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ESTIMATING NITROGEN LOSS FROM A DAIRY FARMING CATCHMENT USING THE SOIL AND WATER ASSESSMENT TOOL (SWAT)

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Introduction

Dynamic, processed-based integrated catchment models have capabilities of simulating the dynamic behaviour of complex processes in the catchment. They help to gain understanding about the complex catchment system where direct measurement are not always feasible at large scales. They are also able to estimate pollutant loads from diffuse sources, and thus useful tools for catchment management supporting decision making if the models can capture the dominant processes in the catchment. Several dynamic catchment models that are able to handle non-point source pollution at catchment scale and are widely used include The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), MIKE-SHE model (Refsgaard and Storm, 1995), The Integrated Nitrogen in Catchments (INCA) (Whitehead et al., 1998) and the Regional Hydrological Ecosystem Simulation System (RHESSys) models.

SWAT is a semi-distributed watershed model that has been worldwide and broadly applied across a wide range of catchment scales and conditions for both hydrologic and environment issues, as in reviews by Gassman et al. (2007; 2010), Douglas-Mankin et al. (2010), and Tuppad et al. (2011). SWAT is a free and open source model, thus gives flexibility to modify and improve the model. It is a distributed model but also a simple conceptual model, which makes it computationally efficient and flexible to build from simple to complex setups. Moreover, SWAT has built-in routines to simulate management practices, therefore, the model has been applied to evaluate the effect of farm best management practices on water quality at catchment scales, for e.g. Strauch et al. (2013), Chaubey et al. (2010), Ullrich and Volk (2009). With all these strengths, SWAT is possibly a suitable model to apply in intensively agricultural catchments in New Zealand. In New Zealand, there are a few SWAT applications available. Two studies were carried out in the Motueka catchment, South Island, New Zealand (Cao et al., 2006, 2009), focused on hydrology in which SWAT performance is quite good for the whole catchment but worse at sub-catchments. Me et al. (2015) applied SWAT to predict water quality concentrations for the Puarenga catchment. A follow-up study (Me et al., 2018) combined SWAT with a one dimensional lake water quality model to simulate the trophic state of Lake Rotorua in response to nutrient reduction and climate change.

The objective of this study is to apply the SWAT model to estimate nitrogen loss from a typical dairy farming catchment in New Zealand. The specific objectives include: (i) evaluate the SWAT model performance in the prediction of streamflow, nitrogen load and concentration, (ii) quantify nitrogen loss and nitrogen transport from different flow pathways. The Toenepi catchment, one of the catchments in long term Dairy Best Practices studies, is chosen as the case study because of the availability of long-term water quality data, information about farm practices and knowledge from previous studies.

Methodology

Study area description: the Toenepi catchment, Waikato, New Zealand

The Toenepi catchment (15.1 km^2) is located in a long-established dairying area near Morrinsville, Waikato, in the North Island of New Zealand. The elevation of catchment ranges from approximately 40 to 130 m above mean sea level. Mean annual rainfall is approximately 1280 mm and mean annual air temperature is 14 °C. The catchment is characterised by lowland alluvial plains in the central portion and at the outlet of the catchment, some hill country in the headwater area and rolling downlands in the remaining areas. The Toenepi catchment has mostly flat (89%) topography with substantial artificial drainage and is fully covered by pasture. The catchment is mostly occupied by dairy farms. The average stocking rate of all dairying land was 3.1 cows/ha, ranging from 2.5 to 4.3 cows/ha on individual farms. The main vegetation in pastures are established ryegrass (*Lolium perenne*) and clover (*Trifolium repens*) (Wilcock et al., 2011).

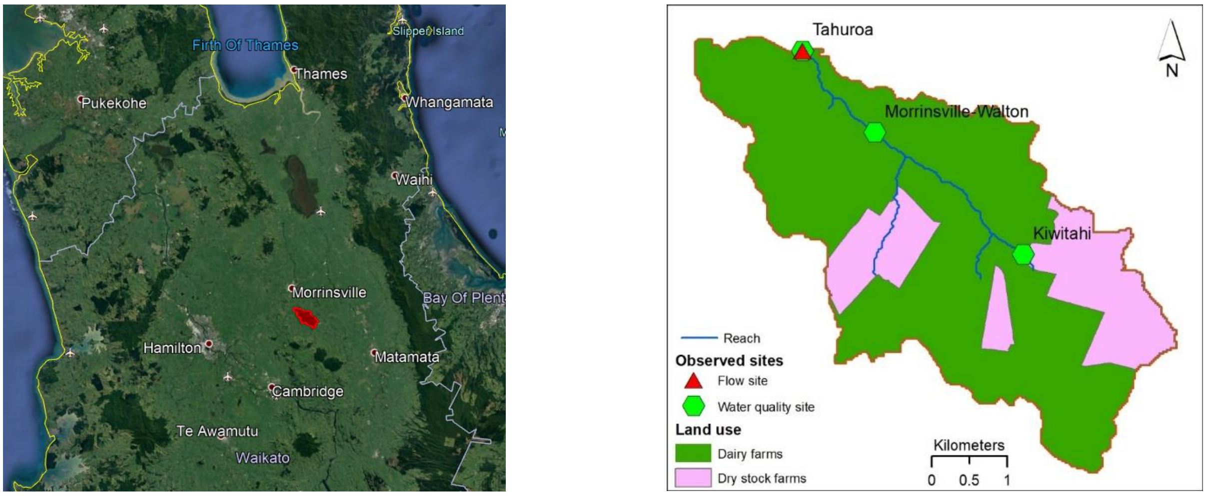


Figure 1: The Toenepi catchment, Morrinsville, Waikato, New Zealand

Flow monitoring is available at the outlet of the catchment (the *Tahuroa Road Bridge* site) from 1995 - present with brief disruption in two periods of April 1997-October 1998 and November 2001- February 2002. Water quality has been monitored at the same location from October 1998 – November 2001 and February 2002 – present at monthly interval.

Brief description of the SWAT model

SWAT divides a catchment into multiple sub-basins, which are then subdivided into hydrological response units (HRUs), each of which has a unique combination of land use, soil characteristic, and slope. All processes modelled in SWAT are lumped at the HRU level.

Flow Simulation

SWAT is typically executed using a daily time step. Simulated hydrological processes include surface runoff estimated using the Soil Conservation Service curve number method (USDA-NRCS, 2004), percolation through soil layers, lateral subsurface flow, subsurface tile drainage, groundwater flow to streams from shallow aquifer, evapotranspiration, snowmelt, transmission losses from streams, water storage, and losses from ponds and reservoirs (Arnold et al., 1998).

Nitrogen Processes

Nitrogen processes and transport are modelled by SWAT in the soil profile, in the shallow aquifer, and in the river reaches. Nitrogen processes simulated in the soil include mineralization, residue decomposition, immobilization, nitrification, ammonia volatilization, and denitrification. Ammonium is assumed to be easily adsorbed by soil particles and is not considered in the nutrient transport. Nitrate, which is very susceptible to leaching, can be lost through surface runoff, lateral flow, tile drainage and can percolate out of the soil profile and enter the shallow aquifer. Nitrate in the shallow aquifer may also be lost due to uptake by the presence of bacteria, by chemical transformation driven by the change in redox potential of the aquifer, and by other processes. These processes are lumped together to represent the loss of nitrate in the aquifer by the nitrate half-life parameter. Processes in the river reaches were not considered in this study.

SWAT model setup for the Toenepi catchment

Catchment delineation and hydrological inputs

The New Zealand National Digital Elevation Model (DEM) with a spatial resolution of 25m (accessible through *https://lris.scinfo.org.nz/layer/48131-nzdem-north-island-25-metre*) was used to calculate flow direction, flow path and delineate the catchment area. For simplification purpose, the whole catchment was simulated as a single subbasin. One point source was created to represent dairy shed wastewater discharged from oxidation ponds in the catchment.

Soil type and soil characteristics were taken from S-map (Lilburne et al., 2012). There are seven main soil types distributed in this catchment (Figure 2). The land use map was taken from the previous NIWA works on the Toenepi catchment which shows two main land use types: dairy farms (76%) and dry stock farms (24%). It was assumed that these areal proportions for two land use types remains the same during the simulation period. As the catchment is mostly flat, slope was assumed to not be a part of HRU division. Accordingly, 21 HRUs were created, each of which is a unique combination of soil and land use types. The illustration of HRU division is shown in Figure 2.

Daily climate data was taken from NIWA Virtual Climate Station Networks (VCSN) which are climate estimates based on the spatial interpolation of observations made at 5x5 km grids all over New Zealand. The climate data required for SWAT include rainfall, maximum and minimum temperature, relative humidity, solar radiation and windspeed.

Nutrient inputs

Table 1 shows the estimates of nitrogen sources, the estimating methods and data sources. The estimates of nitrogen from different sources were input to the SWAT model for the period 1994 – 2015. The range of values in table 1 shows the change of nitrogen inputs over time.

There are two types of nitrogen sources in the catchment: point sources and diffuse sources. Point sources represent the dairy shed effluents discharged to streams, estimated by *typical amount of dairy shed effluent * % discharged directly to streams*. The percentage of effluents discharge directly to streams decreases over time because of the increasing number of farms applying effluents to land. The diffuse sources input a great amount of nitrogen to the catchment. The most important input is the manure from cattle grazing, estimated by *Number of animals * amount of manure/animal * %N in manure*, at around 280 – 325 kg N/ha. Fertilizer application ranks the second greatest N input with 65-120 kg N/ha. Nitrogen fixation is around 40kg/ha according to Parfitt et al. (2012). Parfitt et al. (2012) also reported wet deposition at around 1.5 kg N/ ha, and dry deposition 5 – 10 kg N/ ha, thus 7.5 kg N/ha was input to the SWAT model as dry deposition with the assumption that 50% is N-NH_4, and 50% is N-NO_3. The last source is the amount of dairy shed effluent that is not discharge directly to the stream but applied in land, which is estimated averagely for the entire catchment at 0.12 - 2.4 kg N/ha.

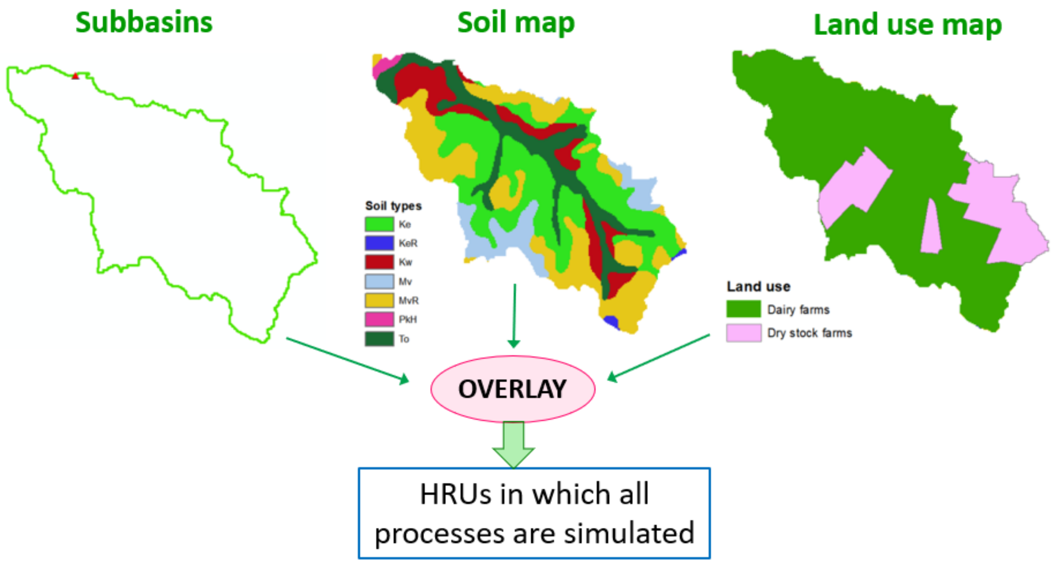


Figure 2: Illustration of the division of the catchment into Hydrological Response Units (HRUs) in the SWAT model

Table 1: Nitrogen input sources in the Toenepi catchment

Type of source	**Details**	**Estimating method**	**Value**
Point sources	Dairy shed effluent discharged to streams	*Amount of dairy shed effluent * % discharged directly to streams*	1-11 kg N/day for 270 lactation days
Diffuse sources	Manure from cattle grazing	*Number of animals * amount of manure/animal * %N in manure* Data was taken from farm surveys and Agricultural Waste manual (Vanderholm, 1984)	280 – 325 kg N/ha
	Fertilizer application	Wilcock et al. (2013) and farm surveys	65-120 kg N/ha
	Nitrogen fixation	Parfitt et al. (2012)	~ 40 kg N/ha
	Dry deposition	Parfitt et al. (2012) reported 5- 10 kg N/ha	7.5 kg N/ha *(50% NH_4, 50% NO_3)*
	Wet deposition	Parfitt et al. (2012)	1.5 kg N/ha *(50% NH_4, 50% NO_3)*
	Application of dairy shed effluent to land	*Amount of dairy shed effluent * % applied on land* (Wilcock et al., 2013)	0.12-2.4 kg N/ha

Model calibration and validation

Model calibration was carried out in two stages: (i) streamflow calibration, and (ii) nitrogen calibration.

Streamflow calibration was carried out using the observed records of streamflow at the outlet of the catchment (at the gauging station at Tahuroa Road Bridge). The calibration period is from 2004 – 2009 while validation period is from 2010 – 2012. Thirteen flow-related parameters were included in the streamflow calibration. The model was calibrated by applying the Monte Carlo sampling method. Ten thousand parameter sets were generated, each of which was then run with SWAT. The optimal parameter set giving the best fit to observations was chosen. Some common statistical metrics for hydrology including Nash-Sutcliffe Efficiency (NSE), logNSE, percent bias and Kling–Gupta efficiency (KGE) were used as measures of goodness of fit to evaluate the model performance.

Based on the calibrated model for hydrology, nitrogen calibration was calibrated. The same methodology was applied with eight N-related parameters involved. The evaluation of SWAT performance on nitrogen concentration was carried out by comparing the model predictions of nitrate and total N load and concentration with measurement. Since water quality monitoring is only limited to grab samples at monthly frequency, the evaluation was not limited to comparison of values, but also correlation assessment and comparison of seasonal variations.

Results and discussion

Model calibration and validation

Streamflow simulation

The comparison between modelled and measured streamflow at the daily and monthly time steps shows that the SWAT model can simulate the occurrence and variation of streamflow very well both in the calibration and validation periods. The model underestimates peak flows at the daily time step, while it fits better to measurement at the monthly time step. Table 2 presents some common statistical metrics for hydrology to evaluate SWAT model performance. The most common one is NSE, NSE equalling to 1 means ‘perfect’ model and NSE greater than 0.75 means ‘very good’ model according to model evaluation guidelines by Moriasi et al. (2015). At daily time step, NSE values are 0.83 and 0.78 in the calibration and validation, respectively. The values are increased to 0.95 and 0.90 at monthly time step. Overall, the SWAT model performs very well on streamflow simulation, especially at the monthly time step.

Table 2: Statistical metrics showing SWAT model performance on streamflow prediction at the outlet of the Toenepi catchment

Time step	Period	NSE	logNSE	PBIAS	KGE
Daily	Calibration	0.83	0.85	3.6	0.85
	Validation	0.78	0.87	-2.6	0.76
Monthly	Calibration	0.95	0.91	3.6	0.95
	Validation	0.92	0.92	-2.6	0.89

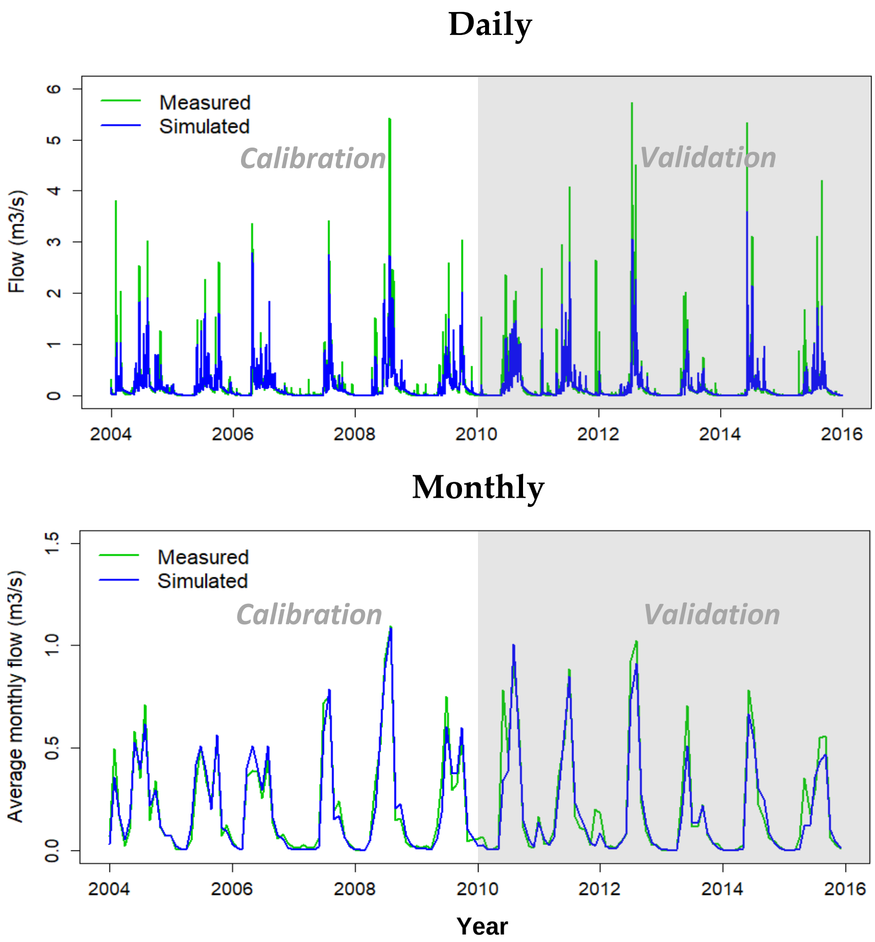
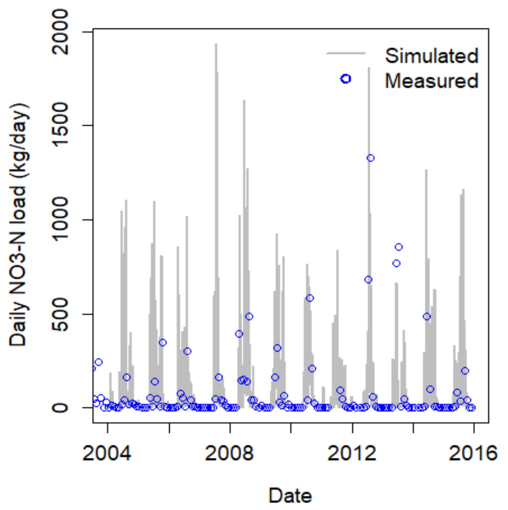
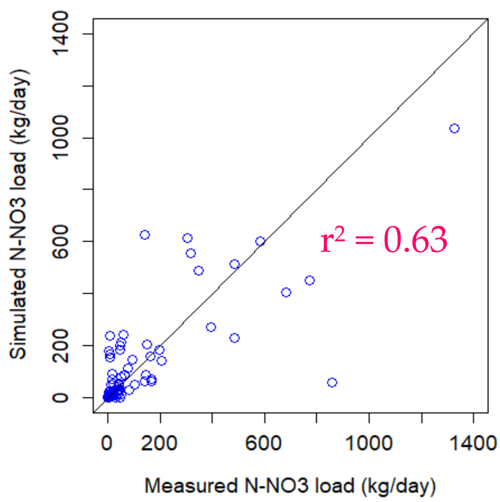


Figure 2: Simulated streamflow versus measurements at daily and monthly time steps in the period 2003-2015

Nitrogen simulation

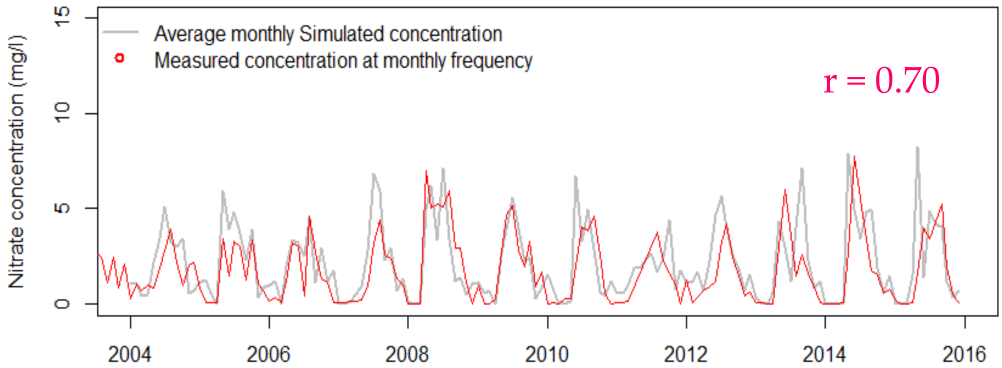
Figure 3a shows the comparison of time series of daily nitrate load and the measured load, figure 3b presents the relationship between simulated and measured load on days that measurements are available. It can be seen that the majority of the measurements were taken at low flows, only a few at storm flows. Coefficient of determination (R^2) between simulated and measured load is 0.63, which is acceptable for the limited and low- frequency data. Figure 3c shows the monthly average concentration compared with the grab sample at monthly frequency. The temporal variation of simulated and measured concentration is compared in this figure to see if the model can predict correctly the behaviour of nitrate in the catchment. It can be clearly seen that the temporal variations of the two datasets correlate with each other reasonably well with correlation coefficient (r) at 0.7. Look at the seasonal variation of the simulated and measured concentration of Nitrate and TN, the modelled results and observations behave quite similarly (Figure 4). The value ranges of observations are mostly within the ranges of simulated concentrations, which is reasonable because model predictions can capture a wider range of conditions than grab samples. For total N, the same behaviours were observed and thus, were not shown here. Based on all above evaluations, it can be concluded that the SWAT model performs reasonably for nitrogen simulation.





(a) Time series of simulated N-NO3 load versus measurements

(b) Scatter plot of simulated N-NO3 load versus measurements



(c) Correlation between monthly average simulated N-NO3 concentration and monthly measurement

Figure 3: N-NO3 load and concentration versus measurement in the period 2004-2015

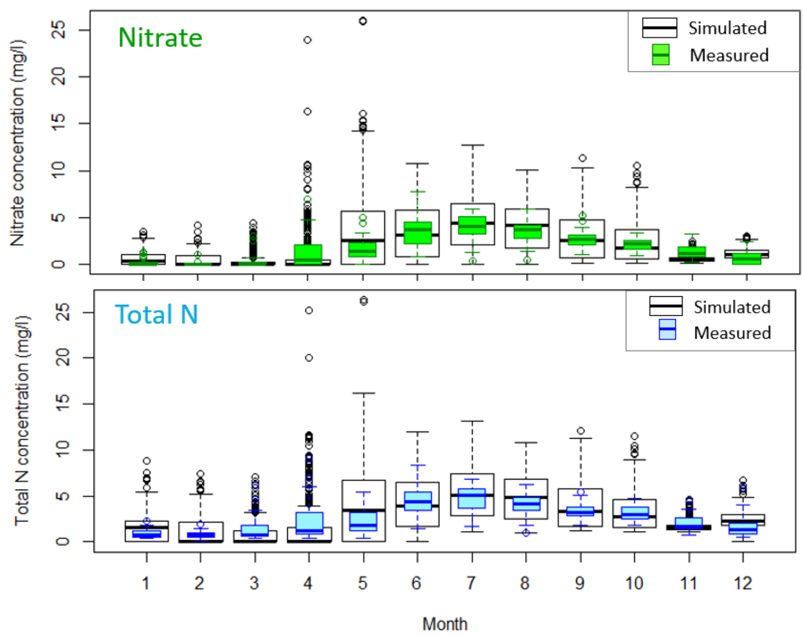


Figure 4: Seasonal variations of simulated nitrate and total N concentration versus measurements

SWAT model predictions

Water balance

Based on the calibrated SWAT simulation, the annual average water balance for the period 2004-2015 is presented in Figure 5. During this period, the annual rainfall is 1010 mm, around 606 mm is lost to evapotranspiration, 127 mm recharges to the groundwater aquifer, a very small amount loss to the deep aquifer which is considered loss from the catchment. Approximately, 394 mm, which is 39% of rainfall input, enters the streams through four different pathways: surface runoff, lateral flow, tile drainage and groundwater flow. Tile drainage is predicted as the most significant contributor with 51%, 18% of streamflow is contributed by surface runoff, and 28% is from groundwater flow and 3% is from lateral flow.

Nitrogen loss

Nitrogen loss from the catchment by different ways. A huge amount of nitrogen in soil is used by plants which then are eaten by cattle (310 kg N/ha). A part of this nitrogen amount comes back to the catchment as manure from cattle. Nitrogen is also removed by denitrification (58 kg N/ha), ammonia volatization (40 kg N/ha), and organic N (5 kg N/ha) can be taken to the streams by erosion. The most concern is the amount of nitrogen transported to streams which is estimated at 19 kg N/ha by the model. It is noted that SWAT only simulates nitrate transport because it is assumed that ammonia is not transported with flow. The model predicted that tile flow is the dominant pathway for nitrate transport to the stream with the contribution of 96.3% the total nitrate loads, surface runoff contributes around 0.4%, lateral flow 0.3%. Nitrate from groundwater flow is very low for two reasons. One reason is the process for nitrate removal occurring in the aquifer. The other reason is that a huge amount of nitrate follows tile flow, which results in less nitrate percolating to the aquifer to follow groundwater flow.

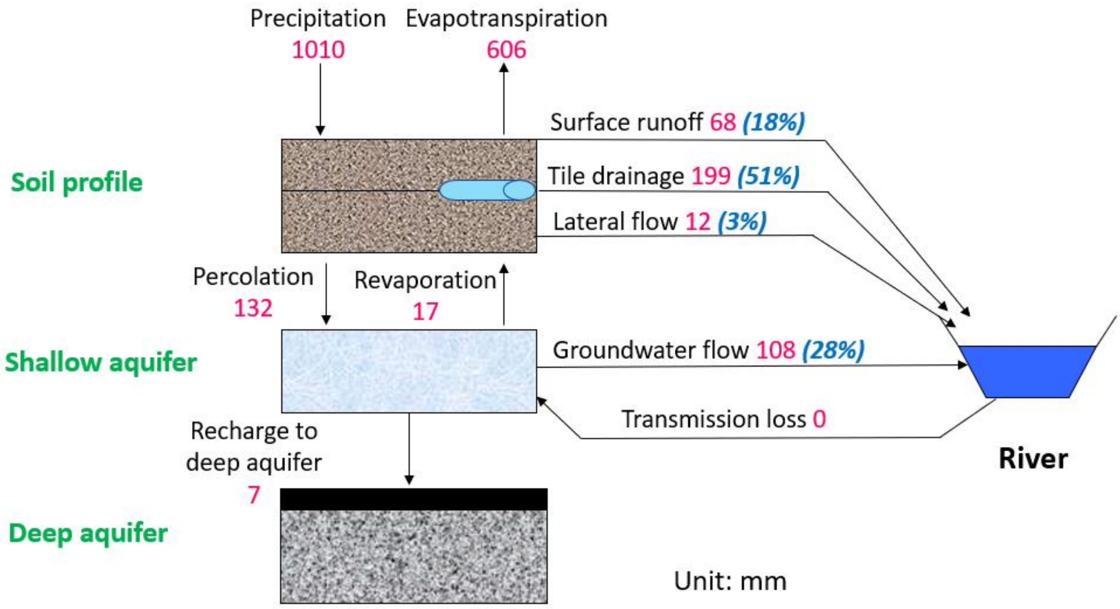


Figure 5: Prediction of annual water balance for the period 2004-2015

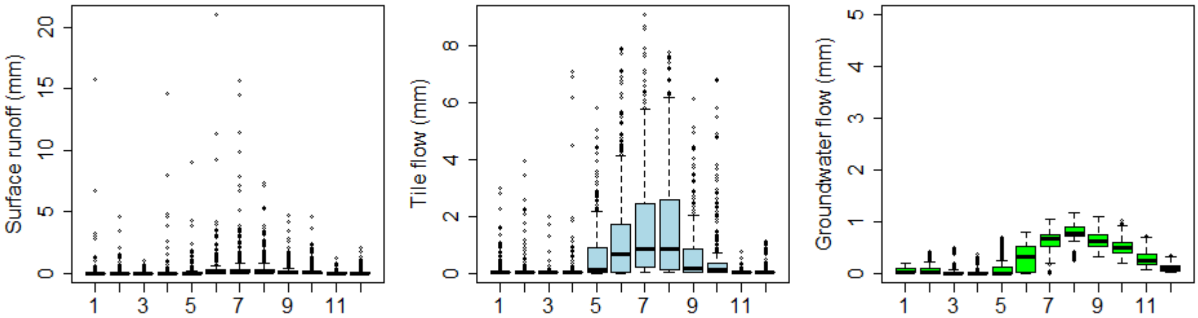
Table 3: Prediction of annual nitrogen loss in the period 2004-2015

No.	Nitrogen loss	Type of Nitrogen	Value (kg N/ha)
1	Loss to biomass eaten by cattle	Fresh N	310
2	Denitrification	$N\text{-}NO_3$	58
3	Ammonia volatization	$N\text{-}NH_4$	40
4	Loss by erosion	Organic N	5
5	Loss to the streams	$N\text{-}NO_3$	19
	- Through surface runoff		0.4 (*2%*)*
	- Through lateral flow		0.3 (*1.5%*)
	- Through tile drainage		18.2 (*96.3%*)
	- Through groundwater flow		0.02 (*0.1%*)

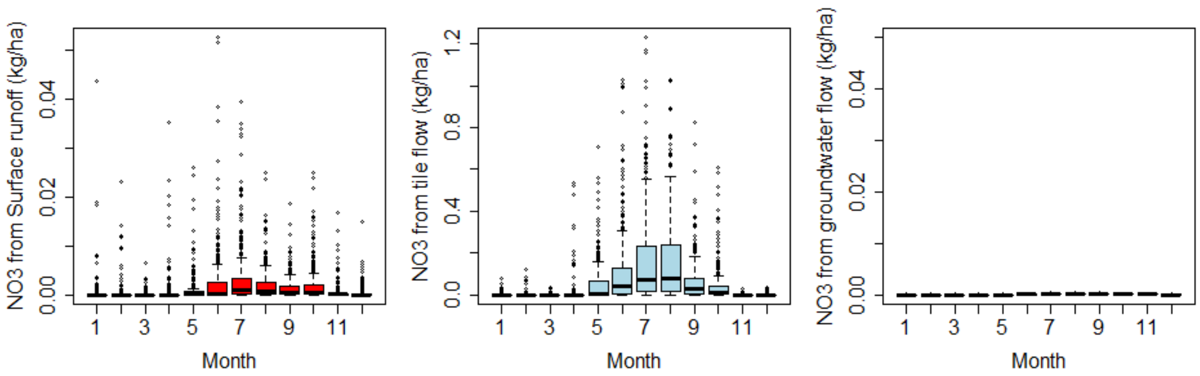
** The number in bracket shows the contributing percentage of nitrate loss to the streams*

Seasonal variation of flow and nitrate yield

Figure 6 shows the seasonal variation of various flow components and their driven nitrate yields. Lateral flow is not shown in this figure because of its insignificant contribution to flow and nitrate yield. As nitrate is mobile, the seasonal variation of nitrate yield is compatible with flow. Surface runoff usually stays low, unless there is high rainfall. However, when there is an extreme event, the generated surface runoff can be very high compared to other types of flow. Surface runoff is higher in winter from June to August, which results in an increase of nitrate yield driven from surface runoff in winter. In terms of tile drainage, May to October is the period that tile drainage generates with the highest occurring in July and August. In the remaining months, it only occurs when there is high rainfall event. Therefore, nitrate yield from tile flow also enters the streams mostly from May to October. For the whole year, groundwater keeps contributing water to the streams, but its contribution is lower from Dec – April and higher from May to November which corresponds to the period with higher rainfall and colder temperature. Nitrate yield from groundwater has the same pattern with the flow, and always stays at very low value.



(a) Seasonal variation of flow components



(b) Seasonal variation of Nitrate yield transported by flow components to streams

Figure 6: Seasonal variation of flows versus their driven nitrate yield for different flow components

Conclusions

The SWAT model was applied in the Toenepi catchment to simulate flow and nitrogen loss. The results showed that the SWAT model could predict flow very well with better prediction at the monthly time step. The flow variation was very well captured, however, flow at storm events were underestimated. SWAT also produced reasonable estimates and seasonal variation for nitrogen yield and concentration. Subsurface tile drainage is the main contribution to streamflow, and consequently is the dominant pathway for nitrogen transport to the streams.

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