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MODELLING NITRATE LOADS TO RIVERS – EVALUATION OF IN-FIELD AND CATCHMENT-SCALE MITIGATION MEASURES

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Abstract

Freshwater accounting and management systems require a robust evaluation of various farm- and catchment-scale mitigation measures to reduce loads of contaminants in receiving waters. However, the effectiveness of in-field, edge-of-field, and catchment-scale practices at reducing the overall nitrate loads to rivers is poorly understood and difficult to quantify accounting for spatially variable nitrate transport and its potential attenuation in different flow pathways at catchment-scale. We applied an integrated farm-scale nutrient budgeting model, Overseer, with catchment-scale hydrology model, eWater SOURCE, to determine the effectiveness of farm- and catchment-scale mitigation practices on the dissolved inorganic nitrogen (*DIN*) loads in rivers within the Tararua sub-catchments, located in upper parts of the Manawatu River catchment. The model included spatially variable nitrate attenuation capacity in different flow pathways.

We modelled the impacts of three contrasting strategies, namely, (1) reductions in the root zone nitrate losses from the main land uses (dairy and sheep & beef farming), (2) matching intensive land use (dairy farming) with high nitrate attenuation capacity lands, and (3) targeted management of artificial drainage from intensive dairy farming areas.

A reduction of 10 to 30% in the average annual root zone nitrate-N losses from the sheep/beef and dairy farms resulted in a decrease of 6 to 19% in the average annual river *DIN* load in the study area. Interestingly, a reduction of 30% in the average annual root zone nitrate-N losses from sheep/beef and dairy farms only on the low to medium nitrate attenuation capacity lands resulted in a similar decrease (15%) in the average annual river *DIN* load. This highlights the crucial need to reduce the root zone nitrate losses from areas with low to medium nitrate attenuation capacity (i.e., highly permeable soils and geology, high rainfall, and low subsurface nitrogen attenuation capacity).

In a scenario of shifting about 5,313 ha of dairying on low nitrate attenuation capacity lands so that it replaced about 4,968 ha of sheep and beef farming on high nitrate attenuation lands (on LUC classes 1 – 4) resulted in a decrease of 13% in the average annual river *DIN* load. Targeted drainage management (considering 25 to 75% nitrate-N attenuated in drainage waters via a combination of controlled drainage, woodchip bioreactors, and constructed wetlands) resulted in a decrease of 4 to 11% in the average annual river *DIN* load. Combining the targeted drainage management with the matching of dairy land use with high nitrate attenuation capacity lands resulted in a decrease of 15 to 18% in the average annual river *DIN* load.

The findings of this modelling study clearly suggest that catchment-scale mitigation practices (i.e., drainage management and matching intensive land use with high nitrate attenuation capacity lands) can potentially deliver significant reduction in the river *DIN* loads, without significantly impacting farm production, and should be targeted to specific areas.

1. Introduction

Intensive pastoral systems are considered a major contributor of increased nitrate concentration in New Zealand waterways (Ball & Ryden, 1984; Quinn et al., 2009). As agriculture is a key industry in New Zealand, steps must be taken to develop targeted and effective water quality measures to reduce nitrate load in rivers, while maintaining or improving farm productivity.

A range of mitigation strategies play a pivotal role in reducing nitrate load in waterways. However, the effectiveness of these in-field, edge-of-field, and catchment-scale practices at reducing the overall nitrate loads to rivers is poorly understood and difficult to quantify. When scale, connectivity, and spatial variation in nitrate transport and its potential attenuation along flow pathways are taken into consideration, a large nitrate leaching source may not necessarily equate to a large nitrate load to rivers (Jarvis et al., 1996; Singh & Horne, 2020).

This study evaluates potential effectiveness of reductions in in-field root zone nitrate losses, and implementation of edge-of-field and catchment-scale mitigation practices, such as matching intensive land uses with high nitrate attenuation capacity land units and targeted drainage management, on reduction of dissolved inorganic nitrogen (*DIN*) loads in Tararua sub-catchments, located in Upper parts of Manawatu River catchment in the lower North Island. It applies an integrated farm-scale nutrient budgeting model Overseer, with catchment-scale hydrology model, eWater SOURCE to model nitrate transport and its potential attenuation in different flow pathways from land to receiving waters (Legarth et al., 2022).

2. Methodology

2.1 Modelling Framework

Modelling typifies the conventional scientific method for assessing nutrient exports as models can represent the complexity of agricultural and nitrogen systems, and the outputs are quantifiable (Anastasiadis et al., 2013). Legarth et al. (2022) integrated the farm-scale nutrient budgeting model, Overseer, with the catchment-scale hydrology model, eWater SOURCE, in which Overseer estimates of spatially variable average annual nitrate-N losses (kg/ha/yr) from the farm root zone of main land uses are integrated into SOURCE simulated quick flow (interflow) and slow flow (baseflow) to rivers and streams. The model included spatially variable nitrate attenuation capacity in different flow pathways and was *successfully* calibrated and validated by comparing the measured and modelling monthly river *DIN* loads in an average climatic (rainfall) year (2010) at six (6) sites in the Tararua sub-catchments (Legarth et al., 2022).

2.2 Scenarios Development

The integrated Overseer and eWater SOURCE model is applied to quantify the effect of various mitigation practices on river *DIN* loads in the Tararua sub-catchments. It is important to note that this model assumed that the mitigation practices are fully functioning, and the system had reached a steady state, resulting in average annual or monthly river *DIN* loads (Legarth et al., 2022). Additionally, this model did not consider the time lag in a stream's response to the implementation of mitigation measures.

We modelled four scenarios, as follows:

2.2.1 Baseline Scenario

The baseline scenario represents current conditions that are modelled to calibrate the integrated models for predictions of current monthly river *DIN* loads in an average climatic (rainfall) year (2010) in Tararua sub-catchments. This provides a reference to quantify the relative changes in the river *DIN* loads as affected by different in-field and catchment-scale measures.

2.2.2 In-field Mitigation Strategies

There is a wide range of in-field strategies such as fertilizer and stock management, pasture species and feeding strategies, and duration-controlled grazing (Menneer et al., 2014) that have the potential to reduce nitrate leaching from the farm root zone. Instead of quantifying effects of individual in-field measures on reduction in nitrate leaching from the farm root zone, this analysis grouped the measures to answer the question: 'if the root zone nitrate leaching is reduced by a certain percent, what would be the effect on the overall river *DIN* loads, accounting for spatially variable nitrate attenuation in different flow pathways?'

To model this scenario, the root zone nitrate losses from Overseer dairy and sheep and beef farms are reduced by 5 – 30% for all nitrate attenuation categories land units (i.e., the functional units), 30% for only those farms on low nitrate attenuation areas (noted as '30_L'), and 30% for those on low and medium nitrate attenuation areas (noted as '30_L_M'). Table 1 presents the areas of sheep and beef and dairy under each nitrate attenuation capacity functional units in Tararua sub-catchments.

Table 1. Area of dairy and sheep and beef land use under different nitrate attenuation capacity functional units modelled in the Tararua Catchment.

Land use	**Nitrate Attenuation Capacity**		
	Low	**Medium**	**High**
Sheep and Beef (ha)	26,792	104,684	66,410
Dairy (ha)	5,313	42,408	5,613

2.2.3 Catchment-scale Mitigation Strategies

Catchment-scale mitigation practises refers to those that aim to reduce river *DIN* loads over the whole catchment or a large part of the catchment, rather than on a specific farm.

Matching Land use to Nitrate Attenuation Capacity

This scenario aimed to match intensive land uses with a high potential for nitrate leaching (dairy) with areas that have a high capacity for nitrate attenuation in subsurface environment.

In this scenario, 5,313 ha of dairy on low attenuation nitrate capacity lands (Table 1) is switched with 4,961 ha of sheep and beef on high nitrate attenuation lands in LUC classes 1 – 4, as shown in Table 2. LUC classes 1 – 4 are considered suitable for dairy farming. The area of each land use type within the catchment is kept almost same to ensure the change in the amount of nitrate leaching and its attenuation rather than the land use change is assessed as a catchment-scale mitigation measure.

Table 2. Area of dairy and sheep and beef land use on high, medium, and low nitrate attenuation potential lands modelled under different land use capability (LUC) classes in Tararua sub-catchments.

LUC	Sheep and Beef (ha)			Dairy (ha)		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
1	0	107	1	-	417	-
2	0	10,615	443	0	17,463	835
3	3,460	15,667	972	1,623	12,816	197
4	1,854	6,865	3,545	1,610	4,348	560
5	669	529	7			
6	15,478	58,528	41,407	714	6,870	3,724
7	5,322	12,043	19,982	1,364	418	297
8	9	330	53	2	76	-
Total	26,792	104,684	66,410	5,313	42,408	5,613

Drainage Management

Manderson (2018) mapped the extent of artificial drainage in New Zealand. This highlights the likelihood of artificial drainage on poorly drained soils under intensive land use activities. In the baseline scenario, nitrate loads in quick flow from dairy on fine-textured (poorly drained) soils are considered as not attenuated representing potential artificial drainage facilitating the quick transfer of nitrate loss from the soil profile. However, there are various ‘edge-of-field’ practices, from controlled drainage to woodchip reactors and drainage water recycling, to manage drainage flows from agricultural lands (Singh & Horne, 2020). This scenario assumed the nitrate loads in drainage waters (interflow) from all areas of dairy on fine-textured soils are attenuated by 25%, 50% or 75% to represent targeted drainage management measures. This drainage management nitrate attenuation is applied to the quick flow component as artificial drainage is modelled as interflow, while the slow flow nitrate attenuation remained the same as the baseline scenario.

3. Results and Discussion

This section presents the simulated effect of each water quality mitigation scenarios on the average annual river *DIN* loads within the Tararua sub-catchments (Table 3). The root zone nitrogen loss refers to nitrate-N losses from the soil profile (based on the Overseer estimates), while the river *DIN* loads refer to the load of dissolved inorganic nitrogen (*DIN*) in the river and it includes nitrate attenuation in its flow pathways from land to rivers (modelled by the calibrated integrated Overseer and SOURCE model).

Table 3. Estimates of reduction in average annual root zone nitrate-N losses and river *DIN* load in the Tararua sub-catchments, modelled under various in-field and catchment-scale mitigation strategies.

Strategy	**Reduction in Average Annual Root Zone Nitrate-N Loss (N t/yr)**	**Reduction in Average Annual River *DIN* Load (N t/yr)**	**Percentage Reduction in Average Annual River *DIN* Load (%)**
In-field Dairy ‘30_all’	513	130	7
In-field Sheep and Beef ‘30_all’	770	205	11
In-field Dairy and Sheep and Beef ‘30_all’	1283	355	19
In-field Dairy and Sheep and Beef ‘30_over low and medium nitrate attenuation lands’	927	280	15
Matching Land use to Nitrate Attenuation Capacity	39	243	13
Drainage Management	0	205	11

3.1 Baseline

The baseline scenario resulted in prediction of a cumulative average annual river *DIN* load of 1,897 t/yr, as compared to estimates of the cumulative average annual root zone nitrate-N loss of 4,279 t/yr in Tararua sub-catchments. The discrete average annual river *DIN* loads in each sub-catchment ranged from 3.06 to 178.59 N t/yr, while the discrete average annual root zone nitrate-N losses in each sub-catchment ranged from 7.05 to 304.95 N t/yr. This highlights a nitrate attenuation variation from 23 to 78% across the sub-catchments depending on their nitrate attenuation capacity functional units. In this scenario, it is apparent that the root zone nitrate-N losses are translated more strongly to the river *DIN* loads in low nitrate attenuation capacity areas, while in high nitrate attenuation capacity areas, there is a significant reduction between the average annual root zone nitrate-N losses and the average annual river *DIN* loads.

3.2 In-field Measures

This scenario assumed a reduction of 5 to 30% in the root zone nitrate-N losses from dairy farming and sheep and beef areas achieved by adoption of appropriate in-field measures such as fertilizer and stock management, pasture species and feeding strategies, and duration-controlled grazing (Menneer et al., 2014).

The results of this modelling analysis indicated that a reduction of 30% in root zone nitrate-N losses assumed over both sheep and beef and dairy farming areas would result in a maximum reduction of 19% in overall average annual river *DIN* load (Table 3; Figure 1). Interestingly, a 30% reduction in the root zone nitrate-N losses over only low to medium nitrate attenuation capacity lands also resulted into a reduction of 15% in overall average annual river *DIN* load (Table 3; Figure 1). This clearly highlights that a uniform reduction in the root zone nitrate leaching may not necessarily equate to an equal reduction in river *DIN* loads in the study sub-catchments. This is attributed to spatial variability of nitrate attenuation capacity of different land units (i.e., combinations of soils, underlying geology, and groundwater redox conditions) in the study catchments. A targeted reduction in the root zone nitrate leaching from low to medium nitrate attenuation capacity land units appears to be more efficient and effective in reducing river *DIN* loads in the study catchments.

These results clearly highlight there is little gain to be made by reducing root zone nitrate losses in dairy and sheep and beef farms over high nitrate attenuation areas as the reduction is already taken care of by the system and by applying reductions to the root zone nitrate losses in dairy areas over only low and medium nitrate attenuation capacity areas, similar reductions in the overall river *DIN* loads can be achieved.

It is also important to note that to achieve a 30% reduction in root zone nitrate losses, it is highly likely that farm production will be compromised. Research by the Dairy NZ Economics Group (2014) found that on a Waikato dairy farm, a 10% reduction in root zone nitrate leaching per hectare can be achieved with a minimal impact on farm profit and production. However, reductions in root zone nitrate leaching of greater than 20% will generally have an impact on farm operating profit and production of more than 10%.

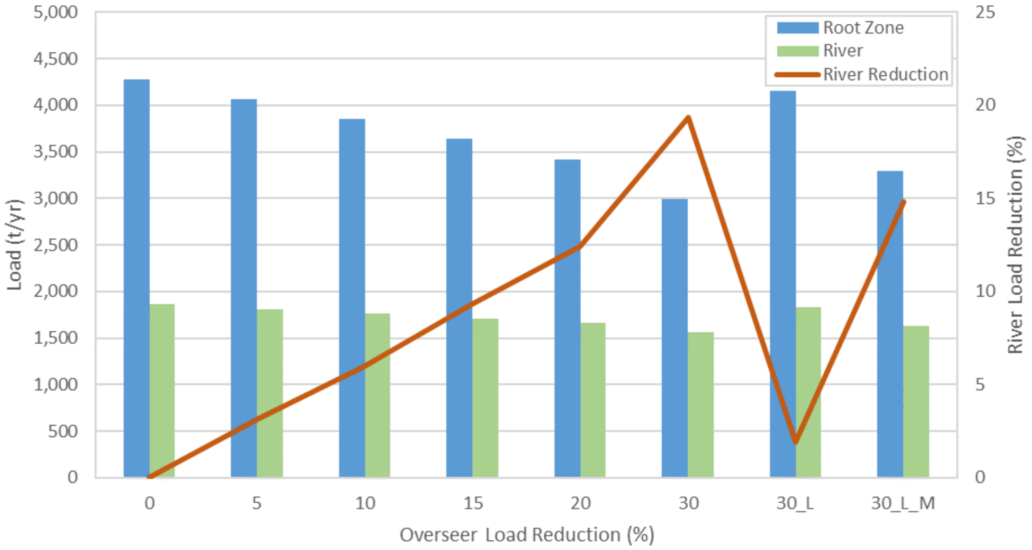

Figure 1. Potential impacts of percent reduction in dairy and sheep and beef root zone nitrate-N losses on the cumulative average annual root zone nitrate-N losses and river *DIN* loads in the Tararua sub-catchments.

3.3 Catchment-scale Measures

Matching Land use to Nitrate Attenuation Capacity

In this scenario of switching 5,313 ha of dairy on low attenuation nitrate capacity lands with 4,961 ha of sheep and beef on high nitrate attenuation lands in LUC classes 1 – 4 (as shown in Table 2) reduced the average annual river *DIN* loads at the catchment outlet by 236 t/yr tonnes or 13% (Table 3; Figure 2). The cumulative root zone nitrate-N losses are simulated very similar between this scenario and the baseline (Table 3) because the decrease in the root zone nitrate losses caused by the shift of dairy off higher permeability soils and geology ‘low nitrate attenuation capacity’ lands is offset by a similar increase in the root zone nitrate losses generated from sheep and beef shifted to higher permeability soils and geology land units.

In this scenario, the reduction of 13% in the average annual river *DIN* loads is mainly driven by higher attenuation of nitrate leaching from dairy farming over high nitrate attenuation capacity functional units. For example, the root zone nitrate-N loss for in the sub-catchment SC 23 increased by 22 t/yr, but the river *DIN* load only increased by 3.7 t/yr due to the high nitrate attenuation capacity functional units in the sub-catchment. This scenario resulted into significant differences in the spatial distribution of the average annual river *DIN* loads compared to the baseline scenario. The river *DIN* loads generated in the southern sub-catchments are significantly decreased, but the river *DIN* loads in the north-eastern sub-catchments are slightly increased.

This indicates that there is scope within the Tararua sub-catchments to reduce river *DIN* loads by further matching intensive land use with high nitrate attenuation capacity areas. However, there could be practical barriers to implementing this scenario. For example, dairy is easier to farm on free draining soils and the true effectiveness of the mitigation strategy depends on the likelihood of uptake by farmers. To implement this strategy, a coordinated approach across the whole catchment would be needed, but dairy farmers may not be willing to switch to operating sheep and beef farms, and vice versa (Samarasinghe et al., 2012). There is also likely to be a significant cost involved with converting sheep and beef to dairy farming. However, the strategy would probably be achievable on a small scale where a single farm operates both dairy and sheep and beef and only farms the dairy on the high nitrogen attenuation lands of their farm. This needs further research on potential alignment of matching intensive land use activities to high nitrate attenuation capacity areas in the sub-catchments.

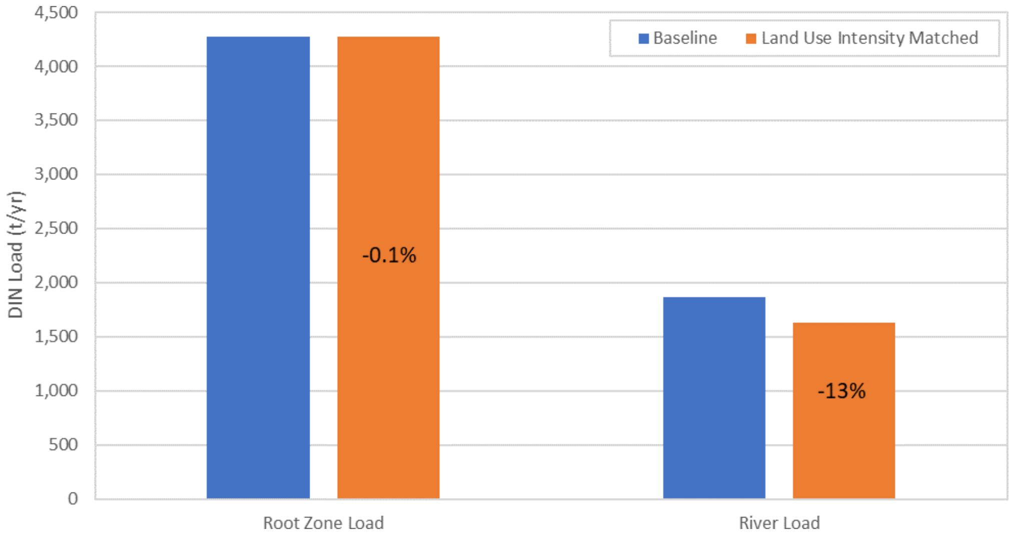

Figure 2. Potential impacts of matching intensive land use (dairy farming) with high nitrate attenuation capacity, on the cumulative average annual root zone nitrate-N losses and river *DIN* loads in the Tararua sub-catchments.

Drainage Management

Modelled drainage management (considering 25 to 75% attenuated nitrate in drainage waters via a combination of controlled drainage, woodchip bioreactors, and constructed wetlands) resulted in a decrease of 4 to 11% in the average annual river *DIN* load (Figure 3).

The temporal profile of river *DIN* loads also changed in this scenario, with the river *DIN* loads similar to the baseline scenario during the summer months November to March but significantly less during other months April to October. This can be explained by less interflow (representing artificial drainage) being simulated during summer months in comparison to winter months.

However, drainage management has no impact on the root-zone nitrate losses and allows production levels to remain the same.

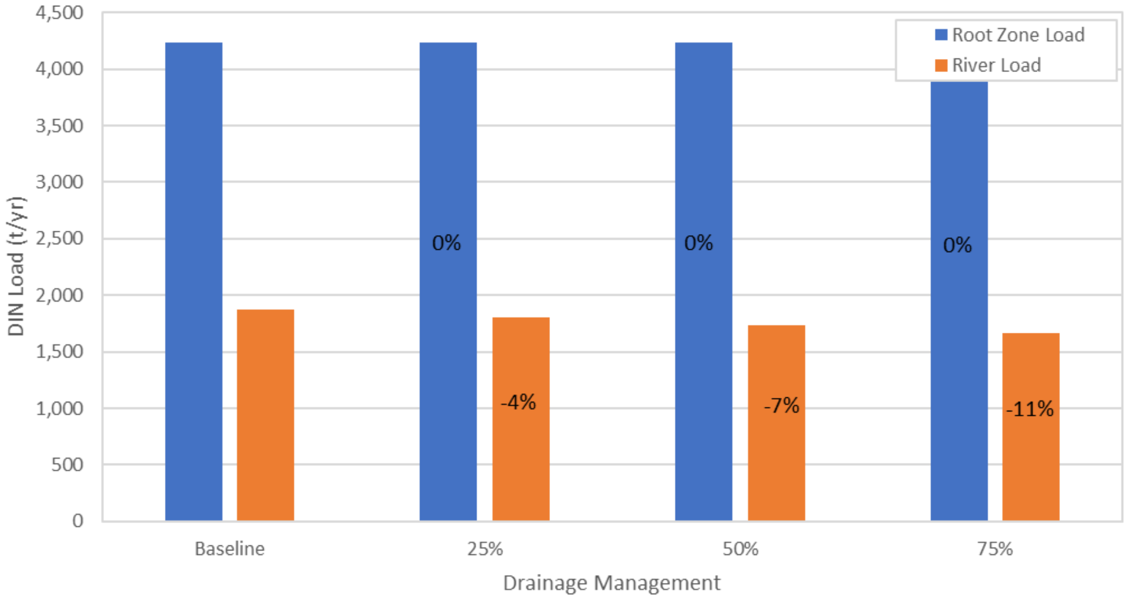

Figure 3. Potential impacts of drainage management on the cumulative average annual root zone nitrate-N losses and river *DIN* loads in the Tararua sub-catchments.

The catchment-scale measures combining the targeted drainage management with the matching of intensive (dairy) land use with high nitrate attenuation capacity lands resulted in a decrease of 15 to 18% in the average annual river *DIN* load (Figure 4).

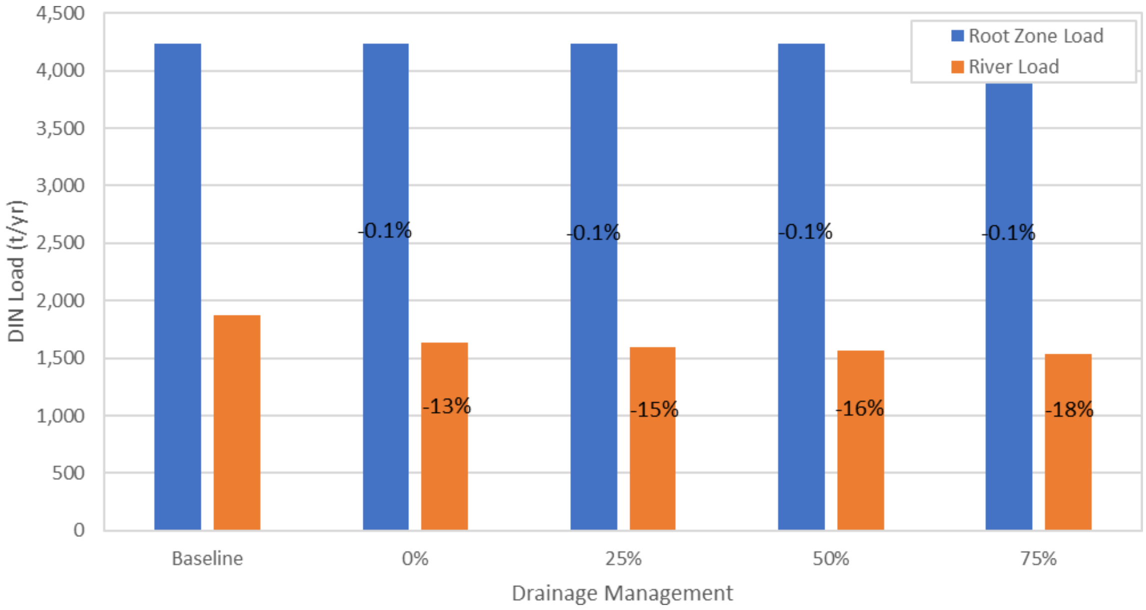

Figure 4. Potential impacts of drainage management and matching of intensive (dairy) land use with high nitrate attenuation capacity lands, on the cumulative average annual root zone nitrate losses and river *DIN* loads in the Tararua sub-catchments.

4. Conclusion

The modelling analysis presented here highlights that catchment-scale mitigation strategies, if developed and utilised effectively, can deliver improved water quality outcomes while maintaining intensive agricultural production systems. The modelling results suggest that targeted management of drainage (quick flow) from fine-textured soils under intensive dairy land use is likely the most effective mitigation practice, especially when the quantity of river *DIN* load reduced, impact on farm production, and ease of its implementation is considered.

This study adds to the growing body of research that indicates catchment characteristics should be considered when managing water quality outcomes. The spatial variability in nitrate attenuation and differences between the root zone nitrate losses and the river *DIN* loads highlight the need to focus on sub-catchments with low nitrate attenuation areas when applying mitigation measures. Targeted mitigation measures should be applied to sub-catchments that have highly permeable geology and soils produce greater groundwater flow as do those with high rainfall, which contributes relatively to large river *DIN* loads. The analysis of in-field practices, simulated as % reduction in the root zone nitrate-N losses, also highlights the need to not just confine mitigation measures to dairy farms as sheep and beef farms can also contribute to large reductions in cumulative river *DIN* in the whole Tararua Catchment due to their large area.

The findings of this research facilitate a more comprehensive understanding of nitrate flow pathways and its potential attenuation options in agricultural catchments. This information is critical to assist with decisions and policy surrounding future use and management options that could be prioritised to improve water quality outcomes in agricultural landscapes. However, this integrated modelling approach requires further ground truthing or ‘validation’, including any potential uncertainty analysis in its results. Also, a natural progression of this work is to conduct a robust cost-effective analysis ($/kg N reduced) to help develop blueprints of cost-effective targeted nitrate reduction strategy in agricultural catchments.

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