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Nutrient generation and transport at the catchment scale

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Abstract: Transport of nutrients (e.g., phosphorus) from different land uses within a catchment can negatively impact on our water resources. Nutrient generation is frequently studied at the paddock or farm scale, while the impacts on water quality occur at the catchment scale. Scaling nutrient generation and transport between the farm and catchment is important in understanding the impacts of land-use and land-cover change on water quality. There are many challenges in bridging these spatial scales including nutrient cycling through the catchment and data availability.

This paper reports on the use of the Catchment Analysis Tool (CAT) linked to 2CSalt to investigate nutrient generation and movement in the Latrobe River Catchment. CAT uses spatially distributed characteristics including land-use, rainfall, slope and soil type, to describe hydrology, and this is coupled with a land-use based nutrient generation rate to describe nutrient mobilisation within the catchment. The study area in the Latrobe River Catchment, Victoria, Australia, contains a number of stream gauging sites, with monthly nutrient data used to validate the model outcomes.

CAT linked to 2CSalt provided a good representation of catchment scale hydrology, with an acceptable coefficient of efficiency for stream flow at all ten gauges (>0.6). Nutrient generation rates based on published literature for each land-use category resulted in a good prediction of total nitrogen and total phosphorus concentrations across the ten gauges within the study area. This modelling approach provided a good prediction that was in agreement with the available input and stream gauge data.

When we included dairy into the land-use layer using three different approaches, recharge rate was the dominant factor determining whether catchment scale nutrient export increased in response. For example, locating dairying in the high flow areas, at the top of the catchment resulted in a significant increase in nutrient concentrations and loads, while locating dairying in the low flow areas, generally in valleys and near streams, resulted in no change to concentrations or loads of nutrients exported from the catchment. However due to nutrient transformations and attenuation during transport, theory would suggest that locating a high generating land use near streams at the bottom of the catchment would have a significantly greater impact than in the hills at the top of the catchment.

While, the processes of nutrient transport and attenuation are understood at a conceptual level, without more detailed knowledge of these processes, including them within the model requires nutrient generation rates to be increased so that the concentrations can be reduced (attenuated) during transport. While increasing nutrient generation rates to account for attenuation appears sensible, there is insufficient information available with which to determine the balance between generation and attenuation.

Keywords: *Nitrogen, Phosphorus, Catchment Analysis Tools (CAT), water quality.*

1. INTRODUCTION

Within Australia and around the world, eutrophication and the increasing occurrence of algal blooms in inland water systems is an important water quality issue that has significant economic and environmental impacts. Nutrients are exported from a range of sources within a catchment, including native and plantation forests, dryland and irrigated agriculture, as well as urban and point sources.

Research into nutrient exports from diffuse sources generally occurs at the plot or paddock scale for agricultural systems up to small catchment scales for forested systems. However, it is at larger scales that the complex interactions between hydrology, nutrient generation from multiple land uses, and nutrient transport through the catchment impact on water quality.

Due to the complex nature of catchments, a range of modelling approaches have been used to understand nutrient export within the catchment, and to investigate the impact of land use and management changes. Modelling approaches range from an annual nutrient loading per land use (eg. CMSS: Davis *et al.* 1996), concentration generation rates per land use (e.g., EMSS: Vertessy *et al.* 2001), to more complex integrated catchment models (eg. CatchMODS: Newham *et al.* 2004).

There are many challenges in modelling nutrient export at the catchment scale, including the availability of data to inform model development, provide model inputs and validate model outputs. For example, the two key limitations investigated in this paper are: (1) the description of land uses across a catchment in broad categories such as grazing, which provides limited detail about the range of production systems and management practices in use, and (2) the calibration and validation of model outputs using monthly nitrogen and phosphorus concentrations, which requires an assumption that single point samples can be used to validate predicted concentrations or to calculate monthly loads.

In this paper, we use the Catchment Analysis Tool (CAT) combined with 2CSalt (Weeks *et al.* 2005) to investigate nutrient generation and movement in a sub-catchment of the Latrobe River, Victoria, Australia. Through the application of the calibrated model to the catchment we investigate the impact of a high input dairy land use incorporated across different spatial locations, on nutrient predictions at the catchment scale. The paper also discusses some of the limitations associated with the available input data to build the model and available in-stream water quality data for model calibration and validation.

2. STUDY AREA

The Latrobe river in West Gippsland, Victoria, drains from the Great Dividing Range to the Gippsland Lakes and ultimately to Bass Strait. The Latrobe Catchment, upstream of Thoms Bridge (Figure 1), was used for this study.

The Thoms Bridge Study Area contained 265,000ha of land with annual rainfall varying from 825mm to 1975mm. The study area has a range of land-uses including urban and mining, forestry, grazing, and small areas of irrigated pasture and horticultural production. Grazing, representing 40% of the catchment area, is predominantly beef and dairy, ranging from low to high input systems. Forestry, representing 50% of the catchment area, includes remnant native vegetation, softwood and hardwood plantations as well as production forestry and National Parks.

The study area contains ten stream gauging stations, where daily flow as well as water quality data has been measured. Most of the gauging stations have data from the 1970's to current day; however several sites only have a few years' data.

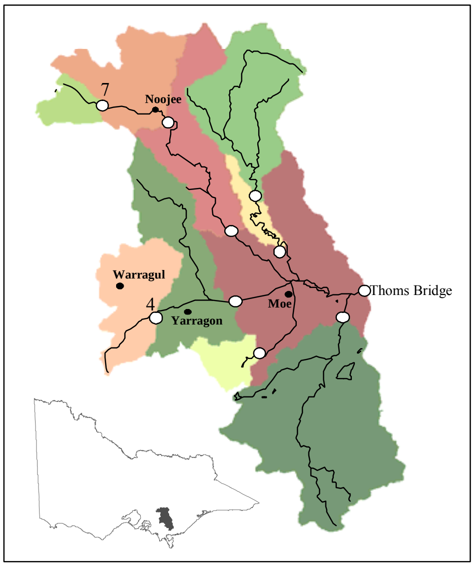

Figure 1. The Thoms Bridge Study Area in West Gippsland, Victoria, Australia, showing the stream gauges (o) and sub-catchment areas. Gauges 4, 7 and Thoms Bridge are discussed in this paper.

3. MATERIALS AND METHODS

3.1. Overview of Modelling Approach

In this study, the 2CSalt model, linked to the Catchment Analysis Tool (CAT) (Weeks *et al.* 2005), was used to describe monthly baseflow and streamflow in the Thoms Bridge study area. Nutrient generation was described for each land use using an effective mean concentration (EMC) and dry weather concentration (DWC) for quick flow and baseflow conditions respectively.

CAT was used to link land-use, soils, topography and climate data for 100x100m grids across the Study Area to the catchment-scale groundwater systems and stream flows (Beverly *et al.* 2005). In this application CAT was used to estimate surface runoff, lateral flow, evapotranspiration and recharge within the Study Area on a daily time step, with the results combined to a monthly time-step for integration into 2CSalt. The 2CSalt model was used to run a mass balance of water on a monthly time step for groundwater response units to predict baseflow and stream flow within the Study Area.

The nutrient model links the hydrological output of 2CSalt, specifically monthly baseflow and quick-flow contributions from each land unit with EMC and DWC generation rates. These are summed across the sub-catchment areas to provide predictions of monthly loads and concentrations for the sub-catchments and the whole Thoms Bridge Study Area.

3.2. Land Use and Nutrient Generation Rates

The DWC and EMC nutrient generation rates were determined for each land use in the catchment. Land use for the study area was based on the Victorian Government Corporate Geospatial Data Library, with the number of land uses reduced to ten, based on the potential ability to differentiate nutrient generation rates (Table 1). For example 'Forestry' includes softwood and hardwood plantations and production forestry. 'Livestock grazing' incorporates dairy, beef and sheep systems, with no differentiation between high and low input production systems which could significantly affect nutrient export (Drewry *et al.* 2006). In order to incorporate an estimate of high input 'dairy' area into the catchment, Australian Bureau of Statistics data were used to determine the number of dairy cows in survey regions. A Dairy Australia (2005) report was used to provide a figure for average stocking rates for Australian dairy farms, allowing an estimate of the area occupied by dairying in the Thoms Bridge Study Area to be calculated. The area of dairying was then incorporated into the land use layer using three different methods:

Table 1. Nitrogen and phosphorus generation rates per land use based on published literature

	Total Nitrogen				Total Phosphorus			
Land Use	DWC		EMC		DWC		EMC	
Remnant native cover (RNC)	0.8	(0.25-6)	1.0	(0.5-6)	0.02	(0.02-0.06)	0.03	(0.02-0.6)
RNC-pasture	1.2	(0.25-6)	1.5	(0.5-6)	0.03	(0.02-0.06)	0.2	(0.02-0.6)
Livestock grazing	2.0	(0.5-7.5)	7.0	(0.5-10)	0.10	(0.02-0.3)	1.5	(0.02-1.5)
Forestry	0.8	(0.25-6)	1.0	(0.5-6)	0.02	(0.02-0.06)	0.03	(0.02-0.6)
Dairy	3.0	(0.5-10)	10.5	(1-15)	0.15	(0.02-0.6)	2.25	(0.3-10)
Cropping	0.9	(0.5-3)	4.0	(1-7)	0.20	(0.02-0.5)	1.5	(0.1-9)
Irrigated pasture	2.0	(0.5-7.5)	7.0	(0.5-10)	0.10	(0.02-0.3)	1.5	(0.02-1.5)
Irrigated horticulture	2.0	(0.1-4)	3.5	(0.5-9)	0.07	(0.02-0.1)	1.0	(0.1-1.5)
Intensive uses	1.5	(0.9-3)	3.0	(0.9-6)	0.05	0.05	0.2	(0.1-0.7)
Water	0.25	(0.25-6)	0.5	(0.5-6)	0.02	(0.02-0.06)	0.02	(0.02-0.6)

* DWC – Dry Weather Concentration, EMC – Effective Mean Concentration.
* Nutrient generation rates based on published DWC and EMC rates as well as paddock scale studies including (Baginska *et al.* 2005; Drewry *et al.* 2006; Grayson and Argent 2002; Waters and Packett 2007).

- using a proportion of every 'Livestock grazing' cell;
- assigning dairy to the grazing land with the highest lateral flow and runoff; and
- assigning dairy to the grazing land with the lowest lateral flow and runoff.

The nutrient generation rates presented (Table 1) show the concentrations used in the model and the range of expected concentrations based on published EMC, DWC and plot/paddock scale studies on nutrient movement from various land uses.

3.3. Calibration and Data Analysis

Daily stream flow data as well as Total Phosphorus (TP) and Total Nitrogen (TN) concentrations were obtained for the ten sub-catchment stream gauges within the study area (VWQMN 2009). Data availability varied between the gauges, however the majority of gauges had continuous stream flow data from 1970-2005 and between 6-25 years of monthly (some gauges had quarterly or fortnightly) TP and TN data.

The groundwater or baseflow contribution to stream flow was estimated using an automated digital filter technique (Arnold and Allen 1999) to separate the daily baseflow data. The daily stream gauge data was then averaged on a monthly time-step to match the time scale of the 2CSalt model.

The 2CSalt model was calibrated against measured monthly stream flow and computed baseflow for each gauge over a 30 year period (1975-2005), using an automated, constrained non-linear optimizer (The MathWorks Inc., 2007). For each stream gauge a Coefficient of Efficiency (CoE) (Nash and Sutcliffe 1970) was calculated, a CoE of 0.6 was viewed as satisfactory while a CoE of 0.8 or higher was considered good.

Analysing the TN and TP concentration data was more difficult due to the infrequent nature of the sampling and the need to compare average monthly concentrations predicted by the model to discrete samples. To determine whether modelled concentrations were realistic the mean (μ) and standard deviation (sd) of the stream gauge and model data were compared.

4. RESULTS AND DISCUSSION

Streamflow and baseflow were calibrated for all of the gauged sub-catchments in the Thoms Bridge Study Area. Reasonably good representation of the hydrology was achieved for the sub-catchments with the CoE at all gauges greater than 0.6 for both Stream flow and Baseflow (Figure 2). Gauge 8, which had the lowest CoE, was immediately down stream of Blue Rock Dam, where there was a time lag between the predicted and measured flow presumably due to dam storage.

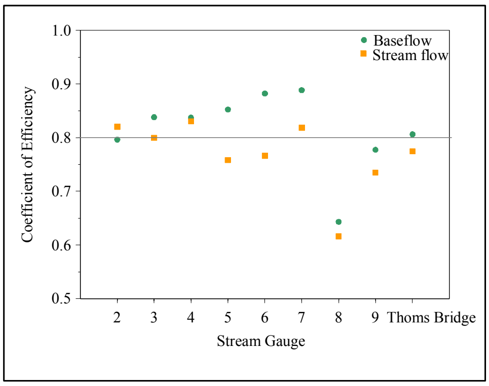

Figure 2. Coefficient of Efficiency calculated for Baseflow and Stream flow at the stream gauges.

Stream flow time series results for three gauging stations are shown (Figure 3) for a 20-year period, Thoms Bridge represents the total study area, Gauge 4 is dominated by livestock grazing industries and Gauge 7 is dominated by forestry. Both Thoms Bridge and Gauge 4 show a good match between measured and predicted stream flow and baseflow, while Gauge 7 shows a good match to baseflow, but seems to over predict the high stream flow events. Overall prediction of stream flow at all gauges was affected by quick flow (runoff + lateral flow) which is not calibrated within the model. Quick flow, which contributes between 20 to 50% of total streamflow, had a CoE ranging from 0.4-0.8. In the higher reaches and higher rainfall areas of the catchment where forestry is the dominant land use, evapotranspiration appears to be under predicted and as a consequence the model over predicts quick flow. This response has been observed in other high rainfall forestry areas in Victoria and is currently being investigated.

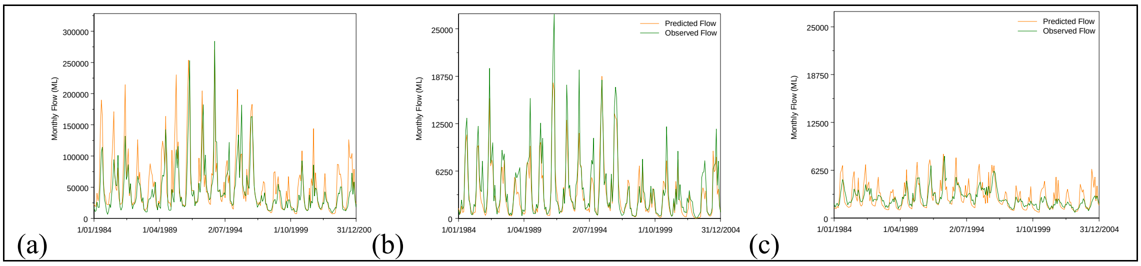

Figure 3. Monthly time series graph of stream flow from 1984 to 2004 at (a) Thoms Bridge, (b) Gauge 4 predominantly grazing and (c) Gauge 7 predominantly forestry.

An accurate description of flow and flow paths is essential to the prediction of nutrient transport. Measured monthly flow at many of the gauges varied by two or more orders of magnitude (e.g., Thoms Bridge ranged from 2300 to 284000ML/month). In contrast, EMC and DWC generally varied by a single order of magnitude, suggesting that loads predictions are significantly affected by flow. While quick flow in the upper catchment was not accurately predicted, the modelling approach presented in this paper generally provided a reliable and accurate prediction of flow throughout the Study Area.

4.1. Nutrient Movement

Total nitrogen and total phosphorus concentrations measured at the stream gauges varied significantly within and between gauges over a 30 year period (Figure 4). Overall TP concentrations ranged between 0.01 and 2.3 mg P/L while TN concentrations ranged from 0.18 to 4.5 mg N/L. An analysis of the stream gauge data showed a strong relationship between the mean TN and mean TP concentrations at each gauge and the percentage of forestry and grazing area upstream, with an exponential relationship (Figure 5) accounting for 95% of variance in mean measured concentrations at the gauge.

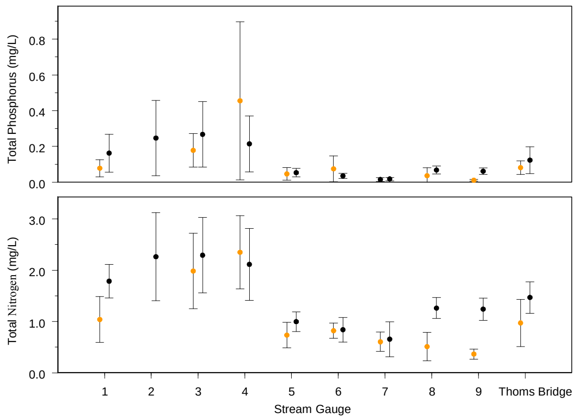

Figure 4. Mean ± 1 standard deviation of phosphorus and nitrogen concentrations, (●) measured in stream, and (●) monthly model predictions.

The combined area of grazing and forestry represents 90% of the study area, therefore the EMC and DWC values used for grazing and for forestry will largely determine model performance. To test the generation rates for grazing and forestry the model was initially run on two sub-catchments, gauge 7 (95% forestry), and gauge 4 (88% grazing).

In the predominantly forested catchment (gauge 7), there was close agreement in terms of mean and standard deviation of the data (Figure 4) for both TN (μ: 0.61 mg/L measured, 0.66 mg/L predicted) and TP (μ: 0.015 mg/L measured, 0.018 mg/L predicted). These concentrations are consistent with studies of nutrient export in forested catchments. Mean annual loads exported from the catchment were also within the range of published data (4.2 kg N/ha and 0.11 kg P/ha), although the N loads were at the higher end of the scale.

In the predominantly grazed catchment (gauge 4), there was a reasonably good agreement in terms of mean and standard deviation of the data (Figure 4) for TN (μ: 1.0 mg/L measured, 1.4 mg/L predicted). At first glance, the predicted TP concentrations appear to be low compared to the stream gauge data (μ: 0.081 mg/L measured, 0.12 mg/L predicted). However, the stream gauge data for this sub-catchment were collected over two discrete periods of time 1978-1988 (μ 0.59 mg P/L ± 0.45 sd) and 2003 to the present day (μ 0.10 mg P/L ± 0.037 sd). The model under predicts TP at gauge 4 over the 1978-88 period, but it is within range of the 2003-2005 concentrations. It is possible that the improved management of dairy shed effluent (often a point source of nutrients to streams) and tertiary wastewater treatment would have contributed to the decrease in measured TP concentrations between 1988 and 2003. As these changes in management are not incorporated into the model, it is not surprising that the model can not describe nutrient generation in both time periods. Average loads per hectare for both N (5.0 kg/ha) and P (0.60 kg/ha) were consistent with published data.

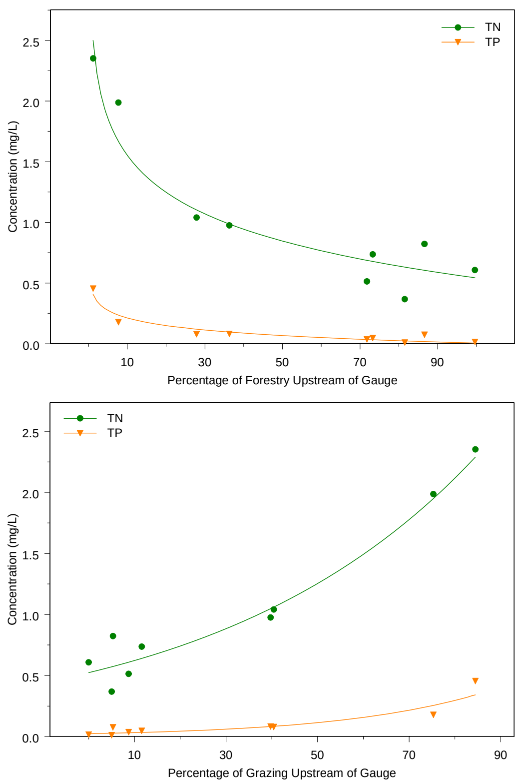

Figure 5. Exponential relationship between mean concentration and percentage of (a) forestry, and (b) grazing upstream of the gauge.

With good nutrient prediction in the sub-catchments dominated by a single land use, the next step was to assess model performance across the whole Study Area. As shown in Figure 4, the μ and sd of both N and P were a good match across most gauges including Thoms Bridge, although there was a tendency for N to be high, but still within 1 sd, at a number of gauges. The poorest prediction of N and P concentrations was at gauges 8 and 9 in which the hydrological models also performed poorly, highlighting the importance of accurately describing the hydrological processes.

EMC and DWC generation rates linked to a hydrological model have been used to predict nutrient movement and generation in previous studies. The results presented in this paper support the use of this simple modelling approach which is consistent with available input and validation data. With no optimisation of the EMC and DWC generation rates, the model results can be compared to, and to some extent be validated, using the available stream data.

The model was used to investigate (1) the potential impact of including a high input grazing (dairy) land use on nutrient export from the catchment, and (2) the importance of the spatial location of grazing within the catchment.

4.2. Dairy Industries

The Thoms Bridge study area contains a significant dairy industry, with an estimated 18000 ha of dairy (20 % of grazing land). While not all dairy farms are high input production systems, dairy farms do generally have higher nutrient inputs and therefore an increased risk of nutrient export (Drewry *et al.* 2006). Current spatial land use layers for the region do not contain dairy as an individual land use, so to investigate the potential impact of dairy on nutrient export it was incorporated into the study area in three ways (Figure 6).

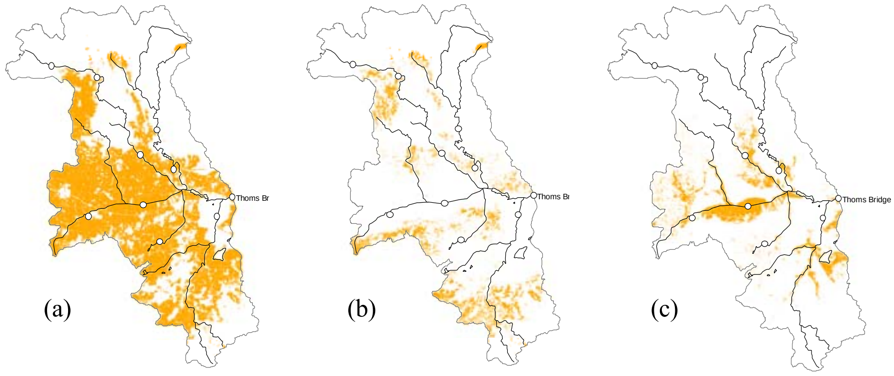

Figure 6. Dairy was assigned within the catchment as: (a) a percentage of all grazing land, (b) grazing land with the highest quick flow component, and (c) grazing land with the lowest quick flow component.

The inclusion of dairy resulted in a slight (<1%) reduction in predicted mean annual flow due to increased evapotranspiration from higher fertility perennial pastures (Table 2). While there was a minor decrease in predicted flow, mean annual P and N export from the study area still increased when dairy was attributed to a percentage of all grazing land or to the high quick-flow areas (Table 2).

Not surprisingly the greatest increase in nutrient load occurred where dairy was assigned to the high quick-flow areas (Table 2). These areas tended to be at the upper ends of the catchment on steep country with higher rainfall (Figure 6). However, the steepness of this country, suggests that locating high production pastures in these areas is unrealistic due to the difficulties associated with improving pastures and applying fertiliser on steep slopes. In contrast, the low quick-flow areas were generally lower down the catchment, often in river valleys (Figure 6). Increased water use by dairy on these areas resulted in a slight decrease in mean annual flow for the study area and no change in nutrient export.

Table 2. Predicted Mean annual nitrogen and phosphorus export from the Thoms Bridge Study area.

	Flow ($\times 10^3$ ML)	N (T)	P (T)
No Dairy	700	1152	118
Dairy – % grazing	696	1207	128
Dairy – high quick-flow	699	1264	138
Dairy – low quick-flow	694	1153	118

4.3. Nutrient Transfer in the Catchment

The use of EMC and DWC generation rates in this application, assumes that both N and P behave as conservative solutes through the catchment. However, we know that nutrient attenuation and transformations occur during transport and that distance to (1) stream and (2) gauging station will influence nutrient concentrations and loads. For example, if routing was taken into account we would expect the positioning of dairy in the high quick-flow regions to have less impact than the model results suggest, due to nutrient transformations and attenuation as water and nutrients moved through the landscape to the stream and then down through the catchment. Conversely, we would expect nutrient loads to increase if dairy was positioned in the low quick-flow regions due to their connectivity to streams and location within the catchment.

While, these processes are understood at a conceptual level and have been measured for specific streams, incorporating them into a nutrient model is challenging due to (1) the limited available knowledge on the rates of nutrient attenuation through the landscape and in streams, and (2) the ability to validate the balance between generation and attenuation using the available stream gauge data.

CONCLUSIONS

The modelling approach presented in this paper, has shown that CAT linked to 2CSalt provides a good description of flow across the Study Area, although the prediction of quick-flow in a couple of the sub-catchments had a low CoE. The use of a monthly time-step combined with EMC and DWC generation rates provided an acceptable prediction of both P and N concentrations and loads that was in-line with the available input data and the stream gauge data available for validation.

When we introduced a high input dairy land-use using three different methods, recharge rate was the dominant factor determining whether catchment scale nutrient export increased in response. However, the spatial location of the high and low recharge areas combined with a theoretical understanding of nutrient attenuation and transformations, suggests that some level of attenuation needs to be incorporated into the model to more accurately describe nutrient dynamics and export within a catchment.

While, the processes of nutrient transport and attenuation are understood at a conceptual level, without more detailed knowledge of these processes, including them within the model requires nutrient generation rates to be increased so that the concentrations can be reduced (attenuated) during transport. While increasing nutrient generation rates to account for attenuation appears sensible, there is insufficient information available with which to determine the balance between generation and attenuation.

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