Journeaux Economics

Critical Pathways Programme: Economics of Attenuation Rates in the Piako and Waiotapu Catchments

Prepared for Lincoln Agritech

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1.0 EXECUTIVE SUMMARY

This report is part of the Critical Pathways Programme led by Lincoln Agritech, investigating land-to-water nitrogen transfers, including nitrogen attenuation, in two catchments (Upper Piako, and Waiotapu) within the Waikato region.

The objectives of the component of the work discussed in this report is around identifying the economic costs and benefits arising from identifying attenuation rates, and how this could be incorporated within a cost/benefit framework.

The analysis was based around case-study farms within each catchment; 5 within Piako, 6 within Waiotapu. These farms were set up in Farmax in order to model changes in farm systems, and also in OverseerFM, in order to model the impact of any system changes on nitrogen losses.

The results of the trials are discussed in the body of the report, but the level of nitrogen attenuation was calculated as; (source N load - delivered N load) ÷ source N load, where:

- delivered N load = the nitrogen load measured at a stream monitoring site; and
- source N load = the nitrogen loss from the root zone as calculated by OverseerFM

The calculated weighted average attenuation figure for the Piako catchment was 53%, and 57% for the Waiotapu catchment (disregarding lag time in case of the latter).

This difference in attenuation rates has several implications:

- A proportional reduction in the source load would result in the same proportional reduction in delivered load. For example, at 20% reduction in the source load leads to a 20% reduction in the delivered load. The absolute reduction though, for the 53% attenuation catchment is 7% greater than for the 57% attenuation catchment.
- Which means that if the same absolute reduction in delivered load is required in both catchments, the reduction in source load has to be 31% higher in the 57% attenuation catchment.
- It also means that, from a policy perspective, it is more cost effective to look to reduce nitrogen loading in low-attenuation catchments compared to high-attenuation catchments.
- Or conversely, a higher nitrogen loading could be tolerated in a high-attenuation catchment given that much of this loading is subsequently attenuated before the nitrogen is delivered to waterbodies.

The economic analysis showed that the cost per kg reduction in delivered load varied significantly, depending on the profitability of the farm, the N loading onto the soil, and the related attenuation rate. In this respect no pattern was discernible, either at the catchment or individual farm level.

If a crude assumption is made on the groundwater lag time in the Waiotapu catchment, the attenuation rate would drop from the upper limit of 57% to 43%. While this was then lower than in the Piako catchment (53%), the differences in the cost of reducing delivered loads was again relatively small, indicating that there needs to be a reasonably large difference in attenuation rates to significantly affect the cost of reducing N loads delivered to waterways.

A cost benefit analysis is a process whereby the present value of the sum of benefits minus costs over a set time period can be evaluated for an investment, or to compare a range of investment options. This can readily be used to evaluate the benefits of reducing environmental contaminants such as nitrogen. While the current trial has provided a good means of evaluating the cost of reducing delivered N loads, the issue that remains in any such cost benefit analysis is in determining the benefits, especially in monetary terms. Monetising the benefits was outside the scope of the current project, but an example using other data is presented in the report to illustrate how a cost benefit approach could work.

The key results from the analysis were:

- The measurement/modelling of the delivered loads has given reasonable data at a sub-catchment and catchment level but is not detailed enough to give results at a farm level.
- Similarly, while it can be extrapolated to a regional level, given some assumptions, it cannot be extrapolated to a national level.
- A crucial element in the "cost/benefit" analysis is that there is very limited information on the "benefit" side - & while this could be generated it is a substantial area of work which is outside the scope of the project.
- Nevertheless, the results have indicated that it is possible to (a) determine attenuation rates, and (b) put a cost on this, which is/will be useful for policy development at a sub-catchment/catchment/regional level.
- It indicates that the cost differential is relatively low give a close difference in attenuation rates, which also has implications for policy development.
- It shows that the cost of reducing delivered N loads is very much driven by farm profitability, which varies widely from farm to farm.
- Plus it has shown that where lag times are important, a methodology needs to be developed in order to differentiate lag times from attenuation rates.
- Perhaps the key policy inference is that the better "value for money" approach is to concentrate on catchments with lower nitrogen attenuation rates first.

2.0 BACKGROUND

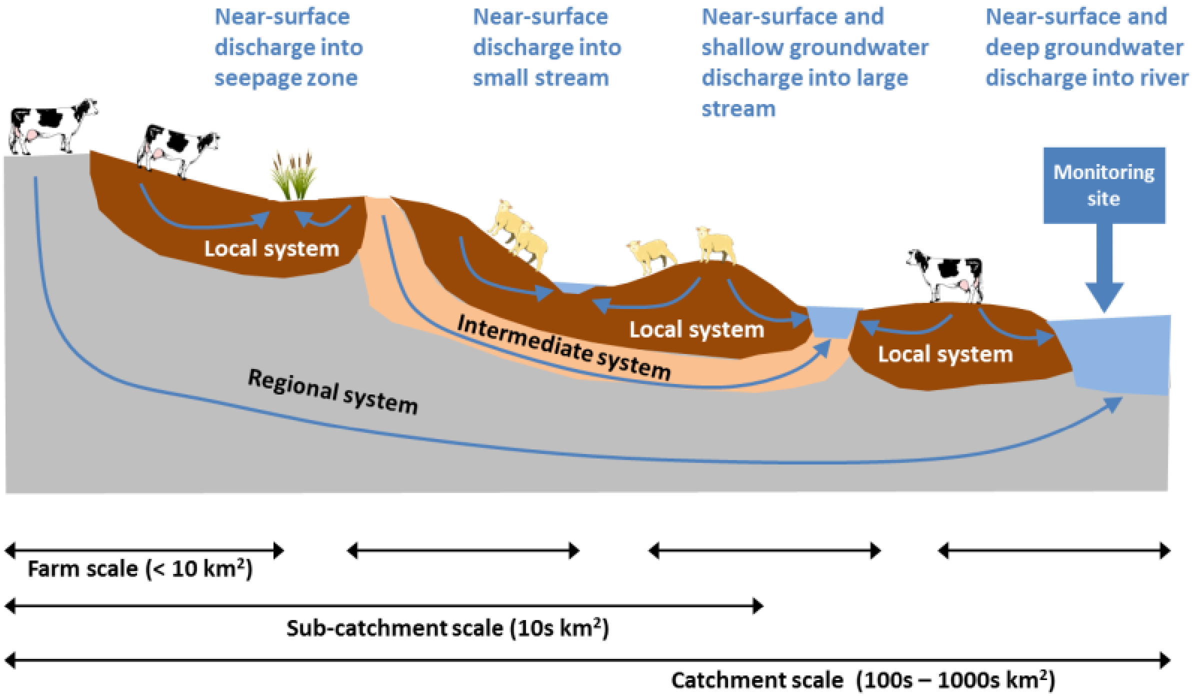
This report pertains to a subsection of the *Critical Pathways Programme: Unravelling Sub-catchment Scale Nitrogen Delivery to Waterways* research project funded by MBIE and overseen by Lincoln Agritech.

To enable effective and efficient decision making on land use, land management, mitigation measures, as well as related policy, a clear understanding of cause-effect relationships is needed.

However, in the large and heterogeneous catchments usually being monitored (100s – 1000s of km^2), it is very difficult to link an observed contaminant flux at the catchment outlet to the many past and present activities that collectively have caused it.

The need to understand and model the dynamic water and contaminant fluxes at the sub-catchment scale (10s of km^2) has therefore been emphasised in recent years.
Accordingly, the aim of the project was to unravel the relatively shallow and relatively short pathways operating in many landscapes at the farm and sub-catchment scales and represent them in water flow and contaminant transfer models.

Figure 1: Illustration of relationships between flow systems and spatial scales



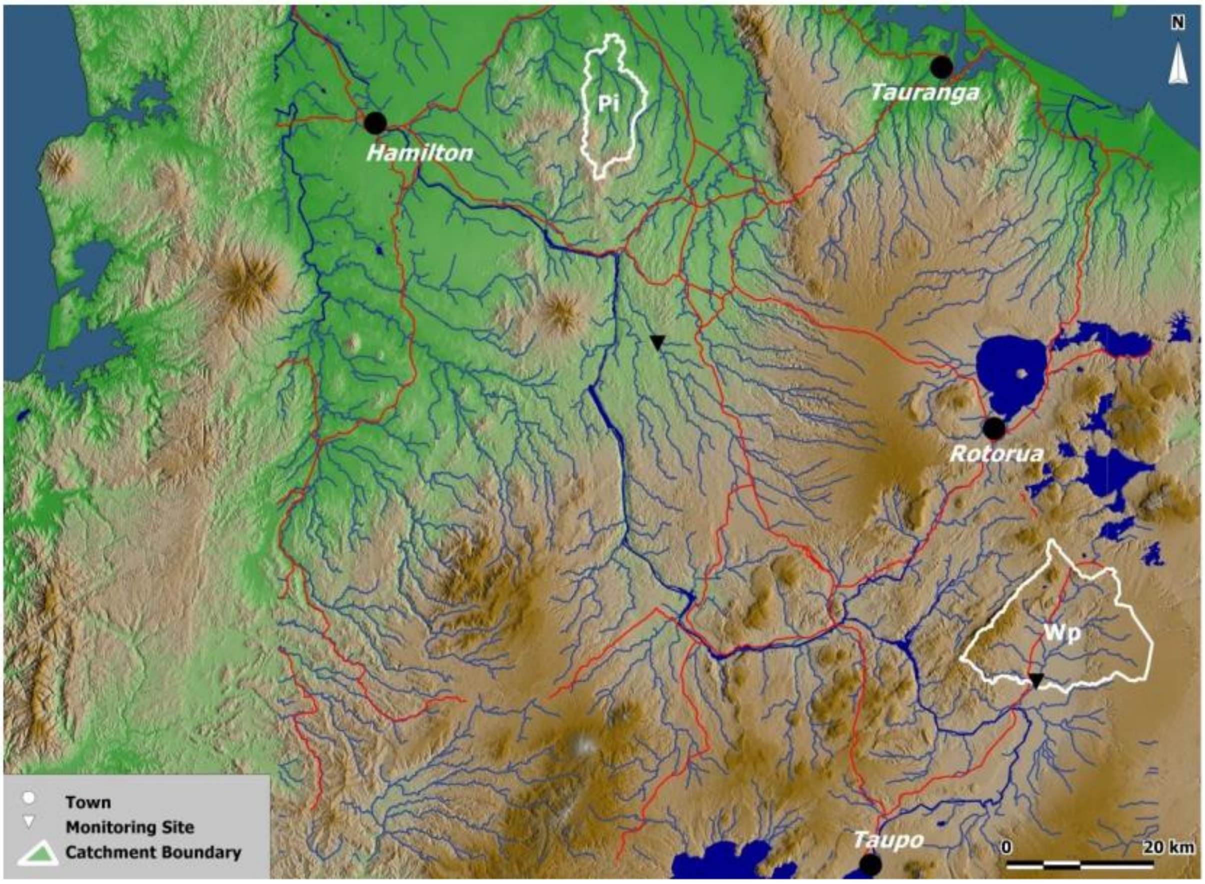
In addition to the biophysical research, the intent was to determine the economic implications of land use and management, mitigation and policy when based on sub-catchment versus catchment scale contaminant fluxes.

The two case studies involved in the project were two intensively farmed catchments with contrasting hydrological and biogeochemical conditions:

(i) The Piako River headwater catchment (Pi), of approximately 104 km^2, is a lowland catchment (38 – 488m amsl) in the upper part of the Hauraki Plains. The dominant soil order is Allophanic soils (approximately 61%) but Granular soils (~ 21%), Brown soils (~ 10%), and Gley soils (~ 8%) also make significant contributions. The catchment is dominated by intensive pastoral land use (~ 84%), with the remainder being largely native bush (~15%).

(ii) The Waiotapu Stream catchment (Wp) (~ 312 km^2) on the North Island's Central Plateau represents a baseflow-dominated upland catchment (297 – 967m amsl) with large groundwater reservoirs in young volcanic deposits. Young Pumice soils of varying permeability dominate the catchment (~ 61%), with smaller contributions made by Gley soils (~ 10%) and Organic soils (~ 6%). Plantation forestry and native bush are the main land covers (~ 55%) and occur largely at higher elevation (e.g. Kaingaroa Plateau), but highly producing pastoral land (~ 45% of catchment area) dominates in the Reporoa basin.

Figure 2: Location of case-study catchments



3.0 OBJECTIVES

Within the wider project, the three key economic objectives were:

(i) Develop a cost/benefit method that enables quantification of the net benefit of identifying and mitigating flows of N at the sub-catchment scale and is capable of taking wider benefits to iwi, land managers, and local government into account.

(ii) The net benefit of identifying and mitigating flows of N at the sub-catchment scale in two pilot catchments (Waiotapu, Piako) at the farm, sub-catchment, and catchment level has been quantified.

(iii) The net benefit of identifying and mitigating flows of N at the sub-catchment scale, regionally and nationally, has been quantified.

4.0 METHODOLOGY

Case study farms were selected from each catchment; 5 in Piako, and 6 in Waiotapu. Each farm was visited, and the farm system incorporated into Farmax[1] (farm systems model), and OverseerFM[2] (nutrient budget model).

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[1] www.farmax.co.nz

[2] www.overseer.org.nz

While it was difficult to obtain accurate data on the number of dairy farms within each sub-catchment, the estimate was that the above numbers represented around a 5% sample. The farms were also spatially spread geographically around the catchments.

Using the models meant that farm system changes, and/or changes in farm inputs, could be varied and analysed as to the impact of these changes on both farm profit and nitrogen loss from the system, relative to the base farm situation.

Several challenges arise in any attempt to link the water quality observed at a stream monitoring site to land use and land management, inevitably resulting in substantial uncertainty. Refer to Appendix 1 for a high-level overview of commonly encountered challenges.

5.0 RESULTS

5.1 Trial Results

Modelling based on the biophysical measurements carried out in the Piako and Waiotapu catchments yielded the following results:

Table 1: Trial results

	Flow (mm)		Flow (%)		TN Conc (mg l^{-1})		TN Yield (kg $ha^{-1}y^{-1}$)		TN Load faction (%)	
	Piako	Waiotapu	Piako	Waiotapu	Piako	Waiotapu	Piako	Waiotapu	Piako	Waiotapu
NS*	108	74	22%	15%	1.77	2.98	1.97	2.23	19%	21%
SGW*	319	145	64%	29%	2.9	3.03	8.49	4.13	81%	41%
DGW*	77	277	13%	58%	0.05	1.45	0.03	4.07	0%	40%
Total	504	496					10.49	10.43		
					Adjusted Total:**		11.84	10.97		

*NS = Near Surface Flow = surface runoff, interflow (within the soil zone), artificial drainage (surface and subsurface drains); this water flows episodically and is very young.

*SGW = Shallow Groundwater = the seasonal, young, local groundwater

*DGW = Deep Groundwater = the perennial, old, regional groundwater

**Adjusted Total: The figures given for the three pathways are individually estimated medians. The "adjusted total" shown is an independent model estimate derived from the total flow (rather than the sum of the three components). The small discrepancies illustrate the uncertainty involved in all modelling.

These can be illustrated graphically:

Figure 3: Mean annual flows

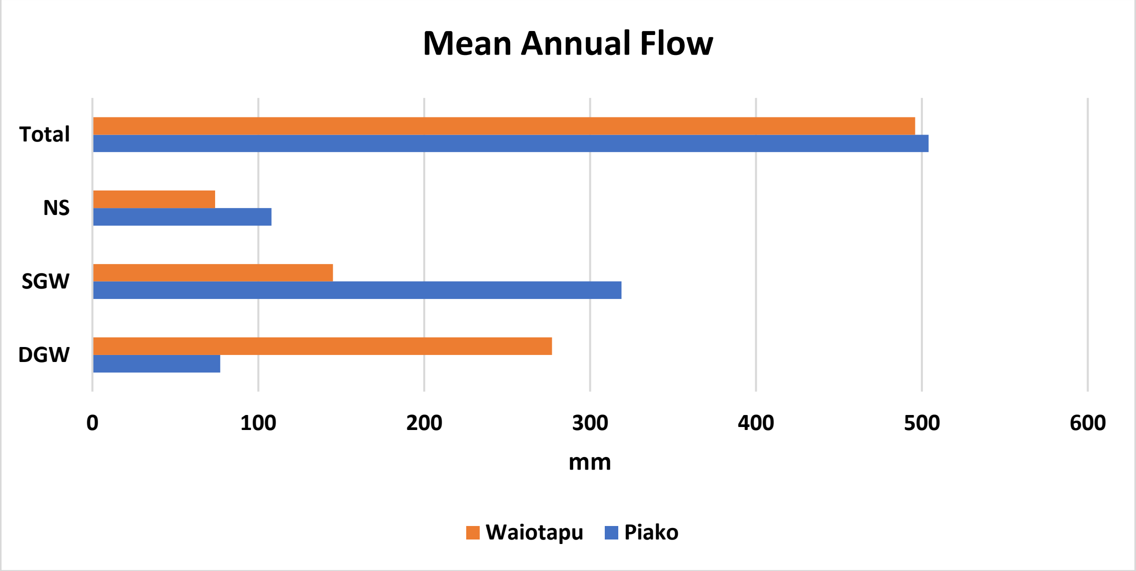


Figure 4: Flow contributions by the three pathways

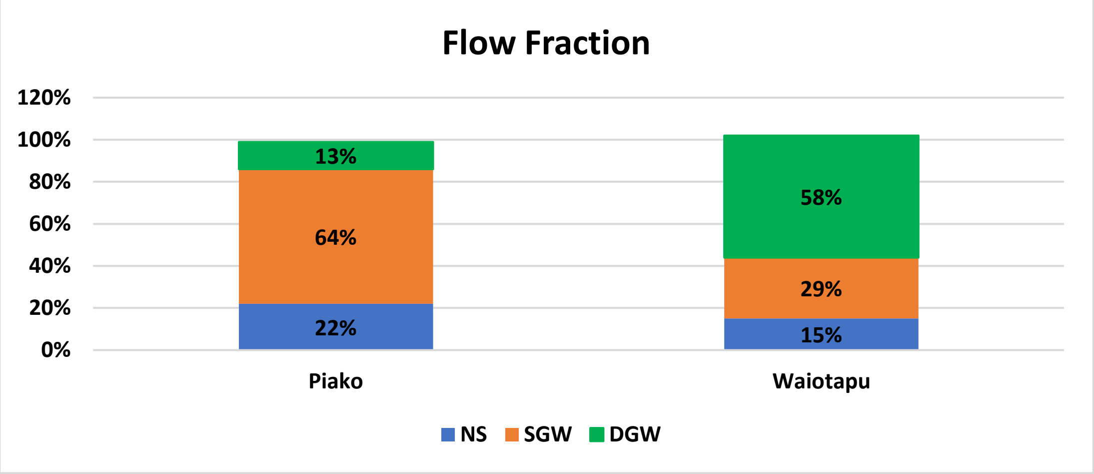


Figure 5: Total Nitrogen Concentration

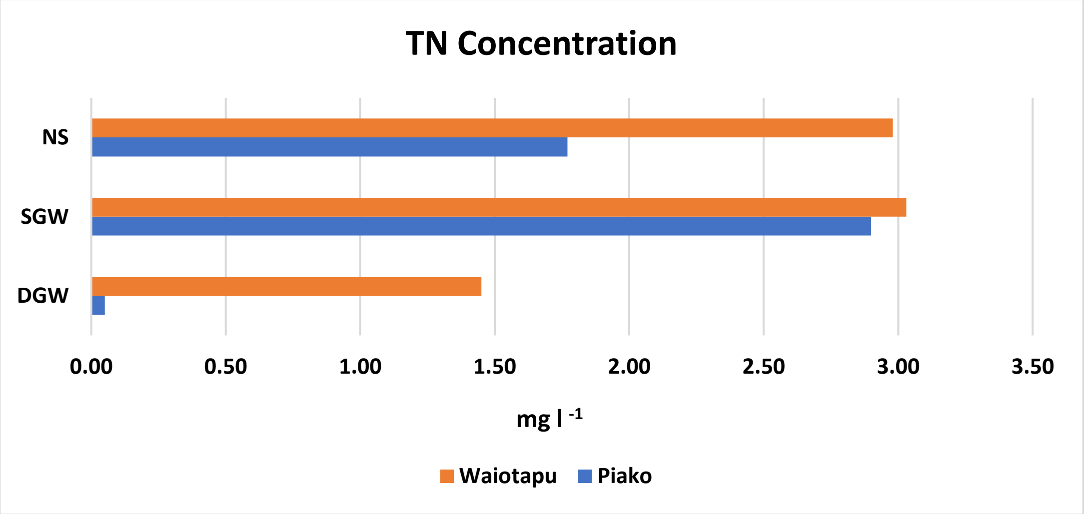


Figure 6: Total Nitrogen Yields

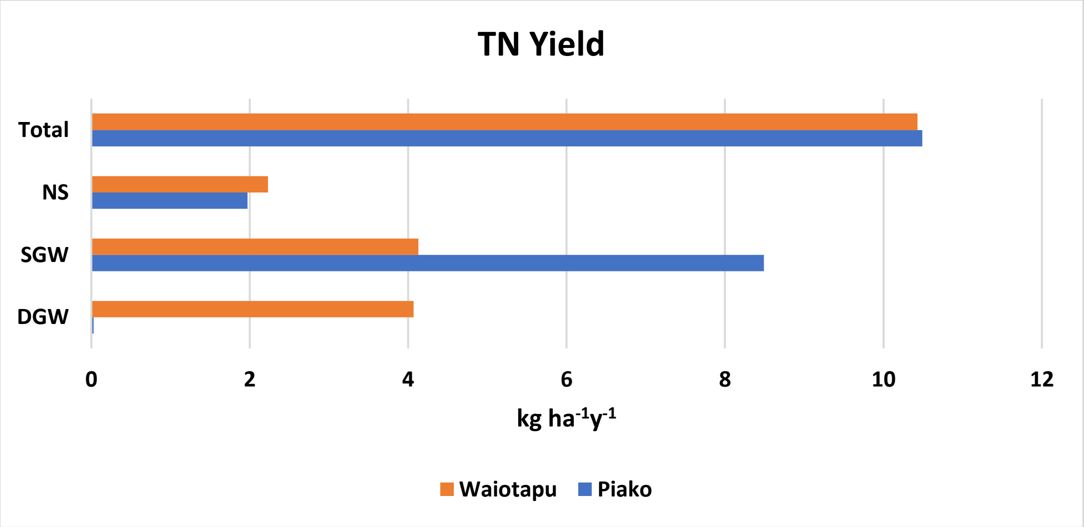
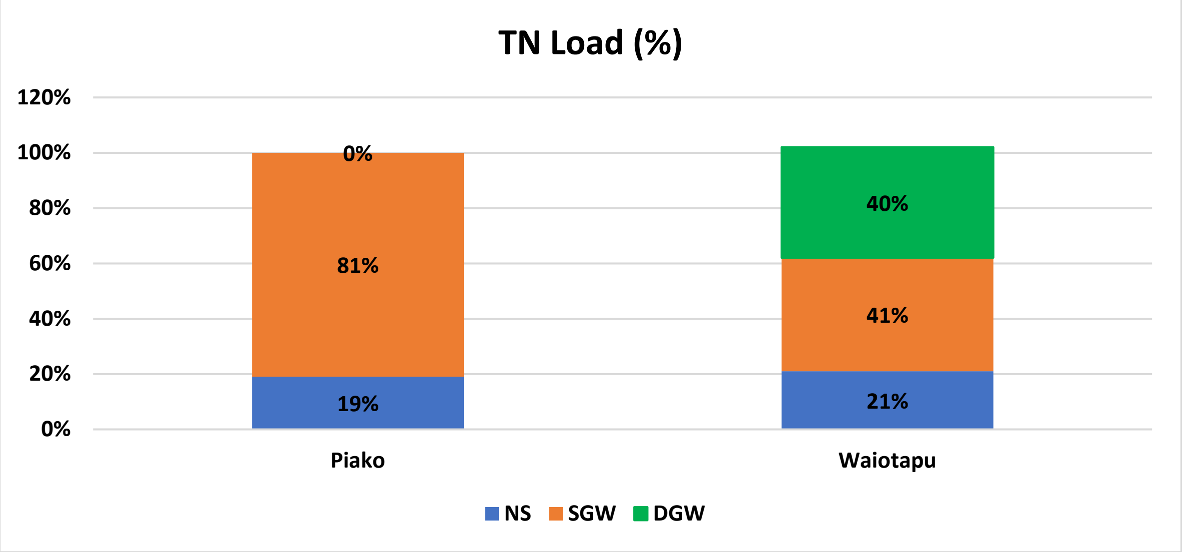


Figure 7: Total Nitrogen Loading percentage



5.2 Nitrogen Attenuation

The extent of nitrogen attenuation occurring between the bottom of the root zone and a surface water monitoring site is very difficult to determine. As it cannot be directly measured, a range of assumptions and modelling tools need to be employed to produce estimates, which inevitably carry substantial uncertainty. Subject to the availability of data and modelling tools, different estimation methods have been applied in this study for different spatial scales:

- At the catchment scale, source loads (from the soil zone) are related to delivered loads (at the stream monitoring site) by employing the BACH and/or SWAT-Modflow-RT3D modelling tools (Sections 5.4 and 5.6).
- Analysis for the Piakonui and Piakoiti sub-catchments of the Piako headwater catchment was enabled by the monitoring sites at the sub-catchment outlets combined with SWAT-Modflow-RT3D modelling (Section 5.7).
- In the absence of any data on delivered loads, farm scale estimates were based on Overseer N loss estimates combined with assumed attenuation rates for different soil types and landscape positions (section 5.8).

For the purposes of this paper, the following definitions are used:

- Source load = the amount of nitrogen lost from the root zone, as estimated by OverseerFM
- Delivered load = the nitrogen load measured at a stream monitoring site.
- Attenuation = the difference between source load and delivered load. The level of nitrogen attenuation within the ground water was calculated as: (source N load - delivered N load) ÷ source N load , where:
  - delivered load = the adjusted total yield figures in Table 1, and
  - source load = the N loss figure calculated by OverseerFM

Note that the terms load and yield can to some extent be used interchangeably. While load describes a mass per unit of time (e.g. kg/yr), the term yield is used if the area the load originates from is additionally taken into account (e.g. kg/ha/yr).

Across the farms modelled by OverseerFM therefore, the relevant figures are:

Table 2: Nitrogen Loading

Piako	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Weighted Average
N loss (kg N/ha/yr)	29	25	19	24	20	23.2

Waiotapu	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6	Weighted Average
N loss (kg N/ha/yr)	42	27	51	53	66	48	46.1

This loading then needs to be adjusted given that the catchments are not entirely in pastoral farming; 16% of Piako is in forestry, and 58% of Waiotapu. Adjusting for this shows:

Table 3: Catchment Net Loading Levels

Piako	Source Load (kg N/ha/yr)	Proportion of Catchment	Net Source Load (kg N/ha/yr)
Agriculture	23.2	84%	19.49
Forestry	2	16%	0.32
			19.81
Waiotapu	Source Load (kg N/ha/yr)	Proportion of Catchment	Net Source Load (kg N/ha/yr)
Agriculture	46.1	42%	19.36
Forestry	2	58%	1.16
			20.52

Issues

(i) Inclusion of Near Surface flows.

The nitrogen loss measured by Overseer is "below the root zone", which is taken as 60cm. It is debatable whether "near surface flows" reach this depth, and as such whether they should be included in the attenuation calculation.

In noting this, within Overseer, the N loss figure can be differentiated into several sub-classes:

- Leaching – urine patches
- Runoff
- Direct (animals, drains)
- Leaching – other
- Septic tank outflow
- Border Dyke outwash
- Direct pond discharge

The largest components of N loss (by far) are the two leaching components. Analysis of a range of Overseer files showed that Runoff on moderate/free draining soils was minimal (usually zero) but was up to 10% of the total loss on heavy soils.

Given this, plus that obviously near surface flows add to the total N loading of water bodies, the Near Surface N yields shown in Table 1 were included in the attenuation calculation.

(ii) Lag times in Deep Ground Water.

Tritium testing of Waiotapu Stream water showed ages varied from 9 years at high flows (when near surface and shallow groundwater flows dominate) to 47 years at low flows (i.e. when deep groundwater discharge dominates stream flow). This then raises the question of a lag in nitrogen loading flowing through, and whether the current delivered load will increase in the future due to previously lost nitrogen still being in transit on deep groundwater pathways.

The Reporoa area was fully developed into dairying by the 1980's, although it intensified through the 1990's and 2000's, via increased nitrogen fertiliser and bought-in supplementary feed inputs. To some extent this intensification has started to reverse itself in recent years. While there may be a degree of lag in the delivered N loads, it is impossible to differentiate this from the denitrification effect, and in this respect the delivered N yield figures are taken in the first instance at their face value. Section 5.6 discusses how the estimated attenuation rate changes if the lag time effect is taken into account.

5.3 Total N versus Nitrate N

Table 1 shows the nitrogen flow in terms of Total Nitrogen (TN). The nitrogen loading as estimated by OverseerFM is in Nitrate Nitrogen (i.e. NO_3-N). To adjust the TN yields to NO_3-N, the BACH Model[3] results were adjusted, with the following results.

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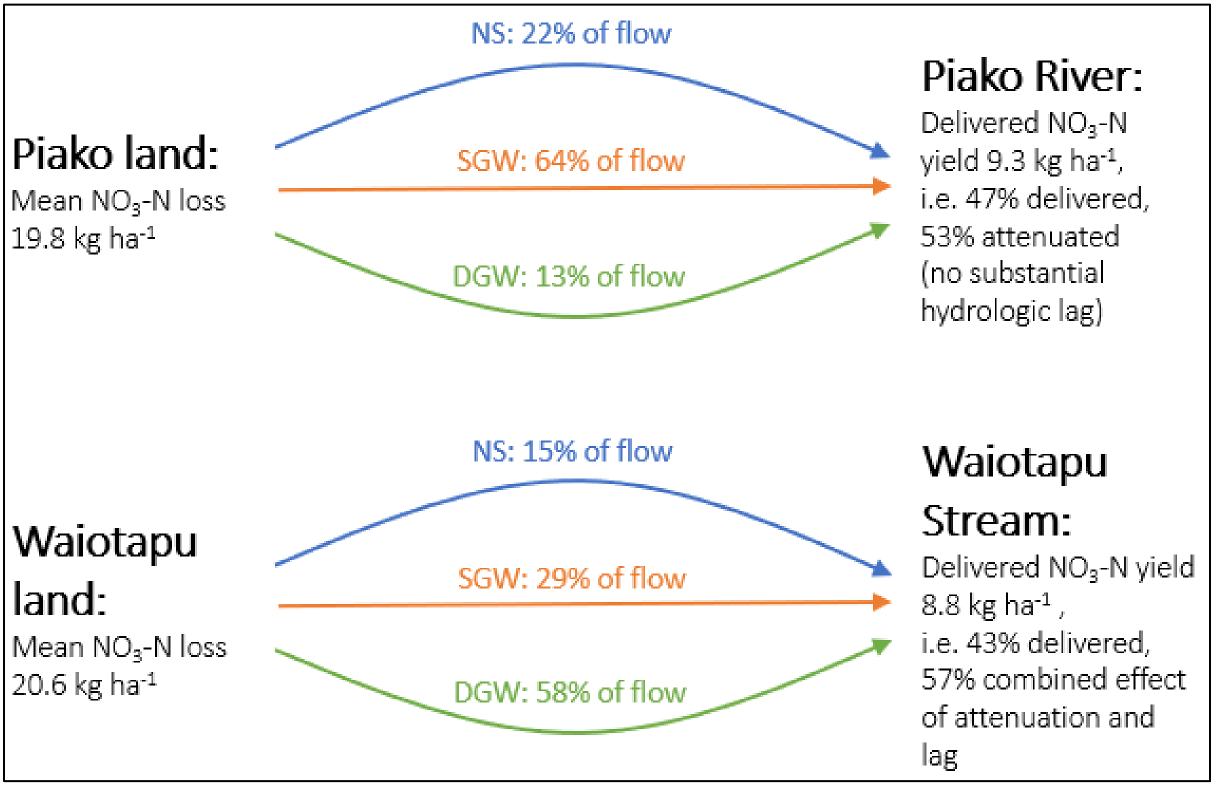
[3] BACH = Bayesian Chemistry-Assisted Hydrograph Separation (Bach) Model (Woodward and Stenger, 2018; Stenger et al., 2022)

Figure 8: Catchment Level NO_3-N Yields/BACH Model



This shows that attenuation in the Piako catchment averaged 53%, and for Waiotapu, 57%, which is the basis for the following analysis (acknowledging that 57% is an upper limit for Waiotapu, see Section 5.6).

5.4 Attenuation Implications

Hypothetical Catchment

In the first instance, assume two catchments with identical N source load (where N loading = N loss as calculated by OverseerFM), but with differing attenuation levels.

Table 4: Hypothetical Catchment Comparison

	Catchment 1	Catchment 2
Current Source Load (kg N/ha/yr)	30	30
Attenuation (%)	53%	57%
Current Delivered Load (kg N/ha/yr)	14.1	12.9
Source Load Reduction (%)*	20%	20%
Source Load Reduced by (kg N/ha/yr)	6	6
Current Source Load minus the Reduction (kg N/ha/yr)	24	24
Delivered Load after the Reduction (kg N/ha/yr)	11.3	10.3
Reduction in Delivered Load (kg N/ha/yr)	2.8	2.6
Reduction in Delivered Load (%)	-20%	-20%

*Arbitrary load reduction required (e.g. by policy), for purposes of illustration

This shows:

(i) While the N source load is the same for each catchment, the difference in attenuation means that the delivered N load in Catchment 2 is lower.

(ii) Assuming an arbitrary source load reduction (20%), the absolute reduction in loading is the same for both catchments, but again the difference in attenuation means that while the proportional reduction in yield is the same (20%), the absolute reduction in delivered yield in catchment 2 is 7% lower than in catchment 1.

Trial Catchments

Applying the same approach to the trial catchments shows:

Table 5: Trial Catchment Comparison, based on a proportional loading reduction

	Piako	Waiotapu
Current Source Load (kg N/ha/yr)	19.8	20.5
Attenuation (%)	53%	57%
Current Delivered Load (kg N/ha/yr)	9.4	8.8
Source Load Reduction (%)	20%	20%
Source Load Reduced by (kg N/ha/yr)	4.0	4.1
Source Load Reduced to (kg N/ha/yr)	15.8	16.4
Delivered Load after the Reduction (kg N/ha/yr)	7.4	7.1
Reduction in Delivered Load (kg N/ha/yr)	2.0	1.8
Reduction in Delivered Load (%)	-20%	-20%

(i) While the source load in the Waiotapu catchment is only 3.5% higher than in the Piako catchment, the delivered load is 6.2% less, due to the (7.5%) higher attenuation rate.

(ii) Assuming an arbitrary source load reduction (20%), this results in a 10% lower reduction in delivered load (1.8kg N/ha versus 2.0kg N/ha) in the Waiotapu catchment versus Piako.

(iii) If, instead of a proportional reduction in loading, an absolute reduction in delivered load is required, then the analysis shows:

Table 6: Trial Catchment Comparison, assuming an absolute reduction in delivered load is required

	Piako	Waiotapu
Reduction in delivered load required (kg N/ha/yr)*	3	3
New Delivered Load required (kg N/ha/yr)	6.4	5.8
New Source Load (kg N/ha/yr)	13.6	13.5
Reduction in Source Load (kg N/ha/yr)	6.2	7.0
New loading as a % of original loading	69%	66%
New load as a % of original load	68%	66%

*Arbitrary load reduction required, for purposes of illustration

In this example, assuming an absolute reduction in delivered load, the Waiotapu catchment farmers would need to reduce their absolute loading by 13% more than in the Piako catchment, with the proportional reduction in loading only slightly higher, by 4%.

5.5 Discussion

(i) Obviously, the level of attenuation has a major impact on the load delivered from the soil into waterways. As can be seen from Table 5, while the source load of nitrogen in the Waiotapu catchment is marginally greater compared with the Piako catchment, the higher attenuation factor means that the delivered load is actually lower.

(ii) While the difference in attenuation between the two catchments is relatively small, a catchment with a much higher attenuation rate would show a much greater actual and proportional difference to one with a much lower attenuation rate.

(iii) A proportional reduction in the loading (i.e. the assumed 20%) means that the amount of the load reduction required in the Waiotapu catchment is higher than that required in the Piako catchment, resulting in a similar proportional reduction in the delivered load.

(iv) An absolute reduction in the delivered load (i.e. the assumed 3 kg N/ha) means that the reduction required in the Waiotapu catchment is 31% higher than that required in the Piako catchment.

(v) If the reduction in loading was the same between the 2 catchments, then the reduction in delivered load is less for the Waiotapu catchment – as essentially illustrated in Table 4. From a policy perspective therefore a reduction in the current source load would be more beneficial in reducing the delivered load in lower attenuation catchments (i.e Piako) hence they should be prioritised as compared to the higher attenuation areas in which natural attenuation is reducing more of the load from the root zone.

(vi) In noting this, the assumption is that the percent attenuation in a catchment remains the same independent of the load and time, which requires further validation.

(vii) Alternatively, a higher nitrogen loss could be tolerated in higher attenuation catchments, in that much of groundwater targets could still be met due to the higher attenuation of the nitrogen source load.

5.6 Impact of Introducing a Lag Period

As discussed in Section 5.2, the nitrogen yield from the Waiotapu catchment is also affected by a lag period – the time taken for nitrogen in the water to eventually flow through into the streams and other water bodies. It was not possible to readily quantify the lag period, so the ratio of non-delivered versus source nitrogen load was taken as the attenuation impact.

Based on the tritium sampling, the Mean Transit Time (MTT) of the stream water leaving the Waiotapu catchment ranges from nearly 50 years at the lowest sampled flow (2.4 $m^3 s^{-1}$) to around 10 years at the highest sampled flow (7.8 $m^3 s^{-1}$). This means that a substantial storage volume exists in the highly porous volcanic deposits underlying the catchment, which causes this substantial hydrological lag time. What is unknow however is how the nitrogen losses from the farmland have developed over the last 50 years. Accordingly, it is not possible to estimate with any certainty the extent to which the hydrological lag translates into a N delivery lag. Moreover, a relatively high percentage of the land associated with the longest pathways and therefore longest hydrological lags is under forestry, where losses are low and stable. Conversely, farmland is overrepresented in those parts of the catchment that have shorter pathways and lag times, particularly the basin and the western slopes.

On the assumption that the lag time accounts for one quarter of the unaccounted-for N (0.25 x 57=14% of the source load), attenuation equates to 43% (0.75 x 57) of the source load. This now means that the attenuation in the Waiotapu catchment (43%) is less than that in the Piako catchment (53%).

Given this difference, recalculation of Tables 5 and 6 show:

Table 7: Trial Catchment Comparison, based on a proportional loading reduction/Lower Waiotapu attenuation

	Piako	Waiotapu
Current Source Load (kg N/ha/yr)	19.8	20.5
Current Delivered Load (kg N/ha/yr)	9.4	8.8
Unaccounted-for load (kg/ha/yr)	10.4	11.7
Load still in transit due to time lag (kg/ha/yr)	0	2.9
Attenuated load (kg/ha/yr)	10.4	8.8
Attenuation (%)	53%	43%
Assumed source Load Reduction (%)	20%	20%
Source Load Reduced by (kg N/ha/yr)	4.0	4.1
Source Load Reduced to (kg N/ha/yr)	15.8	16.4
Delivered Load after Load Reduction (kg N/ha/yr)	7.5	6.5
Reduction in Delivered Load (kg N/ha/yr)	1.9	2.3
Reduction in Delivered Load (%)	-20%	-27%

If an arbitrary 20% source load reduction was introduced, it would result in a 20% reduction in delivered yield at Piako (53% attenuation), but a higher reduction of 27% at Waiotapu (43% attenuation). This result re-enforces that mitigation measures have a greater effect in catchments with lower natural attenuation capacity.

A key assumption for the Waiotapu analysis in Table 7 is that the "lagged N" is not attenuated. In reality it is quite likely there will be attenuation to some degree, but it is not possible to ascertain this.

Table 8: Trial Catchment Comparison, assuming an absolute reduction in yield is required/Lower Waiotapu attenuation

	Piako	Waiotapu
Reduction in delivered load required (kg N/ha)	3	3
New delivered load required (kg N/ha)	6.4	5.8
New source loading allowed (kg N/ha)	13.6	10.2
Reduction in loading (kg N/ha)	6.2	10.3
New loading as a % of original loading	69%	50%
New delivered load as a % of original yield	68%	66%

This changes the situation relative to that illustrated in Table 6. The reduction in source loading for the Waiotapu catchment increases to 67% relative to the Piako catchment, with the proportional reduction in loading now 27% greater than in the Piako.

The change in attenuation rates also means a change in the cost per kilogram of yield reduction, as illustrated in Table 9.

Table 9: N Yield reduction for the average Waikato dairy farm (Update on Table 16)

	Base	Scenario 1	Scenario 2
Cows	352	310	300
kg MS/cow	394	393	395
Total kg MS	133,917	117,615	114,148
EBITDA*	$390,555	$403,405	$362,170
EBITDA/ha	$3,255	$3,362	$3,018
Kg fertiliser N/ha	135	37	30
Total N/ha**	271	198	193
Kg N/ha loss (load)	32	25	24
kg N/ha delivered load			
At 53% attenuation	15.0	11.8	
at 43% attenuation	18.2	14.3	13.7
Reduction in delivered load (kg N/ha)			
At 53% attenuation		3.3	
at 43% attenuation		4.0	3.3
% Reduction in N loading			
At 53% attenuation		20%	
at 43% attenuation		20%	25%
Cost per kg reduction in delivered load			
At 53% attenuation		-$32.52	
at 43% attenuation		-$26.82	$71.82
▨	= changes relative to Table 16.		

This shows that the N yield is higher at the lower attenuation rate, with the cost of the yield reduction now 18% lower.

In the initial analysis, the difference in attenuation rates was 4% (53% vs 57%) and in this latter scenario 10% (53% vs 43%). While this does generate a difference in economic cost, the difference is relatively small. Obviously a much greater difference in attenuation rates (say 30% vs 70%) is needed to generate a significant difference in economic cost.

5.7 Attenuation Using a Different Model

The Piako catchment was also modelled using the SWAT-Modflow-RT3D model[4], which estimated a NO_3-N load of 7.2kg per hectare, as compared to 11.8 kg TN per hectare estimated with the BACH model (Table 1). Assuming NO_3-N accounts for 80% of TN, then the BACH model results would equate to a source load of 9.4 kg NO_3-N per hectare, i.e. somewhat higher than the SWAT-Modflow-RT3D model estimate.

This means the SWAT-Modflow-RT3D model is indicating a delivered load of 7.2kg NO_3-N (i.e. 36% of source load), giving an attenuation rate of 64%, compared to the 9.4 kg NO_3-N delivered load (47%) and 53% attenuation estimated by the BACH model.

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[4] SWAT = Soil & Water Assessment Tool. WAT-MODFLOW is an integrated hydrological model that couples SWAT land surface processes with spatially explicit groundwater flow processes https://swat.tamu.edu/software/swat-modflow/. Durney et al., 2021)

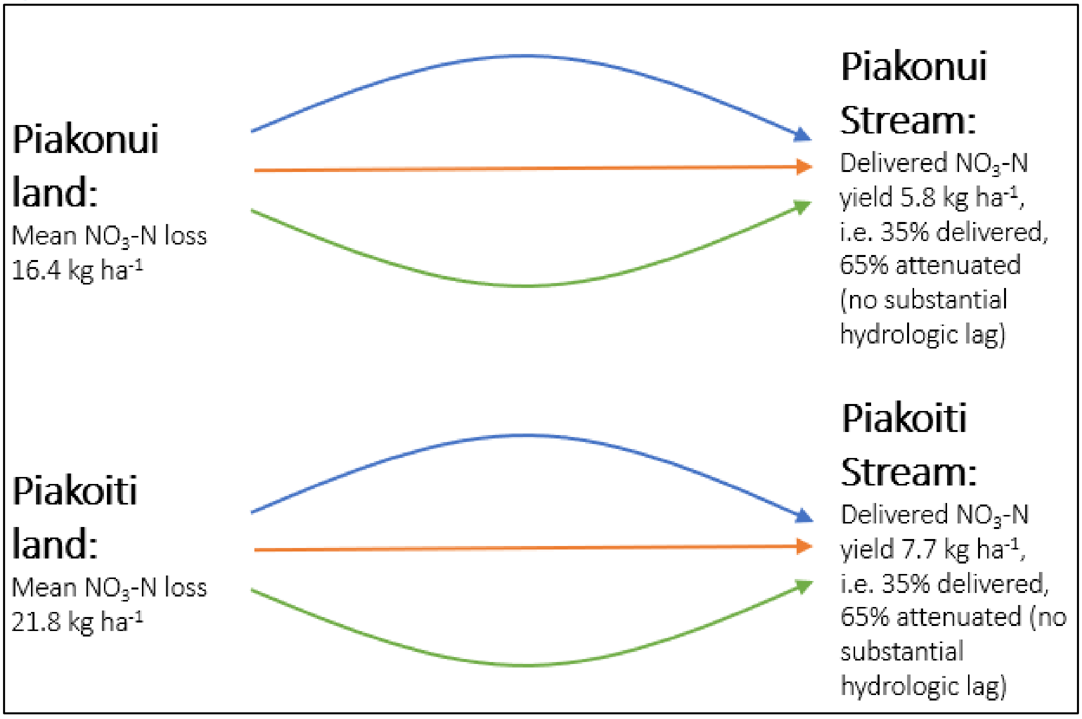
The lower delivered load modelled by SWAT-Modflow-RT3D would appear to be due to an under-estimated flow (relative to BACH), as estimated concentrations within the flow paths are very similar between the two models.

This highlights that any model is only a reflection of the unknown reality; there is always a significant portion of uncertainty involved. High-frequency flow and nitrate concentration measurements would enable determining the delivered load more accurately, which would markedly improve the evidence-base for any policy/management decisions. However, estimated attenuation rates would still remain relatively uncertain, as source load estimates (typically from OverseerFM modelling) carry a high degree of uncertainty.

5.8 Sub-Catchment Measurements

Delivered loads and attenuation rates were also estimated at a sub-catchment level within the Piako catchment. This was possible at Piako given that it was possible to monitor nitrate concentrations and flow in the two relatively large sub-catchments. In contrast, this was not possible within the Waiotapu catchment given it consisted of 10 sub-catchments. The results are illustrated in Figure 9.

Figure 9: Piako Sub-Catchment Estimates



These estimates are based on the SWAT-Modflow-RT3D model, and as can be seen, while the source and delivered NO_3-N loads differ between the 2 sub-catchments, the percentage of delivered load is the same, as is the attenuation rate. The attenuation rates also directly line up with the attenuation rate estimated for the catchment as a whole.

5.9 Farm Scale Modelling

At the farm scale, no measurements are available that would allow estimation of the delivered load. However, it is feasible to consider the fate of the N lost from the soil zone in scenarios based on a few assumptions:

- S-Map information on the soil drainage status as provided in the Overseer files was the main basis for the assumed flow path splits, and

- Different percentages were used for both catchments to account for the differences between them in topography and hydraulic properties of the subsurface environment below the soil depth (more deep groundwater recharge in the coarser volcanic deposits at Waiotapu and more lateral flows in the fine-textured Piako deposits).
- It was assumed that no significant attenuation occurs on NS pathways (as largely oxic[5]).
- N attenuation was assumed to occur in SGW and DGW where mixed or reduced redox[6] conditions were predicted for the groundwater system (Wilson et al., 2021).
- Attenuation was assumed to be 0% in oxic groundwater, 50% in groundwater with mixed redox status, and 100% in reduced groundwater.

This gave rise to the following pathway splits:

Table 10: Flow Path Splits

Assumed Splits (%)		NS	SGW	DGW
Well-drained	Waiotapu	5	10	85
	Piako	15	70	15
Imperfectly drained	Waiotapu	10	40	50
	Piako	n/a	n/a	n/a
Poorly drained	Waiotapu	40	40	20
	Piako	50	40	10

Applying this across the individual farms resulted in:

As can be seen from Table 11 below, applying this approach to the 11 farms of the study catchments results in substantially lower N attenuation estimates than what had been estimated for the catchment and sub-catchment scale. Estimated attenuation rates varied from 4 – 17% for the Piako farms, and 2 – 39% for the Waiotapu farms. Given the list of assumptions shown above, it cannot be ascertained with any certainty, which factors might be responsible for this discrepancy. However, it should be noted that the groundwater redox status predictions used originate from a national model that may not sufficiently reflect the variation within the study catchments. Moreover, the fraction of area with a particular groundwater redox status may be a poor predictor for the likelihood of nitrate being denitrified. A small section of the total flow path (e.g. a riparian zone) may be enough to denitrify a substantial fraction of the nitrate delivered on predominantly oxic pathways up to the riparian zone. Accordingly, farm-scale estimates should be interpreted as very indicative.

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[5] Oxic = Habitat where oxygen is present

[6] Redox = reduction in the oxidation state

Table 11 Individual Farm Nitrogen Flows

Piako	% flow in NS	% flow in SGW	% flow in DGW	N Loss (kg/ha)	N into NS (kg/ha)	N into SGW (kg/ha)	N into DGW (kg/ha)	N into GW (kg/ha)	GW Oxic (%)	GW Mixed (%)	GW Reducing (%)	N in Oxic GW (kg/ha)	N in Mixed GW (kg/ha)	N in Reduced GW (kg/ha)	N from GW	N from NS+GW	% of GW N delivered	% of source load delivered
Farm 1	15	70	15	29	4	20	4	25	93%		7%	23	0	0	23	27	93%	94%
Farm 2	18	67	15	25	5	17	4	21	95%		5%	20	0	0	20	24	95%	96%
Farm 3	21	65	14	19	4	12	3	15	78%		22%	12	0	0	12	16	78%	83%
Farm 4	18	68	15	24	4	16	4	20	95%		5%	19	0	0	19	23	95%	96%
Farm 5	15	70	15	20	3	14	3	17	78%		22%	12	0	0	12	16	84%	87%
Waiotapu																		
Farm 1	15	40	45	42	6	17	19	36	49%	11%	41%	17	2	0	19	25	54%	61%
Farm 2	28	39	34	27	7	10	9	20	77%	14%	9%	15	1	0	16	24	84%	89%
Farm 3	7	11	82	51	3	6	42	48	52%	32%	16%	25	8	0	32	36	68%	70%
Farm 4	22	40	38	54	12	22	20	42	94%	6%		39	1	0	41	53	97%	98%
Farm 5	19	24	57	66	13	16	37	53	49%	49%	2%	26	13	0	39	52	74%	79%
Farm 6	6	13	82	48	3	6	39	45	79%	21%		36	5	0	41	43	90%	90%

6.0 ECONOMIC IMPLICATIONS

The changes in management/farm systems to reduce nitrogen losses, and the costs and benefits therein, at a farm level, tend to vary by farm, given differences in the way farms are managed, the intensity of the farm system and the level of inputs into the system.

A number of system changes were applied to the farms in each of the catchments, using Farmax to model the farm system and calculate changes in farm profitability, and OverseerFM to calculate any resultant changes in nitrogen loss from the farm.

The systems modelled were:

Table 12: Farm System Change Scenarios

Scenario	Description
No N fertiliser	All nitrogen fertiliser was removed from the farm system, with stock numbers reduced accordingly, while per cow production was held
½ Supplements	Half of the bought-in supplements were removed, with stock numbers again reduced accordingly, while per cow production was held
Reduce Stocking Rate by 10%	Stock numbers were reduced by 10%, with per cow production increased to accommodate the surplus feed
Wintering Pad	A wintering pad was developed on the farm, to allow for on-off grazing over the winter. Most N loss occurs over the winter/early spring, which on-off grazing over this period ameliorates
Wintering Pad + Reduce SR by 10%	A wintering pad was introduced to the farm, plus stock numbers reduced by 10%, and per cow production increase accordingly

The impacts of these scenarios, on farm profitability, nitrogen source load and delivered load, based on a weighted average across the farms, were:

Table 13: Scenario Impacts Piako Catchment

	EBITDA* ($/ha)	% Reduction relative to base	N source load (kg N/ha/yr)**	% Reduction relative to base	N delivered load (kg N/ha/yr)**	% Reduction relative to base	Cost per kg N Reduction in delivered load
Base	$3,048		23.2		10.9		
No N Fertiliser	$2,874	-6%	19.8	-15%	9.3	-15%	$109
$^1/_2$ Supplements	$2,911	-4%	23.7	2%	11.1	2%	-$583
Reduce SR 10% (SR10)	$3,326	9%	22.6	-2%	10.6	-3%	-$986
Wintering Pad	$2,888	-5%	21.4	-8%	10.1	-8%	$189
SR10 + Pad	$3,166	4%	20.7	-11%	9.7	-11%	-$100

*EBITDA – Earnings before interest, tax, depreciation, amortisation

**These figures pertain to the actual farm data, not the weighted average for the catchment

Table 14: Scenario Impacts Waiotapu Catchment

	EBITDA ($/ha)	% Reduction relative to base	N source load (kg N/ha/yr)	% Reduction relative to base	N delivered load (kg N/ha/yr)	% Reduction relative to base	Cost per kg N Reduction in delivered load
Base	$4,539		46		19.8		
No N Fertiliser	$4,125	-9%	36	-22%	15.5	-22%	$96
$^1/_2$ Supplements	$4,251	-6%	47	1%	20.2	2%	-$670
Reduce SR 10%	$4,446	-2%	43	-6%	18.5	-7%	$72
Wintering Pad	$4,385	-3%	42	-9%	18.1	-9%	$90
SR10 + Pad	$4,292	-5%	39	-15%	16.8	-15%	$82

As can be seen from Tables 13 and 14, the cost per kg of reduction in delivered N load varies significantly between mitigation scenarios and between the two catchments. There is no real pattern between the two catchments, given the variation in profitability. In some instances, the cost is negative, due to one of the factors, either change in profitability or change in delivered nitrogen load being positive while the other is negative. In most instances the changes are both negative, resulting in a positive cost.

6.1 Calculations at a Farm Level

The same approach can be used to determine the cost of reducing nitrogen yield at a farm level, using the data from Table 11.

Table 15: Farm Level Cost of Reducing N Yield

Farm 1 Waiotapu	Base	Reduce SR 10%	No N Fertiliser	SR 10 + Wintering Pad
EBITDA/ha	$4,115	$3,867	$3,577	$3,682
Kg N/ha/yr loss (source load)	42	39	33	34
Attenuation	39%			
Delivered Yield kg N/ha/yr	25.6	23.8	20.1	20.7
Cost per kg reduction in delivered load		$23,285	$16,860	$10,466
Farm 3 Waiotapu	Base	Reduce SR 10%	No N Fertiliser	SR 10 + Wintering Pad
EBITDA/ha	$7,188	$6,704	$6,729	$6,606
Kg N/ha/yr loss (source load)	51	47	35	44
Attenuation	30%			
Delivered Yield kg N/ha/yr	35.7	32.9	24.5	30.8
Cost per kg reduction in delivered load		$31,143	$7,380	$21,378
Farm 3 Piako	Base	Reduce SR 10%	No N Fertiliser	SR 10 + Wintering Pad
EBITDA/ha	$5,136	$4,643	$4,883	$4,487
Kg N/ha/yr loss (source load)	19	18	17	16
Attenuation	17%			
Delivered Yield kg N/ha/yr	15.8	14.9	14.1	13.3
Cost per kg reduction in delivered load		$594	$152	$261
Farm 5 Piako	Base	Reduce SR 10%	No N Fertiliser	SR 10 + Wintering Pad
EBITDA/ha	$2,090	$1,898	$2,641	$2,484
Kg N/ha/yr loss (source load)	20	18	20	17
Attenuation	13%			
Delivered Yield kg N/ha/yr	17.4	15.7	17.4	14.8
Cost per kg reduction in delivered load		$111	$0	-$151

As can be seen from Table 15, the cost per kg reduction in delivered N load again varies significantly, depending on the profitability of the farm, the N loading onto the soil, and the related attenuation rate.

Perhaps a key observation from the analysis is that the correlation between attenuation rate and the cost of reducing delivered nitrogen load is low, as a number of other factors are also involved, especially farm profitability, with all the attendant factors that drive profitability.

6.2 Extrapolation to Average (mean) Waikato Farm

The above differential attenuation rates were extrapolated out to an average (mean) Waikato dairy farm, as a means of analysing the impact of adjusting the farm system to achieve various nitrogen loading/yield reductions.

Scenario 1: In this scenario, nitrogen loading was reduced by 20% to ascertain the difference in nitrogen load reduction, and the cost involved.

Under this scenario, the N loss from the farm was reduced down to 25.6kg N/ha from the base of 32 kg N/ha. This was achieved by removing the bulk of the nitrogen fertiliser used on the farm, which then resulted in a 12% reduction in cow numbers. Milksolids production per cow was held at the base level, which meant that total MS production also declined by 12%.

Scenario 2: in this scenario the farm system was adjusted so that the reduction in the nitrogen delivered load under the 57% attenuation was the same in absolute terms, as the reduction in delivered load achieved via the 20% load reduction under the 53% attenuation situation.

In order to achieve this, nitrogen fertiliser input was reduced further (by 9%). Consequently, this necessitated a further reduction in cow numbers. Per cow production was maintained, so the reduction in total MS production was again directly in line with the reduced cow numbers.

The results of this analysis were:

Table 16: N Yield reduction for the average Waikato dairy farm

	Base	Scenario 1	Scenario 2
Cows	352	310	300
kg MS/cow	394	393	395
Total kg MS	133,917	117,615	114,148
EBITDA*	$390,555	$403,405	$362,170
EBITDA/ha	$3,255	$3,362	$3,018
Kg fertiliser N/ha	135	37	30
Total N/ha**	271	198	193
Kg N/ha loss (source load)	32	25	24
kg N/ha delivered load			
At 53% attenuation	15.0	11.8	
at 57% attenuation	13.8	10.8	10.3
Reduction in delivered load (kg N/ha)			
At 53% attenuation		3.3	
at 57% attenuation		3.0	4.2
% Reduction in N loading			
At 53% attenuation		20%	
at 57% attenuation		20%	25%
Cost per kg reduction in delivered load			
At 53% attenuation		-$32.52	
at 57% attenuation		-$35.55	$71.82

*Note that the total EBITDA for Scenario 1 has increased: while gross income drops as a result of the reduction in cows/milksolids production, Farm Working Expenses dropped by more, given the current high cost of nitrogen fertiliser and supplementary feed.

**Total N/ha reflects the total amount of nitrogen inputted into the farm system via; fertiliser, supplements, and clover fixation. As external nitrogen inputs are reduced, clover fixation increases to partially offset this.

The results reflect the earlier discussion:

- A proportional reduction in N source load is directly reflected in N delivered load
- The absolute reduction in delivered N load under the 57% attenuation scenario is 9% less than under the 53% attenuation scenario
- If the absolute reduction in N delivered load under the 57% attenuation situation is to be achieved as per the reduction under the 53% attenuation, then the N loading reduction needs to be 4% higher
- The cost per kg N reduction in delivered N load is slightly higher under the 57% attenuation scenario compared with the 53% scenario, for the proportional reduction, and around twice as much for the absolute reduction.
- Obviously these differences would be accentuated given a greater difference in attenuation rates
- Perhaps the key policy inference is that the better “value for money” approach is to concentrate on catchments with lower nitrogen attenuation rates first.

7.0 COST BENEFIT ANALYSIS

A cost benefit analysis (CBA) is a process whereby the present value of the sum of benefits minus costs over a set time period can be evaluated for an investment, or to compare a range of investment options.

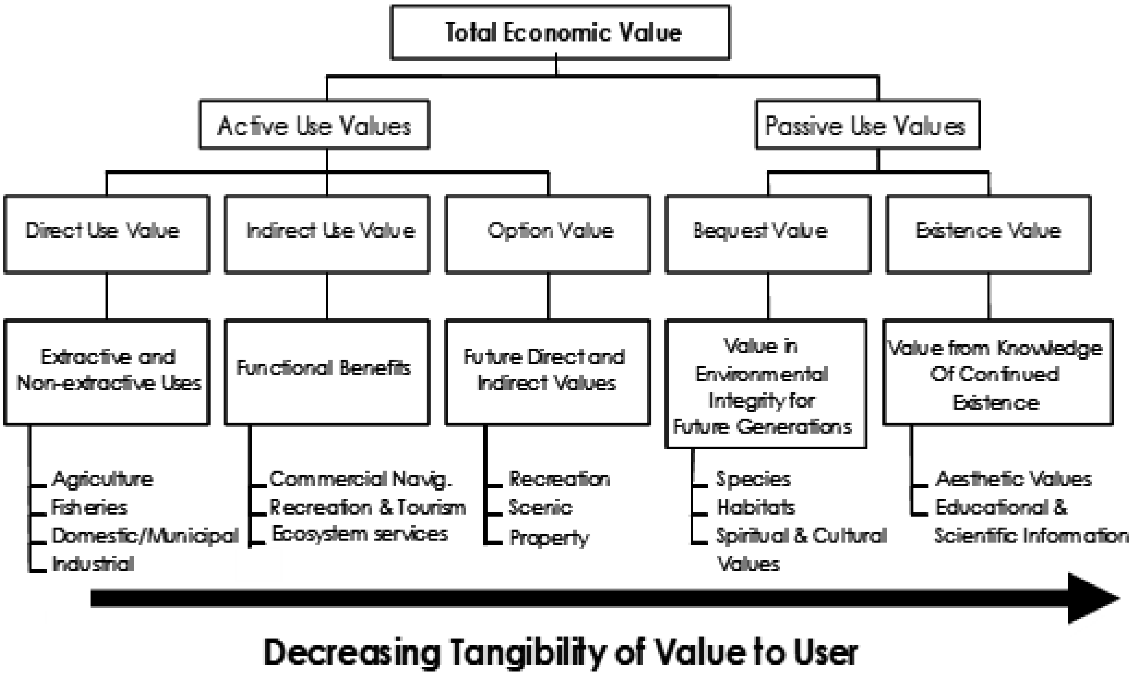
This approach can be applied to considering the economic costs and benefits, and environmental benefits, of reducing nitrogen inflows into water bodies. The issue that arises is that while the costs of reducing nitrogen flows can usually be readily calculated, it is very difficult to monetise the benefits from nitrogen inflow reductions and as such include them in the CBA. This was demonstrated in the Journeaux et al (2011) analysis of reducing nitrogen input into the Upper Waikato River catchment.

The current research has greatly aided in quantifying the physical reduction in the yield of nitrogen flowing into the waterways in the respective catchments, and the costs around this, both with respect to either a proportional or absolute reduction. The issue remains, however, around determining benefits.

The interaction of demand and supply dynamics in the marketplace reveals an individual's market value for some goods and services. However, for some goods and services a tradable market does not exist and can thus be categorised as non-market goods and services. These may include, but are not limited to, such things as air quality, ecosystem services and outdoor recreation.

Benefits from non-market goods and services can be divided into three categories, direct use values, indirect use values, and passive values. Direct use values are those associated with tangible uses or environmental resources, such as recreational use or environmental quality that impacts on human health. Indirect use values are those associated with ecosystem services while passive values are the more intangible values of environmental resources such as aesthetics. This is illustrated below:

Figure 10: Constituents of Total Economic Value



In Journeaux et al 2011

They can be further categorised as follows:

Existence value	Preservation of a resource without any current or potential active use of the resource.
Bequest value	Desire to make current sacrifices to raise the well-being of future descendants.
Altruistic value	Occurs from individual's valuing the opportunity for other people to enjoy high environmental quality.
Option value	Desire to preserve the option to use a resource in the future.
Ecological services	Include nutrient cycling, atmospheric processes, carbon cycling, clean air, clean water and biodiversity.

The valuation of environmental benefits relates to the values reflecting the well-being of society in relation to that resource and techniques have been developed to understand and measure individuals' preferences for the use of environmental resources. The two categories of techniques are revealed preference techniques and stated preference techniques.

Revealed preference techniques such as the travel-cost method (TCM) collect data on number of trips taken and the financial outlay. An example of this is the amount a fisherman may spend to travel to, and stay near, a favoured fishing spot. The TCM tends to be restricted to site specific studies such as the use of recreation parks and it fails to capture indirect use values.

The stated preference techniques of contingent valuation (CV) and choice modelling (CM) on the other hand are able to elicit these indirect use values along with the direct use values. The contingent valuation method (CV) presents hypothetical situations to respondents who reveal economic values of environmental resources through a bid vehicle. The bid vehicles ask respondents their willingness-to-pay (WTP) or willingness-to-accept (WTA) in dollar terms the hypothetical situation.

A Choice Modelling exercise was carried out by Marsh (2010) who investigated the community's willingness to pay for improvements in the water quality of the Karapiro and Arapuni hydro lakes. Respondents were asked a series of questions around their WTP with respect to suitability for swimming, water clarity, the ecological health of the lakes, and potential job losses in dairying.

A summary of the results is shown in the following table:

Table 17: WTP for environmental factors for Karapiro and Arapuni Lakes

Compensating surplus: welfare gain for change from status quo to improved outcomes (NZ$ per household per year over 10 years)				
Attribute	**Status Quo**	**Policy 1**	**Policy 2**	**Policy 3**
Swim (Chance of algal bloom)	50%	20%	10%	2%
Clarity (metres)	1m	1.5m	2m	4m
Ecology (% excellent)	40	50	60	80
Median welfare gain (assuming no job losses)		$26/year	$51/year	$86/year

The purpose of mentioning the Marsh 2010 study is that they (a) pertain to water quality, of which nitrogen contamination is a major factor, and (b) to use the WTP figures as a means of illustrating how a CBA could incorporate this data.

In the discussion on the impacts of the average Waikato dairy farm, the cost of achieving a 20% reduction in the nitrogen loading was:

- Scenario 1 (20% reduction in N loading): -$107/ha
- Scenario 2 (Absolute reduction in N yield for the 57% attenuation situation is the same as for the 53% attenuation situation): $237/ha

On the assumption that these reductions would achieve the outcomes for Policy 3 as per Table 15, then the CBA (details in Appendix 1) show:

- For scenario 1 the NPV is -$285 million
- For Scenario 2 the NPV is -$763 million

Or, turning the equation around somewhat, the "breakeven" WTP amount would need to be:

- For scenario 1 the WTP amount per household per year would need to be $311
- For Scenario 2 the WTP amount per household per year would need to be $688

Just to reiterate that these figures are not "real" – they are being used to demonstrate the CBA methodology. The key advantage of having the attenuation data is that it gives landowners and policy makers a much clearer idea of where the greatest gains can be made, for the lesser cost.

This methodology could be used at any level – farm, sub-catchment, catchment, region, or national. The key issue remains that of deriving a monetised benefit. Inasmuch as they don't exist at a farm or sub-catchment level, a cost/benefit analysis at these levels was not attempted.

8.0 GREENHOUSE GAS EMISSIONS

Due to the prominent role of agricultural greenhouse gas (GHG) emissions in the public debate and policy development in NZ (e.g. He Waka Eke Noa), changes in GHG emissions were analysed relative to the N losses to water. Actions taken to reduce nitrogen loss to water bodies often also affect GHG emissions. This represents an opportunity to identify any possibly existing synergies between them, which would minimise the economic cost of introducing mitigation measures.

The OverseerFM/Farmax analysis allows investigation into the implications of a range of mitigation measures on farm profitability, N leaching, and GHG emissions for the case-study farms as illustrated below.

Table 18: Changes in EBITDA, N Leched, and GHG Emissions. Case Study farms

Piako					**Waiotapu**				
Farm 1	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)	**Farm 1**	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)
Base			29	7.3	Base			42	11.6
No N Fert	-2%	-1%	-10%	-3%	No N Fert	-13%	-13%	-21%	-17%
1/2 Supplements	-11%	-9%	0%	-7%	1/2 Supplements	-12%	-7%	2%	1%
Reduce SR 10	-6%	3%	0%	-7%	Reduce SR 10	-6%	-6%	-7%	-10%
Wintering Pad	0%	-3%	-10%	7%	Wintering Pad	0%	-5%	-12%	1%
SR10 + Pad	-6%	0%	-7%	-5%	SR10 + Pad	-6%	-11%	-19%	-6%
Farm 2	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)	**Farm 2**	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)
Base			25	10.4	Base			27	8.0
No N Fert	-8%	-7%	-20%	-13%	No N Fert	-3%	-3%	-4%	-5%
1/2 Supplements	-6%	-9%	8%	-2%	1/2 Supplements	-7%	-3%	-7%	-4%
Reduce SR 10	-1%	0%	-4%	-5%	Reduce SR 10	2%	9%	-11%	-4%
Wintering Pad	0%	-4%	0%	2%	Wintering Pad	0%	-5%	-7%	1%
SR10 + Pad	-1%	-4%	-4%	-4%	SR10 + Pad	2%	4%	-15%	-3%
Farm 3	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)	**Farm 3**	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)
Base			19	9.6	Base			51	14.0
No N Fert	-5%	-5%	-11%	-6%	No N Fert	-7%	-6%	-31%	-10%
1/2 Supplements	-6%	-5%	5%	-2%	1/2 Supplements	-11%	-11%	2%	-5%
Reduce SR 10	-7%	-10%	-5%	-8%	Reduce SR 10	-6%	-7%	-8%	-8%
Wintering Pad	0%	-3%	-11%	1%	Wintering Pad	0%	-1%	-2%	1%
SR10 + Pad	-7%	-13%	-16%	-7%	SR10 + Pad	-6%	-8%	-14%	-7%

Table 18 continued

Piako					Waiotapu				
Farm 4	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)	**Farm 4**	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)
Base			24	8.2	Base			53	11.4
No N Fert	-9%	-4%	-21%	-28%	No N Fert	-13%	-21%	-32%	-15%
1/2 Supplements	0%	-1%	0%	0%	1/2 Supplements	-7%	-9%	4%	0%
Reduce SR 10	21%	22%	-4%	2%	Reduce SR 10	-3%	-3%	0%	-3%
Wintering Pad	0%	-8%	-8%	1%	Wintering Pad	0%	-3%	-17%	0%
SR10 + Pad	21%	14%	-13%	3%	SR10 + Pad	-3%	-6%	-17%	-3%
Farm 5	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)	**Farm 5**	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)
Base			20	6.8	Base			66	13.2
No N Fert	-9%	-9%	-10%	-10%	No N Fert	-11%	-10%	-36%	-16%
1/2 Supplements	0%	0%	0%	0%	1/2 Supplements	-9%	-7%	2%	-3%
Reduce SR 10	16%	26%	0%	-1%	Reduce SR 10	-6%	-6%	-5%	-6%
Wintering Pad	0%	-7%	-10%	1%	Wintering Pad	0%	-3%	-12%	0%
SR10 + Pad	16%	19%	-15%	2%	SR10 + Pad	-6%	-9%	-17%	-6%
					Farm 6	Kg MS	EBITDA ($)	N leached (kg/ha)	GHG (T/ha)
					Base			48	7.9
					No N Fert	-5%	-5%	-6%	-10%
					1/2 Supplements	-1%	-1%	2%	0%
					Reduce SR 10	-2%	-1%	-6%	-5%
					Wintering Pad	0%	-4%	-6%	0%
					SR10 + Pad	-2%	-5%	-13%	-6%

As can be seen from Table 18, scenarios designed to reduce nitrogen leaching have, in most instances, also reduced GHG emissions. Not applying any N fertiliser would on all 11 farms concurrently reduce N leaching and GHG emissions. However, the extent of the reductions varies substantially between farms, and would result in a drop in profitability for most of them. Halving supplements predominantly had relatively small effects, with often different directions for N leaching and GHG emissions. Moreover, this measure would decrease profitability on most farms. The implications of stocking rate reduction by 10% with increased productivity vary strongly from farm to farm, but stable or increasing profitability with concurrent environmental benefits are indicated for nearly half of them. Wintering pads can in some instances reduce N leaching without strong negative effect on profitability, but they tend to increase GHG emissions slightly. Considering economic and environmental effects, combining stocking rate reduction with a wintering pad rarely seems more beneficial than only reducing the stocking rate.

The key drivers for nitrogen leaching are the amount of nitrogen in the system, rainfall, and the drainage characteristics of the soil. The key drivers of greenhouse gas emissions at a farm level are the amount of dry matter consumed, the protein level of the feed, and the amount of nitrogen fertiliser used (which boosts dry matter production).

The correlation between the two is therefore not that straightforward. A reduction in nitrogen fertiliser can reduce nitrogen leaching, but again this is not linear, as (for pastoral farms) there is some degree of compensatory increase in nitrogen fixed by clovers, and often farmers can increase the amount of supplementary feed input, which is often a major source of nitrogen into the farming system.

Analysis of the relationship between the reduction in nitrogen leaching and change in greenhouse gas emissions across the various scenarios and across all farms involved in the trial are:

Table 19: N Leaching vs GHG Emission Correlations

		No N Fertiliser	½ Bought in Supplements	Reduce Stock Numbers 10%	Develop Wintering Feed Pad	Reduce SR 10% + Feed Pad
All farms	Correlation	0.515	0.247	0.341	-0.006	0.050
	R^2	0.265	0.061	0.116	0.000	0.002
Piako	Correlation	0.806	0.088	0.116	-0.254	-0.277
	R^2	0.649	0.008	0.013	0.064	0.077
Waiotapu	Correlation	0.707	0.472	0.336	0.204	-0.208
	R^2	0.500	0.223	0.113	0.042	0.043

Note that these figures are based on a quite small sample.

This shows across all the farms that the relationships are weak. But when the analysis is split across the two different catchments, which takes out the overlap around soil type and rainfall, the relationship between N leaching and GHG emissions for the "No nitrogen fertiliser" scenario is markedly tighter, indicating that reducing nitrogen fertiliser will result in both a reduction in nitrogen leaching, and a reduction in GHG emissions.

A similar analysis based on a different research project shows:

Table 20: N Leaching vs GHG Emission Correlations – outside project

Dairy	Reduce Stock Numbers 10%	Reduce SR 10%/Improve Productivity	½ Nitrogen Fertiliser	No Bought-in Supplement	Replace High Protein Supplement with Low Protein Supplement	10% of farm into forestry	10ha Horticulture	10ha Arable crop
Correlation	0.333	0.835	0.803	0.158	-0.261	0.793	0.536	0.344
R^2	0.111	0.698	0.644	0.025	0.068	0.628	0.288	0.118
Sheep & Beef	Reduce Stock Numbers 10%	Reduce SR 10%/Improve Productivity	10% of farm into forestry	40 ha Horticulture	100ha Arable crop			
Correlation	0.538	0.327	0.192	-0.225	-0.272			
R^2	0.290	0.107	0.037	0.051	0.074			

This shows a relatively moderate relationship for the dairy farms for the following scenarios:

- Reduce Stocking Rate 10%/Improve Productivity
- ½ Nitrogen Fertiliser
- 10% of farm into forestry

Whereas the remaining dairy scenarios and all of the sheep & beef scenarios show a relatively poor relationship.

A key outcome from this analysis is that the impact of mitigation measures on N leaching, GHG emissions, and farm profitability varies substantially between all farms. This is a direct reflection of both the intensity of the farm system, and the way the farm is managed, and as such there is no “recipe” which works equally well across all farms. Accordingly, farm-level analysis is necessary in any attempt to devise ‘ideal’ mitigation measures that are concurrently beneficial for water quality, GHG reduction, and farm profitability.

9.0 APPENDIX 1: CHALLENGES

Several challenges arise in any attempt to link the water quality observed at a stream monitoring site to land use and land management.

Firstly, there is a need to define the **'catchment area'** that is thought to contribute water, and agricultural contaminants transported by it, to the monitoring site. This catchment area is usually delineated as the area that would contribute water if excess rain would be running on the ground surface from anywhere in the catchment to the monitoring site, which represents the lowest elevation of the contributing catchment area. This 'topographical' catchment area is usually deduced from digital elevation models that are increasingly being available for all of NZ in very high spatial resolution from LiDAR surveys. However, surface runoff typically contributes only a relatively small fraction to the flow in a stream, while subsurface flows as shallow local and deeper regional groundwater contribute most of the flow. Unfortunately, groundwater catchments may differ from the surface water catchments, e.g. due to subsurface geological heterogeneity affecting flows (e.g. flow impediments or preferential flow paths). Particularly in headwater areas, it is also conceivable that not all water recharged into the groundwater system is captured at the stream monitoring site, as a fraction of the water may leave the topographical catchment as deeper groundwater that discharges into the stream at lower elevation further down in the (river) catchment. Analysis of catchment water balances can indicate if the catchment in question can be considered a 'closed' one, i.e. all water leaves on the surface water pathway. In this case, stream flow equals rainfall minus actual evapotranspiration (using long-term averages). In practice, lacking data on the area-weighted rainfall input creates a substantial level of uncertainty, particularly in catchments at higher elevation or strong topographical gradients. This is due to most existing weather stations being located in lowland areas and methods to estimate rainfall between stations (e.g. NIWA's Virtual Climate Station Network dataset) carry a substantial degree of uncertainty at higher elevations.

Secondly, it needs to be ascertained whether **lag times** in the subsurface environment need to be accounted for when linking land use to water quality. This becomes particularly important where land use intensity or stream water quality change substantially over time (years, decades). Hydrologic lags are relevant in catchments with substantial aquifer storage capacity where deep groundwater pathways are important. While transfers on the near-surface pathway (surface runoff, interflow, artificial drainage) typically occur within days to weeks, and in shallow groundwater within months to a few years, several years to decades are usually required for transfers on the deep groundwater pathway. Long hydrologic lags are therefore only an issue, where a large fraction of the water reaches the stream on the deep groundwater pathway. Additionally, biogeochemical lags may have to be considered in the case of nitrogen transfers. The most commonly described situation reported overseas is that past intensive land use has resulted in the build-up of a large pool of organic nitrogen that is immobile and residing in the soil zone. After a change to less intensive management, nitrate nitrogen concentrations only drop slowly, as gradual mineralisation of this organic pool continues to release mobile nitrate nitrogen into the percolating water. It is currently not well understood if or where biogeochemical N lags occur in NZ. Long-term average concentration or loads (e.g. 5 to 15-year periods) are often used in modelling studies to reduce the effect of hydrologic or biogeochemical lag times on the modelling results.

Thirdly, as all forms of nitrogen can undergo transformation processes during transfer in the subsurface environment, it needs to be considered whether **attenuation** processes may occur. This is particularly important for nitrate nitrogen, which under oxygen-depleted conditions often gets reduced by microorganisms to gaseous forms of N, particularly N_2 (and smaller fractions of N_2O). While denitrification within the root zone of crops is unwanted as it represents the loss of a production factor and results in the emission of the GHG N_2O, denitrification in the groundwater zone can be considered an essential ecosystem service that protects our freshwater resources against rising nitrate concentrations. Due to the much steadier and typically more reduced groundwater redox conditions, groundwater denitrification typically progresses to the production of environmentally benign N_2, while the more dynamic soil zone conditions result in a higher fraction of N_2O being released. While the vertical distribution of conditions conducive to denitrification are site specific, the NS pathway is usually much less affected than the two groundwater pathways.

It should be noted that long lag times and N attenuation both result in land use intensity changes not quickly being reflected in stream water quality changes. Accordingly, attenuation will inevitably be overestimated if lag times exist, but are not taken account of. As lag times are unknown in most instances, calculated attenuation should be considered an upper limit wherever lag times may be relevant.

10.0 APPENDIX 2: COST BENEFIT ANALYSIS

Discount Rate	5%	Govt discount rate
Number of Waikato Households	164,196	Stats NZ 2018
WTP Benefit/Household	$86	Table 17
EBITDA differential/ha, 20% N reduction		
Scenario 1	-$107	Table 16
Scenario 2	$237	Table 16
Hectares in dairying in the Waikato	476,717	Dairy Statistics 2021

Scenario 1	**NPV:**	-$284,838,300	
	Cost	**Benefit**	**Net**
Year 1	-$51,008,719	$14,120,856	-$36,887,863
Yr 2	-$51,008,719	$14,120,856	-$36,887,863
Yr 3	-$51,008,719	$14,120,856	-$36,887,863
Yr 4	-$51,008,719	$14,120,856	-$36,887,863
Yr 5	-$51,008,719	$14,120,856	-$36,887,863
Yr 6	-$51,008,719	$14,120,856	-$36,887,863
Yr 7	-$51,008,719	$14,120,856	-$36,887,863
Yr 8	-$51,008,719	$14,120,856	-$36,887,863
Yr 9	-$51,008,719	$14,120,856	-$36,887,863
Yr 10	-$51,008,719	$14,120,856	-$36,887,863
Scenario 2	**NPV:**	-$763,379,001	
	Cost	**Benefit**	**Net**
Year 1	$112,981,929	$14,120,856	-$98,861,073
Yr 2	$112,981,929	$14,120,856	-$98,861,073
Yr 3	$112,981,929	$14,120,856	-$98,861,073
Yr 4	$112,981,929	$14,120,856	-$98,861,073
Yr 5	$112,981,929	$14,120,856	-$98,861,073
Yr 6	$112,981,929	$14,120,856	-$98,861,073
Yr 7	$112,981,929	$14,120,856	-$98,861,073
Yr 8	$112,981,929	$14,120,856	-$98,861,073
Yr 9	$112,981,929	$14,120,856	-$98,861,073
Yr 10	$112,981,929	$14,120,856	-$98,861,073

11.0 APPENDIX 3: NITROGEN LEACHING/GHG EMISSION RELATIONSHIP

	No Nitrogen Fertiliser		1/2 Supplements		Reduce SR 10%		Wintering Pad		SR10 + Pad	
	N leach	GHG	N leach	GHG	N leach	GHG	N leach	GHG	N leach	GHG
Piako	-10%	-3%	0%	-7%	0%	-7%	-10%	7%	-7%	-5%
	-20%	-13%	8%	-2%	-4%	-5%	0%	2%	-4%	-4%
	-11%	-6%	5%	-2%	-5%	-8%	-11%	1%	-16%	-7%
	-21%	-28%	0%	0%	-4%	2%	-8%	1%	-13%	3%
	-10%	-10%	0%	0%	0%	-1%	-10%	1%	-15%	2%
Waiotapu	-21%	-17%	2%	1%	-7%	-10%	-12%	1%	-19%	-6%
	-4%	-5%	-7%	-4%	-11%	-4%	-7%	1%	-15%	-3%
	-31%	-10%	2%	-5%	-8%	-8%	-2%	1%	-14%	-7%
	-32%	-15%	4%	0%	0%	-3%	-17%	0%	-17%	-3%
	-36%	-16%	2%	-3%	-5%	-6%	-12%	0%	-17%	-6%
	-6%	-10%	2%	0%	-6%	-5%	-6%	0%	-13%	-6%

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