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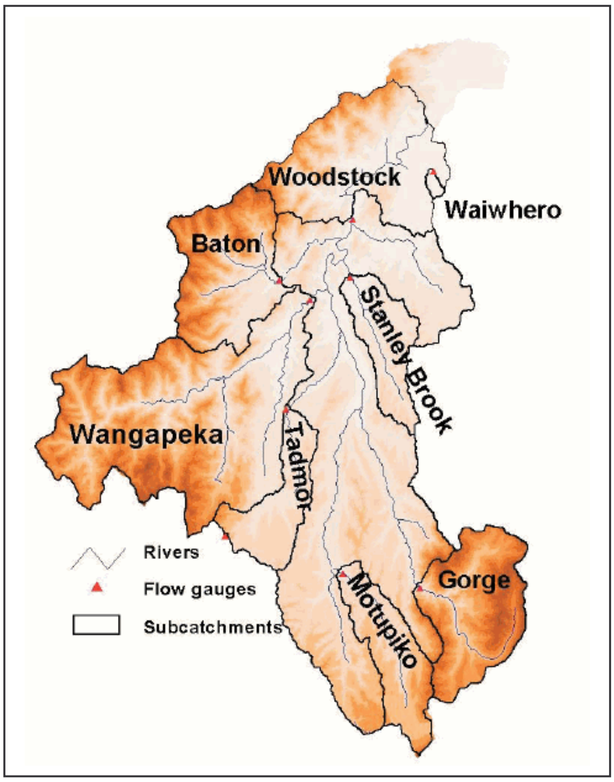
The SWAT model applied to simulating Nitrogen fluxes in the Motueka River catchment



Prepared for

Stakeholders of the
Motueka Integrated Catchment Management Programme

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The SWAT model applied to simulating Nitrogen fluxes in the Motueka River catchment

Motueka Integrated Catchment Management (Motueka ICM) Programme Report Series

by

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Cover Photo: Main subcatchments of the Motueka River above Woodstock, as used in the SWAT model.

PREFACE

An ongoing report series, covering components of the Motueka Integrated Catchment Management (ICM) Programme, has been initiated in order to present preliminary research findings directly to key stakeholders. The intention is that the data, with brief interpretation, can be used by managers, environmental groups and users of resources to address specific questions that may require urgent attention or may fall outside the scope of ICM research objectives.

We anticipate that providing access to environmental data will foster a collaborative problem-solving approach through the sharing of both ICM and privately collected information. Where appropriate, the information will also be presented to stakeholders through follow-up meetings designed to encourage feedback, discussion and coordination of research objectives.

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Introduction

The Motueka River delivers 65% of the fresh water to Tasman Bay from a 2170 km^2 catchment area. Water quality has been identified as an influential issue in the economic, ecological, sustainable management and development goals outlined for Integrated Catchment Management (Basher, 2003). A key question identified by the local Motueka community has been: "what determines water quality, and how is it changing through time?" (Basher 2003, p101). In order to answer this type of question, it is necessary to extend current modelling capabilities to include nutrient transport. Ability to predict the amount of nutrient transported and when it is transported helps to build understanding of nutrient - water discharge characteristics and delta ecosystem functions. As the first part of the nutrient modelling research this report documents the modelling of nitrogen transport in the Motueka Catchment.

Reliable estimation of nitrogen movement relies to a very large extent on the accurate prediction of hydrology. The Soil Water Assessment Tool (SWAT) model has been calibrated and successfully applied to predict water flow rates at selected measuring stations along the Motueka River to support decision making concerning long term sustainability of water and land management in the Motueka catchment (Cao et al 2003, 2005). SWAT is a physically based, distributed hydrological model that operates on a daily time-step (Arnold *et al*., 1998). In addition to the hydrological component SWAT has been developed with nutrient transport capability through its precursors: SWRRB (Simulator for Water Resources in Rural Basins); CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems); and GLEAMS (Groundwater Loading Effects on Agricultural Management Systems).

In SWAT a catchment is first split into sub-basins according to the terrain and river channels, and then into multiple hydrological response units (HRUs) based on the soil and land cover types within the sub-basins. An HRU is a fundamental spatial unit upon which SWAT simulates the water balance. Briefly, the hydrological processes modelled in SWAT are precipitation, surface runoff, soil and root zone infiltration, evapotranspiration and soil and snow evaporation, and baseflow. Nitrogen is modelled through the notrogen cycle including plant uptake and growth, mineralisation in the soil and release into water bodies. A comprehensive description of all the components in SWAT can be found in the literature (e.g. Arnold and Allen, 1996; Arnold *et al*., 1998; Srinivasan *et al*., 1998).

This study

As the first part of nutrient modelling, our objective is to extend the current SWAT hydrological modelling capability to estimate the nitrogen fluxes at any given stream location within the Motueka catchment. The model has been set up using all available data on nitrogen stores in the soil and plants and no optimisation has been attempted. As validation, the predictions from the SWAT model have been compared with measured nitrogen concentrations at 3 locations in the Motueka River.

Nitrogen in the Motueka catchment

Totalling the monthly spot measurements of the Motueka River at Woodstock for 1989 gives an estimated total of 574, 400 kg of nitrogen (National Rivers Water Quality Network Data- NIWA-Hamilton -20-10-2004).

Although this appears a relatively large amount it is small when compared to the annual load of many rivers; however Young et al (2005) note an increase in nitrogen concentrations in the record from 1989.

Sources of nitrogen to soil

Agriculture

The total nitrogen in a cultivated soil tends to remain constant over a period of years. The amount of nitrogen harvested by crop plants is less than might be assumed. Recovery of 50% of the applied N is a good average. 30 –50% of applied N may be lost by runoff or leaching and presents a potential source of pollution (Baird 1990). Therefore a major portion of N entering our streams is wastage from management of agriculture. For example 85% of N in Piako and 75% of nitrogen in Waihou rivers is from agriculture (Environment Waikato 1999).

Another source of nitrogen to soil comes from legumes. It has been estimated that under optimal conditions clovers can fix up to 300-600 kg/N/ha/year. In grazed pastures the greatest point source of nitrate is the urine patch. Typical cattle urination applies N at 1000kg/ha. For sheep it is 500kg N/ha.

Other sources

Rain water adds a significant amount of N to soil. Annual N deposition high as 6.7 kg/ha has been reported in Gore and 2.8 kg/ha was reported in Maimai (Adams, 1999).

Nitrogen is naturally cycled through plants and soil. Therefore anywhere with vegetation, whether indigenous or introduced, will naturally have nitrogen releases from plant to soil and then into surface water bodies. A large controlling factor on this is the amount of carbon in a soil, the higher the carbon the higher amount of nitrogen able to be held in the soil.

N transport estimation in SWAT

SWAT is a physically-based model with a GIS interface, requiring wide range of input data covering weather, soil physical and chemical properties, vegetation, and land management practises within the watershed, (Neitsch et al., 2001). It creates the sub basins and stream networks from a digital elevation model and estimates water daily balances from metrological, soil and land-use data. SWAT models water flow, sediment transport, vegetative growth, and nutrient cycling.

The hydrological component of the SWAT model has been calibrated and successfully used to predict the water flow at any given stream location in Motueka river (Cao et al 2003, 2005). SWAT also models the complete nutrient cycle for N as well as the degradation of any pesticides applied in an HRU. SWAT monitors five different pools of N in the soil. Two pools are inorganic forms of N, NH_4^+ and NO_3^- while the other three pools are organic forms of N. Fresh organic N is associated with crop residue and microbial biomass while the active and stable organic N pools are associated with the soil humus.

SWAT simulates N fixation by legumes when the soil does not supply the plant with the amount of N for growth. The N obtained by fixation is incorporated directly into the plant biomass and never enters the soil.

SWAT simulates the nitrogen store by adding the nitrogen in the rainfall and/or fertiliser input into the top 10 mm of soil. Then the model allows N to be transported from the first 10 mm of topsoil layer. SWAT calculates the N leaching to the stream or river by accounting for N in surface runoff and lateral flow. Although there is a significant groundwater component to flow simulation there is no nitrogen storage budget attached to this groundwater. Therefore SWAT essentially simulates nitrogen movement through the landscape as a surface process.

Data input

The main data SWAT requires for successful simulation of N without different land use scenarios with fertilizer applications are given below.

1. Initial Soil NO_3 and humic organic Nitrogen levels
2. Material in the residue pool for the top 10mm soil.
3. Bulk density of soil
4. Rate coefficients of mineralisation of humus and residue organic nutrients.
5. Amount of Organic C in the layer
6. Concentration of N in the rain

Some parameters needed for the N simulation are available from the New Zealand Soil Data Base when the hydrological component of SWAT was implemented. Organic N levels are assigned assuming that the C:N ratio for humic material is 14:1 and Eq-10.1.2 (Neitsch et al. 2001). The amount of organic C on soil layers was extracted from New Zealand Soil Data Base.

Sample data inputs for soils are shown in Fig-1. The parameters from Fig. 1 taken from the soil user database are: *Amount of organic carbon* (SOL_CBN) and *Bulk density* (SOL_BD). Other important parameters taken from other input screens (i.e. not shown in Fig 1) are: *Rate coefficient for mineralisation of active humus active organic nutrients* (CMN); *Rate coefficient for mineralisation of the residue fresh organic nutrients* (RSDCO) and *Concentration N in the rain* (RCN).

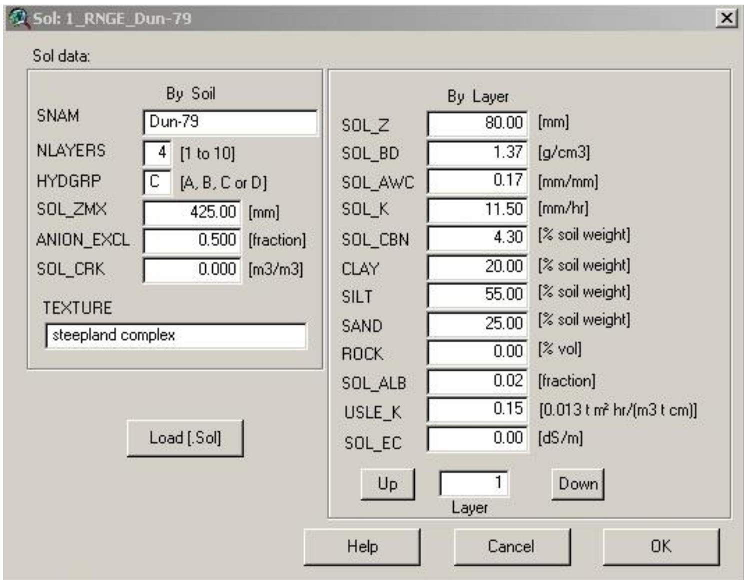


Figure 1 Sample data inputs for soil

The spatial configuration of SWAT for the full catchment is shown in Fig 2, with the sub-basins used in the simulation above the Motueka Gorge recording gauge shown in Fig 3.

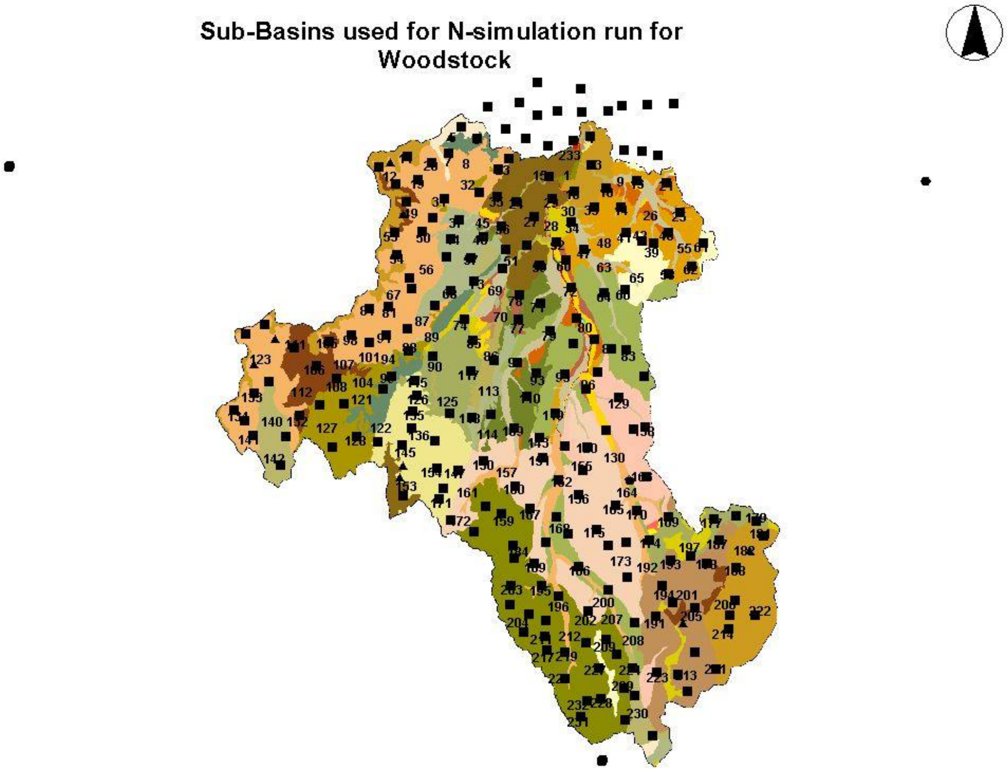


Figure 2 Sub-basins used in SWAT for Nitrogen simulation at Woodstock.

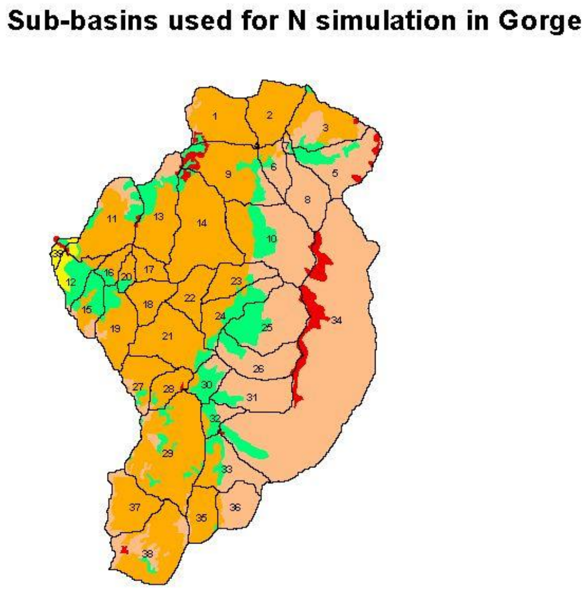


Figure 3 Sub-basins used in SWAT for Nitrogen simulation at Motueka Gorge.

Results

Time series of mean annual and mean monthly estimations nitrogen concentration at Woodstock and at the Motueka Gorge gauging site are plotted against mean values estimated from spot measurement of nitrogen concentration by NIWA (Figs 4 and 5).

Figs 6-8 present the same data as in Figs 4 and 5, except as scatter plots showing correlations between observed and predicted results. Fig 6 shows daily results for five subcatchments and the Motueka at both Woodstock and Woodmans Bend during the period October 200 until November 2003. Fig 7 shows SWAT monthly means (i.e. average of simulated daily nitrate concentrations) against spot measurements taken monthly against both Woodstock and the Motueka Gorge gauging site for the period 1989 until 2004. Fig 8 is the same data as for Fig 7 except both data sets averaged to annual values.

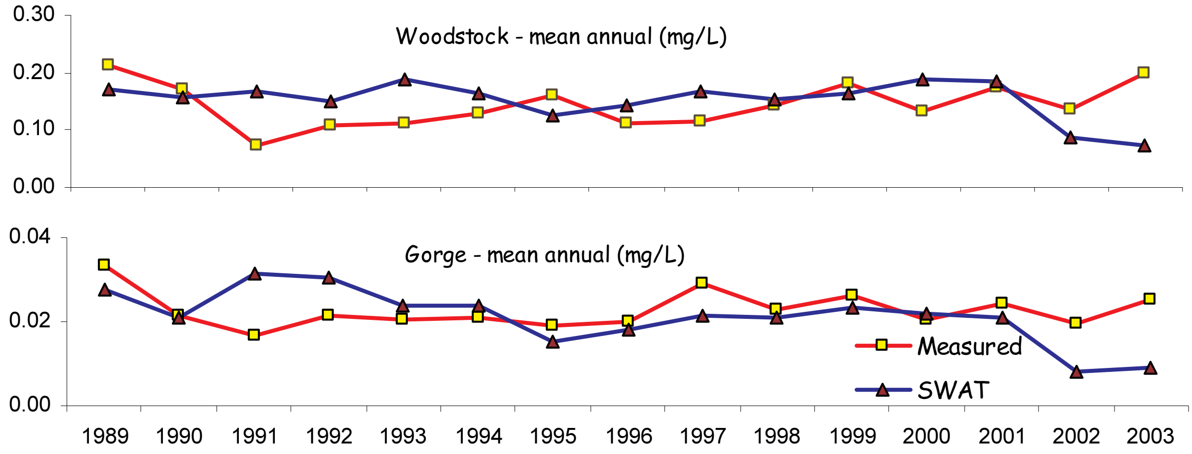


Figure 4 Mean annual nitrogen loads (simulated and observed) for Woodstock and Motueka Gorge. Measured values are from National Rivers Water Quality Network Data- NIWA.

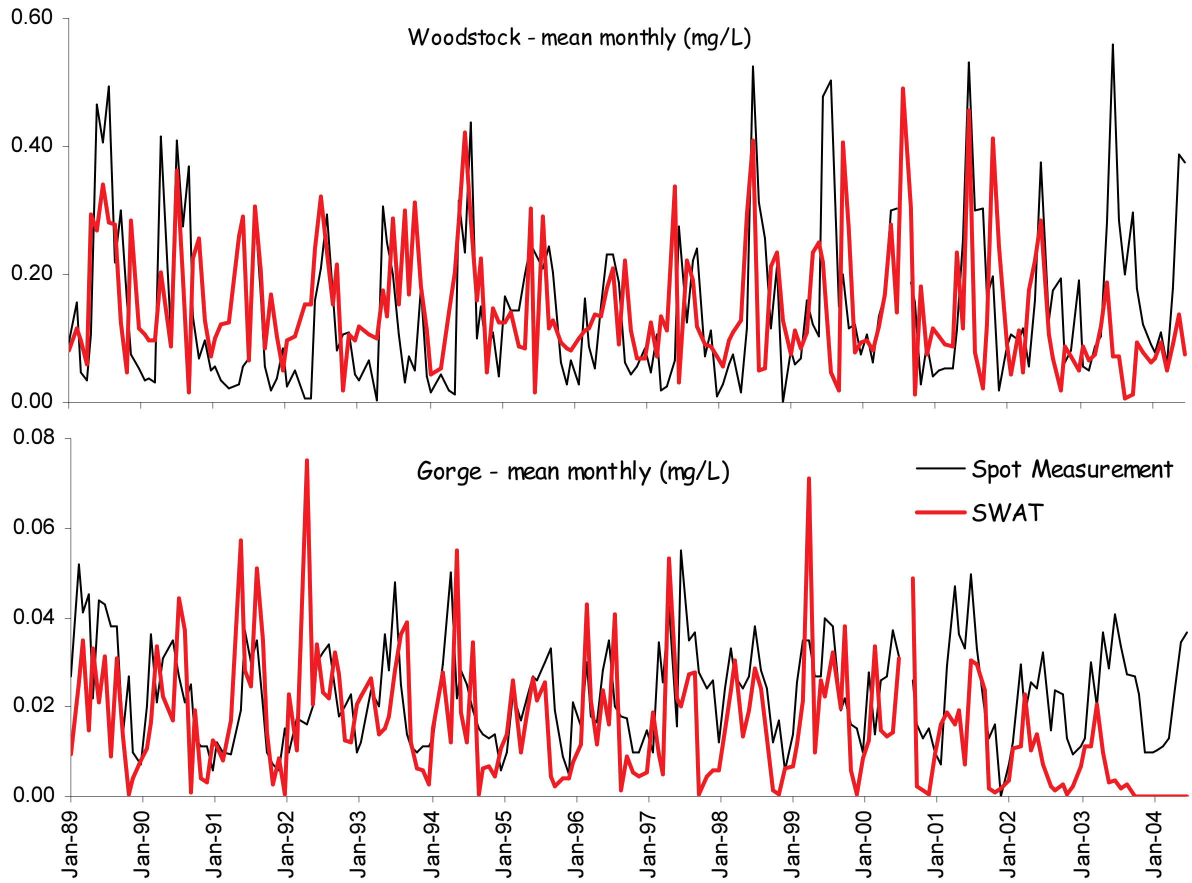


Figure 5 Mean monthly nitrogen loads (simulated and observed) for Woodstock and Motueka Gorge. Measured values are spot measurements (one per month) from the National Rivers Water Quality Network Data, NIWA.

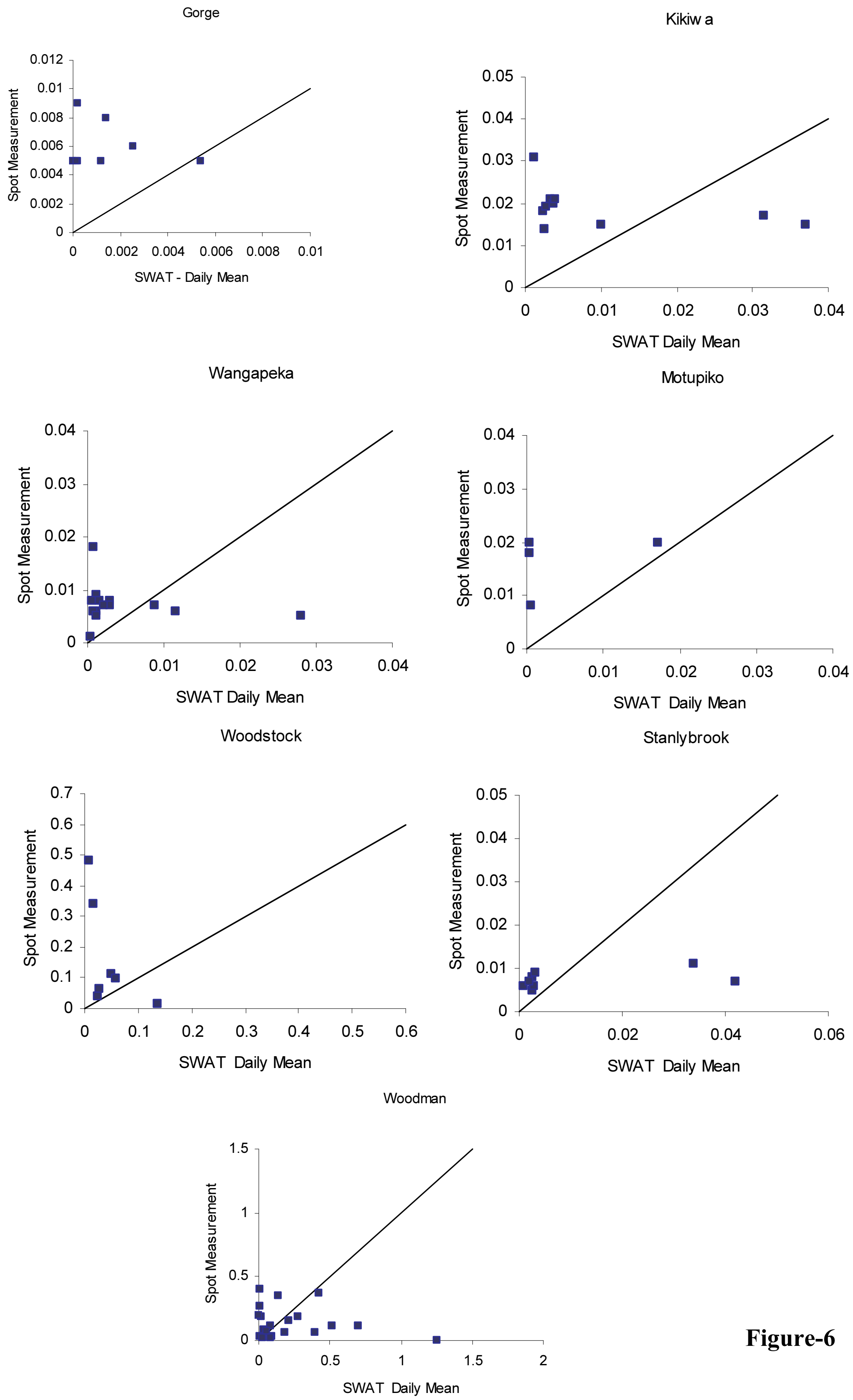
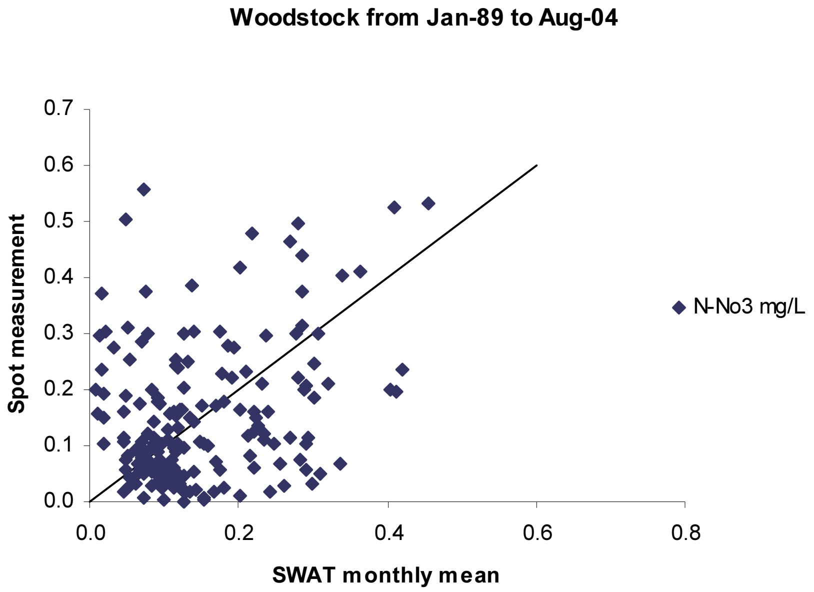


Figure-6

Figure 6 N-NO3 concentration daily spot measurements and daily mean modelled by SWAT from Oct-2000 to Nov-2003. Measured data from National Water Quality network National Rivers Water Quality Network Data- NIWA-Hamilton -20-10-2004.



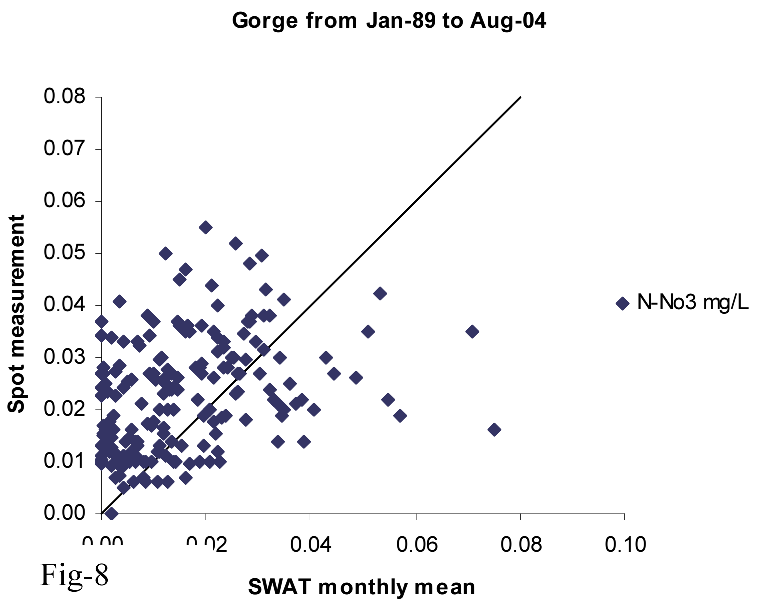
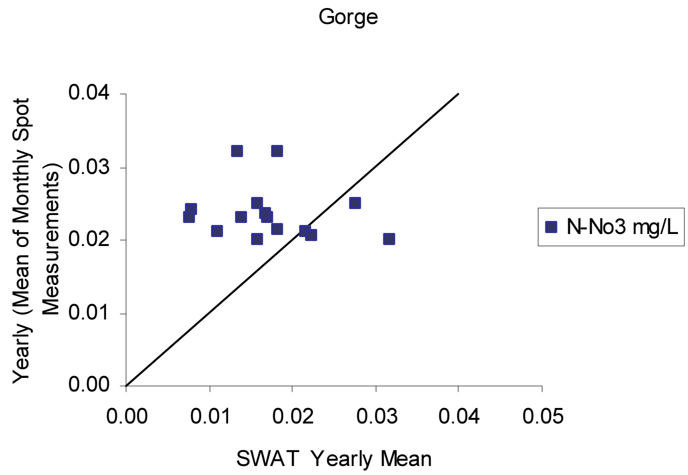


Fig-8

Figure 7 N-No3 concentration - monthly spot measurement and monthly mean predicted by SWAT from Jan-1989 to Aug-2004. Measured data from National Water Quality network National Rivers Water Quality Network Data- NIWA-Hamilton -20-10-2004.



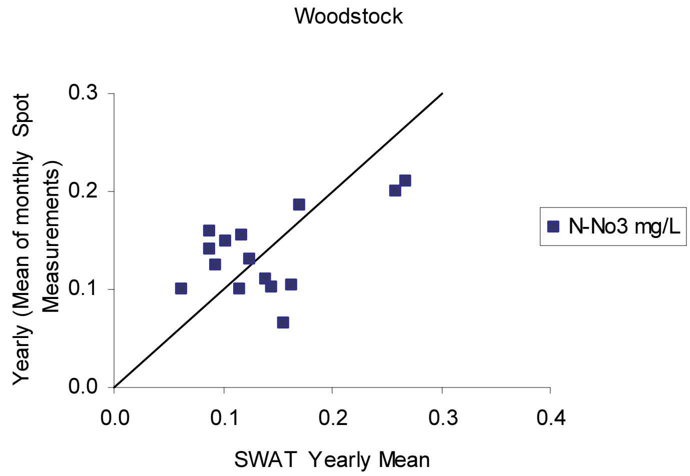


Fig-8

Figure 8 N-No3 concentration – Yearly - Mean of monthly spot measurements and Yearly mean predicted by SWAT from Jan-1989 to Aug-2004. Measured data from National Water Quality network National Rivers Water Quality Network Data- NIWA-Hamilton -20-10-2004.

Discussion

At an annual scale the time series of predicted and measured stream N-NO_3 loading visually appears to be a reasonable match (Fig 4). The monthly time series shown in Fig 5 does not visually correlate as well as for the annual time series however there seems to be some ability to predict the timing of spikes. In Fig 6 the predicted nitrate levels return almost to zero between spikes, whereas the measured values stay higher. It is worth noting that the nitrate levels, both predicted and observed, in the Motueka at Woodstock, and particularly at the Gorge site are very low. Although the discrepancies may appear large they are not particularly significant in terms of eutrophication or other nutrient problems that may occur

The differences between the measured and predicted values became more evident when the spot measurements are plotted against the predicted mean values for the same periods (Figs 6-8). In Fig 6 the daily values are plotted against simulated values for the same day; the line shown is 1:1, representing what would be hoped for in a perfect simulation. These are a small number of data in order to show the range of different subcatchments, the majority of which have only had a regular measurement regime since 2000. A particularly noteworthy feature of the Gorge site, Kikiwa, Wangapeka and Stanley Brook is the lack of variation in the spot measurements (y-axis) compared to the SWAT peredictions. The lack of variation would tend to suggest a groundwater dominated system (for nitrate), something that SWAT is not able to suitably simulate.

In Fig 7 the SWAT monthly averages are plotted against spot measurements for Woodstock and the Gorge site. There is a very wide scatter in these data. This can be partly accounted for by the difference between monthly averages and spot measurements but it is still disappointing that there is not a better relationship at this timescale.

In Fig 8 the monthly spot measurements are averaged up to annual amounts and the daily values averaged to annual predictions. It is not surprising that with this averaging comes a better correlation as it takes out extremes in the data. However for the Gorge site there is still very little variation in the observed data compared to the predicted. This is the same as for the daily data and may reflected a groundwater dominated nitrate system rather than through surface processes. Correlation coefficients for monthly and yearly values are given in Table-1.

Table 1 r^2 values for stream N loading at Gorge and Woodstock

	Monthly	Yearly
Gorge	0.12	0.038
Woodstock	0.07	0.297

A this stage different management practises with fertilizer applications have not been simulated. Therefore, only limited number of parameters from the total required parameters for N modelling was used in the model. Although this assumption is not completely accurate for the entire catchment, it is not unreasonable for subcatchments like above the Gorge and the Wangapeka. In both of these subcatchments the land use is dominated by conservation estate where there is no fertiliser management taking place. However, SWAT failed to predict N-NO_3 any where close to the measured N loadings for Gorge or the Wangapeka. The only time SWAT reaches some “accuracy” in prediction is when data are averaged to an annual series.

Most of the parameters used for N modelling shown in Fig 2 were obtained from the National Soil data base. Taking these as essentially fixed, the N input from rainfall and the initial N concentration in the soil layers were the only available parameters for sensitivity analysis. Initial N concentration of soil layers affected the prediction of N loading in the stream in the first few time steps and diminishes with time. The use of entire range of rain-N input estimated for the North or South island (2.8 – 6.7 kg/ha/year Adams, 1999) did not improve the N loading prediction.

While carrying out this modelling exercise it became evident that several studies in the literature point to SWAT having some limitations in N and P modelling (Sophecleous, Koelliker et al., 1999, Sophecleous and Perkins, 2000, Hu, 2004). Some of the limitations are:

- Sensitivity of stream flow to curve number (CN) (King, Arnold et al., 1999)
- Determination of the base flow component of stream flow (Arnold and Allen, 1999)
- Scale effects of aggregation (FitzHugh and Mackay, 2000)
- In ability of SWAT to simulate ground water contribution accurately (Canon et al., 2003).

It is particularly the last point that is of concern here. The inability of SWAT to account for nitrogen in groundwater may be a significant factor in the poor predictions evident in this study. The observed and predicted time series for the Motueka Gorge gauging site in Fig 5 shows that SWAT underestimates the background concentration that could be expected to be provided by groundwater. SWAT currently simulates nitrate loading as a surface and near surface flow process dominated by storm runoff. It may be possible to rectify this by “adding” a background baseflow concentration but this would negate the ability of the model to predict effects of long term land use change.

There are examples in the literature where the SWAT model hydrological component has been coupled with other models and show success in predicting N and P loading in streams. For example, Conan et al., (2003) coupled SWAT with the ground water model MODFLOW and solute transport model MT3DMS to predict nitrate loading in the Brittany region of France. This form of coupling might be possible for the Motueka catchment but would require a considerable extra effort in time and resources. It is disappointing to know that the SWAT development team has not been explicit about the limitations of the SWAT to simulate N loading in streams. Although the SWAT development team is aware of the issues associated with the SWATs nutrient prediction limitations and steps have been taken to improve the model (Ramnarayan et al., 2005), the technical manuals and background information supplied with the model; make no mention of possible limitations.

In conclusion it must be stated that SWAT has shown a poor ability to predict nitrate concentrations in a relatively untouched situation. Although SWAT has considerable ability to simulate the effects of land management change through the nitrogen cycle it has difficulty predicting absolute amount of nitrate in the river. This means that predictions on effects of land use change will be limited to broad scale changes in nutrient concentration rather than more precise predictions. There is still some value in these broad scale predictions, so long as they are acknowledged as such, but it is likely that other, simpler models will give similar results. The current levels of nitrogen in the Motueka are low (although they have been rising over the past decade; Young et al., 2005) so that small inaccuracies in prediction look far greater than at a higher concentrations but the overall difficulties in making good predictions for the Motueka severely limit the use of SWAT for the ICM programme.

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