# Modelling the Effects of Groundwater Lags on Nitrate Inputs to Lakes Rotorua & Taupo, New Zealand

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**EXTENDED ABSTRACT**

A conceptual rainfall-runoff model has been adapted for predicting nitrate concentrations in streams draining the volcanic plateau, central North Island, New Zealand. The model is similar to HBV-N (Pettersson et al. 2001) and the nitrate model of Tamura et al. (1999). It has been developed in response to increasing trends in stream nitrate concentration observed recently in streams draining to both Lake Rotorua and Lake Taupo – iconic water bodies important for recreation and tourism. In these catchments land-use has changed from native bush in the 1930s to low intensity grazing in the 1950-1970s and more intensive grazing (including some dairying) in the 1990s. Riparian fencing was implemented in both regions during the 1970-1980s and while this has reduced particulate loads in the streams, it has done nothing to halt the increasing trend in nitrate concentration. Many of the catchments in the volcanic plateau are underlain by thick layers of fractured ignimbrite and the streams have a high proportion of baseflow supplied by deep groundwater. The water in some of the streams has been aged using tritium (and more recently CFC and $SF_6$) and found to have mean residence times of 30-80 years. There is concern that nitrate liberated when land was first developed 35-45 years ago is still making its way through the groundwater towards the lakes. It is intended to use the model to address management questions such as: where in the catchment is it possible to intercept nitrate (e.g., in riparian buffer strips and wetlands); where is it necessary to reduce nitrate fluxes leaving the root zone (e.g., by retiring pasture); and how long will it take before the benefits of remediation become apparent.

The model simulates rainfall, infiltration, evapo-transpiration and percolation in the root-zone. Surface runoff is simulated by Hortonian infiltration excess runoff during heavy rain and direct runoff of rain falling on saturated soils near the stream, although the pumice soils of the central volcanic plateau are generally free-draining. Streamflow is driven by the outflow from 3 conceptual reservoirs that represent quick shallow sub-surface flow (time scale 1-2 days), slow sub-surface flow (2-10 days), and groundwater (weeks-years). To date the rainfall-runoff model has been calibrated in the Waiteti Stream, Rotorua, and the Tutaeaua Stream, Taupo, where it replicates the observed spring-fed baseflow which is a feature of the study streams. It is currently being calibrated and tested in the 8 major catchments of Lake Rotorua.

The nitrate model is still being perfected. Currently our knowledge of how leachate concentration increased during the 1930-1970s is incomplete and two different models have been trialled. In Model 1 the nitrate concentration in water leaching from the root-zone is specified. Model 1 successfully simulates an increase in baseflow nitrate driven by slowly increasing groundwater nitrate concentration – which mimics long-term trends in stream nitrate. However, Model 1 predicts a positive correlation between stream nitrate concentration and flow whereas Hoare (1980) observed a negative correlation during floods. In Model 2 nitrate is generated (by mixing and/or mineralization) in the conceptual reservoirs as suggested by Tamura et al. (1999). Model 2 successfully simulates the observed negative correlation between stream nitrate and flow. Further work is underway to refine the nitrate component of the model. Agricultural statistics are being combined with recent leaching studies under different intensities of land-use in an attempt to reconstruct past trends in leachate concentration.

## 1. INTRODUCTION

Lakes Rotorua and Taupo lie on the volcanic plateau in the central North Island, New Zealand. Taupo is a large (950 $km^2$), deep (max 160 m) lake with high clarity (15 m secchi disc) and low nutrient concentrations (5.8 mg TP $m^{-3}$, 70 mg TN $m^{-3}$). Rotorua is smaller (80 $km^2$), fairly shallow (mean 10 m) with moderate clarity (1-2 m) and moderately high nutrient concentrations (40 mg TP $m^{-3}$, 400 mg TN $m^{-3}$). Both are tourist destinations and their water quality is an important management issue.

During the 1970s it was recognised that water quality was deteriorating in Lake Rotorua as a result of increased nutrient loads, notably from treated sewage, streams draining pasture and aerial top-dressing. Water quality problems included increasing chlorophyll concentrations, sporadic blooms of nuisance blue-green algae, decreasing water clarity and more frequent de-oxygenation during summer stratification. Anoxia in the bottom waters adversely affected fish and resulted in nutrient releases from the lakebed. Public concerns about water quality prompted several scientific studies (Fish 1975; Hoare 1980, Williamson et al. 1996, Gibbons-Davies 2003). Commencing in the late 1970s measures were put in place to reduce external nutrient loads: phosphorus stripping at the Rotorua sewage treatment plant prior to its discharge to the lake (1973-1990); land disposal of treated sewage in the Whakarewarewa Forest (1991-present); fencing of stream margins to exclude stock, and retirement and/or planting of erosion prone land.

Conventional wisdom during the 1970s was that fencing streams and retiring eroding land would reduce soil erosion and particulate nutrient load, reduce overland flow and its particulate and soluble nutrient load, and direct inputs of nutrient from stock in streams. Williamson et al. (1996) found that 10-12 years after retirement particulate nitrogen and phosphorus loads had declined by 30-40%, soluble phosphorus loads had declined by 25% but soluble nitrogen loads (predominantly nitrate) had increased by 25% in the Ngongotaha Stream (NGO). Rutherford (2003) found the same pattern in 8 of the 9 major inflows to Rotorua (Fig. 1). In contrast to nitrogen, there was no clear evidence of increasing phosphorus concentrations in the major streams from 1967-2003.

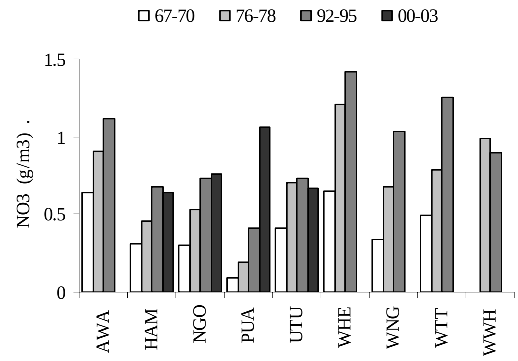


**Figure 1.** Trends in mean baseflow nitrate in the major inflows to Lake Rotorua. WTT = Waiteti.

Nitrate comprises a significant fraction of the total nitrogen concentration in Rotorua streams and consequently the increasing trend in stream baseflow nitrate caused an increasing trend in nitrogen load (Fig. 2). The benefits from sewage diversion in 1991 have been offset by an increase in stream nitrate load.

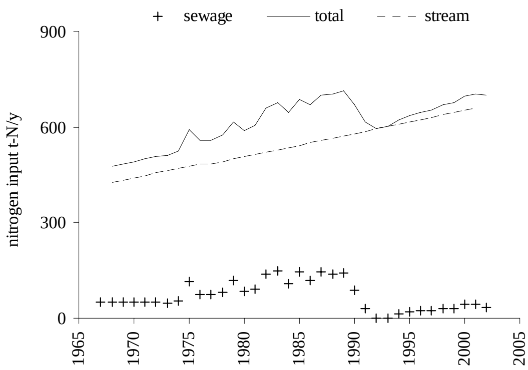


**Figure 2.** Trends in nitrogen load to Lake Rotorua from sewage and streams. Sewage diversion was complete in 1991.

At Lake Taupo, Gibbs (2005) detected the early signs of eutrophication: decreasing lake water clarity, increasing chlorophyll and increasing nutrient concentrations. Vant (2000) reported increasing trends in the nitrate concentration of streams draining volcanic soils underlain by fractured ignimbrite aquifers on the north-western side of the lake. A large proportion (80-90%) of the total water yield occurs as baseflow implying a significant groundwater component. Vant & Smith (2004) reported that the mean residence time (MRT) of stream water estimated using tritium (Stewart et al. 2001) varied from 30-80 years. Waters with long MRT had high dissolved reactive phosphorus (because the volcanic rock dissolves leading to high concentrations in old groundwater) and low nitrate (because the old water originated prior to land development). Vant & Smith (2004) estimated that in addition to the current stream nitrate load (288 t/y) there was a considerable amount of nitrate (45 t/y) ‘yet to come’ – nitrate that had been liberated by land development during the last 35-45 years but which is still making its way through the groundwater. Environment Waikato has responded with a catchment management plan that aims to reduce the nitrogen load to the lake to 80% of the value in 2003 progressively over the next few years, through better stock and fertilizer management plus retirement of some farmland. In response to serious erosion in the 1960-1970s the Taupo Management Scheme made provision for the fencing and replanting of many of stream margins. Despite this, nitrate concentrations have continued to increase and now appear to be affecting lake water quality.

## 2. CONCEPTUAL MODEL

A conceptual rainfall-runoff-nitrate model has been developed to address management questions such as: where in the catchment is it possible to intercept nitrate (e.g., riparian buffer strips and wetlands); where is it necessary to reduce nitrate fluxes leaving the root zone (e.g., retiring pasture); and how long will it take before the benefits of remediation become apparent. The model is a daily time-step conceptual reservoir model, similar to the rainfall-runoff model HBV (Bergstrom 1995).

The model predicts the depth of water in each of 5 soil water stores (see Figure 3) - soil, rootzone (RTZ), quickflow (QFZ), slowflow (SFZ) and regional aquifer (RAQ). In the soil reservoir, the model predicts soil moisture based on daily rainfall, a maximum infiltration rate, a simple evapotranspiration sub-model and a linear percolation rate to the root-zone. Surface runoff is simulated by Hortonian inflitration excess runoff during very heavy rain and direct runoff of rain falling on saturated soils, although the pumice soils of Rotorua and Taupo are free-draining and surface runoff is rare. The RTZ, QFZ, SFZ and RAQ are each modelled as a non-linear reservoir with two outflows: (1) to the stream (or spring) and (2) to one or more of the underlying reservoirs. The user can specify the % drainage from the RTZ to the QFZ, SFZ and RAQ. The coefficients relating outflow to reservoir water depth are estimated by calibration.

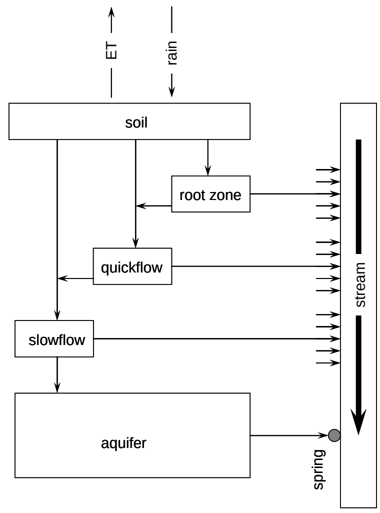


**Figure 3.** Diagram of the conceptual rainfall-runoff-nitrate model.

The concentration of nitrate in leachate leaving the root-zone is specified as a function of land-use. In each reservoir the model calculates losses (denitrification, uptake) following Pettersson et al. (2001) and sources (nitrification) following Tamura et al. (1999). Streamflow is driven by the outflow from 3 conceptual reservoirs that represent quick shallow sub-surface flow (time scale 1-2 days), slow sub-surface flow (2-10 days), and groundwater (weeks-years) (Figure 3).

## 3. MODEL RESULTS

### 3.1. Calibration of runoff model

The rainfall-runoff model has been calibrated in the Waiteti Stream, Rotorua which has a catchment area of 71 km$^2$ (c.f., 437 km$^2$ for Lake Rotorua). Coefficients for the Waiteti are summarised in Table 1.

| Aquifer | | RZ | QFZ | SFZ | RAQ |
|---|---|---|---|---|---|
| soil porosity | (-) | | 0.3 | | |
| thickness | m | 1 | 1 | 1 | 20 |
| max infiltration | m/d | 0.1 | - | - | - |
| max drainage | m/d | 0.015 | 0.01 | 0.002 | 0 |
| RZ drainage to | % | - | 100 | 0 | 0 |
| drainage to stream | m/d | 0.5 | 0.5 | 0.025 | 0.0002 |
| % drainage to spring | % | - | - | - | 30 |

**Table 1.** Summary of coefficients for the Waiteti. Reservoirs are RZ = root zone, QFZ = quickflow aquifer, SFZ = slowflow aquifer, RAQ = regional aquifer.

Flow in the Waiteti (Figure 4) has a baseflow of 0.7-0.9 m$^3$ s$^{-1}$ that originates from several springs draining groundwater. The catchments that contribute to groundwater flow in the springs in the volcanic plateau are not known accurately, and Figure 4 assumes that only 30% of the surface catchment of the Waiteti contributes to flow in the Waiteti springs. This is plausible because the nearby Hamurana spring has a very small topographic catchment but a large, steady spring flow. The Hamurana spring must be supplied by rain that infiltrates in adjacent topographic catchments such as the Waiteti.

### 3.2. Nitrogen Model 1

Following Pettersson et al. (2001) the nitrate concentration in leachate from the groundwater was specified *a priori* and the denitrification and nitrate uptake rates set to zero in the quick, slow and aquifer reservoirs.

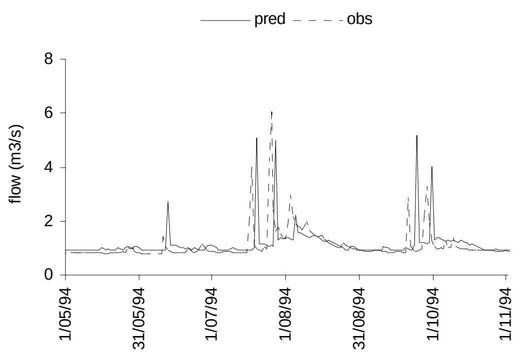


**Figure 4.** Observed and predicted stream flow in the Waiteti Stream.

Figure 5 shows predicted nitrate concentrations assuming that leachate nitrate concentration increases from a background of 0.2 g m$^{-3}$ (a value typical of undeveloped native bush) at a rate of 1 g m$^{-3}$ y$^{-1}$ (as might occur following a dairy conversion) to a maximum of 5.2 g m$^{-3}$. Rainfall used for these simulations was that measured during the 2-year period 1994-1995 repeated. As expected, quickflow and slowflow nitrate concentrations respond rapidly to the change in land-use. Aquifer nitrate concentration responds more slowly because it contains a large volume of water whose concentration increases only slowly in response to a gradual influx of high nitrate leachate. There is a discernible increasing trend in predicted stream nitrate concentration at baseflow (Figure 6) as has been detected in the Rotorua and Taupo streams.

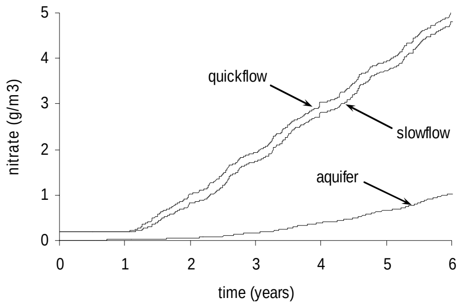


**Figure 5.** Model 1: predicted nitrate concentration in the 3 conceptual reservoirs.

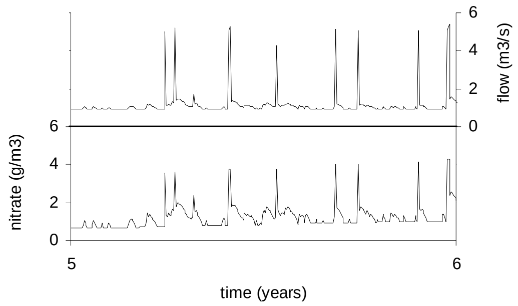


**Figure 6.** Predicted stream flow (upper) and nitrate concentration (lower) in Year 6.

Figure 7 shows the predicted relationship between flow and nitrate concentration during Year 6. In the model low flows are dominated by spring flow from the aquifer that has low nitrate. High flows are dominated by quickflow and slowflow which both have high nitrate.

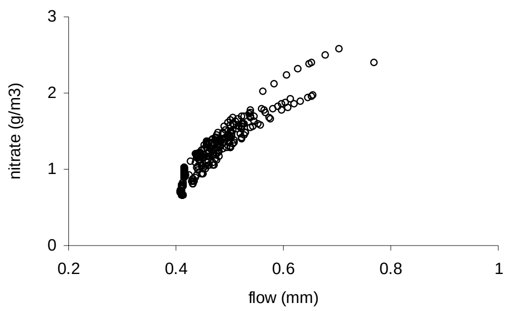


**Figure 7.** Model 1: variation of nitrate with flow.

In the adjacent Ngongotaha Stream, Hoare (1980) found a positive correlation between flow and suspended solids, total phosphorus and total nitrogen concentrations. However, during a storm Hoare found that the nitrate concentration decreased during high flows (Figure 8) and there was a negative correlation between nitrate and flow over the period of the storm. This is at variance with the predictions of Model 1.

### 3.3. Nitrogen Model 2

Model predictions were repeated but assuming a nitrification rates of 0 and 0.05 g $m^{-3}$ $d^{-1}$ in the quickflow and slowflow aquifers respectively. The % of drainage from the root zone to the quickflow aquifer (100% in Table 1) was reduced (eventually to 2.5%) and the fraction to the slow flow aquifer increased (eventually to 97.5%) by trial and error until the pattern in Figures 8 and 9 were similar.

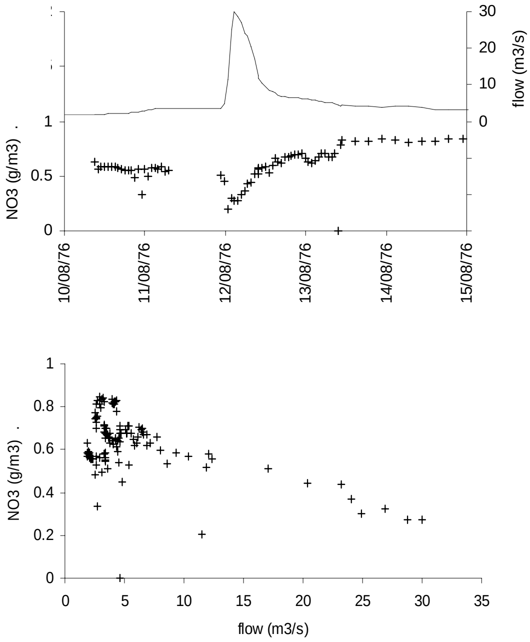


**Figure 8.** Variation of nitrate with flow observed in the Ngongotaha Stream (R.A. Hoare unpub. data).

The resulting Model 2 simulates 2.5% of drainage from the rootzone not mixing with or displacing high nitrate soil water. During dry periods streamflow is dominated by flow from the spring and the slowflow aquifer which both have high nitrate concentration. During wet periods spring and slowflow remain constant, but infiltration excess surface flow and quickflow increase and make a large contribution to streamflow. In Model 2 surface and quick flow have zero nitrate concentration and hence dilute the high nitrate flow from the slow and spring flow. This gives the strong negative correlation between nitrate concentration and flow in Figure 9 and mimics the observed behaviour in Figure 8.

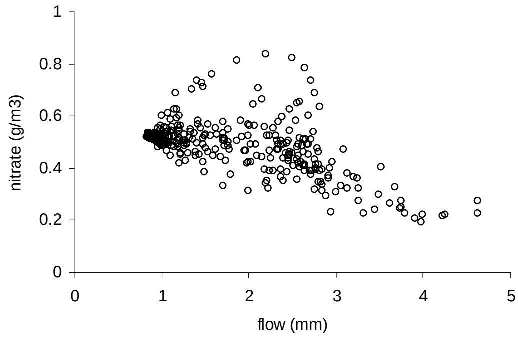


**Figure 9.** Model 2: variation of nitrate with flow.

## 4. DISCUSSION

Both Model 1 and 2 show promise for simulating groundwater lags. However, Model 1 does not accurately simulate short-term nitrate dynamics during storms. This may be of minor concern to managers interested in long-term trends. Nevertheless, it is desirable to capture the dominant processes accurately in the model and Model 1 has clear short-comings. Work is continuing to refine the calibration of Model 2 in the Waiteti and apply it to other catchments at Rotorua.

The rate at which leachate nitrate concentration increased in the Waiteti following land settlement during the 1930-1960s is not known accurately, and further work is needed to collate agricultural statistics (stocking rate, fertilizer use etc) in the catchment or region and combine this with recent data on nitrate leaching from different land-use intensities.

At Taupo there is only a 1-year record (2004-2005) of flow and water quality in the Tutaeaua Stream for model calibration and testing. However, the Tutaeaua Stream is the focus of a collaborative field study involving several research agencies that will enable nitrate delivery pathways to be identified.

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