# USE OF A MODEL TO PREDICT THE EFFECTS OF LAND USE CHANGES ON NITROGEN DELIVERY TO LAKE ROTORUA, ESPECIALLY THE LAGS INVOLVED WITH GROUNDWATER

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**Abstract**

The effects on the nitrogen load to Lake Rotorua of four scenarios of land use change are predicted using the ROTAN model, aimed at achieving the target of 435 tN/yr (405 from the catchment plus 30 tN/yr in rainfall). Scenarios assume a step reduction to nitrogen export from the land in 2015 and make predictions until 2100. The effects of climate change were investigated, but found to be minor. ROTAN simulations indicate that if total nitrogen exports were to be reduced by about 320 tN/yr from the current level of 725 tN/yr and held constant, then the lake load is likely to decrease quite quickly and to approach the target of 405 tN/yr within about 35 years. The predicted recovery time of about 35 years is a faster than expected given that groundwater age (estimated by GNS from tritium measurements) ranges from 15-170 years (Morgenstern et al. 2005, Morgenstern and Gordon 2006). There is a plausible explanation for the fast response provided the aquifers are well-mixed and there is no storage of nutrient in the unsaturated zone. The actual recovery rate is likely to be slower than 35 years for two reasons. First, in ROTAN the nitrogen export rate from pasture changes immediately there is a land use change. In practice it may take 5-10 years for nitrogen stores in the soil to be depleted and for the nitrogen export to decrease to a new steady state value after a land use change. Second, the scenarios assume a step change in land use in 2015 but in practice land change is likely to occur gradually. One might argue that the quickest way to reduce lake load would be to reduce nitrogen exports from catchments with ‘young’ groundwater. Simulations indicate, however, that export reductions in catchments with widely differing mean residence times (Waingaehe 107 years and Ngongotaha 16 years) result in significant load reductions within a similar period. Thus, nutrient export reductions may be equaly effective regardless of the groundwater age of the catchment in which they occur.

## Introduction

The nitrogen load[1] to Lake Rotorua from streams is now significantly higher than the ‘target’ load of 435 tN/yr (including rainfall) set for the lake (EBoP 2007, 2009). The ROTAN model (<u>RO</u>torua and <u>TA</u>upo <u>N</u>itrogen) has been developed by NIWA to predict the effects of land use on nitrogen loads in catchments with groundwater lags. ROTAN is a GIS-based, daily-weekly time step, conceptual land use-surfacewater-groundwater-nitrogen model. Previous work describes the model in detail including its calibration to observed flow and nitrogen concentration data in Rotorua streams using historical land use data, rainfall and leaching rates (Rutherford et al. 2008, Rutherford et al. 2009). The model contains 5 layers: 2 soil layers, 2 shallow aquifers (quickflow and slowflow), and 1 deep aquifer. Springflow emerges

[1] Hereafter ‘export’ refers to the flux of nitrogen that leaves a parcel of land or a point source, and ‘load’ refers to the flux that reaches Lake Rotorua after allowing for attenuation.

from the deep aquifer into streams at specified locations. The surface catchments (Figure 1) contain the top 4 layers and the deep aquifer (Figure 2) the bottom layer. Deep aquifer parameters were selected to match groundwater mean residence times (MRTs) reported by Morgenstern & Gordon (2006) which range from 16 (Ngongotaha) to 127 (Waingaehe) years.

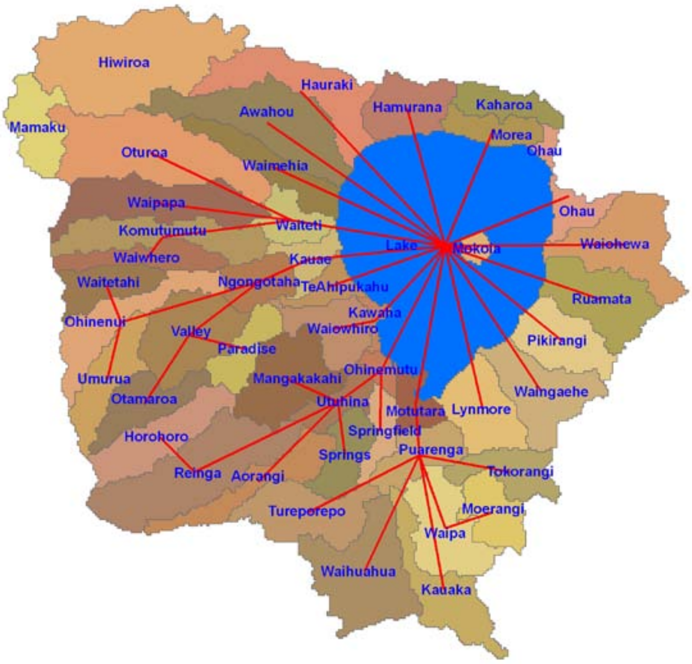


Figure 1: Surface catchments used in the ROTAN model. Red lines show the surface flow connections. Catchments without lines contribute groundwater to the lake but not surface flow.

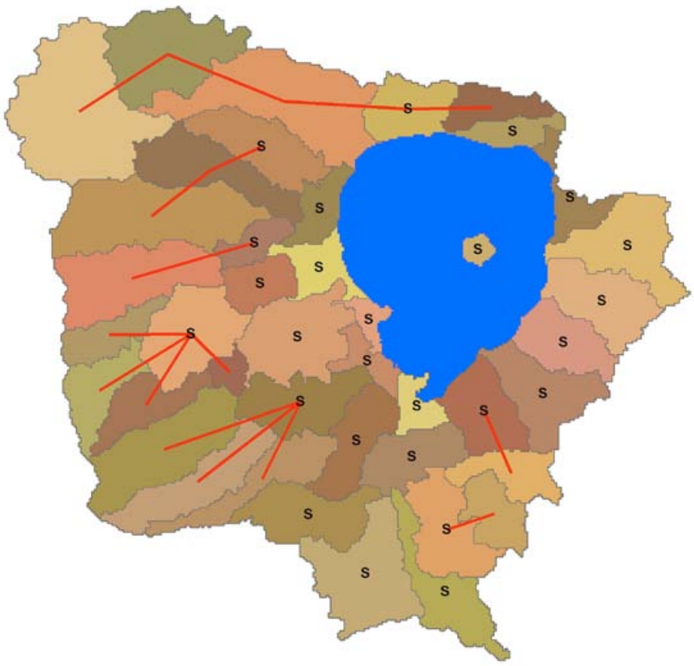

Figure 2: Deep aquifers used in the ROTAN model. Lines show the groundwater flow connections. ‘S’ denotes where the groundwater emerges as springflow which then joins the stream flow in the surface catchment (see Figure 1 for the surface catchments).

The Lake Rotorua catchment contains several large springs fed by groundwater. Dating using tritium has shown that spring and stream water varies in age from 15-170 years (Morgenstern et al. 2005). Long groundwater residence times mean that historic nitrogen exports from the land surface are needed and so GIS maps of land use or land cover for 1940, 1958, 1974, 1986, 1996, 2001, 2003, 2005 and 2010 were developed. Agricultural statistics for the Rotorua district were used to help estimate land use from land cover and to estimate stocking rates. These data were then used in Overseer® (www.overseer.org.nz) to estimate nitrogen (N) leaching rates (kgN/ha/yr). The land use categories modelled are: Dairy, DryStock, Forest, SepticTanks, SewageTreatmentPlant (STP, treated sewage discharged into the lake prior to 1991), LifeStyle, Urban, UrbanOpenSpace (UOS), Tikitere (geothermal field), Whakarewarewa (Whaka, geothermal field), RotoruaLandTreatmentSystem (RLTS, treated sewage sprayed into Whakarewarewa Forest from 1991) and Water. Figure 3 shows the distribution of the land use categories for 2010 (as an example) and Table 1 gives the areas of the land use categories.

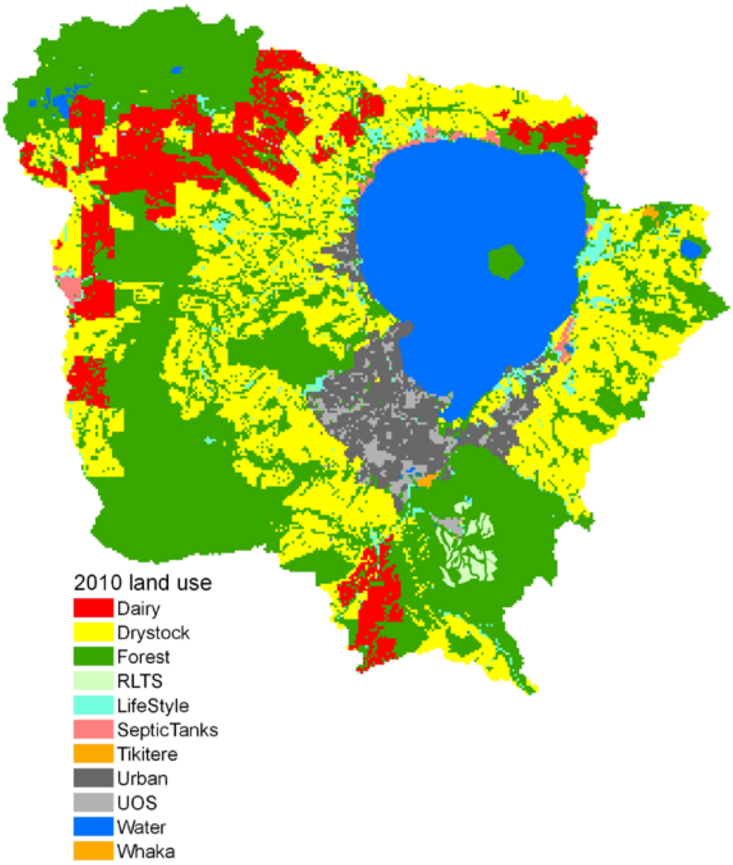


Figure 3: Land use distribution in the Lake Rotorua catchment 2010.

During calibration, ROTAN was run from 1920-2010 using several different estimates of land use distribution, nitrogen leaching rates, the timing of land use changes, and deep aquifer depth. ROTAN can only accommodate a limited number of land use maps (currently 8). The model assumes that a step change in land use occurs at some date between land use maps[2] (see Start and End dates in Tables 2 and 3). There is some uncertainty about when land use changes occurred in the past. During calibration, the Start and End dates were adjusted to

[2] The model user can, if they choose, interpolate between land use maps – but this option was not used in this report.

achieve a good match to observed stream nitrogen concentrations. This match is affected not only by the Start and End dates but also by the volume of the deep aquifers (which affects the mean residence time (MRT) of the groundwater in the deep aquifers). Tables 2 and 3 give the nitrogen leaching rates and historic nitrogen exports used in ROTAN. ROTAN estimated the current (2010) N load to the lake to be 650 tN/yr, and the steady state load (assuming no change in exports) to be 725 tN/yr (viz., the same as the total exports) (Table 3). There is evidence that nitrogen attenuation is negligible in most of the catchment – with the possible exception of parts of the Puarenga where there are numerous wetlands.

Table 1: Areas (ha) of the land use (LU) categories used in ROTAN for the years 1940, 1958, 1974, 1986, 1996, 2001, 2003, 2005 and 2010.

| **LU category** | **Year** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **1940** | **1958** | **1974** | **1986** | **1996** | **2001** | **2003** | **2005** | **2010** |
| Dairy | 565 | 1,073 | 1,627 | 2,838 | 4,742 | 5,532 | 5,731 | 5,412 | 5,050 |
| DryStock | 13,642 | 15,818 | 18,716 | 17,788 | 17,157 | 16,842 | 16,891 | 14,710 | 15,072 |
| Forest | 31,755 | 27,404 | 22,481 | 22,553 | 20,638 | 20,056 | 19,721 | 21,182 | 21,182 |
| RLTS | | | | | 300 | 300 | 300 | 300 | 300 |
| LifeStyle | | | | | | | | 1,053 | 1,053 |
| SepticTanks | 355 | 908 | 940 | 324 | 258 | 268 | 304 | 308 | 308 |
| STP | | | 4 | 4 | | | | | |
| Tikitere | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 |
| Urban | | | 1,811 | 2,070 | 2,339 | 2,508 | 2,565 | 2,548 | 2,548 |
| UOS | | 1,114 | 738 | 740 | 883 | 811 | 805 | 805 | 805 |
| Water | 8,257 | 8,257 | 8,257 | 8,257 | 8,257 | 8,257 | 8,257 | 8,257 | 8,257 |
| Whaka | 31 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | 31 |
| **Total (ha)** | **54,633** | **54,633** | **54,633** | **54,633** | **54,633** | **54,633** | **54,633** | **54,633** | **54,633** |

ROTAN was run for 4 scenarios of possible land use and nitrogen leaching rate changes (R-0, R-250, R-300 and R-350) aimed at achieving the 'target' N load to the lake of 435 tN/yr (including 30 tN/yr in the rainfall) (EBoP 2007, 2009). All scenarios were run from 1920-2010 using historical land use distribution, nitrogen leaching rates, and timing of land use changes. For the R-0 scenario, the current (2010, see Tables 1, 2, 3) land use distribution and nitrogen leaching rates were used from 2010-2100 (Tables 4 and 5). For the R-250, R-300 and R-350 scenarios, R-0 was used from 2010-2015, then there was a step change in land use and nitrogen leaching rates in 2015 (Tables 4, 5 and 6) such that the current N export of 725 tN/yr (Table 3) was reduced by 250, 300 and 350 tN/yr respectively to give exports of 475, 425 and 375 tN/yr respectively. These changes persisted until the end of the simulation or run in 2100. The R-0 scenario was run with, and without, climate change to assess the effect on lake load. The effects of climate change on lake load were found to be minor and so the scenarios R-250, R-300 and R-350 were only run with climate change.

## Results

Figure 4 shows predicted annual nitrogen loads to the lake for the 4 scenarios of land use. It can be seen that the three scenarios of land use change (R-250, R-300 and R-350) all result in significant reductions to lake load that approach the lake target towards the end of the simulation period.

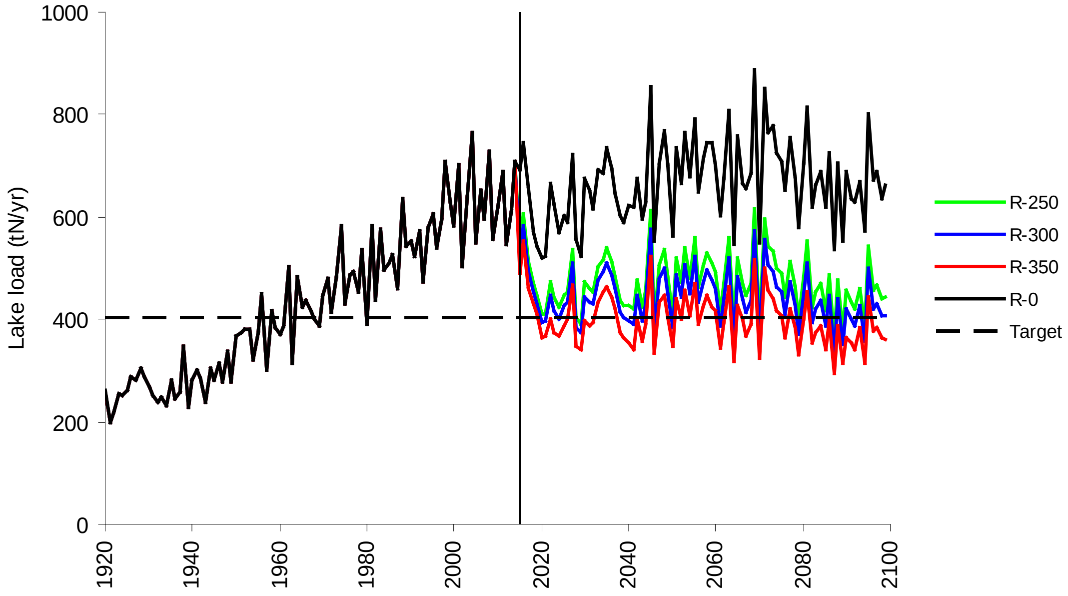


Figure 4: Predicted total nitrogen loads to the lake for the current land use (R-0) and three scenarios of land use change (R-250, R-300 and R-350). Also shown is the 'target' load of 405 tN/yr. Simulations assume climate change. Land use change occurs in 2015 (vertical line).

### Comparing the Ngongotaha and Waingaehe catchments

One might expect a catchment whose deep aquifer has a short MRT (like the Ngongotaha at 16 years) to respond to land use (and consequent nitrogen export) change more quickly than a catchment whose deep aquifer has a long MRT (like the Waingaehe at 105 years). The finding in Figure 5, therefore, seems counter-intuitive.

Table 2: Nitrogen leaching rates (kgN/ha/yr). LU Map denotes the date of the map used to describe the spatial distribution of each land use category. Start-End denotes the period for which the land use spatial distribution and the leaching rates apply.

| **LU Map** | **1940** | **1958** | **1974** | **1986** | **1996** | **2003** | **2010** |
|---|---|---|---|---|---|---|---|
| **Start-End** | **1920–1949** | **1950–1970** | **1971–1980** | **1981–1990** | **1991–2000** | **2001–2007** | **2008–2010** |
| Dairy | 30 | 32 | 40 | 46 | 51 | 56 | 56 |
| DryStock | 7 | 11 | 12 | 13 | 14 | 16 | 16 |
| Forest | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| RLTS | | | | | 160 | 112 | 112 |
| LifeStyle | | | | | | | 16 |
| SepticTanks | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| STP | | | 15,000 | 30,000 | | | |
| Tikitere | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 |
| Urban | | | 10 | 10 | 10 | 10 | 10 |
| UOS | | 10 | 10 | 10 | 10 | 10 | 10 |
| Water | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Whaka | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **Average[1]** | **6.4** | **9.3** | **12.3** | **14.1** | **15.0** | **17.0** | **16.1** |

[1] Area-weighted.

Table 3: Historic nitrogen exports used in ROTAN simulations (tN/yr).

| **LU Map** | **1940** | **1958** | **1974** | **1986** | **1996** | **2003** | **2010** |
|---|---|---|---|---|---|---|---|
| **Start-End** | **1920–1949** | **1950–1970** | **1971–1980** | **1981–1990** | **1991–2000** | **2001–2007** | **2008–2100** |
| **Land use** | | | | | | | |
| Dairy | 17.0 | 34.3 | 64.1 | 124.0 | 234.5 | 309.3 | 272.7 |
| DryStock | 94.1 | 170.7 | 219.4 | 227.2 | 235.9 | 265.6 | 236.4 |
| Forest | 115.7 | 98.7 | 79.8 | 80.0 | 73.0 | 69.5 | 75.4 |
| RLTS | | | | | 48.1 | 33.7 | 33.7 |
| LifeStyle | | | | | | | 16.7 |
| SepticTanks | 30.2 | 77.2 | 79.9 | 27.5 | 21.9 | 25.8 | 26.2 |
| STP | | | 60.0 | 120.0 | | | |
| Tikitere | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 | 30.0 |
| Urban | | | 18.1 | 20.7 | 23.4 | 25.7 | 25.5 |
| UOS | | 11.1 | 7.4 | 7.4 | 8.8 | 8.0 | 8.0 |
| Water | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Whaka | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Total** | **287.3** | **422.4** | **558.9** | **637.2** | **675.9** | **768.0** | **724.8** |

Table 4: Land use and nitrogen leaching rate changes for the four future scenarios.

| ROTAN scenario | Reduction in tN/yr | Dairy relative to current | | Drystock relative to current | |
|---|---|---|---|---|---|
| | | Area (ha) | Nitrogen leaching rate (kgN/ha/yr) | Area (ha) | Nitrogen leaching rate (kgN/ha/yr) |
| R-0 (current) | 0 | Current | 56 | Current | 16 |
| R-250 | 250 | 50% comprising: 319 ha to LifeStyle and the rest to DryStock | 40 (= 56 minus 29%) | 1196 ha to LifeStyle and the rest to Forest until 250 reduction met | 14.4 (= 16 minus 10%) |
| R-300 | 300 | Nil dairy: 319 ha to LifeStyle and the rest to DryStock | | 1196 ha to LifeStyle and the rest to Forest until 300 reduction met | 14.4 |
| R-350 | 350 | Nil dairy: 319 ha to LifeStyle and the rest to DryStock | | 1196 ha to LifeStyle and the rest to Forest until 350 reduction met | 14.4 |

Table 5: Areas (ha) of the land use (LU) categories used in ROTAN for the future scenarios.

| LU category | Future scenarios | | | |
|---|---|---|---|---|
| | R-0 (= 2010) | R-250 | R-300 | R-350 |
| Dairy | 5,050 | 2,525 | | |
| DryStock | 15,072 | 9,016 | 12,668 | 7,856 |
| Forest | 21,182 | 28,248 | 27,121 | 31,933 |
| RLTS | 300 | 300 | 300 | 300 |
| LifeStyle | 1,053 | 2,577 | 2,577 | 2,577 |
| SepticTanks | 308 | 300 | 300 | 300 |
| STP | | | | |
| Tikitere | 28 | 28 | 28 | 28 |
| Urban | 2,548 | 2,548 | 2,548 | 2,548 |
| UOS | 805 | 805 | 805 | 805 |
| Water | 8,257 | 8,257 | 8,257 | 8,257 |
| Whaka | 31 | 31 | 31 | 31 |
| **Total (ha)** | **54,633** | **54,633** | **54,633** | **54,633** |

Table 6: Percentage change in the areas of land use for R-250, R-300 and R-350 compared to R-0.

| **LU category** | **Future scenarios** | | |
|---|---|---|---|
| | **R-250** | **R-300** | **R-350** |
| Dairy | Decreases 50% (to LifeStyle or DryStock) | Decreases 100% (to LifeStyle or DryStock) | Decreases 100% (to LifeStyle or DryStock) |
| DryStock | Decreases 40% (to LifeStyle or Forest) | Decreases 16% (to LifeStyle or Forest) | Decreases 48% (to LifeStyle or Forest) |
| Forest | Increases by 33% | Increases by 28% | Increases by 51% |
| LifeStyle | Increases by 145% | Increases by 145% | Increases by 145% |

The reasons stream nitrogen load in the Waingaehe is predicted to decrease quickly following land use change are:

1. Only some of the nitrogen export (in these simulations 52.5%) drains into the deep aquifer to subsequently emerge as springflow. In these simulations 47.5% of the nitrogen export enters the stream via quickflow or slowflow.
2. Nitrogen that drains into the quickflow and slowflow aquifers reaches the stream within months-years and, therefore, responds quickly to land use change. Thus, in these simulations about half the nitrogen export responds quickly to land use change.
3. The other half the nitrogen export enters the deep aquifer, and responds to land use change more slowly. The model assumes that aquifers are well-mixed and that there is no storage of nutrient in the unsaturated zone.
4. In the Waingaehe, nitrogen exported to the deep aquifer mixes into a large volume of water. Figure 6 indicates that concentrations in the deep aquifer hardly change from 1960-2015 despite land use intensification and a significant increase in nitrogen exports. The reason is that the volume of the deep aquifer in the Waingaehe is very large, the model assumes the aquifer is completely mixed, and so by 2015 nitrogen concentrations in the deep aquifer have not fully responded to the intensive land use of the 1970-2000s.
5. Consequently:
    a. For scenario R-350 land use changes in 2015 reduce exports close to pre-development levels,
    b. Quickflow and slowflow loads decrease quickly after 2015 to pre-development levels,
    c. Springflow load hardly changes after 2015. But springflow load in 2015 is only slightly higher than it was pre-development.
    d. Consequently total load decreases quickly soon after 2015 and by 2030-2040 is close to pre-development levels.

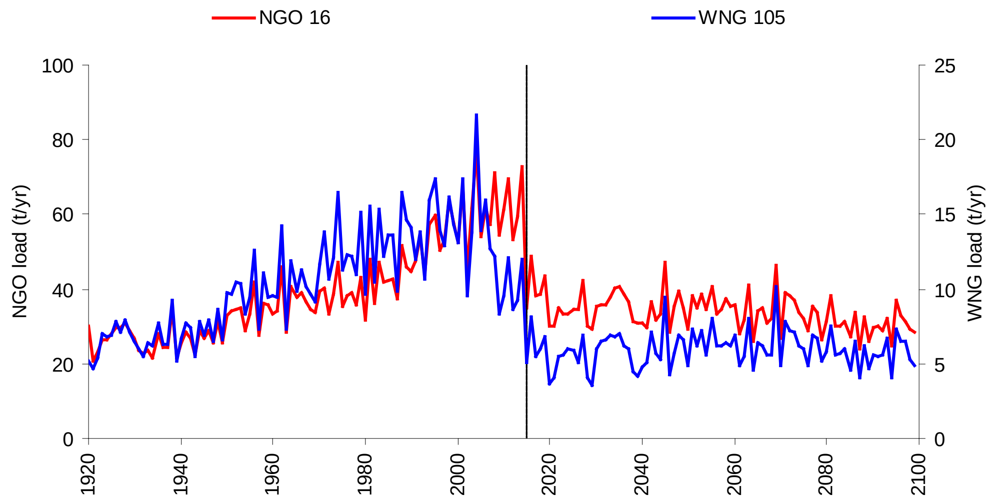


Figure 5: Scenario R-350: The predicted nitrogen loads from the Ngongotaha (NGO) and Waingaehe (WNG) catchments whose deep aquifers have MRTs of 16 and 105 years respectively in ROTAN. Note that the decrease in the Waingaehe load in 2008 is because of the land use change that occurred when the Wharenui block converted from Dairy to DryStock – no comparable land use change occurred in 2008 in the Ngongotaha.

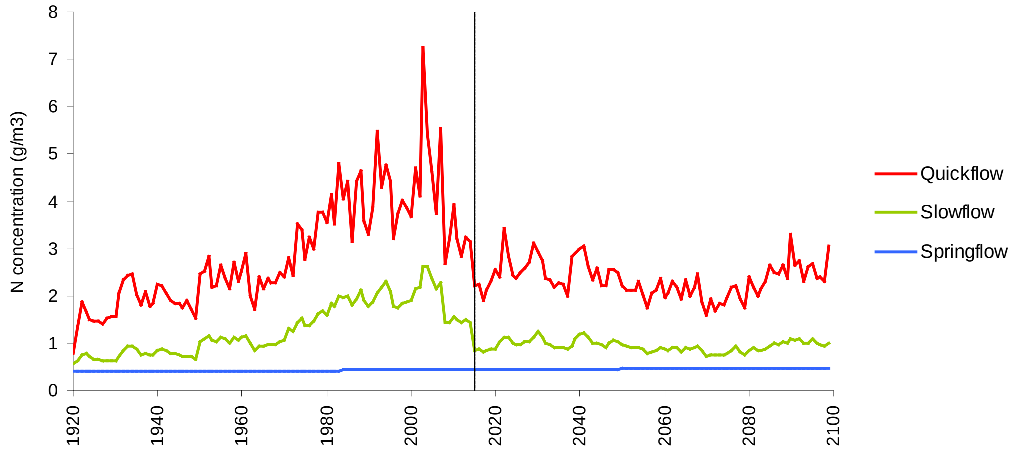


Figure 6: Scenario R-350: Predicted annual average nitrogen concentration in the quickflow, slowflow and deep aquifers of the Waingaehe catchment.

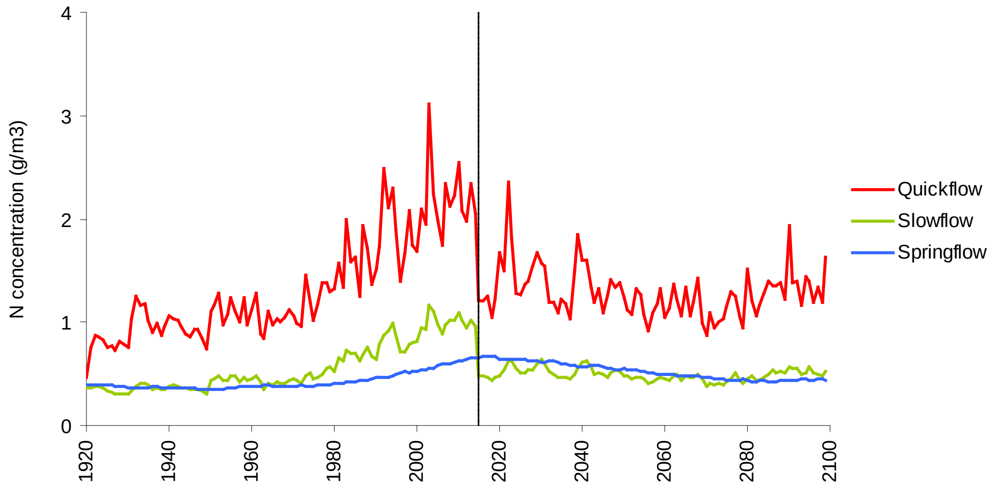


Figure 7: Scenario R-350: Predicted annual average nitrogen concentration in the quickflow, slowflow and deep aquifers of the Ngongotaha catchment.

By comparison, in the Ngongotaha Stream:

6. By 2015 nitrogen concentrations in the deep aquifer have increased significantly as a result of land use intensification (Figure 7). The reason is that the volume of the deep aquifer in the Ngongotaha is small and by 2015 the springflow load lies close to the steady state value for the intensive land use in the 1970-2000s.
7. In 2015 when land use changes:
    a. Quickflow and slowflow loads decrease quickly after 2015 to pre-development levels.
    b. Springflow load decreases over about 32 years (twice the MRT of 16 years).
    c. In 2015 springflow load is significantly higher than its was pre-development because nitrogen concentrations in the deep aquifer lie close to the steady state value for the intensive land use of the 1970-2000s.
    d. After the land use change in 2015, springflow load takes about 32 years to decrease from close to the steady state value for intensive land use before it reaches pre-development levels.
    e. Consequently, the total load (47.5% quickflow/slowflow + 52.5% springflow) decreases at a moderate rate.

In both the Ngongotaha and Waingaehe streams, total load appears to approach a steady state by about 2030-2040 (after 15-20 years). However, in the Ngongotaha springflow concentrations reach a true steady state after about 32 (twice the MRT of 16 years) for the constant nitrogen exports in scenario R-350. In the Waingaehe, it would take about 210 years (twice the MRT of 105 years) for springflow concentrations to reach a true steady state. However, because predicted springflow concentrations in 2015 are not significantly different from pre-development values, the very slow response of springflow concentration has little effect on lake load.

## Discussion and conclusions

### Scenario assumptions

Scenarios R-250, R-300 and R-350 assume that:

1. Land use changes (e.g., Dairy to DryStock) all occur as a step change in 2015.

In practice any land use change is likely to occur progressively over several years.

2. When a land use change occurs, the nitrogen export rate changes immediately (e.g., if land use changes from DryStock to Forest then nitrogen export immediately decreases from 16 to 4 kgN/ha/yr).

In practice it will take several years for nitrogen stores in the soil to be depleted and for the nitrogen export to decrease to a steady state value for the new land use. Assumptions 1 and 2 mean that these simulations furnish a 'lower bound' estimate of the how quickly the lake load can be reduced.

### Meeting lake load targets

Figure 5 indicates that the average of the predicted lake loads 2080-2100 are close to the target of 405 tN/yr for scenarios R-300 and R-350. To exactly match the lake load target, total nitrogen export would need to be reduced by 320 tN/yr from the current value of 725 tN/yr.

**Rate of response to land use changes**

ROTAN simulations indicate that the lake load would decrease within about 35 years following a step reduction in nutrient export. This finding seems counter-intuitive given that some aquifers have long mean residence times. However, ROTAN simulations show that following a step reduction of nitrogen export, the stream loads leaving a catchment with a short groundwater lag time (Ngongotaha, MRT 16 years) and a catchment with a long groundwater lag time (Waingaehe, MRT 105 years) both decrease quickly and at a similar rate (Figure 5). There is a plausible explanation for this behaviour which assumes that: (1) aquifers are well-mixed and that (2) there is no storage of nutrient in the unsaturated zone. This finding has implications for which catchments to 'target' when considering land use change.

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