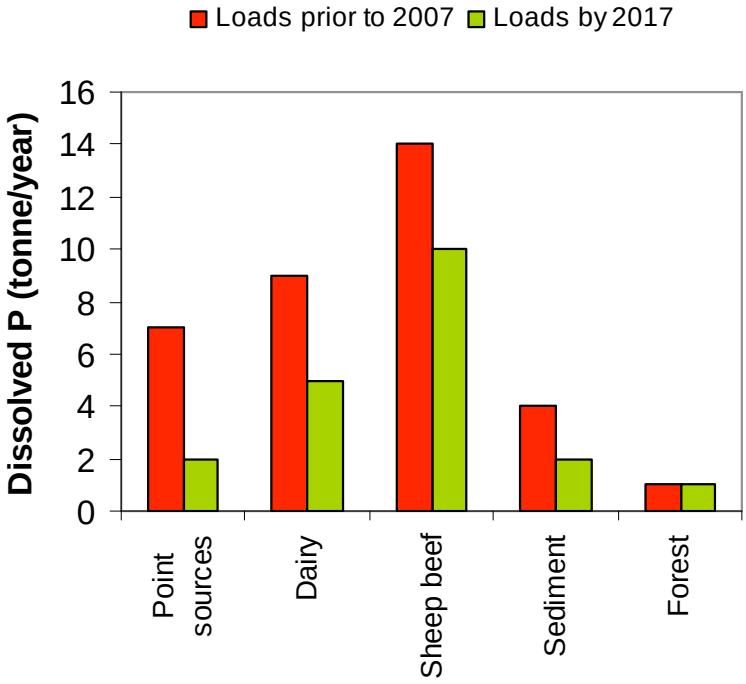


Figure 8. Estimates of sources of dissolved phosphorus (DRP+DOP) in the Manawatu River at Hopelands in 2007, and loads achievable by 2017 if recommendations are implemented (tonnes P per year). Note: Some of the 511 tonnes of particulate phosphorus (PP) remains on the bed of the river and generates about 4 tonnes of dissolved P yr^{-1}

The sum of all these savings could reduce the average DRP + DOP (dissolved-P) load at Hopelands from 35 to 19 tonnes P yr^{-1}. The SLUI plan could reduce the sediment P losses from pasture land from 511 to 280 tonnes P yr^{-1} with targeted planting of the most erodible land, and to 193 tonnes P yr^{-1} from planting all of slopes that are likely to erode during major storms. Since it takes several years for tree roots to bind the soil, the achievement of these gains may take 10 to 20 years should all land at risk to erosion is planted on day one. The time scales will be longer if planting of eroding land through whole farm plans is staggered over a number of years. Targeting the SLUI whole farm plans to the highest priority farms is the best way to achieve gains in the shortest time. By reducing the introduction of fresh sediment into the bed of the Manawatu River there would also be reductions in P released from the river bed that is available to periphyton.

The ANZECC (2000) recommended guideline for slightly disturbed lowland ecosystems for DRP has been set at 0.010 g P m^{-3}. Current concentrations at Hopelands are usually > 0.010 g P m^{-3}, except when periphyton are actively stripping DRP in summer. It should be possible to reduce current DRP concentrations down towards the guideline concentration with these mitigation measures. Since the Upper Manawatu catchment has some P rich rocks, which contain the mineral apatite, and calcareous materials with P inclusions, it may not be possible to lower the peak DRP further than the guideline concentrations (Eden & Parfitt 1992; Parfitt et al. 2004).

8. Conclusions

We have separated the P losses above Hopelands into those that occur at all flows except the 10% highest flows, those flows that occur in "background" years when there are no major storms, and the long-term average flows that include major storms.

At Hopelands at low flows (such as in summer) DRP losses are 8 t P yr^{-1} of which 3.5 t P yr^{-1} arises from point sources (Dannevirke, PPCS Oringi, etc.) with the remainder coming from pastures and forests (Table 9).

At all flows (except the largest 10% of flows) DRP losses are 12 t P yr^{-1}, of which approximately 5.3 t P yr^{-1} arise from point sources, 4 t P yr^{-1} from sheep and beef land, 2.5 t P yr^{-1} from dairy land, and 0.4 t P yr^{-1} from forest.

For "background" years, total-P losses are estimated at 76 t P yr^{-1}, of which approximately 7 t P yr^{-1} arise from point sources, 4 t P yr^{-1} from forest 51 t P yr^{-1} from sheep and beef land, and 14 t P yr^{-1} from dairy land.

The long-term average losses, which include major storms, yield total-P losses of 546 t P yr^{-1}, of which approximately 406 t P yr^{-1} arise from erosion in sheep and beef pastures, 48 t P yr^{-1} from erosion in dairy land, and 57 t P yr^{-1} from erosion in forests, with 35 t P yr^{-1} from background losses of dissolved-P. There will of course be uncertainty in these estimates, and monitoring of phosphorus (DRP, DOP, PP) in the Manawatu River should be carried out on a regular basis to give more precise numbers, to get a base line, and to monitor improvements to water quality.

Mitigation measures that would improve water quality during times of low flow include reducing losses from point sources, removing animals from water ways, and better management of effluent. In terms of managing P, this should be the focus of Farm Strategies. Decreasing the load of sediment depositing on the bed of the river also will improve water quality during times of low flow since less P will be released from the sediment in the bed of the river. Planting trees on erodible land under pasture could reduce total-P losses by up to 70%. In terms of managing PP from sediment, this should be the focus of whole farm plans.

9. Acknowledgements

John Scott (LCR) reviewed the report. Maree Clark, Kate McArthur and Jon Roygard provided valuable data and input. The funding was from Envirolink.

10. Glossary

Allophane – a very reactive soil mineral that retains large amounts of P and humus through chemical binding to its surface

Allophanic Soil – a soil with large amounts of the mineral allophane; usually found in volcanic ash under rainfall greater than 1200 mm

Alluvial soil – a general term for soils on the flood plain

Anion storage capacity – this is identical to P-retention

DRP – dissolved reactive phosphorus; this is dissolved inorganic phosphorus that is readily available to plants and periphyton; measured by filtering waters and analysing for phosphorus

DFP – dissolved filtered phosphorus; this is similar to DRP

DOP – dissolved organic phosphorus; this is measured by filtering waters and analysing them for total-P and then subtracting DRP

Farm dairy effluent – The wash-down water and waste from milking parlour and yard

Mole & Pipe – An artificial drainage system installed on heavy soil types to alleviate water logging during wet periods. Mole and pipe drainage provides preferential flow of water to expedite this process. However, this provides a rapid pathway for contaminant movement

Olsen-P – soil test number in ug ml^{-1} that estimates the P that is available to plants and is available to be dissolved. The quick test units approximate to mg kg^{-1}. The agronomic optimum depends on the number of stock units per ha on a farm, etc., but is usually about 18 for sheep and beef soils in hill country, and about 30 for dairy soils.

P-retention – a number that indicates how much DRP will be chemically sorbed and stored in a soil; it is more a guide to the amount of iron and aluminium in soils that will react with DRP; it is a % between 0 and 100.

PP – particulate P (i.e. P in suspended sediment particles)

Shape file – popular geospatial vector (points, lines, etc.) data format for geographic information systems software

TP - total P in a water sample. This will include dissolved and particulate, or sediment P.

11. References

ANZECC. 2000. Australia and New Zealand guidelines for fresh and marine water quality. Vols 1 and 2. Australia and New Zealand Environment and Conservation Council, Canberra, ACT, Australia.

Clothier B, Mackay A, Carran A, Gray R, Parfitt R, Francis G, Manning M, Deurer M, Green S. 2007. Farm strategies for contaminant management, SLURI report to Horizons.

Dymond, J., Shepherd, J. 2006. Highly erodible land in the Manawatu/Wanganui region. Landcare Research contract report 0607/027, September 2006. 10pp.

Eden DN, Parfitt RL 1992. Amounts and sources of phosphate in hill country rocks, SE North Island. Australian Journal of Soil Research 30: 357–370.

Ellwood NTW, Whitton BA 2007. Phosphatase activities of the aquatic moss *Warnstorfia fluitans* (Hedw.) Loeske from an acidic stream in North-East England. Hydrobiologia 575: 95–107.

Gillingham AG, Gray MH 2006. Measurement and modelling of runoff and phosphate movement from seasonally dry hill-country pastures. New Zealand Journal of Agricultural Research 49: 233–245.

Hart MR, Quin BF, Nguyen ML 2004. Phosphorus runoff from agricultural land and direst fertiliser effects: a review. Journal of Environmental Quality 33: 1954–1972.

Hedley MJ 1978. Assessment of the biological availability of particulate-phase phosphorus. Unpublished PhD thesis. Massey University, Palmerston North.

Henderson R, Diettrich J 2007. Statistical Analysis of River Flow Data in the Horizons Region. Prepared for Horizons Regional Council, NIWA Client Report CHC2006-154, NIWA Project ELF07202/HZLC22

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO 2003. The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. Proceedings of NZ Grassland Association 65: 179–184.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR, Snow VO 2004. Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. New Zealand Journal of Agricultural Research 47: 405-415.

Houlbrooke DJ, Monaghan RM, Smith LC, Nicolson C 2006. Reducing contaminant losses following application of farm dairy effluent to land using a K-line irrigation system. In: Curie LD, Hanly JA eds Implementing sustainable nutrient management strategies in agriculture. Occasional report No 19. Fertiliser and Lime Research Centre, Massey University, Palmerston North. Pp. 290–300.

Lambert MG, Devantier BP, Nes P, Penny PE 1985. Losses of nitrogen, phosphorus and

sediment in runoff from hill country under different fertiliser and grazing management regimes. New Zealand Journal of Agricultural Research 28: 371–379.

Ledein E, Ausseil O, Roygard J 2007. Identifying point source and non-point source contributions to nutrient loadings in water ways in three catchments in the Manawatu-Wanganui region. Horizons Region Council Technical Report

Menneer JC, Ledgard SF, Gillingham AG 2004. Land use impacts on nitrogen and phosphorus loss and management options for intervention. Environment Bay of Plenty. AgResearch Client Report, June 2004. 52 p.

Mackay, A.D., Syers, J.K. & Gregg, P.E.H. 1987. Potential animal transfer losses of fertiliser phosphorus. Fertilizer Research 14: 125–134.

McArthur K, Roygard J, Ausseil O, Clark M 2007. Development of water management zones in the Manawatu-Wanganui region. Horizons Region Council Technical Report

McDowell RW 2006. Phosphorus and sediment loss in a catchment with winter forage grazing of cropland by dairy cattle. Journal of Environmental Quality 35: 575–583.

McDowell RW, Condron LM 2004. Estimating phosphorus loss from New Zealand grassland soils. New Zealand Journal of Agricultural Research 47: 137–145.

McDowell RW, Wilcock RJ 2007. Sources of sediment and phosphorus in stream flow of a highly productive dairy farmed catchment. Journal of Environmental Quality 36: 540–548.

McDowell RW, Sharpley AN, Brookes PC, Poulton P 2001. Relationship between soil test phosphorus and phosphorus release to solution. Soil Science 166:137–149.

Monaghan RM, Smith LC 2004. Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. New Zealand Journal of Agricultural Research 47: 417–428.

Monaghan RM, Hedley MJ, Di HJ, McDowell RW, Cameron KC, Ledgard SF 2007a. Nutrient management in New Zealand pastures: recent developments and future issues. New Zealand Journal of Agricultural Research 50: 181–201.

Monaghan RM, de Klein CAM, Muirhead RW 2007b. Prioritisation of farm scale remediation efforts for reducing contaminant losses to waterways: A case study of New Zealand dairy farming. Journal of Environmental Management [in press]

Parfitt RL 2006. Estimates of the loads of dissolved phosphate and nitrate in streams flowing into the Manawatu River between Dannevirke and Hopelands in late spring and early summer. Landcare Research Contract Report 0506/098.

Parfitt RL, Hill L 2004. N and P in the Manawatu River since the great flood: new and improved data. Soil News 52: 89–91.

Parfitt RL, Mackay AD. 2007. Phosphorus filtering by soils, and movement from soils to waters. Occasional report to SLURI.

Parfitt RL, Baisden WT, Elliott AH 2008. Phosphorus inputs and outputs for New Zealand in 2001 at national and regional scales. The Journal of the Royal Society of New Zealand (submitted).

Parfitt RL, Mackay AD, Yeates GW, Ross DJ. 2007. Movement of N, P, and C from soils to waters in hill country pastures. In: Currie LD, Yates LJ. Designing sustainable farms: critical aspects of soil and water management. Occasional Report No. 20. Palmerston North, New Zealand: Fertilizer and Lime Research Centre, Massey University. Pp.177–185.

Parfitt R, Sutherland A, Wilde H, Dymond J, Ausseil A-G 2004. GIS risk layers of phosphorus loss from soil to rivers for the Manawatu-Wanganui Region. Unpublished Contract Report NUMBER

Roygard J, McArthur K 2007. A framework for managing non point source and point source nutrient contributions to water quality. Technical Report to Support Policy Development, Draft Horizons Regional Council Report.

Schierlitz, C., Dymond, J., Shepherd, J. 2006. Erosion/sedimentation in the Manawatu catchment associated with scenarios of whole farm plans. Landcare Research contract report LC0607/028, September 2006. 10 pp.

Turner BL, Baxter R, Whitton BA 2003. Nitrogen and phosphorus in soil solutions and drainage streams in Upper Teesdale, northern England: implications of organic compounds for biological nutrient limitation. Science of the Total Environment 314: 153–170.

Walker TW, Syers JK 1976. The fate of phosphorus during pedogenesis. Geoderma 15:1–19.

Wilcock RJ, Biggs B, Death R, Hickey C, Larned S, Quinn J 2007a. Limiting nutrients for controlling undesirable periphyton growth. NIWA report to Horizons.

Wilcock RJ, Monaghan RM, Thorrold BS, Meredith AS, Betteridge K, Duncan MJ 2007b. Land-water interactions in five contrasting dairying catchments: issues and solutions. Land Use and Water Resources Research 7: 2.1–2.10

Wheeler DM, Sparling GP, Roberts AHC 2004. Trends in some soil test data over a 14-year period in New Zealand. New Zealand Journal of Agricultural Research 47: 155–166.

12. Appendices

Appendix 1 -Whole farm plan

What Is In A Whole Farm Plan?

SLUI Whole Farm Plans include environmental and business assessments. Both these elements go hand in hand in the search for sustainability.

Your unique plan will provide you with useful information about your farm's resources.

Including:

- An inventory of your core resources such as soils, subdivision, vegetation, land and water resources.
- Review of your existing farm business and how it is placed to achieve your personal and business goals.
- Identification of the current level of environmental risk, the potential for sustained production, any production yield gaps (pasture) and the opportunities for your farm to perform better.
- Combined long-term business and resource management plans that outline what needs to be done to achieve new goals.
- Suggestions of the best ways to improve farm sustainability for your farm.

Contents

Land Resource Inventory: A description of your farm's land resources according to the Land Resource Inventory (LRI) system. Rock type, soil, slope, erosion type and severity and vegetation cover will be covered.

Soil Map And Extended Legend: What major soil types are on your property, where they can be found and how they influence your farm's management.

Resource Capability Map And Extended Legend: How your farm's land resources are suited for sustained production under usual land uses using the Land Use Capability (LUC) system of land classification.

Subdivision And Effective Area: Demarcation of paddock boundaries including total paddock areas and estimations of efficient pasture area calculated by mapping out all non-pastoral vegetation including scattered scrub, space planted trees, etc.

Pasture Production And Yield Gap: Using regional classifications of land production against existing stocking rates and using effective pasture totals, it is possible to calculate existing annual pasture production. This is then compared against potential production estimations to spot any yield gaps.

Nutrient Budget: Land resources and current management procedures are assessed against the Overseer Nutrient Budgets model so land management units can be developed for optimum results.

Works Plan: This is the nuts and bolts of what can be done and when to get the most from your farm while achieving environmental sustainability at the same time.

horizons
regional council

2007/296

Appendix 2
Paper submitted to Environmental Modelling and Software (July, 2007).

An erosion model for evaluating regional land-use scenarios in New Zealand

John R. Dymond and Harley D. Betts
Landcare Research, Private Bag 11052, New Zealand

Abstract

The conversion to pasture of indigenous forest on New Zealand hill country has led to increased mass-movement erosion and consequently increased sedimentation of waterways. Effective soil conservation requires a model that can evaluate erosion and sedimentation for different land-use scenarios. In this paper, we develop a model of mean sediment discharge related to mean erosion rates through a sediment delivery ratio. Mean erosion rate in a particular terrain ("erosion terrain") is proportional to the square of mean annual rainfall multiplied by a cover factor. Measurements of mean sediment discharge are used to estimate erosion coefficients for each erosion terrain. We demonstrate the utility of the model for three different applications: evaluating land use scenarios in the Motueka catchment; setting priorities for soil conservation in the Manawatu catchment; and determining national trends in agricultural erosion over a 30-year period.

Introduction

Over the last 150 years following european settlement, much of the original indigenous forest in New Zealand has been converted to pastoral agriculture. In hill country, where tree roots are important for stabilising slopes, deforestation has led to increased soil erosion and consequently increased sedimentation in waterways. This can have detrimental effects on aquatic ecosystems by smothering fish habitat and significantly reducing the penetration of photosynthetically active light. In major catchments where stop banks have been constructed to reduce the risk of flooding, deposition of sediment in floodways reduces flood capacity. Increased storminess associated with climate change can only exacerbate these negative environmental effects. To mitigate sedimentation in waterways, catchment-wide approaches to reducing soil erosion are required. For large rivers, this is tantamount to regional approaches to soil conservation. Because the implementation of farm plans and retirement of steep hill country over large areas is expensive, it must be guided by predictive models that explicitly link erosion and sedimentation with land use.

Erosion in New Zealand is dominated by mass movement processes, especially landslides, large gullies, and earthflows (Eyles 1983). Modelling of these processes in New Zealand has been confined to a limited number of study areas (Dymond et al., 1999; Meuller, 1998; Claessens et al., 2005; Ekanayake and Phillips, 1999; Hovius et al., 1997; Crozier, 1996). For national and region-wide modelling, Griffiths and Glasby (1985) used an empirical approach to relate measurements of mean sediment discharge at 80 river sites around New Zealand to annual rainfall. They found that mean sediment discharge was proportional to annual rainfall raised to the power of 2.3. In a more comprehensive study, Hicks et al. (1996) used 203 sites to determine that mean sediment discharge was a function of rock type and mean annual rainfall (raised to the power of 1.7). The difficulty with using either the Griffiths and Glasby (1985) or the Hicks et al. (1996) model is that neither involves land cover as a factor and yet we know from other studies that at the hillslope scale erosion rate depends significantly on land cover (Crozier, 1996; De Rose, 1996; Dymond et al., 2006; Dymond et al., 1999; Fransen, 1996; Griffiths and Glasby, 1985; Hicks, 1991; Marden and Rowan, 1993; Pain, 1969; Pain and Stephens, 1990; Page and Trustrum, 1997).

What is required is a spatial model of mean erosion rate that makes use of both land cover and land management factors. Proposed land-use scenarios could then be evaluated in advance to ensure region-wide plans for soil conservation were effective in achieving objectives for reducing erosion and sediment yield. In this paper, we formalise the relationship between mean erosion rate and mean sediment discharge through the use of a sediment delivery ratio. This permits the application of *a priori* knowledge of the influence of land cover on hillslope erosion into an erosion model for use at region-wide (and national) scales. The model requires stratification of the New Zealand landscape into erosion terrains within which erosion processes are similar. We demonstrate the utility of the model for three different applications: evaluating sediment discharge into Tasman Bay when different land use scenarios are considered for the Motueka catchment; determining national trends in erosion associated with agriculture over a 30-year period; and setting priorities for soil conservation in the Manawatu catchment.

Erosion Terrains

Erosion processes vary throughout New Zealand, depending on rock type, landform (especially slope angle), and rainfall. We partitioned New Zealand on the basis of these factors at the scale of 1:50 000 to produce areas with similar erosion processes; these we

called erosion terrains. While differences in land use or management and vegetation cover are important, these were omitted from the definition in order to represent intrinsic erosion susceptibility independently from factors that can change with time. A three-level hierarchical classification was used for both the North and South Islands (Appendices 1 and 2). For the North Island, we differentiated nine groups at the top level on the basis of landform and slope. At the second level, 26 groups were differentiated on rock type. At the third level we differentiated fifty-two groups on the basis of erosion processes and further detail of rock type. For the South Island, we differentiated nine groups at the top level, based on landform and slope. At the second level 18 groups were differentiated on rock type, induration, and presence of loess, and at the third level 37 groups were differentiated on erosion processes and further detail of rock type.

Model Equations

The model describes long-term mean erosion rates at the source and the resulting long-term mean sediment discharge in rivers. The erosion rate at a geographic point (x,y) is defined as the rate of soil mass loss per unit area (kg.m^{-2}.s^{-1}). Erosion rates vary in space and time, so may be denoted by $e(x,y,t)$. The long-term mean erosion rate is denoted by $\bar{e}(x,y)$, and defined by

$$\bar{e}(x,y) = \frac{\int_t^{t+\mathrm{T}} e(x,y,t)\,dt}{\mathrm{T}} \qquad (1)$$

where T is of the order of decades.

Similarly the sediment discharge at a point (x,y) in a river is defined as the rate at which sediment mass passes a point (kg.s^{-1}). Sediment discharge varies in space and time, so may be denoted by $s(x,y,t)$. The long-term mean sediment discharge is denoted by $\bar{s}(x,y)$, and defined by

$$\bar{s}(x,y) = \frac{\int_t^{t+\mathrm{T}} s(x,y,t)\,dt}{\mathrm{T}} \qquad (2)$$

The relationship between long-term mean sediment discharge and long-term erosion rate is simple if all sediment mobilised by erosion reaches a stream where fluvial forces transport the sediment through the river network. In this case, sediment discharge is the integral of erosion rate over the watershed above the discharge point. However, landscapes are sometimes disconnected from streams, or erosion processes deliver only a proportion of eroded sediment to streams, and so a sediment delivery ratio needs to be considered. The sediment delivery ratio at a point, denoted by $D(x,y)$, is defined as the ratio of mass of sediment delivered to a point in the stream network (x_0, y_0) from (x,y) over the mass of eroded soil at (x,y):

$$D(x,y) = \frac{\Delta\bar{s}(x_0,y_0)\,\mathrm{T}}{\bar{e}(x,y)\,\Delta x\,\Delta y\,\mathrm{T}} \qquad (3)$$

where Δ represents a small change. The relationship between long-term mean sediment discharge at a point (x_0, y_0) and long-term mean erosion rate may then be written as

$$\bar{s}(x_0, y_0) = \iint_{\substack{catchment \\ above\ (x_0, y_0)}} D(x, y)\, \bar{e}(x, y)\, dx\, dy \qquad (4)$$

Hicks et al. (1996) and Griffiths and Glasby (1985) showed that for medium to large New Zealand catchments, geology and annual rainfall were important factors in explaining long-term mean sediment discharge. Although these studies found land cover was not an explanatory factor, other studies show it is important (Crozier, 1996; De Rose, 1996; Dymond et al., 2006; Dymond et al., 1999; Fransen, 1996; Hicks, 1991; Marden and Rowan, 1993; Pain, 1969; Pain and Stephens, 1990; Page and Trustrum, 1997); moreover, there were insufficient data in the Hicks et al. (1996) and the Griffiths and Glasby (1985) studies to investigate the full interaction of geology, rainfall, and land cover, as there are few instances of paired catchments with the same geology and with homogeneous but differing land cover. Therefore, we postulate that mean erosion rate is controlled by three factors: erosion terrain; annual rainfall; and land cover:

$$\bar{e}(x, y) = a(x, y)\, C(x, y) R(x, y) \qquad (5)$$

where $a(x,y)$ is a constant depending on the erosion terrain (termed the *erosion coefficient*); $R(x,y)$ is the rainfall factor; and $C(x,y)$ is the erosion rate of the land cover at (x,y) relative to forest.

If $C(x,y)$, $R(x,y)$, and $D(x, y)$ are known, then a can be estimated for each erosion terrain by applying Equations (4) and (5):

$$a_i = \frac{\bar{s}_i}{\iint_{\substack{erosion \\ terrain\ \ i}} D(x, y)\, C(x, y)\, R(x, y)\, dx\, dy} \qquad (6)$$

where a_i is $a(x,y)$ in the i-th erosion terrain, and $\bar{s}_i$ is the long-term mean sediment yield (kg.s^{-1}) from the i-th erosion terrain.

Model calibration

To estimate the erosion coefficients of the model for each erosion terrain, a_i, the cover factor, $C(x,y)$, the sediment delivery ratio, $D(x, y)$, the rainfall factor, $R(x,y)$, and the mean annual sediment yield for each erosion terrain, $\bar{s}_i$, in equation (6) must be known.

Cover factor

The cover factor, $C(x,y)$, is the long-term mean erosion rate of the land cover at (x,y) relative to forest at the same point. In tectonically active New Zealand, erosion rates are dominated by mass movement erosion. Studies in North Island hill country have shown that when forest is converted to pasture, long-term erosion rates increase by approximately an order of magnitude (Page and Trustrum, 1997), as do landsliding events (Dymond et al., 2006). We assume that $C(x,y)$ depends on three land covers: woody vegetation, herbaceous vegetation, and bare ground.

$$C(x,y) = 1 \text{ if land cover is woody vegetation}$$
$$= 10 \text{ if land cover is herbaceous vegetation} \qquad (7)$$
$$= 10 \text{ if land cover is bare ground}$$

We assign pasture and bare ground the same cover factor as they neither has deep and strong roots sufficient for strengthening soil to the depth of bedrock: even though bare ground has a much higher surficial erosion rate than herbaceous vegetation, we consider this unimportant as surficial erosion is dominated by mass movement erosion. A national map of cover factor at 1:50 000 scale (i.e. 15 m pixels) was produced from ETM+ satellite imagery using the method of Dymond and Shepherd (2004). Imagery dates varied between the summers of 1999/2000 and 2002/2003.

Sediment delivery ratio

In New Zealand, where tectonic uplift is active, hillsides will adjust their slope so that very long-term mean erosion rates (i.e. over thousands of years) will balance uplift. This implies that mean sediment delivery ratio over very long periods is 1 everywhere because all parts of the landscape must erode to keep in balance with uplift. In brief, specific erosion events, sediment delivery ratio will be less than 1. For example, Dymond et al. (1999) and Reid and Page (2002) measured the sediment delivery ratio of shallow landslides in a major cyclonic storm to be approximately 0.5. But in the long-term, landslide debris remaining on the hillsides will be reworked down to the nearest stream by other erosion processes. For a national scale model, we do not have enough knowledge of erosion processes over current time scales of decades to define $D(x, y)$ everywhere, so we set it to 1 everywhere. In a regional context when more spatial detail about $D(x, y)$ is required, a digital terrain model can be used to determine whether hillsides are connected to streams. Thus, later in the paper we discuss the Manawatu catchment, where erosion processes are dominated by landsliding and gullying; for that example we assign

$$D(x, y) = 1 \quad \text{if } (x,y) \text{ is connected to stream network} \qquad (8)$$
$$= 0 \quad \text{if } (x,y) \text{ is disconnected from stream network}$$

Connectivity to a stream network is determined from a 15-m grid digital elevation model (DEM). A pixel in the DEM is connected if it is possible to traverse down the flow line from the pixel to the nearest stream without encountering a sediment deposition zone, defined as 30 m or more of contiguous low slope (below 4 degrees).

Rainfall factor

Griffiths and Gladsby (1985) used a national dataset of mean sediment discharge of 80 rivers to derive a rainfall factor of $P^{2.3}$. Hicks et al. (1996) used a more comprehensive dataset to derive a rainfall factor of $P^{1.7}$. We evaluated both $P^{1.7}$ and $P^{2.3}$ and found little difference for the accuracy of the erosion model predictions when compared with measured sediment discharge at the 80 sites, so for the sake of simplicity we assign

$$R(x,y) = P^{2} \qquad (9)$$

A national map of mean annual precipitation on a 100-m grid was provided by the Land Environment data layers (Leathwick et al., 2003).

Long-term mean sediment yield for each erosion terrain

A digital map of mean specific sediment yield ($kg.s^{-1}.m^2$) was produced by NIWA and Landcare Research as part of a FRST funded project for studying carbon transfers associated with erosion (www.niwascience.co.nz/ncwr/tools#ssy_large.jpg). This map was produced similarly to the model presented here, but had no cover factor or sediment delivery ratio, and the rainfall factor had an index of 1.7 rather than 2. Measurements of mean sediment discharge at 200 sites were used to calibrate the coefficients for each erosion terrain at the second subgroup level. At the third subgroup level, different methods were adopted, ranging from regression fitting where there were sufficient data, through to defaulting to the second-level subgroup value where there were insufficient data. Predicted sediment discharge was then compared with the 200 measurements and systematic bias was removed by introducing correction factors. This was performed twice. For this paper, we summed the mean specific sediment yield over each erosion terrain to produce estimates of $\bar{s}_i$.

Results

The erosion coefficients estimated from the model calibration are shown in Appendix 1. The model was run on the national datasets of rainfall, erosion terrains, and land cover, to produce a national 1:50 000 scale (i.e. 15-m pixel) map of long-term mean erosion rates. Figure 1a shows the North Island, and Figure 1b shows the South Island. We assessed the accuracy of the model by comparing predictions of specific sediment discharge (assuming a sediment delivery ratio of 1 everywhere, as in the calibration) with measurements at the 80 sites used by Griffiths (1981) and Griffiths(1982): specific sediment discharge is the sediment discharge divided by catchment area. The log-log plot, shown in Figure 2, has an R^2 of 0.65 and a residual standard error of 0.91.

Examples

Motueka catchment land-use scenarios

The Motueka river drains an area of 2075 km^2 in the Tasman district of the South Island, New Zealand. It flows into Tasman Bay, a productive coastal water body of high economic, ecological, and cultural significance. The estuarine and coastal area around the river mouth is important for a range of commercial fish and shellfish, including scallops, oysters, mussels, cockles, and snapper. The Motueka river contributes about 60% of the total freshwater inflow to Tasman Bay, carrying with it nutrients and organic matter (Basher, 2003). During floods, high sediment loads restrict recruitment and growth of shellfish. Land use in the Motueka catchment is dominated by indigenous forest, production forestry, and pastoral grazing. As pastoral grazing (especially dairying) is presently achieving greater economic returns than production forestry, there is pressure to convert from forestry to pastoral agriculture. To determine whether changing land use might have detrimental impacts on the ecology of Tasman Bay, we use the erosion model under three different land use scenarios:

(1) Prehuman vegetation (i.e. indigenous forest everywhere);
(2) Present land use;
(3) Intensive land use (i.e. conversion of all production forestry in present land use to pastoral agriculture).

To drive the erosion model, a map of land cover with three classes (woody vegetation,

herbaceous vegetation, and bare ground) is required for each scenario. The land cover map for scenario (2) was created by clipping out the Motueka catchment from the 1:50 000 national map (described in the "Cover factor" section). The land cover maps for scenarios (1) and (3) were created from scenario (2) by recoding classes. These land cover maps were used to produce cover factor maps, $C(x,y)$, for each scenario. There is little information on sediment delivery ratios in the Motueka catchment, so we assume it is 1 everywhere. We applied the model to produce maps of mean erosion rates for each scenario, and then applied equation (4) to predict the mean sediment discharge into Tasman Bay for each scenario (Table 1). The model shows that the mean sediment discharge of the present land-use scenario is twice that of the prehuman vegetation, while for the intensive land-use scenario it is 5 times greater. The environmental impact of these sediment discharges on aquaculture has yet to be determined.

Table 1

Land-use scenario	**Predicted mean sediment discharge** (t/yr)
(1) Prehuman vegetation (indigenous forest everywhere)	150 000
(2) Present land use	320 000
(3) Intensive land use (no production forestry)	750 000

National trends of erosion from agriculture

Ecological economists wish to develop an indicator of genuine progress (GPI), in contrast to the gross domestic product (GDP) which indicates only economic progress. A component of the GPI is the total erosion associated with agriculture. The erosion model presented in this paper was used along with statistics on trends in agricultural land use to define trends in annual sediment yield with time. A national land-use map (the Land Cover Data Base version 2) was used to define agricultural land as at 2002. This agricultural land map was overlaid with the national map of mean erosion rates (Figure 1) to determine the mean erosion rate from agricultural land. The resulting mean erosion rate was then multiplied by the area of agricultural land to estimate the annual sediment yield from agricultural land in 2002 as 80 million tonnes. Assuming the mean erosion rate from agricultural land is constant with time, trends in the total area of agricultural land, as reported regularly by the Department of Statistics, gave a time sequence of annual sediment yields from agriculture (as shown in Figure 3).

Setting priorities for soil conservation in the Manawatu catchment

Much of the hill country of the Manawatu-Wanganui region in the North Island has been converted from indigenous forest to pastoral agriculture. Consequently, erosion has accelerated, causing slope failure and river bed aggradation. On the 15–16 February 2004 a rainstorm (varying between 150 and 200 mm) hit the region, causing 62 000 landslides over c. 10 000 km^2 (Dymond et al., 2006). The cost of damage from landsliding, flooding, and siltation was 170 million (NZ) dollars (Trafford, 2004). To mitigate damage from future events, the local regional council is planning to identify highly erodible land and to encourage the implementation of farm plans designed to reduce erosion and increase

productivity. Soil conservation typically involves space-planting poplars on slopes susceptible to landsliding, planting poplars to control gully erosion, and planting willows on stream banks to control bank erosion.

We used the erosion model to assess the effectiveness of implementing farm plans in the Manawatu catchment in reducing sediment yield. A realistic scenario of 500 farm plans, at an approximate cost of 10 million (NZ) dollars, was assessed. We assumed that a well-implemented farm plan would reduce long-term average erosion by 70% (Hawley and Dymond (1988) reported 80% for landsliding; Hicks (1995) reported 50–80% for landsliding and 30–80% for gullying; Thompson and Luckman (1993) reported 42% for gullying and 63% for earthflow). In the Manawatu catchment, mean erosion rates are dominated by hillslope processes. We used a 15-m pixel DEM to produce a map of the sediment delivery ratio, as defined earlier. The erosion coefficients for erosion terrains in the Manawatu were then recalculated using equations (6) and (7). For each farm we calculated the annual sediment yield for the present management and for a fully implemented farm plan (by applying a farm plan factor of 0.3 on pastoral areas). The 500 farms with the largest differences of annual sediment yield between the present management and implemented farm plan were chosen for the scenario. The erosion model predicts that after maturation of the soil conservation plantings the mean sediment discharge of the Manawatu River would reduce from 3.8 to 2.0 million tonnes per year.

Discussion

The model presented in this paper has extended a previously existing sediment yield model to incorporate land cover and land management factors. We assumed the previous model produced reliable estimates of sediment yield over whole erosion terrains. Imputation of total sediment yield in each erosion terrain to spatially variable erosion was made possible by spatially defining sediment delivery ratio and relative land cover factors. Sediment delivery ratio was inferred by considering sediment transport pathways in a digital elevation model and relative land cover factors were inferred from previous erosion studies applied to a national land cover map. Erosion coefficients for the new model were estimated so that the total sediment yield for each erosion terrain was consistent with the previous model. The new erosion coefficients depend only on erosion terrain and, unlike the erosion coefficients of the previous model, are not influenced by the dominant land cover in the erosion terrain.

Figure 2 shows the erosion model can predict log of mean sediment discharge with an uncertainty of plus or minus 0.91 at 68% confidence. Not all this variation can be ascribed to the uncertainty of the model; some variation will be caused by errors in measuring sediment yield (sediment rating curves often have large uncertainty). The implications of model uncertainty depend on model use. In the national example, both the total amount of agricultural sediment yield (95 million tonnes in the mid 1980s) and the relative trend are important. While the total amount will have little uncertainty because it is the sum of many independent estimates, the range of the trend line depends strongly on cover factor, as in the Motueka example, so the uncertainty of the range is controlled primarily by the uncertainty of the cover factor, which is large. In the Manawatu example, achieving a target reduction in mean sediment discharge depends on how many farm plans (and the associated cost) need to be implemented , and the priority order of those farms. The uncertainty of the number of farms is primarily controlled by the uncertainty of the farm-plan factor, which again is large. In contrast, the priority order of farms is controlled more by the uncertainty of the erosion coefficients associated with each erosion terrain, and these have moderate uncertainty.

The erosion model relates long-term mean sediment discharge with long-term mean erosion rates through a sediment delivery ratio, which is not always known. It requires an understanding of the dominant erosion processes, which can vary in time. If landslides are dominant, the sediment delivery ratio will tend to be midway between 0 and 1 as landslides usually leave material behind on the slopes as they travel down to the nearest stream (Crozier, 1996; Page et al., 1999). If gully erosion is dominant, the sediment delivery ratio will be close to 1, as gullies by definition are connected directly with the stream network. In the example applications where sediment delivery ratios are not well known, we have recommended that a sediment delivery ratio of 1 everywhere be adopted. For very long periods (thousands of years) we would expect this, as most eroded sediment eventually travels through a catchment system; however, over shorter periods (decades) this is not necessarily so, and the assumption of unity everywhere would distort the predicted spatial pattern of erosion rates. However, the predicted sediment discharge will not be affected to the same extent. Where the spatial pattern of erosion is important—as it is for individual farm plans—the dominant erosion processes would have to be identified to better estimate the sediment delivery ratio. In future, we intend investigating the possibility of using physically based models of erosion processes at the hillslope scale to estimate sediment delivery ratios.

The erosion model bears similarities with the well-known Universal Soil Loss Equation model of surficial soil erosion (Wischmeier and Smith, 1978): this uses rainfall and cover factors, and the erosion coefficient acts in a similar manner to the soil erodibility factor. The main difference is that our erosion model excludes an explicit slope factor. However, because the erosion terrains are differentiated at the top level on the basis of slope and topography, a slope factor is implicit in the erosion coefficients shown in Appendix 1. Indeed, the general trend of increasing erosion coefficient with the label number is caused by increasing slope angle. This implicit handling of slope means erosion rates will not be differentiated where there is slope variation within a particular hillside. While it is theoretically possible to introduce an explicit slope factor and to further modify the erosion coefficients as for the cover factor, we prefer to consider the hillside rather than the hillslope component as the minimum element for the model.

The erosion model is useful for estimating mean erosion rates and sediment discharge under land-use scenarios where there is a comprehensive network of sediment discharge data. Measured sediment discharge is essentially spread around the landscape through an empirical relationship involving GIS layers of mean annual rainfall, land use, and erosion terrains. The inclusion of the land-use layer permits the evaluation of land-use scenarios, and the model can be applied rapidly and simply over large areas, such as large catchments, districts, or regions. The modelling approach can be used wherever there is a good network of sediment discharge data and GIS layers of biophysical data. Therefore, the approach provides a useful alternative to physically-based models (e.g., Ewen et al., 2000; Beasley et al., 1980; Doten et al., 2006), which, because they need many input parameters and intensive computation, are limited in catchment-wide applications. Future work would see development of a more accurate land cover factor dependent upon spatially-variable physical factors.

Conclusions

Over a diverse range of New Zealand landscapes, long-term erosion rates are dominated by terrain type, the square of mean annual rainfall, and vegetation cover. Sediment discharge measurements can be used to calibrate the relationship and derive an erosion coefficent for each erosion terrain type. This erosion model can be combined with a sediment delivery ratio to produce predictions of mean sediment discharge in response to land-cover/land-use scenarios. The model is easy to execute and uses input data readily available in GIS layers in New Zealand, providing a useful alternative to physically based models.

Acknowledgements

Mike Page and the late Murray Jessen, of Landcare Research, constructed erosion terrains for the North Island. Les Basher and Ian Lyn, also of Landcare Research, constructed erosion terrains for the South Island. This research was funded by the Foundation for Research Science and Technology under contract xxxxxxx.

References

Basher, L.R., 2003. The Motueka and Riwaka catchments. Landcare Research, Lincoln, New Zealand.

Beasley, D.B., Huggins, L.F., Monke, E.J. 1980. ANSWERS – a model for watershed planning. Transactions of the American Society of Agricultural Engineers 23**,** 938–944.

Claessens, L, Lowe, D.J., Hayward, B.W., Schaap, B.F., Schoorl, J.M., Veldkamp, A., 2005. Reconstructing high-magnitude/low-frequency landslide events based on soil redistribution modelling and a late-holocene sediment record from New Zealand. Geomorphology 74**,** 29–49.

Crozier, M.J. 1996. Runout behaviour of shallow, rapid earthflows. Zeitschrift fur Geomorphologie NF 105**,** 35–48.

De Rose R.C. 1996. Relationships between slope morphology, regolith depth, and the incidence of shallow landslides in eastern Taranaki hill country. Zeitschrift fur Geomorphologie NF 105**,** 49–60.

Doten, C.O., Bowling, L.C., Lanini, J.S., Maurer, E.P., Lettenmaier, D.P. 2006. A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds. Water Resources Research 42**,** W04417.

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

Dymond, J.R., Shepherd, J.D., 2004. The spatial distribution of indigenous forest and its composition in the Wellington region, New Zealand. Remote Sensing of Environment 90, 116–125.

Dymond, J.R., Jessen, M.R., Lovell, L.R. 1999. Computer simulation of shallow landsliding in New Zealand hill country. International Journal of Applied Earth Observation and Geoinformation 1**,** 122–131.

Ekanayake, J.C., Phillips, C.J., 1999. A model for determining thresholds for initiation of shallow landslides under near-saturated conditions in the East Coast region, New Zealand. Journal of Hydrology (NZ) 38**,** 1–28.

Ewen, J., Parkin, G., O'Connell, P.E., 2000. SHETRAN: distributed river basin flow and transport modeling system. ASCE Journal of Hydrologic Engineering 5, 250–258.

Eyles, G.O., 1983. The distribution and severity of present soil erosion in New Zealand. New Zealand Geographer 39**,** 12–28.

Fransen, P., 1996. A model of slip erosion risk, Central Hawkes Bay coastal hill country. Logging Industry Research Organisation, No. 59, Rotorua.

Griffiths, G.A., 1981. Some suspended sediment yields from South Island catchments, New Zealand. Water Resources Bulletin 17**,** 662–671.

Griffiths, G.A., 1982. Spatial and temporal variability in suspended sediment yields of North Island basins, New Zealand. Water Resources Bulletin 18**,** 575–584.

Griffiths, G.A., Glasby, G.P., 1985. Input of river-derived sediment to the New Zealand continental shelf: I. Mass. Estuarine, Coastal and Shelf Science 21**,** 773–787.

Hawley, J.G., Dymond, J.R., 1988. By how much do trees reduce landsliding? Journal of Soil and Water Conservation 43**,** 495–498.

Hicks, D.L., 1991. Erosion under pasture, pine plantations, scrub and indigenous forest: a comparison from cyclone Bola. New Zealand Forestry 1991**,** 21–22.

Hicks, D.M., Hill, J., Shankar, U., 1996. Variation of suspended sediment yields around New Zealand: the relative importance of rainfall and geology. 149–156. IAHS. Erosion and sediment yield: global and regional perspectives: IAHS publication No. 236.

Hicks, D.L., 1995. Control of Soil Erosion. Ministry of Agriculture, No. 95/4, Wellington.

Hovius, N., Stark C.P., Allen P.A., 1997. Sediment flux from a mountain belt derived by landslide mapping. Geology 25**,** 231–234.

Leathwick, J., Wilson, G., Rutledge, D., Wardle, P., Morgan, F., Johnston, K., McLeod, M., Kirkpatrick, R., 2003. Land Environments of New Zealand. David Bateman, Auckland.

Marden, M., Rowan, D., 1993. Protective value of vegetation on Tertiary terrain before and during cyclone Bola, east coast, North Island, New Zealand. New Zealand Journal of Forestry Science 23**,** 255–263.

Mueller, M.U. 1998. Geomorphometric gully erosion modelling using GIS, Waipaoa catchment, New Zealand. Diplomarbeit, University of Bonn.

Page, M.J., Reid, L.M., Lynn, I.H., 1999. Sediment production from Cyclone Bola landslides, Waipaoa catchment. Journal of Hydrology (NZ) 38, 289–308.

Page, M.J., Trustrum, N.A., 1997. A late Holocene lake sediment record of the erosion response to land use change in a steepland catchment, New Zealand. Zeitschrift fur Geomorphologie NF 41**,** 369–392.

Pain, C.F., 1969. The effect of some environmental factors on rapid mass movement in the Hunua Ranges New Zealand. Earth Science Journal 3**,** 101–107.

Pain, C.F., Stephens, P.R., 1990. Storm damage assessment using digitised aerial photographs: Eltham, New Zealand, 24–25 February 1986. New Zealand Geographer 46**,** 12–25.

Reid, L.M., Page, M.J., 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology 49, 71–88.

Thompson, R.C., Luckman, P.G., 1993. Peformance of biological erosion control in New Zealand soft rock hill terrain. Agroforestry Systems 21, 191–211.

Trafford, L., 2004. Storm: Civil Emergency – Storm and Flood Report, February 2004.

Horizons Regional Council, Palmerston North

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses – A guide to conservation planning. USDA Agricultural Handbook 537. United States Government Print Office, Washington

Appendix 1. North Island erosion terrains and their erosion coefficients ($t.km^{-2}.yr^{-1}.mm^{-2}$)

Label	**Description**	**Erosion coefficient (by 106)**
	Active flood plains	
1.1.1	Undifferentiated alluvium from modern overbank depositional events. Parts may be Peaty. Includes non-peaty wetlands.	
	Sand country	
2.1.1	Recent fresh dune sand.	
2.1.2	Mature moderately weathered dune sand.	
	Peatland	
3.1.1	Organic soils on deep peat.	
	Terraces, low fans, laharic aprons (most slopes <8o)	
4.1.1	Loess	
4.1.2	Young tephra, mostly pumiceous (waimihia and younger).	
4.1.3	Basins infilled with taupo tephra flow deposits—intensely gullied.	
4.1.4	Mid-aged (late pleistocene/early holocene) tephra, older tephra, or tephric loess.	
4.2.1	Fine grained, weathered, undifferentiated terrace alluvium—above the level of modern Flood plains.	
4.3.1	Gravelly soils on alluvial terrace gravels or on gravelly laharic aprons—above the level of modern flood plains.	
	Downland (most slopes 8–15o)	
5.1.1	Loess	
5.1.2	Young tephra (waimihia and younger), over older tephra.	
5.1.3	Mid-aged (late pleistocene/early holocene) tephra, older tephra, or tephric loess.	
5.2.1	Young basalt lava fields and low domes (parts are flatter than typical downland).	
5.3.1	Weathered sedimentary and non-tephric igneous rocks.	
	Hill country (most slopes 16–25o)	
6.1.1	loess	
6.1.2	Young tephra (waimihia or younger), usually over older tephra—shallow (0.3–1.0 m).	
6.1.3	Young tephra (waimihia or younger), usually over older tephra—deep (>1.0 m).	
6.1.4	Mid-aged (late pleistocene/early holocene) tephra, or tephric loess.	
6.2.1	Relatively young basalt domes and cones.	
6.3.1	Weak to very weak tertiary-aged mudstone.	
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.	
6.3.3	Crushed mudstone or argillite with severe earthflow-dominated erosion.	
6.3.4	Crushed argillite, sandstone, or greywacke, with severe gully-dominated erosion.	
6.4.1	Cohesive, generally weak to moderately strong tertiary-aged sandstone.	
6.4.2	Non-cohesive tertiary-aged sandstone.	
6.5.1	Limestone	

6.6.1	Unweathered to moderately weathered greywacke/argillite.	
6.6.2	Unweathered to slightly weathered white argillite.	
6.7.1	Residual weathered to highly (often deeply) weathered tertiary-aged sedimentary rocks.	
6.7.2	Residual weathered to highly (often deeply) weathered ancient basalt and andesite.	
6.7.3	Residual weathered to highly (often deeply) weathered welded rhyolite.	
6.7.4	Residual weathered to highly (often deeply) weathered greywacke/argillite.	
	Hilly steeplands (most slopes >25o)	
7.1.1	Young tephra (waimihia or younger), usually over older tephra—shallow (0.3–1.0 m) covers.	
7.1.2	Young tephra (waimihia or younger), usually over older tephra—deep (>1.0 m).	
7.1.3	Mid-aged (late pleistocene/early holocene) tephra.	
7.2.1	Fresh to slightly weathered welded rhyolitic rock, or bouldery, andesitic lahar deposits.	
7.3.1	Weak to very weak tertiary-aged mudstone.	
7.3.2	Crushed argillite with gully-dominated erosion.	
7.4.1	Cohesive, generally weak to moderately strong tertiary-aged sandstone.	
7.4.2	Non-cohesive tertiary-aged sandstone, and younger sandy gravels and gravelly sands.	
7.5.1	Limestone	
7.6.1	Unweathered to moderately weathered greywacke/argillite.	
7.6.2	Unweathered to slightly weathered white argillite.	
7.7.1	Residual weathered to highly (often deeply) weathered ancient basalt and andesite.	
7.7.2	Residual weathered to highly (often deeply) weathered welded rhyolite.	
7.7.3	Residual weathered to highly (often deeply) weathered greywacke/argillite.	
	Upland plains and plateaux	
8.1.1	Upland plains and plateaux with tephra covers.	
	Mountain steeplands	
9.1.1	Greywacke/argillite or younger sedimentary rocks of the main ranges prone to landslide erosion.	
9.1.2	Greywacke/argillite or younger sedimentary rocks of the main ranges prone to sheet/wind/scree erosion.	
9.2.1	Volcanic rocks in mountain terrains and upland hills.	
9.2.2	Upper flanks of volcanoes.	

Appendix 2. South Island erosion terrains and their erosion coefficients ($t.km^{-2}.yr^{-1}.mm^{-2}$)

Label	Description	
	Active flood plains	
1.1.1	Recent (young), active floodplains and fans flat to gently sloping.	
	Sand country	
2.1.1	Coastal sand dunes, beach ridges, flat to moderately sloping sand flats, sand dunes.	
	Peatland	
3.1.1	Peat deposits flat to gently undulating peat swamps, domed and upland peat deposits.	
	Terraces and fans	
4.1.1	Flat to gently sloping terraces and fans of older alluvium above the floodplain.	
4.2.1	Loess on flat to gently sloping terraces and fans of older alluvium above recent floodplain.	
	Downland (most slopes 4–15 degrees)	
5.1.1	Moraine and dissected alluvium.	
5.2.1	Loess > 1m deep.	
5.3.1	Soft sedimentary rocks.	
5.4.1	Hard sedimentary rocks.	
5.4.2	Hard schist rocks.	
5.4.3	Hard coarse grained igneous or metamorphic and fine igneous rocks.	
	Hill country (most slopes 16–25 degrees)	
6.1.1	Moraine or dissected alluvium.	
6.2.1	Loess > 1m deep.	
6.3.1	Soft sedimentary mudstone.	
6.3.2	Soft sedimentary sandstone.	
6.3.3	Soft sedimentary conglomerate.	
6.3.4	Soft calcareous sediments.	
6.4.1	Hard sedimentary rocks.	
6.4.2	Hard schist rocks.	
6.4.3	Hard coarse grained igneous or metamorphic rocks.	
6.4.4	Hard fine grained igneous rocks.	
	Hilly steeplands (most slopes > 25 degrees)	
7.1.1	Soft mudstone.	
7.1.2	Soft sandstone.	
7.1.3	Soft conglomerate.	
7.2.1	Hard sedimentary rocks.	
7.2.2	Hard schist rocks.	
7.2.3	Hard coarse grained igneous or metamorphic rocks.	
7.2.4	Hard carbonate rocks.	
7.2.5	Fine grained igneous rocks.	
7.3.1	Weathered hard schist & greywacke rocks.	
7.3.2	Weathered coarse grained igneous rocks.	
	Mountain steeplands	
8.1.1	Hard sedimentary rocks.	
8.1.2	Hard schist rocks.	
8.1.3	Hard coarse grained igneous and metamorphic rocks.	
8.1.4	Hard fine grained igneous.	
8.1.5	Weathered coarse grained igneous rocks.	
9	Alpine slopes – very steep to precipitous mountain slopes.	

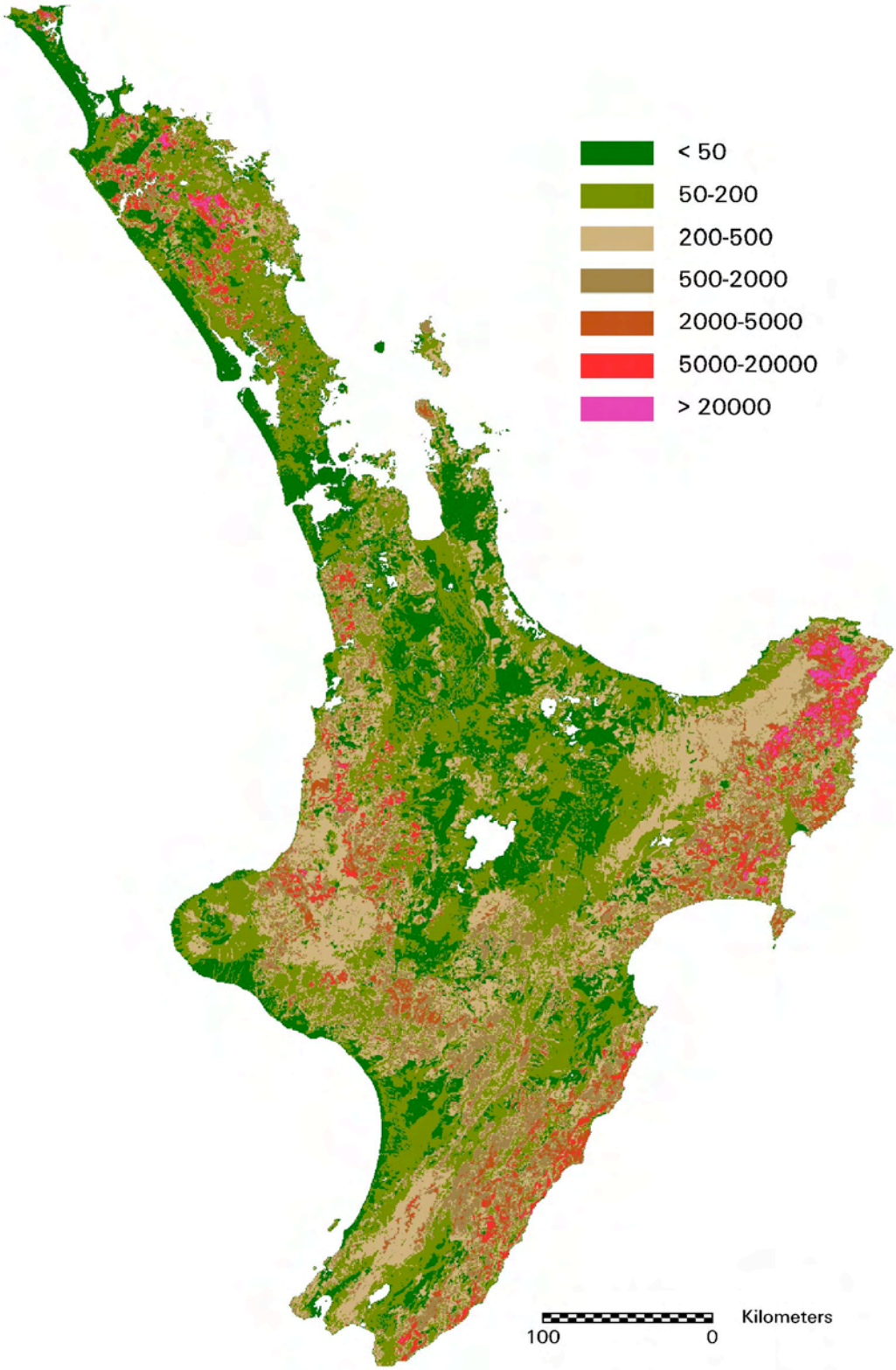
List of figures:

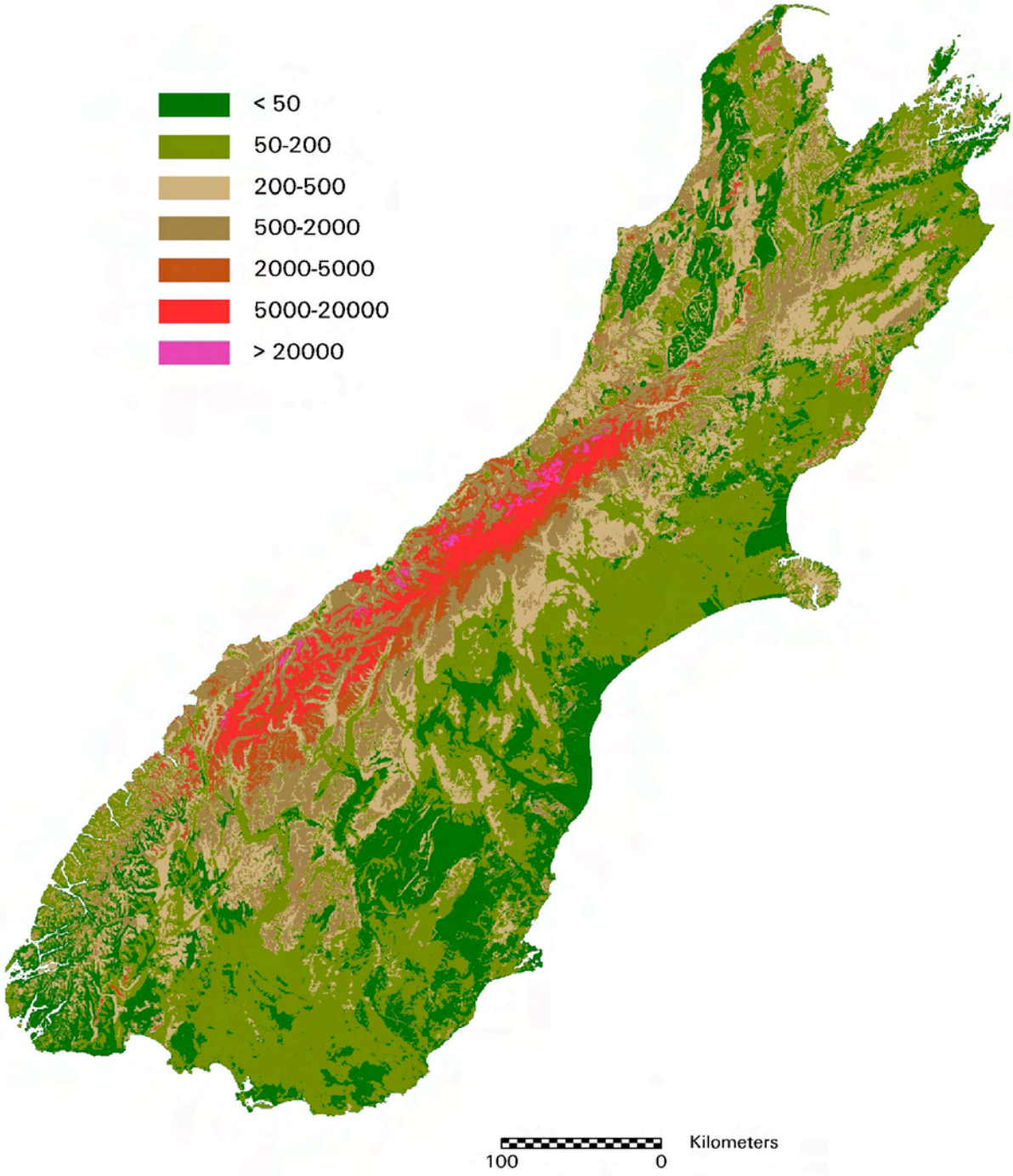
Figure 1a: Predicted mean erosion rates for the North Island of New Zealand under current land cover. Units are tonnes.km^{-2}.yr^{-1}.

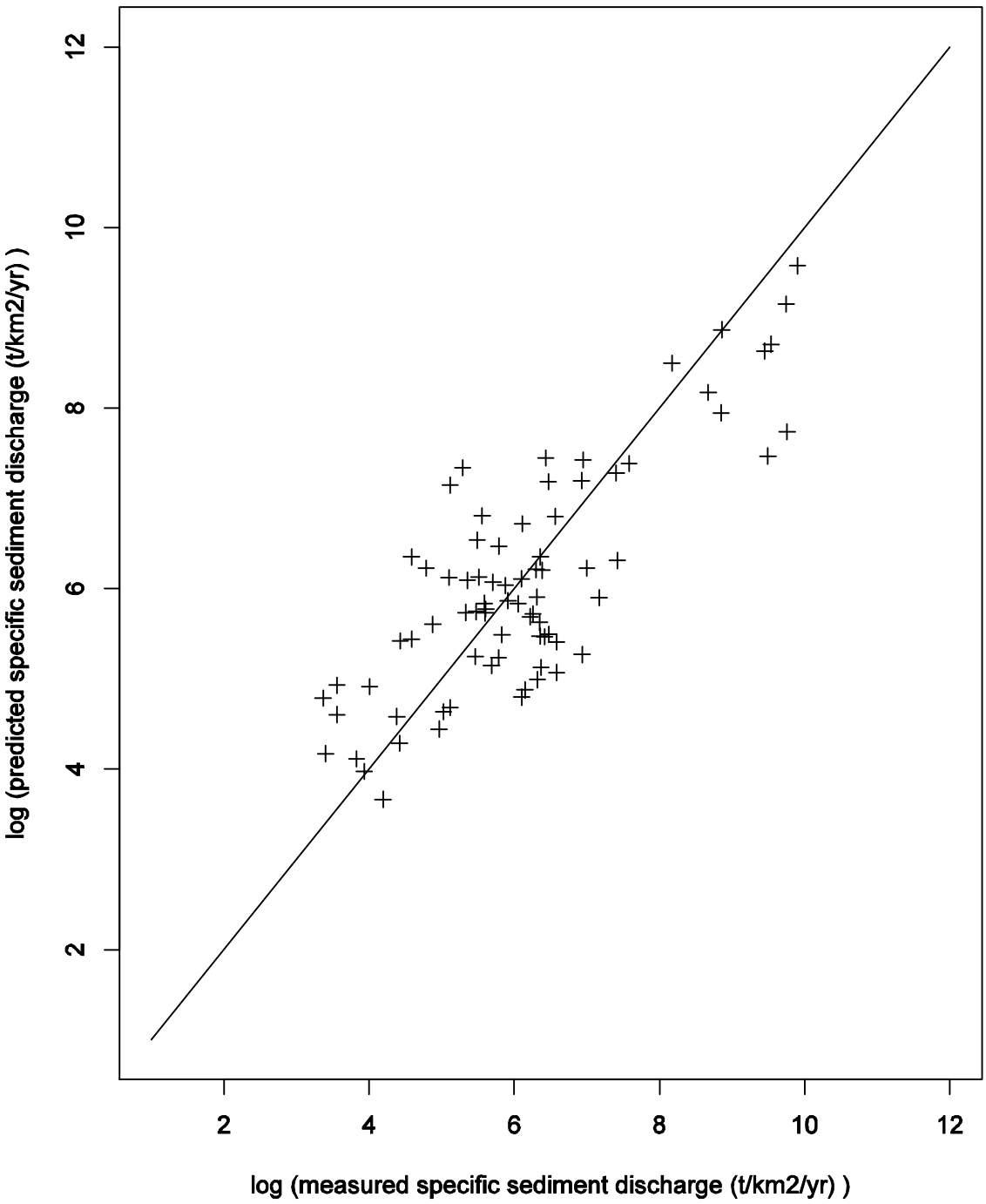
Figure 1b: Predicted mean erosion rates for the South Island of New Zealand under current land cover. Units are tonnes.km^{-2}.yr^{-1}.

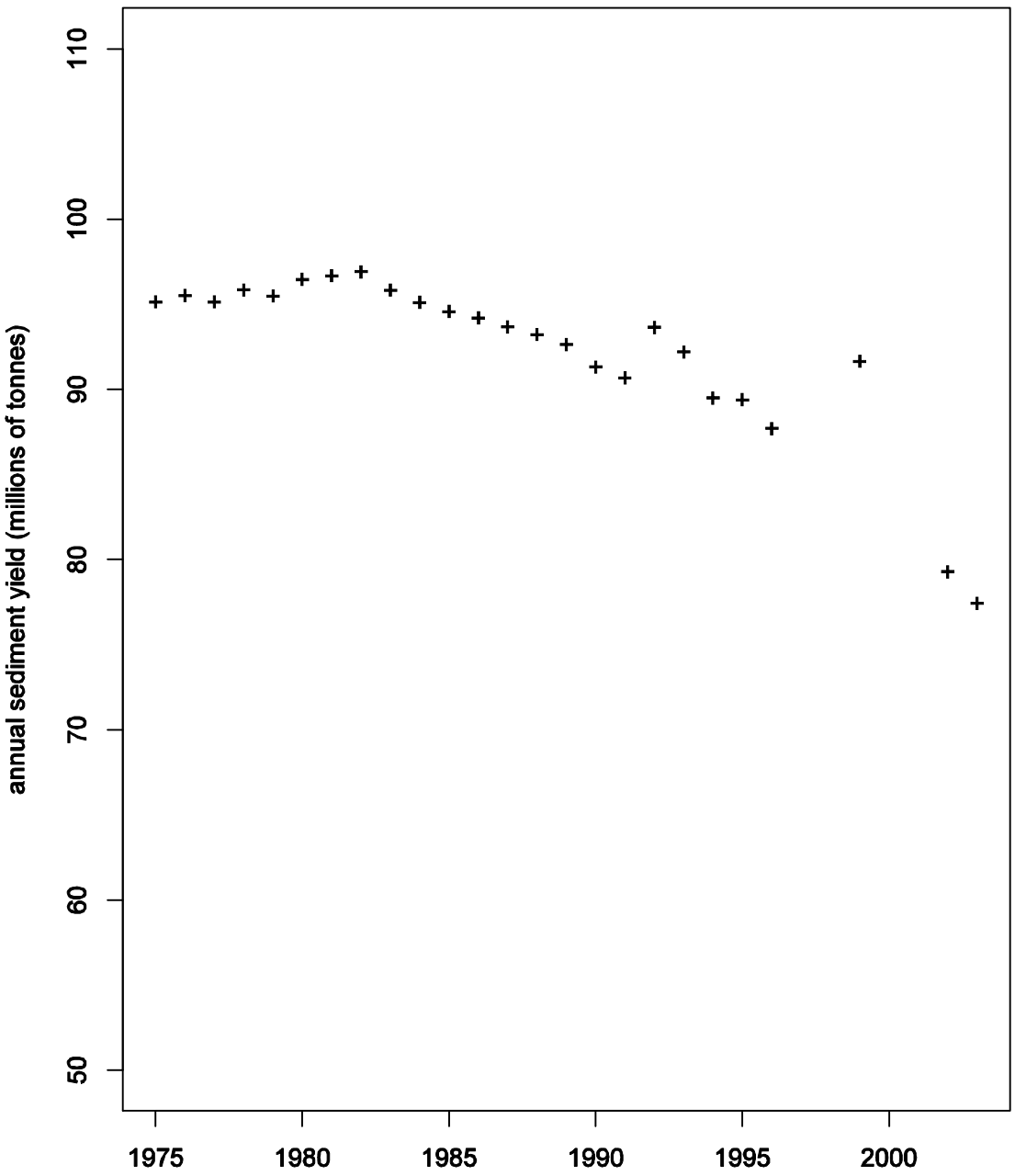
Figure 2: Log-log plot of predicted versus measured specific sediment discharge for 80 sites spread throughout New Zealand. R^2 is 0.65.

Figure 3: Total annual sediment yields from agriculture in New Zealand over the past 30 years.


< 50
50-200
200-500
500-2000
2000-5000
5000-20000
> 20000
100
0
Kilometers


< 50
50-200
200-500
500-2000
2000-5000
5000-20000
> 20000
Kilometers
100
0


log (predicted specific sediment discharge (t/km2/yr))
log (measured specific sediment discharge (t/km2/yr))
2
4
6
8
10
12


annual sediment yield (millions of tonnes)
110
100
90
80
70
60
50
1975
1980
1985
1990
1995
2000

Appendix 3.
NZEEM manuscript- Mitigation practices for reducing the losses of P from pastoral systems

Mitigation option	Explanation
Soil erosion	Limiting sediment movement to waterways from erosion during storm events offers the single biggest opportunity for reducing P loss to waterways. Whole farm planning offers a systematic land evaluation and planning approach for tackling this environmental problem. Because this issue is tackled elsewhere in the One Plan, no further comment is made here.
Optimum soil phosphorus fertility	The target range should be the agronomic optimum soil Olsen levels for each of the soil types on the farm. Soil fertility above the agronomic optimum makes little economic sense and increases the P run-off risk. The optimum agronomic soil Olsen levels for each of the major soils orders are listed in the booklets on fertiliser use published by the fertiliser industry.
Fertiliser practices	The timing of fertiliser application (summer rather than winter), form of application (sparingly water soluble versus water soluble) and avoiding direct contamination of water ways by fertiliser all offers scope for reducing P losses from the farm. The fertiliser industry Fertiliser code of good practices provides reference to all these options.
Land disposal of dairy shed effluent	By treating effluent as a source of nutrients (N, P, K, S, Ca, Mg, etc.) rather than waste and applying effluent to ensure that the amount of nutrient applied does not exceed optimum levels (e.g., Olsen levels <35 ug ml^{-1}) will ensure maximum use of the nutrients for pasture growth and limit the impact of land based application of effluent to the wider environment. The Overseer® nutrient budget model can be used to calculate the optimum area for application of dairy shed effluent.
Deferred and low application effluent irrigation rates	Limiting effluent applications to periods when soils are less than field capacity, limiting the loading on an annual basis and using low application rates all offer options for limiting surface run-off and preferential flow of effluent. Practices which increase the opportunity for effluent to be absorbed into the soil matrix will reduce P losses.
Preventing autumn-winter-spring soil and pasture treading damage	Removing heavy weight animals when soils are wet to free draining soils or a stand-off or feed pad will limit soil and pasture damage. Soils damaged by livestock will have reduced physical function (e.g., infiltration rates). Pastures damaged by livestock will have reduced plant number, which in turn reduces canopy cover exposing the soil surface to rain drop damage. A soil and pasture damaged by treading will contribute more surface run-off and sediment than a well managed soil.
Stand-off/Winter feed pads/herd homes	Management of the P in the effluent is critical if the benefits of a stand-off area in reducing P losses to the wider environment are to be realised.
Stock exclusion from all streams	Preventing access to perennial streams will reduce direct nutrient contamination from dung and urine and indirectly reduce the amount of vegetation and sediment entering the water ways. Preventing damage to the stream banks will also reduce the amount sediment and total-P entering the waterway.
Creation of wetland and riparian attenuation zones	Trapping and retaining nutrients and sediment in wetlands and in vegetation buffers alongside water courses will decrease direct contamination of waterways. There is a lack of area specific metric data on P attenuation rates with both these mitigation options. The creation of grass buffer-strips may not be effective if periodic grazing is allowed. The main action of buffer strips is not filtration, but to act as an area close to the stream, which contributes much streamflow, but has no dung deposits (i.e. is fenced-off).
Lanes and bridges	Engineering lanes and bridges so that run-off flows away from stream channels.
Whole farm nutrient budgeting	Nutrient budgets are useful tools for assessing P flows within the farm system and identifying opportunities for reducing P losses. The Overseer® nutrient budget provides an estimate of P run-off risk for parts of the farm under different management.