Legarth, L., Singh, R., and Horne, D.J. 2022. Modelling nitrate loads to rivers - integration of farm-scale and catchment-scale models including spatially variable nitrate attenuation capacity. In: *Adaptive Strategies for Future Farming*. (Eds. C.L. Christensen, D.J. Horne, and R. Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 34. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand. 17 pages.

# MODELLING NITRATE LOADS TO RIVERS - INTEGRATION OF FARM-SCALE AND CATCHMENT-SCALE MODELS INCLUDING SPATIALLY VARIABLE NITRATE ATTENUATION CAPACITY

**Elise Legarth[1], Ranvir Singh[1,2], and David J. Horne[1,2]**

[1]*School of Agriculture and Environment, Massey University, Palmerston North, New Zealand.*
[2]*Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand.*

## Abstract

Modelling offers a practical and resource efficient tool to determine effectiveness of various farm- and catchment-scale management and mitigation practices on leaching and/or runoff of nutrients (e.g., nitrogen and phosphorus) from agricultural lands to receiving waters. We developed a model framework to simulate the impact of a range of in-field and edge-of-field mitigation practices, including catchment-scale initiatives, on dissolved inorganic nitrogen (*DIN*) loads to a river. The modelling framework integrates a farm-scale nutrient budgeting model, Overseer, with a catchment-scale hydrology model, eWater SOURCE, and accounts for spatially variable nitrate attenuation capacity in different flow pathways. We explored the model's utility using a case study of Tararua sub-catchments, located in upper parts of the Manawatu River catchment.

The spatial variability of relevant catchment characteristics including climate (rainfall), land use, soils, and underlying geology is defined and mapped into a total of 3,996 functional units to parameterise the model inputs. The spatially variable average annual nitrate-N losses (kg/ha/yr) from the farm root zone (modelled by Overseer) of main land uses are integrated into the catchment-scale hydrological model assuming a mixing of the root zone nitrate-N losses into interflow and percolation to groundwater flows (modelled by SOURCE).

Nitrate attenuation factors are used to practically model the effects of different functional units' hydrogeological characteristics on spatially variable nitrate attenuation in different flow pathways. The modelled functional units are classified into low, medium, and high nitrate attenuation capacity categories according to their soil drainage class and underlying geology characteristics. Nitrate attenuation factors for each nitrate attenuation capacity category (low, medium, and high) functional units are then *effectively* calibrated for different flow pathways (i.e., quick flow and slow flow) by comparing the modelled with the observed river *DIN* loads at six (6) sites during an average climatic (rainfall) year in the study sub-catchments.

The model predicted the river *DIN* loads, on both the average year's annual and monthly basis, more accurately when spatially variable nitrate attenuation factors, based on soil drainage and underlying geological characteristics, are applied to both quick flow and slow flow pathways from different functional units across the study sub-catchments. Overall, the calculated Nash-Sutcliffe efficiency (*NSE*) values (0.6 to 0.9) and the percent bias (*PBIAS*) (-2.7 to 1.8) suggested a very good performance of the model in prediction of the monthly river *DIN* loads during the average climatic (rainfall) year in the study sub-catchments.

The innovative method of integrating farm-scale models (such as Overseer) and catchment-scale models (such as SOURCE), including spatially variable nitrate attenuation capacity in different flow pathways, as described here is recommended to be further developed, evaluated, and applied in other catchments. This will help to identify targeted and effective water quality management measures from farm- to catchment-scale.

## 1. Introduction

This research aims to develop a modelling framework to integrate farm-scale and catchment-scale models, including spatially variable nitrate attenuation capacity, to determine effectiveness of various farm- and catchment-scale management and mitigation practices on dissolved inorganic nitrogen (*DIN*) loads in rivers.

Modelling offers a practical tool to assess water quality management measures. However, most of currently available models are classified as either farm-scale or catchment-scale models (McDowell et al., 2014). Farm-scale models provide estimates of nutrient loss on a farm, paddock, or plot scale, and are often used to assess effectiveness of farm management decisions on nutrient losses from the farm boundary (Anastasiadis et al., 2013). Farm-scale models such as Overseer (Wheeler, 2016) account for nutrients inflows, cycling and losses from the soil profile and generally estimate the amount of nutrients that are lost from the topsoil layers (~60 cm soil profile) (Drewry et al., 2006). In contrast, catchment-scale models consider nutrient loss from the entire catchment and are typically used to model nutrient transport including their spatial and temporal variability in different flow pathways (Bouraoui & Grizzetti, 2014). However, catchment-scale models are generally limited in their capability to account for details of nutrients cycling and losses from the soil profile at a farm-scale.

There are many inadequacies with using either farm-scale or catchment-scale models independently. Farm-scale models are very limited in their ability to account for nutrient transport and transformation processes, including spatially variable nitrate attenuation capacity as affected by different hydrogeological settings (Elwan et al., 2015). Conversely, catchment-scale models are limited in their ability to fully model nutrient cycling and losses from the soil profile at farm-scale, particularly in pastoral systems. Hence, integration of farm- to catchment-scale models is necessary, including spatially variable nitrate attenuation capacity, to help assess potential effects of both farm- and catchment-scale mitigation measures on *DIN* loads in receiving waters.

In this study, we aimed to integrate the farm-scale nutrient budgeting model, Overseer, with the catchment-scale hydrology model, eWater SOURCE, and account for spatially variable nitrate attenuation capacity in different flow pathways. We explored the model's utility using a case study of Tararua sub-catchments, located upstream of the Manawatū Gorge in the south of New Zealand's North Island. The sub-catchment's area is approximately 3200 $km^2$ and comprises of a range of forest, sheep and beef and dairy farming land uses on a range of soils and underlying geology land units, representative of typical landscape characteristics of lower North Island of New Zealand.

## 2. Methodology

### *2.1 Model Framework*

Figure 1 presents a schematic overview of the modelling framework to integrate the Overseer and eWater SOURCE models as an integration of farm-scale and catchment-scale nutrient transport and transformation processes, including spatially variable nitrate attenuation capacity, of different land units.

Overseer is a commonly used model in New Zealand which produces estimates of long-term average annual nutrient losses (kg/ha/yr) via drainage and runoff at a farm scale (Wheeler, 2016). eWater SOURCE is a catchment-scale hydrological modelling platform, with flexible architecture that allows plugins and external data to be provided and integrated in hydrological processes and flow-pathways (Vaze et al., 2012). In this study, eWater SOURCE is used in conjunction with the embedded catchment-scale rainfall-runoff model, SIMple HYDrology (SIMHYD), and the farm-scale nutrient generation model, Overseer to predict average annual and monthly loads of *DIN* in receiving rivers & streams (Fig. 1).

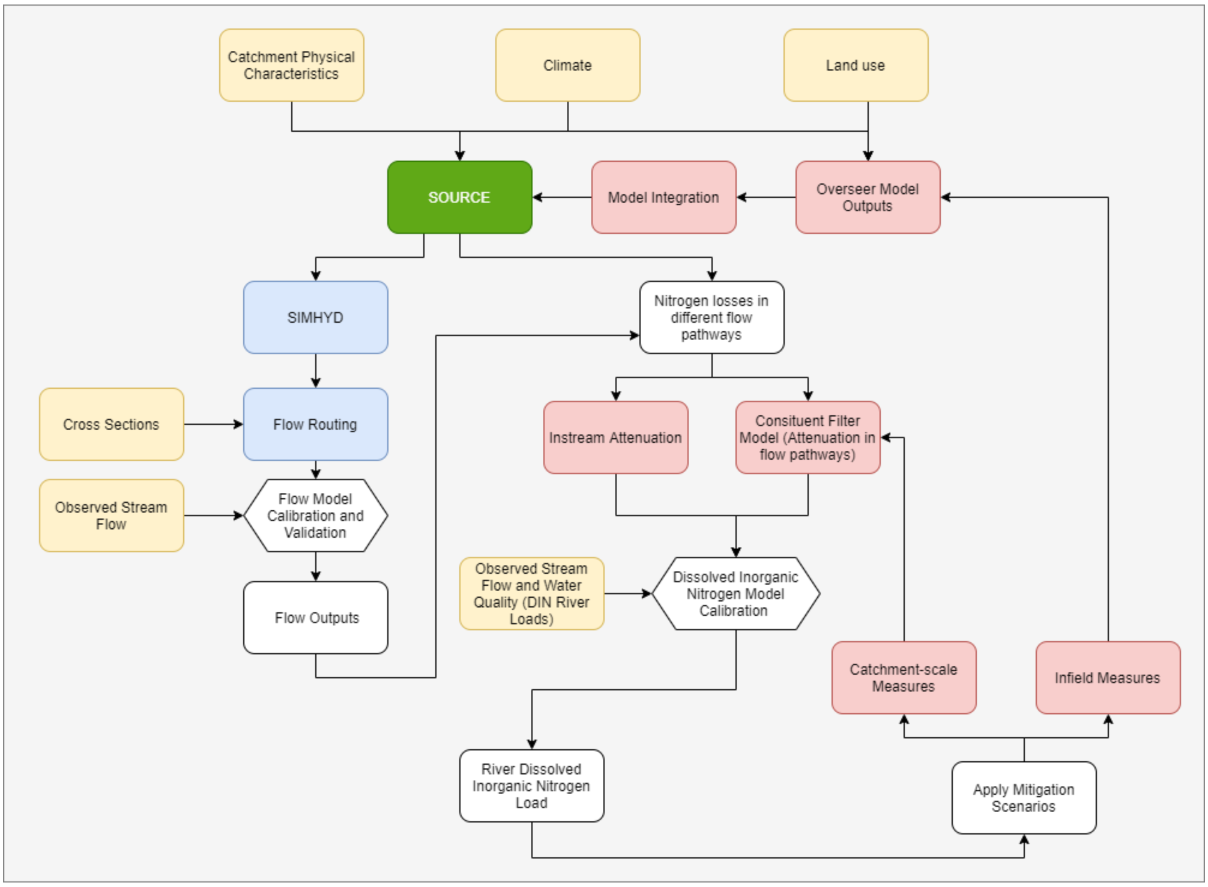



Figure 1. A schematic overview of integration of farm-scale, Overseer and catchment-scale, eWater SOURCE models for simulation of average annual and monthly river dissolved inorganic nitrogen (*DIN*) loads in the Tararua sub-catchments.

### *Functional Units*

A total of 3,996 functional units (i.e., hydrologic response units) are used to model the spatial variability of relevant catchment characteristics including climate, land use, soils, and underlying geology across the sub-catchments. The functional units divided each sub-catchment into areas of similar hydrological behaviour and informed the parameterisation of the model's inputs related to: rainfall runoff, water flow pathways, and nitrate generation and its potential attenuation in different flow pathways. Use of a semi-distributed approach, by separating sub-catchments into spatially separate areas, allowed parameters to remain consistent across each functional unit and increased the model's ability to represent spatially variability of physical characteristics within each sub-catchment.

Functional units are developed based on the relevant catchment characteristics as follows:

- Sub-catchments (incl. topography, slope and for flow a unique climate for each sub-catchment).
- Climate (for nutrient generation, climate is split into 3 regimes of low, average, and high rainfall areas).
- Land use (main land uses including dairy, sheep and beef, urban, and forest areas).
- Soils (fine texture, poor natural drainage, intermediate texture, imperfect drainage, coarse textures, well-drained and stony soils, excessive drainage).
- Geological permeability (a classification of 'Low' was assigned to mudstone and peat, 'Medium' was assigned to sandstone and limestone, and a classification of 'High' was assigned to gravels).
- Nitrate attenuation capacity (assigned as low, medium, and high based on combinations of soils, their drainage classes, and underlying geology).

***Water flow pathways***

The lumped conceptual rainfall-runoff model, SIMHYD, available in SOURCE (eWater, 2018), is used to model different water flow pathways (i.e., surface runoff, interflow, and percolation to groundwater) from the soil profile. SIMHYD is a mass balance model that is based on conceptual relationships between different hydrological processes and estimates daily stream flow from daily rainfall and potential evapotranspiration data (Singh et al., 2009). The model contains three water stores, for interception loss, soil moisture, and groundwater, and estimates runoff generation from three processes - infiltration excess runoff, interflow (and saturation excess runoff), and baseflow.

The SIMHYD requires input parameters such as baseflow coefficient, infiltration coefficient and shape, interflow coefficient, rainfall interception store capacity, recharge coefficient, and soil moisture store capacity (Singh et al., 2009, eWater, 2018). In this study, a range is defined for each input parameter of SIMHYD for each functional unit and sub-catchment. This sets boundaries for the parameter's calibration based on the associated catchment characteristics and their variability across the sub-catchments. Using the Shuffled Complex Evolution calibration process (eWater, 2018), the input parameters are adjusted within their defined ranges, which allowed a consistent relationship between the model parameters and the physical characteristics of the functional unit to be maintained.

There is a high level of confidence in the model's ability to predict river flow in the study sub-catchments. The simulated hydrographs indicated the timing of river flow and seasonal trends are successfully simulated (Figure 2) and the simulated flow duration curves demonstrated that the frequency distribution of the modelled and measured flows are similar (Figure 3). Figures 4 and 5 present the low performing calibration of the hydrology model for the Mangatainoka river at Pahiatua. Even, at this site, the model achieved a Nash–Sutcliffe model efficiency coefficient (*NSE*) of 0.6 and a percent bias (*PBIAS*) of 15.3 for average daily river flow simulations for the Mangatainoka river at Pahiatua. Overall, the calibrated model performance statistics ranged from 0.6 to 0.8 for *NSE* and 15 to -2 for *PBIAS* for average daily river flow simulations across the six sites in the study sub-catchments, resulting in the model performance evaluations of between Satisfactory and Very Good (Moriasi et al. 2015).

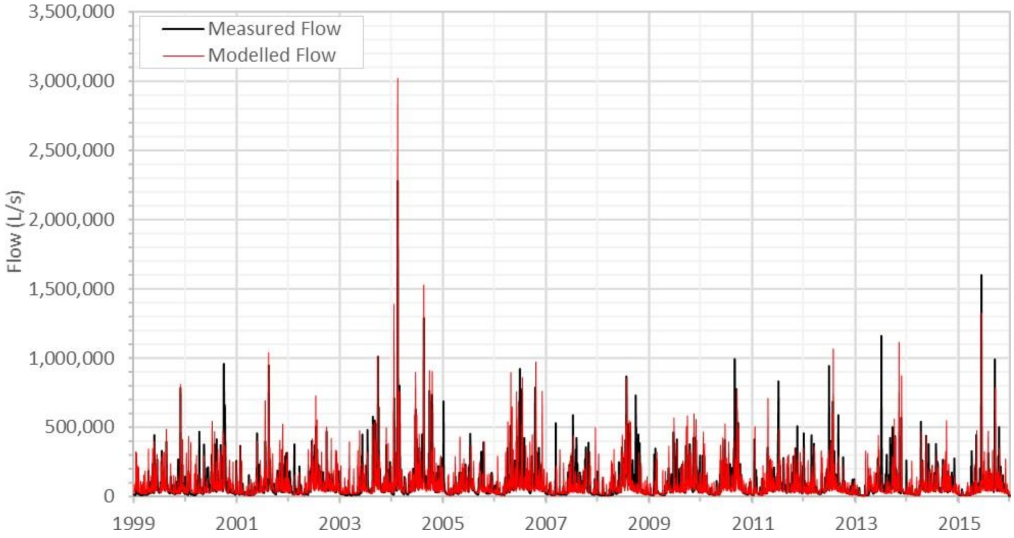



Figure 2. Hydrograph of the measured and modelled daily flow (litres per second) at Manawatū at Upper Gorge over 16 years from 1999 to 2015.

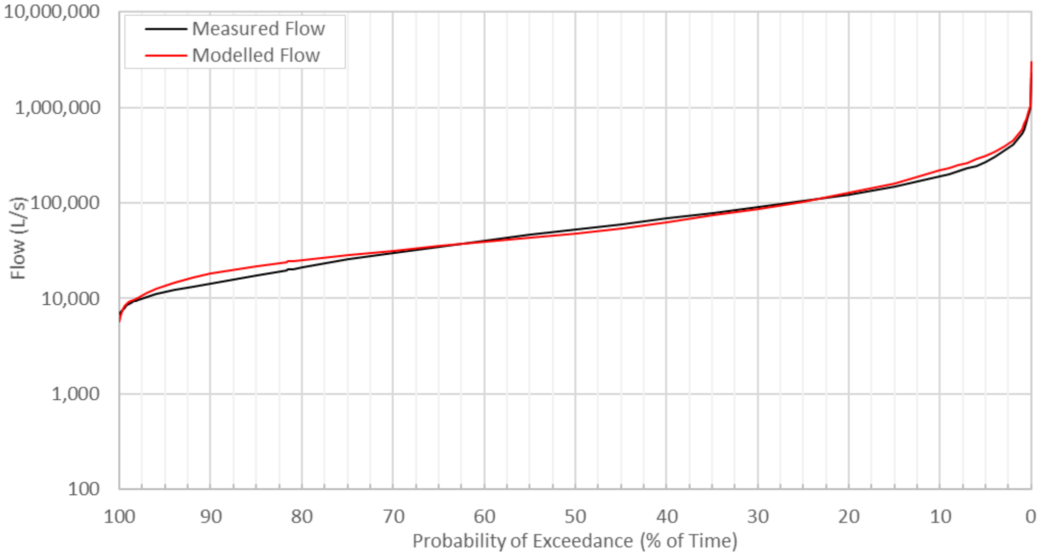



Figure 3. Flow duration curve of the measured and modelled daily flow (litres per second) at Manawatū at Upper Gorge over 16 years from 1999 to 2015.

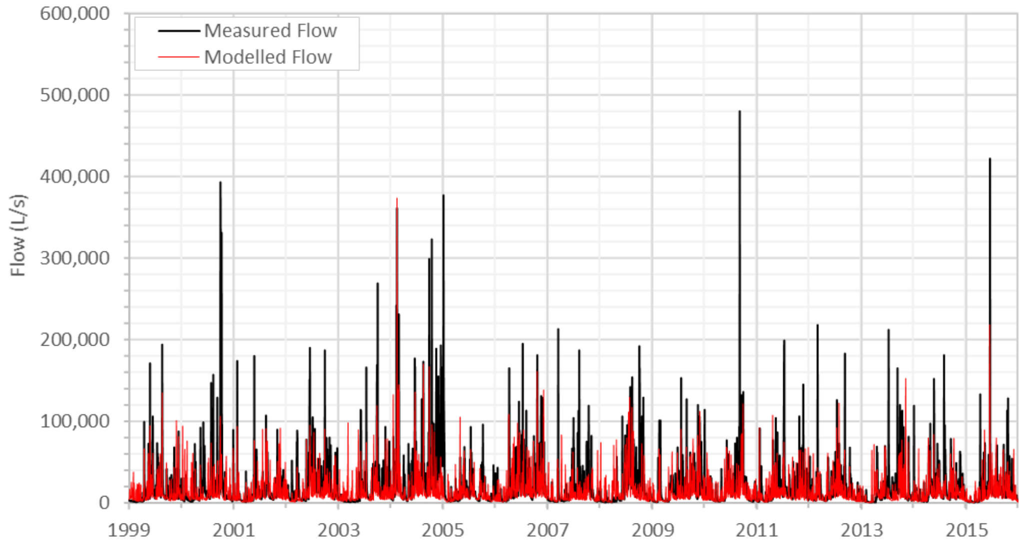



Figure 4. Hydrograph of measured and modelled daily flow (litres per second) at Mangatainoka at Pahiatua over 16 years from 1999 to 2015.

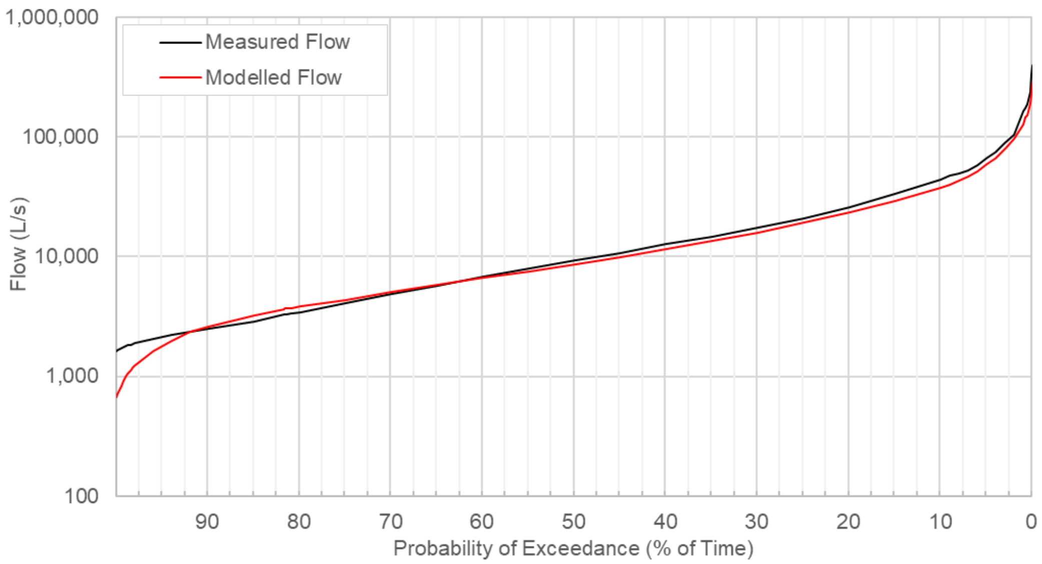



Figure 5. Flow duration curve of measured and modelled daily flow (litres per second) at Mangatainoka at Pahiatua over 16 years from 1999 to 2015.

### *2.2 Integration of the farm root zone nitrate losses into different (quick and slow) water flow pathways*

Ensuring both Overseer and SIMHYD are simulating water flows similarly is key to achieving successful integration of Overseer estimates of the farm root zone nitrate losses into different water flow pathways. Overseer simulates the leaching of nitrate from the bottom of the root zone (~ 60 cm soil profile) (Wheeler, 2016). However, nitrate leached from the root zone flows as interflow and percolation to groundwater, where the nitrate mass is temporally transposed as it travels through the unsaturated 'vadose' and saturated 'groundwater' zones beyond the soil profile. SIMHYD simulates groundwater flow processes such as percolation to groundwater and horizontal saturated groundwater flow as baseflow (slow flow) contribution streamflow, while interflow and surface run off processes are simulated as quickflow contribution streamflow (Singh et al., 2009, eWater, 2018).

However, SOURCE simulates nitrogen and water flow independently and attaches nitrogen to the model water flow pathways after it has been simulated (eWater, 2018). Therefore, the nitrogen flow does not follow through the same routing process as water flow in SOURCE simulations (eWater, 2018). This means the Overseer estimates of the farm root zone nitrate losses need to be routed and mixed with interflow and groundwater before being applied to SOURCE.

In this study, the known nutrient concentration component available in SOURCE is used, in which a monthly average nitrate-N concentration time series is applied to the quick flow (surface runoff and interflow) and slow flow (baseflow) components of each functional unit in the model. However, Overseer does not distinguish between surface runoff and groundwater nutrient transport pathways and instead estimates average annual nitrogen (mostly nitrate-N) losses from the soil profile (Wheeler, 2016). To integrate the Overseer results into SOURCE, a nitrate-N concentration calculation model is developed, described as follows.

This model assumes that the average annual nitrate-N losses from the farm root zone are perfectly mixed in all water flow pathways (except for surface runoff) throughout the year. In this, interflow is used to generate nitrate-N concentrations in quick flow, and percolation to groundwater is used to generate nitrate-N concentrations in slow flow, to better represent the seasonal nature of soil drainage and baseflow to the river.

Firstly, the annual mean nitrate-N concentration of soil drainage (interflow + groundwater percolation) is calculated by dividing the average annual root zone nitrate-N losses (i.e., Overseer output) with the annual drainage (interflow + groundwater percolation) from the soil profile 'root zone' (i.e., SIMHYD output). Then, for quick flow, the calculated mean annual soil drainage nitrate-N concentration is multiplied by the interflow for each month to give the interflow load, which is subsequently divided by the quick flow for the month to give the quick flow nitrate-N concentration for each month (Equation 1). For slow flow, the calculated annual mean soil drainage nitrate-N concentration is multiplied by the percolation to groundwater and then divided by the slow flow for each month to give the slow flow nitrate-N concentration (Equation 2). This method meant both quick flow and slow flow nitrate-N concentrations are generated for each month, as follows:

$$QF_{ci} = m\frac{\frac{N}{(P+IF)}_i * IF}{QF_i} \tag{1}$$

$$SF_{ci} = m\frac{\frac{N}{(P+IF)}_i * P}{SF_i} \tag{2}$$

where:

$m$ = Unit conversion factor;

$N$ = Annual average annual nitrate-N load from Overseer (kg/ha/yr);

$Q_i$ = Flow at $i$th month (mm);

$SF_i$ = Slow flow at $i$th month (mm);

$QF_{ci}$ = Monthly quick flow nitrate-N concentration (g/m$^3$);

$SF_{ci}$ = Monthly slow flow nitrate-N concentration (g/m$^3$);

$IF$ = Annual interflow (mm);

$IF_i$ = Interflow at the $i$th month;

$P$ = Annual percolation to groundwater (mm);

$P_i$ = Percolation to groundwater at $i$th month (mm); and

$QF_i$ = Quick flow at $i$th month (mm).

***Nitrate Attenuation***

Nitrate can be attenuated in the subsurface environment beyond the farm root zone by biogeochemical transformations in its flow pathways before entering surface waters (Singh et al., 2014; Elwan et al., 2015; Rivas et al., 2017). Singh et al. (2017) developed a nitrate attenuation factor approach to account for effects of different hydrogeological settings on potential nitrate attenuation in subsurface flow pathways. In this approach, the root zone nitrate losses estimated at the sub-soil interface are reduced by a spatially variable nitrate attenuation factor (depending on the hydrogeological settings) to match the dissolved inorganic nitrogen loads measured at the catchment outlet (Singh et al., 2017; Snelder et al., 2020). This represents a simplification of the total biogeochemical transformations of nitrate which occurs in water flow pathways. However, it is a practical solution to account for *effective* nitrate attenuation factors in catchment-scale modelling while managing complexity. Nitrate attenuation factor is defined as the difference between the root zone nitrogen (nitrate-N) losses and the measured *DIN* loads in the river (Eq. 3). The nitrate attenuation factor could vary from 0 (i.e., no nitrate attenuation) to 1 (i.e., 100% nitrate attenuation) (Singh et al., 2014; Elwan et al., 2015; Singh et al., 2017).

$$AF = \frac{Rootzone\ N\ losses - River\ DIN\ load}{Rootzone\ N\ losses} \quad (3)$$

In this study, four approaches ‘models’ are tested to apply effective nitrate attenuation factors to the simulated river *DIN* loads in the study sub-catchments. Firstly, the ‘Model1 (i.e., no nitrate attenuation)’ assumes no nitrate attenuation in its flow pathways.

In the ‘Model2 (i.e., uniform nitrate attenuation)’, a uniform factor of 0.55 is applied to represent uniform nitrate attenuation across all functional units in the sub-catchments. This is determined by calculating the nitrate attenuation at the catchment outlet (Manawatū at Upper Gorge), by comparing the Overseer estimates of the cumulative average annual nitrate-N losses from the root zone and the measured average annual *DIN* loads in the river at the catchment outlet. The average annual river *DIN* loads are quantified by applying the flow-stratified load calculation method to the daily river flows and monthly water quality samples over a period of 10 years (from 2006 to 2016) at the catchment outlet (Manawatū at Upper Gorge). In Model2 the uniform nitrate attenuation factor is applied to both slow flow and quick flow pathways.

Singh et al. (2017) and Elwan (2018) developed a simple hydrogeologic-based nitrate attenuation capacity classification of different land units defined as combinations of soil types and their underlying geology. In the 'Model3 (i.e., spatially variable nitrate attenuation)', the nitrate attenuation capacity classification is built into each functional unit to allow modelling of spatially variable nitrate attenuation capacity of different functional units in the sub-catchments. The nitrate attenuation capacity classification is displayed in Table 1, noting that greywacke differs from this classification and is assigned a low nitrate attenuation classification although it has low permeability due to the high likelihood of it being inert (Zarour, 2008).

Table 1. A preliminary classification of soils and geology to represent spatially variable nitrate attenuation capacity of different land units in Tararua sub-catchments.

| **Soil Texture / Drainage** | **Geological Permeability** | **Overall Attenuation Class** |
|---|---|---|
| Fine textured / poor drainage | High | Medium |
| Fine textured / poor drainage | Medium | High |
| Fine textured / poor drainage | Low | High |
| Intermediate textured / fair drainage | High | Medium |
| Intermediate textured / fair drainage | Medium | Medium |
| Intermediate textured / fair drainage | Low | High |
| Coarse textured / good drainage | High | Low |
| Coarse textured / good drainage | Medium | Medium |
| Coarse textured / good drainage | Low | Medium |
| Stony soils / well drained | High | Low |
| Stony soils / well drained | Medium | Medium |
| Stony soils / well drained | Low | Medium |

As per Singh et al. (2017) and Elwan (2018), the Model3 used a spatially variable nitrate attenuation factor for the classified low, medium and high nitrate attenuation capacity functional units (Table 1) in each sub-catchment. SOURCE allowed application of a spatially variable nitrate attenuation factor based on the functional units, using the percentage filter model to reduce nitrate-N loads in different water flow pathways. In the Model3, nitrate attenuation factor is only applied to slow flow, with the reasoning being that the majority of nitrate attenuation occurs in groundwaters.

However, there could be nitrate attenuation occurring in favourable conditions in both interflow as well as groundwater flow pathways. Therefore, the Model4 (i.e., spatially variable nitrate attenuation applied to different flow pathways) applied spatially variable nitrate attenuation factors for both quick flow and slow flow pathways. The basis for this is that interflow, which is included in quick flow, could be attenuated to a degree.

In the Model3 and Model4, the spatially variable nitrate attenuation factors are calibrated within a pre-defined range (in Table 2) with the aim of achieving the best possible match between the modelled and measured river *DIN* loads during an average climatic (rainfall) year

(2010) at six (6) sites in the study sub-catchments. As interflow is only one component of quick flow and is expected to be attenuated less than slow (groundwater) flow, a lower range is provided for the quick flow nitrate attenuation factor than the slow flow (Table 2). However, in the case of Model4, no nitrate attenuation factor is applied to quick flow (including interflow) for dairy fine-textured functional units (Manderson, 2018), as artificial drainage is assumed to occur, meaning that nitrate attenuation in the interflow will be bypassed.

Table 2. Calibration range for spatially variable nitrate attenuation factors when applied to both quick flow and slow flow pathways of different hydrogeological settings 'functional units' in Tararua sub-catchments.

| Nitrate Attenuation Class | Slow Flow Nitrate Attenuation Factor Range | Quick Flow Nitrate Attenuation Factor Range |
|---|---|---|
| Low | 0.10 – 0.30 | 0.0 – 0.20 |
| Medium | 0.35 – 0.70 | 0.20 – 0.40 |
| High | 0.70 – 0.95 | 0.40 – 0.60 |

## 3. Model Integration Results

### *3.1 Overseer estimates of root-zone nitrate-N losses*

The Overseer estimates of dairy farming root zone nitrate-N losses varied from 36 to 84 kg N/ha/yr depending on the rainfall regime and soil type, while the estimates of sheep and beef farming root zone nitrate-N losses ranged from 14 to 24 kg N/ha/yr. Using the Eq. 1 and 2 these estimates of average annual root zone nitrate-N loss (kg/ha/yr) are translated into the resultant monthly nitrate-N concentrations for quick flow (interflow and surface runoff) and slow flow (groundwater) from the soil profile as nitrate-N inputs into SOURCE for catchment-scale simulations.

Overall, the average monthly nitrate-N concentrations ranged from 0.1 – 7.1 mg/L in slow flow and from 0.6 - 11 mg/L in quick flow from sheep and beef functional units. In contrast, under dairy land use functional units, the average monthly nitrate-N concentrations ranged from 0.3 - 15.7 mg/L in slow flow and from 0.7 - 41 mg/L in quick flow. Limited studies have reported nitrate-N concentrations on a paddock scale, generally tending report nitrate-N losses as loads (kg/ha/yr). However, Cameron and Di (2004) found that nitrate-N concentration in leachate on a sandy loam soil under a dairy urine patch ranged from 0.5 to 60 mg/L, under a dairy urine patch and effluent the nitrate-N concentration ranged from 5 to 140 mg/L, and the control (grass) tended around 0.5 mg/L, dependant on drainage volume. Similarly, Singh et al. (2014) observed nitrate-N concentrations of between approximately 0 and 50 mg/L on a dairy farm in the Manawatu catchment. These results indicate that nitrate-N concentrations from our model are likely to be within a suitable range. However, this needs more observations to further validate the assumptions of the mixing modelling approach (Eqs. 1 and 2) used here to integrate the root zone nitrate-N losses (estimated by Overseer) into different water flow pathways (simulated by the eWater SOURCE).

### *3.2 Calibration of river dissolved inorganic nitrogen (DIN) loads*

Figure 3 shows a scatter plot comparison of the measured and modelled annual *DIN* loads in the rivers during an average climatic (rainfall) year (2010) for each nitrate attenuation scenario applied. Due to the time-consuming nature of developing Overseer models for different years and management strategies, Overseer and the integrated SOURCE model were run for an 'average' climatic year. The rainfall in 2010 compared to the annual average rainfall between 1999 and 2016 for different sub-catchments is presented in Table 5. The annual and monthly river *DIN* loads calculated for 2010 are also similar to the average annual and monthly river *DIN* loads across the six measuring sites in the study sub-catchments. For Manawatu at Upper Gorge, the river *DIN* load in 2010 was calculated at 1932.9 t/yr, compared to an annual average load of 1830.9 t/yr (2007 to 2019), while at Manawatū at Hopelands the river *DIN* load in 2010 was calculated at 672.4 t/yr compared to the average annual load of 686.9 t/yr (1989 to 2019).

Table 3. Comparison of annual rainfall in 2010 and annual average rainfall between 1999 and 2016.

| Rainfall Regime | Annual Rainfall in 2010 (mm) | Annual Average Rainfall Between 1999 and 2016 (mm) |
|---|---|---|
| Low | 1,068 | 1,103 |
| Medium | 1,358 | 1,465 |
| High | 2,275 | 2,302 |

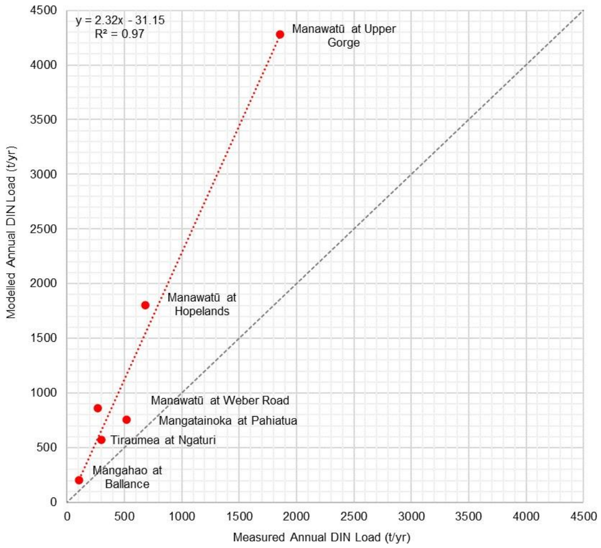
In the Model1 (i.e., no nitrate attenuation), the high *R-squared* value indicates the model's ability to simulate the spatial variation in the measured *DIN* loads between the sub-catchments. However, the gradient of the best-fit line is far greater than one (2.3), indicating that the modelled average climatic (rainfall) year's (2010) annual river *DIN* loads are significantly over-predicted and there is large attenuation of nitrate in its flow pathways from land to rivers in the study sub-catchments. Also, the nitrate attenuation needed to achieve a good calibration varied spatially, with higher nitrate attenuation needed in the northern catchments (68% at Manawatū at Weber Rd) than in the southern catchment (32% at Mangatainoka at Pahiatua).

Comparing the estimates of average annual root zone nitrate-N losses with the measured annual river *DIN* loads during the average climatic (rainfall) year (2010), this study estimated that the nitrate attenuation at each gauge ranged from 0.23 at Makuri at Tuscan Hills to 0.78 at Manawatū at Weber Road. Elwan (2018) also measured the Makuri at Tuscan Hills site as having the lowest (0.14) and at the Manawatū at Weber Road having the higher (0.74) nitrate attenuation in the Tararua sub-catchments. Based on Elwan (2018), this study estimated in-stream attenuation on nitrate-N at about 3% of the cumulative root zone nitrate-N losses in the sub-catchments. This highlights that majority of nitrate attenuation occurs in water flow pathways before entering surface waters. Considering the hydrological premise that these sub-catchments have reasonably different soil and sub-soil hydraulic properties and underlying geology, these results aid to confirm that spatial variability in nitrate attenuation occurs due to soil and geological characteristics (Singh et al., 2017; Rivas et al. 2017, Rivas et al., 2020).

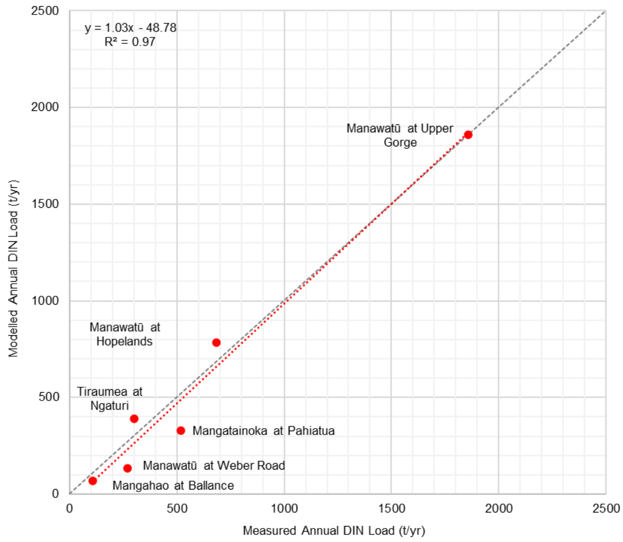
In case of the Model2 (i.e., uniform nitrate attenuation) the calibration of the average climatic (rainfall) year's (2010) annual river *DIN* load at Manawatū at Upper Gorge is evaluated 'Very Good' (Figure 3). However, the calibration of the average climatic (rainfall) year's (2010) annual river *DIN* loads varied at the rest of the monitoring sites, with both over- and under-estimation such as Manawatū at Weber Road and Tiraumea at Ngaturi (Figure 3). The difference between the modelled and the measured average climatic (rainfall) year's (2010) annual river *DIN* loads varied from -195 to +105.2 t/yr across the study monitoring sites. Moreover, Figure 4 also highlights a mismatch between the modelled and the measured average climatic (rainfall) year's (2010) monthly river *DIN* loads at Manawatū at Upper Gorge, when the Model2 of uniform nitrate attenuation is applied across the study sub-catchments.

The Model3 (i.e., spatially variable nitrate attenuation) improved prediction of the average climatic (rainfall) year's (2010) annual river *DIN* loads (Figure 3), but failed to accurately predict the average climatic (rainfall) year's (2010) monthly river *DIN* loads across the study sub-catchments (Figure 4). The Model3 resulted in underestimation of the average climatic (rainfall) year's (2010) monthly river *DIN* loads during the winter months (June – Oct.) and over-estimation during the spring, summer, and autumn months (Nov. – May) (Figure 4). The overestimation of the monthly river *DIN* loads in the summer months suggested a potentially higher attenuation of nitrate in slow (base) flow that dominates the summer flows. Similarly, the underestimation of the monthly river *DIN* loads in the winter months suggested a potentially lower nitrate attenuation in quick (surface runoff and interflow) flow that dominates the winter flows.

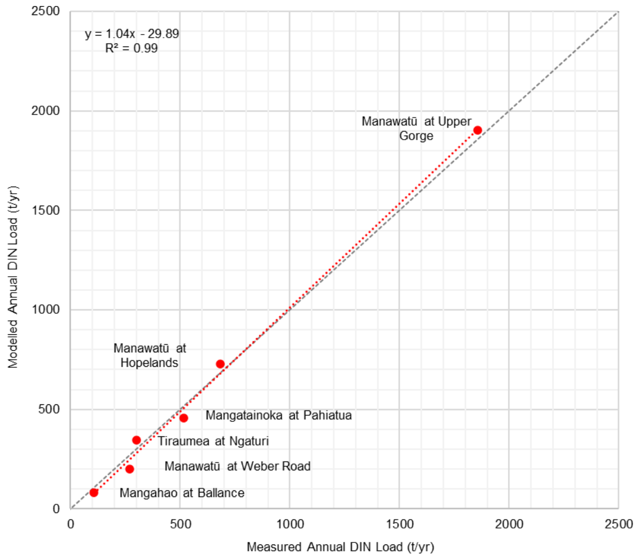
The ability of the model to simulate the average climatic (rainfall) year's (2010) annual and monthly river *DIN* loads improved significantly by applying the Model4 as spatially variable nitrate attenuation factors to different flow pathways (Figures 3 & 4). The modelled and measured the average climatic (rainfall) year's (2010) annual river *DIN* loads differed by only -4.8 to 2.9 t/yr for the study sub-catchments. The modelled and measured the average climatic (rainfall) year's (2010) monthly river *DIN* loads differed by only -6 to 98 t/yr for the Manawatu at Upper Gorge site (Figure 4). These results are confirmed by the model performance statistics in Table 4 and a comparison of the modelled and the measured river *DIN* concentrations across the study sites (Figure 5). The Model4 resulted in the lowest *RMSE* (< 23) and *PBIAS* (< 1.8), and highest *NSE* (> 0.6) in prediction of the average climatic (rainfall) year's (2010) monthly river *DIN* loads across the study sites (Table 4). This highlights the influence of spatially variable soils and underlying geology on nitrate attenuation in different flow pathways. The Model4 predicted that 15% to 81% of nitrate-N in slow flow (groundwaters) and about 6% to 46% in quick flow (interflow) is attenuated before it reaches surface water, depending on the nitrate attenuation classification for each functional unit based on their soil texture, soil drainage and underlying geology (Table 1). A comparison of the modelled average annual root zone nitrate-N losses with the modelled average annual river *DIN* loads suggested that between 12 and 86% of the root zone nitrate-N losses are attenuated across the sub-catchments.



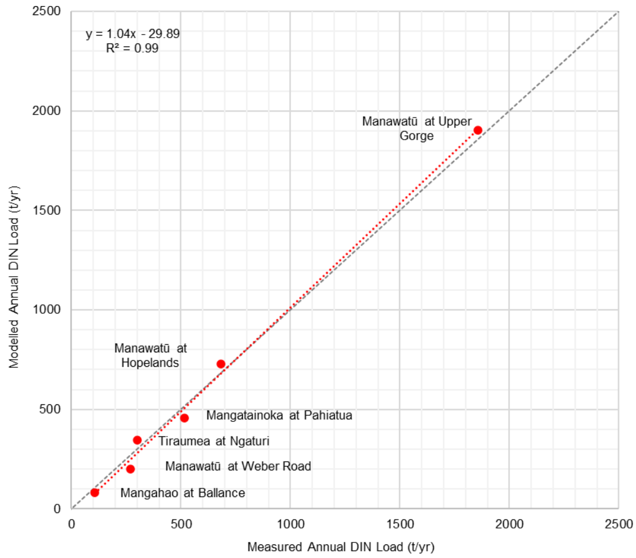

*No Nitrate Attenuation*




*Uniform Nitrate Attenuation*




*Spatially Variable Nitrate Attenuation*




*Spatially Variable Nitrate Attenuation Applied to Different Flow Pathways*

Figure 3. Comparison of the measured vs modelled river dissolved inorganic nitrogen (*DIN*) load (t/yr) during an average (rainfall) climatic year (2010) in the Tararua sub-catchments, modelled with different nitrate attenuation factors applied.

Table 4. Comparison of different nitrate attenuation models performance measures in simulating monthly river dissolved inorganic nitrogen (*DIN*) loads at different monitoring sites during an average (rainfall) climatic year (2010) in Tararua sub-catchments.

| **Model Performance Statistic** | **Nitrate Attenuation Factor (AF)** | **Overall** | **Manawatū at Hopelands** | **Manawatū at Upper Gorge** | **Manawatū at Weber Road** | **Mangahao at Ballance** | **Mangatainoka at Pahiatua** | **Tiraumea at Ngaturi** |
|---|---|---|---|---|---|---|---|---|
| ***RMSE*** | Model1, 'No nitrate AF' | 74.7 | 95.7 | 199.5 | 50.4 | 8.8 | 24.1 | 23.3 |
| | Model2, 'Uniform nitrate AF' | 28.0 | 23.6 | 79.6 | 15.4 | 2.8 | 23.1 | 9.2 |
| | Model3, 'Spatially variable nitrate AF' | 19.8 | 21.0 | 38.3 | 11.0 | 4.4 | 12.3 | 5.5 |
| | Model4, 'Spatially variable nitrate AFs applied to different flow pathways' | 13.3 | 19.5 | 23.0 | 9.1 | 4.5 | 10.9 | 4.1 |
| ***PBIAS*** | Model1, 'No nitrate AF' | -130.9 | -164.4 | -124.5 | -221.4 | -97.3 | -50.5 | -90.3 |
| | Model2, 'Uniform nitrate AF' | 24.9 | -44.5 | 4.9 | -59.2 | 57.8 | 37.1 | 36.5 |
| | Model3, 'Spatially variable nitrate AF' | 3.4 | -4.2 | 1.3 | -5.1 | 4.3 | 7.0 | 5.0 |
| | Model4, 'Spatially variable nitrate AFs applied to different flow pathways' | -0.1 | -0.1 | -0.1 | 1.8 | -2.7 | 0.4 | 0.5 |
| ***NSE*** | Model1, 'No nitrate AF' | -0.6 | -5.0 | -2.4 | -6.2 | -3.4 | 0.1 | -1.0 |
| | Model2, 'Uniform nitrate AF' | 0.8 | 0.3 | 0.7 | 0.3 | 0.5 | 0.1 | 0.5 |
| | Model3, 'Spatially variable nitrate AF' | 0.9 | 0.7 | 0.5 | 0.7 | 0.7 | 0.7 | 0.9 |
| | Model4, 'Spatially variable nitrate AFs applied to different flow pathways' | 0.9 | 0.9 | 0.6 | 0.8 | 0.7 | 0.8 | 0.9 |

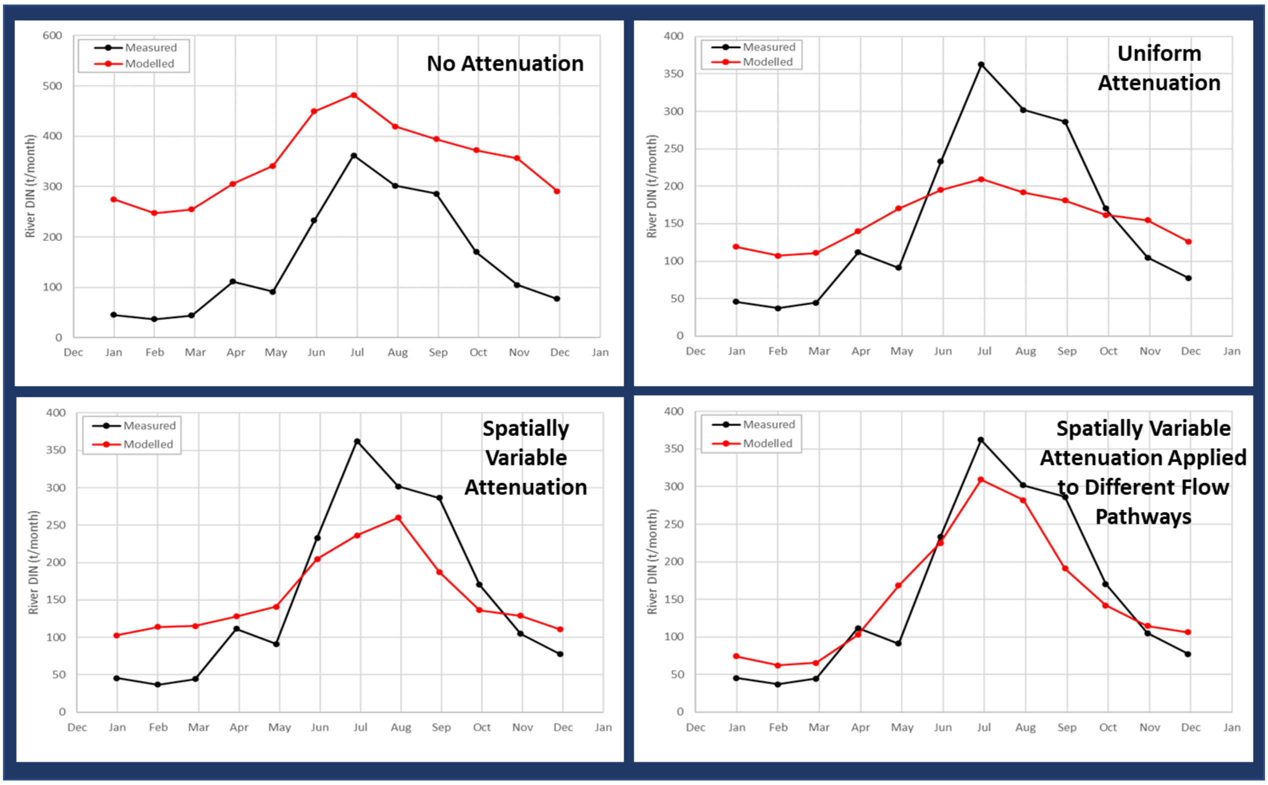



Figure 4: Comparison of the measured and the modelled monthly dissolved inorganic nitrogen (*DIN*) river loads at Manawatu at Upper Gorge during an average (rainfall) climatic year (2010), with various nitrate attenuation factor methods applied.

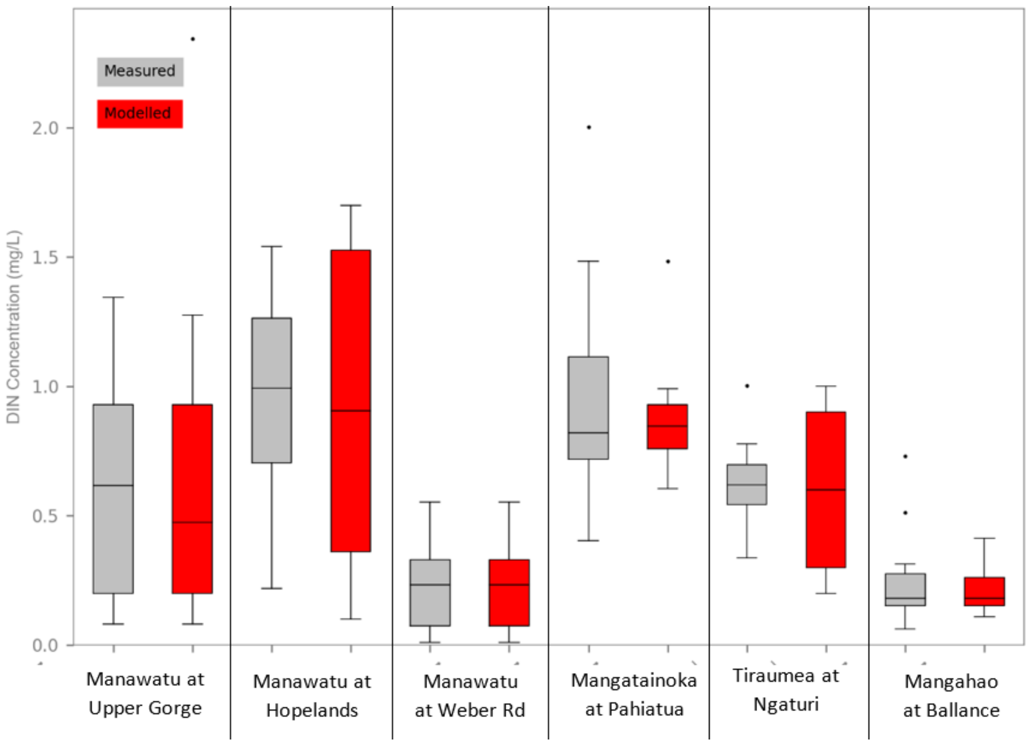



Figure 5. Comparison of the measured and the modelled monthly river dissolved inorganic nitrogen (*DIN*) concentrations at different monitoring sites during an average (rainfall) climatic year (2010) in Tararua sub-catchments.

## 4. Conclusion

Our study demonstrates potential integration of farm-scale and catchment-scale models to predict river dissolved inorganic nitrogen (*DIN*) loads in agricultural landscapes. It integrated Overseer and eWater SOURCE models to predict average annual and monthly river *DIN* loads in the Tararua sub-catchments. The developed modelling framework accounts for influences of spatially variable catchment characteristics, including soil, geology, climate, land use on nitrate losses and its potential attenuation in different flow pathways.

The SOURCE model provided the framework to integrate the Overseer outputs by setting up the sub-catchment structure and modelling the transport and transformation of flow and nitrate losses on a functional unit basis across the sub-catchments. Central to integration of the SOURCE and Overseer models is the assumption of perfect mixing of the Overseer estimates of root zone nitrate-N losses with the SOURCE flow outputs, and calibration of *effective* spatially nitrate attenuation factors applied to both the quick flow and slow flow pathways. The use of constituent filter models in SOURCE proved to be practical to calibrate and validate *effective* spatially variable nitrate attenuation capacity in different flow pathways. Application of spatially variable nitrate attenuation factors applied to different flow pathways significantly improved the model's performance, resulting in lowest *RMSE* (< 23) and *PBIAS* (< 1.8), and highest *NSE* (> 0.6) in prediction of monthly river *DIN* loads during an average (rainfall) climatic year (2010) across the study sites. This corroborates the association between physical catchment characteristics and spatially variable nitrate attenuation capacity of different land units (a combination of soil and underlying geology). However, further uncertainty analysis of in the river *DIN* loads prediction is needed to confirm the impact of *effective* parameterisation of nitrate attenuation factors, considering the potential uncertainties in the OVERSEER estimates of root zone nitrate-N losses and the measured river flows and *DIN* loads, including in-stream nitrate attenuation.

The framework developed and applied in this study to integrate farm-scale (such as Overseer) and catchment-scale models (such as SOURCE) will be instrumental to expand the scope of water quality scenarios assessment which can be helpful to plan and implement targeted and effective water quality management measures across agricultural catchments.

## References


Anastasiadis, S., Kerr, S., Arbuckle, C., Elliott, S., Hadfield, J., Keenan, B., McDowell, R., Webb, T., & Williams, R. (2013). *Understanding the practice of water quality modelling*. Motu Economic and Public Policy Research.

Bouraoui, F., & Grizzetti, B. (2014). Modelling mitigation options to reduce diffuse nitrogen water pollution from agriculture. *Science of the total environment*, *468-469*, 1267-1277. https://doi.org/10.1016/j.scitotenv.2013.07.066

Cameron, K. C., & Di, H. J. (2004). Nitrogen leaching losses from different forms and rates of farm effluent applied to a Templeton soil in Canterbury, New Zealand. *New Zealand Journal of Agricultural Research*, *47*(4), 429-437.

Drewry, J., Newham, L., Greene, R., Jakeman, A., & Croke, B. (2006). A review of nitrogen and phosphorus export to waterways: context for catchment modelling. *Marine and Freshwater Research*, *57*(8), 757-774.

Elwan, A. (2018). *Accounting of nitrogen attenuation in agricultural catchments* [Doctoral dissertation, Massey University]. http://hdl.handle.net/10179/15189

Elwan, A., Singh, R., Horne, D., Roygard, J., & Clothier, B. (2015). Nitrogen attenuation factor: Can it tell a story about the journey of nutrients in different subsurface environments? In Eds L. D. Currie and L. L. Burkitt, *Moving Farm Systems to Improved Attenuation.* Occasional Report No. 28. Fertilizer and Lime Research Centre, Massey University.

eWater. (2018). *Source User Guide 4.7*. eWater Ltd.

Manderson, A. (2018). Mapping the extent of artificial drainage in New Zealand. Report prepared for Lincoln Agritech. Contract report LC2690, Manaaki Whenua Landcare Research, Palmerston North, New Zealand.

McDowell, R., Moreau, P., Salmon-Monviola, J., Durand, P., Leterme, P., & Merot, P. (2014). Contrasting the spatial management of nitrogen and phosphorus for improved water quality: Modelling studies in New Zealand and France. *European Journal of Agronomy*, *57*, 52-61.

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Transactions of the ASABE*, *58*(6), 1763-1785. https://doi.org/10.13031/trans.58.10715

Rivas, A., Singh, R., Horne, D. J., Roygard, J., Matthews, A., & Hedley, M. J. (2020). Contrasting subsurface denitrification characteristics under temperate pasture lands and its implications for nutrient management in agricultural catchments. *Journal of Environmental Management*. 272.

Rivas, A., Singh, R., Horne, D., Roygard, J., Matthews, A., & Hedley, M. J. (2017). Denitrification potential in the subsurface environment in the Manawatu River catchment, New Zealand: Indications from oxidation-reduction conditions, hydrogeological factors, and implications for nutrient management. *Journal of environmental management*, *197,* 476-489.

Singh, R., Rivas, A., Espanto, P., Elwan, A., Horne, D. J., Roygard, J., ... & Clothier, B. (2014). Assessment of transport and transformation of nitrogen in the subsurface environment of Manawatu River catchment–work in progress. In Eds L. D. Currie and C. L. Christensen, *Nutrient Management for the Farm, Catchment and Community.* Occasional Report No. 27. Fertilizer and Lime Research Centre, Massey University.

Singh, R., Elwan, A., Horne, D., Manderson, A., Patterson, M., & Roygard, J. (2017). Predicting land-based nitrogen loads and attenuation in the Rangitikei River catchment—The model development. *Science and policy: nutrient management challenges for the next generation. Fertilizer and Lime Research Center Occassional Report, 30,* 1-13.

Singh, R., Maheshwari, B., & Malano, H. M. (2009). *Understanding the water cycle of the South Creek Catchment in Western Sydney: Catchment water balance modelling*. Cooperative Research Centre of Irrigation Futures.

Snelder, T., Cox, T., Kerr, T., Fraser, C., & Collins, S. (2020). *Manawatū-Whanganui Region catchment nitrogen models: Supporting Regional Plan Change 2*. Land Water People.

Vaze, J., Jordan, P., Beecham, R., Frost, A., & Summerell, G. (2012). *Guidelines for rainfall-runoff modelling: Towards best practice model application.* eWater Cooperative Research Centre.

Wheeler, D. M. (2016). *Technical Manual for the description of the OVERSEER® Nutrient Budgets engine*. AgResearch Ltd.

Zarour, H. (2008). *Groundwater Resources in the Manawatu-Wanganui Region*. Horizons Regional Council.