Prediction of nitrogen loads to Lake Rotorua using the ROTAN model

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February 2011, Revised April 2011

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Executive Summary

This report is the third in a series prepared for Bay of Plenty Regional Council. It outlines recent refinements made to the ROTAN model, and describes several scenarios of land use change and mitigation. Findings are intended to help managers develop policy by estimating the extent of export reduction required to meet the lake target of 435 tN/yr, and how quickly the load to the lake is likely to respond to such reductions. The results will be used by the University of Waikato to predict likely changes in lake water quality.

We reviewed the history of the target lake load. A limit of 435 t/yr on the nitrogen input to the lake was first suggested in 1986 by the National Water & Soil Conservation Organisation. Their figure included nitrogen in streams and groundwater (375 tN/yr), rainfall on the lake (30 tN/yr), and treated sewage (30 tN/yr). Since the advent of the Rotorua Land Treatment System (RLTS) in 1991, the allowance for treated sewage enters the Puarenga Stream in drainage from the RLTS. Therefore, we compare model results for nitrogen in streams and groundwater with the figure of 405 tN/yr which is the target for streams and groundwater (375 tN/yr) plus the consented input from the RLTS (30 tN/yr) but excludes 30 tN/yr in rainfall on the lake.

This study estimates that currently the total nitrogen export from forests, farmland, geothermal, urban and treated sewage is 725 tN/yr which is similar to values in the Proposed Action Plan of 783 and 746 tN/yr. To meet the target of 405 tN/yr in streams and groundwater, we estimate that exports need to be reduced by about 320 tN/yr. If the total nitrogen export remains constant at the current level, the lake load is likely to increase slowly over the next 60-70 years and to approach a steady state of 725 tN/yr by about 2080. If the total nitrogen export is reduced by 320 tN/yr and held constant, the lake load is likely to decrease quickly and to approach the target of 405 tN/yr within about 35 years.

The predicted recovery time of about 35 years is faster than expected, but plausible assuming that: the average proportions of nitrogen reaching the lake via deep groundwater (slowly) and near-surface flow (quickly) are 53% and 47% respectively; and that deep groundwater is well-mixed. The actual recovery rate is likely to be slower than this because all the land use change is unlikely to occur in a single year.

It has been assumed that the best way to reduce the lake load is to reduce nitrogen exports in catchments with short groundwater lag times. However, modelling indicates that catchments with widely differing groundwater lag times respond at a similar rate in terms of nitrogen export. Consequently, the best strategy for most of the Lake Rotorua catchment may be to focus mitigation measures on those land parcels where it is easiest to reduce nitrogen exports, regardless of where these are located. The response time of the Hamurana Stream catchment is unique because of its very small surface catchment, and it will take many years for nitrogen export loads to fully reflect changes in land use.

Technical Summary

New input data was introduced, changes were made to the model to facilitate long model runs, and the model was re-calibrated – a new version of the model called ROTAN-1 was the result. Some problems remained. These included matching groundwater nitrogen loads owing to uncertainties in the extent of aquifer boundaries, groundwater age, land use patterns, and nitrogen export rates. However, the model fit is sufficiently good for scenario modelling. Several alternative versions of the ROTAN model were developed to test the sensitivity of predictions to uncertainties in key model coefficients and input data. These versions were named ROTAN-2 to ROTAN-9. While they were not calibrated as carefully as ROTAN-1, they provided valuable insights into model behaviour and reliability.

This report estimates that currently exports from forest, farmland, geothermal, septic tanks, sewage and urban runoff total 725 tN/yr. Independent assessments commissioned by Bay of Plenty Regional Council (EBoP, 2007) provided estimates of similar magnitude – 746 and 783 tN/yr.

ROTAN-1 simulations indicate that if the total nitrogen export remains at the current level, the lake load is likely to increase slowly over the next 60-70 years and to approach a steady state of 725 tN/yr by about 2080. ROTAN-1 simulations also indicate that if total nitrogen exports were reduced by about 320 tN/yr in 2015 and held constant, then the lake load is likely to decrease fairly quickly and approach the target of 405 tN/yr within about 35 years. The predicted response time of about 35 years takes into account the time required for nitrogen stores in the soil to be depleted following land use change. The actual recovery time is likely to be slower than this because land use change is unlikely to all occur in 2015 as assumed, but will occur gradually over several years.

The response time of about 35 years is faster than expected. It is a likely lower bound which assumes that on average the proportions of nitrogen reaching the lake via deep groundwater and near-surface flow are 53% and 47% respectively, and that deep groundwater is well-mixed. By calibrating ROTAN-1 to observed stream concentrations and flows, we have determined that on average about 47% of the total nitrogen export load travels via shallow groundwater, reaching the lake within a period of months-years. The figure of 47% was derived by matching the observed week-to-week variability in stream concentration and flow, with historic lake loads. Nitrogen concentrations in shallow groundwater respond very quickly to land use changes. The remaining 53% of total nitrogen export travels via deep groundwater, reaching the lake after 'lag periods' of the order 16-127 years. In ROTAN these proportions are assumed to be spatially uniform. There is, however, evidence that more water infiltrates (and hence more nitrogen enters deep groundwater) in some parts of the catchment than others – some parts of the catchment have little or no permanent stream flow (e.g., Hauraki, or Waiteti headwaters etc.). The relative locations of intensive land use and high infiltration soils may affect the response times, but further modelling work would be required to quantify this effect.

The time required for deep groundwater concentrations to respond to land use change depends on four factors: groundwater lag time, the steady state groundwater concentration for historic land use, the difference between groundwater concentrations and historic steady-state concentrations when land use changes, and the steady state groundwater concentration for the new land use.

In catchments with a very long lag time, groundwater concentrations change very slowly after a land use change. In such catchments (e.g., Waingaehe), groundwater concentrations were predicted to increase very slowly as land use intensified from 1920-2010. When land use intensity decreased in 2015 groundwater concentrations were elevated slightly above background, and well below steady state for current land use. Consequently, it was predicted that following the land use change in 2015, the deep groundwater load would remain small. It was predicted that the shallow groundwater load would decrease quickly (as in all catchments) and that the total load would decrease rapidly.

In catchments with a short lag time, it was predicted that groundwater concentrations would change rapidly after a land use change. In these catchments (e.g., Ngongotaha), groundwater concentrations were predicted to increase as land use intensified from 1920-2010. At the time land use intensity decreased in 2015, groundwater concentration had risen well above background levels and was near the steady state value for current land use. Following the land use change in 2015, the nitrogen load in deep groundwater was predicted to decrease at a moderate rate. As in all catchments, shallow groundwater load decreased very quickly. The total load decreased at a similar rate to that in the Waingaehe.

The finding that catchments with short and long MRTs have a similar response time is partly dependent on the proportion of nitrogen reaching the lake via deep or shallow groundwater and partly on the assumption that groundwater is well-mixed. Aquifers are commonly assumed to be well-mixed (e.g., Morgenstern et al. 2005) but if this assumption is not valid then response times may be longer than predicted.

It has been argued that the quickest way to reduce lake load would be to reduce nitrogen exports in catchments with short groundwater lag times. Our simulations indicate that export reductions in catchments with widely differing lag times result in significant load reductions within a similar time period. Consequently, it may not be sensible to focus solely on catchments with short groundwater lags. A more effective strategy may be to focus on properties where it is easiest to reduce nitrogen exports (for economic or social reasons) regardless of where these occur.

The Hamurana is unusual in that its surface catchment is very small and shallow groundwater flows are minimal. It has a long groundwater lag time and consequently nitrogen loads take a long time to respond to land use changes. Simulations suggest that its load will take nearly a century to approach steady state following land use change.

1. Introduction

1.1 Background

Lake Rotorua is important for recreation and tourism, and deteriorating water quality has been a concern since the 1960s (Rutherford et al. 1989).

While short-term bioassays indicate that the lake is nitrogen limited (White et al. 1977), recent studies (Burger et al. 2007) indicate that phosphorus limitation is beginning to occur. Baseflow nitrate concentrations in major streams draining into Lake Rotorua increased significantly over the period 1968-2003 (Rutherford 2003) and this trend is believed to have contributed to recent poor lake water quality. The nitrogen load[1] to Lake Rotorua is now significantly higher than the target load of 435 tN/yr set for the lake (EBoP 2007, 2009).

There is no apparent increase in baseflow soluble phosphorus concentration or load.

The geology of the Rotorua catchment is complex. Three separate ignimbrite layers have been identified which are punctured in several places by rhyolite domes, while the lake shores comprise sedimentary rocks (White et al. 2004). Aquifers occur in all three formations. The Lake Rotorua catchment contains several large springs fed by groundwater. Pang et al. (1996) identified 10 groups of springs with a total flow of 6.5 m3/s (32% of lake inflow) the largest being Hamurana (2.7 m3/s), Awahou (1.7 m3/s) and Rainbow/Fairy (0.3 m3/s). Geothermal springs in the lakebed have been identified in shallow water on the south and south-eastern shoreline (John and Lock 1977) and there may be geothermal and coldwater springs elsewhere in the lake. White et al. (2007) summarised information about the many springs and spring-fed streams in the Lake Rotorua catchment.

Dating using tritium has shown that spring and stream water varies in age from 15-170 years (Stewart and Morgenstern 2001; Morgenstern et al. 2005; Morgenstern and Gordon 2006). There was a period of land clearance in the 1940s and it has been hypothesised that current trends in stream concentration are the effects of these historic land use changes making their way slowly through the groundwater (Williamson et al. 1996). Recent land use intensification may be contributing to lake inputs where groundwater lags are small, and this contribution will increase in the future.

[1] Hereafter 'export' refers to the flux of nitrogen (tN/yr) that leaves a parcel of land or a point source, 'yield' refers to the export per unit area of land (kgN/ha/yr), and 'load' refers to the flux (tN/yr) that reaches Lake Rotorua after allowing for attenuation (viz., any permanent losses (e.g., denitrification) and temporary storage (e.g., groundwater lags)).

This report, the third in a series prepared for Bay of Plenty Regional Council (BoPRC), describes predictions of nitrogen load to Lake Rotorua, made using the model ROTAN (ROtorua and TAupo Nitrogen[2]), for several scenarios of possible future land use.

Strategies for lake restoration include land use change and measures to reduce nitrogen and phosphorus exports from farmland. BoPRC requires effective tools for predicting the cumulative effect of land use change and mitigation measures on nutrient inputs to the lakes. Two challenges for managers are:

- Determining which properties contribute diffuse nitrogen via runoff to the lake, given that the boundaries of aquifers draining to the lake may not coincide with the boundaries of the surface catchment.

- Predicting how quickly reductions of nutrient export from different parts of the catchment will reduce inputs to the lakes, given the groundwater lags in the system.

Morgenstern and Gordon (2006) estimated the effects of a step change in land use during the 1940s-1950s, including predictions of the nitrogen ‘loads to come’. This series of reports complements Morgenstern and Gordon (2006) by simulating temporal and spatial variations in rainfall, infiltration, land use and nitrogen export and refining estimates of the magnitude and timing of the nitrogen ‘loads to come’.

ROTAN hydrology calibration

The first report in this series, Rutherford et al. (2008), described fitting ROTAN to the observed daily flows in the nine major streams that flow into Lake Rotorua and to the observed lake outflow in the Ohau Channel over the period 1975-1979. The spatial distribution of rainfall was estimated by interpolation between rain gauges, making use of the very dense network of rain gauges deployed in the mid-1970s by Hoare (1980a). It was found that in order to achieve a water balance, the model needed to include an ‘extra’ area of land, outside the boundary of the surface catchment of Lake Rotorua, whose groundwater drained to the lake. The external aquifer boundaries encompassed the surface catchment of the lake plus ‘extra’ land whose most likely area was estimated to be 60 km^2. Because of uncertainties in rainfall and evapotranspiration, the area of ‘extra’ land could range from 5-80 km^2. White et al. (2007) suggested this ‘extra’ area lay mainly to the northwest of the lake.

[2] The ROTAN model is described in detail elsewhere (Rutherford et al. 2008, 2009).

ROTAN nitrogen calibration

The second report (Rutherford et al. 2009), described fitting ROTAN to measured total nitrogen (TN) concentrations in the major streams and published estimates of nitrogen input to the lake. Aquifer parameters were selected to match groundwater mean residence times (MRTs) reported by Morgenstern and Gordon (2006) which ranged from 16 to 127 years. Long groundwater residence times meant that historic nitrogen exports from the land surface needed to be estimated. GIS maps of land use or land cover for 1940, 1958, 1986, 1996, 2001 and 2003 were obtained. No map was available for the 1970s – a period of land use intensification. Land use (e.g., Forest, Dairy, Sheep, Beef etc.) was only described for 1958 and 2003 – land cover (e.g., NativeForest, Scrub, ImprovedPasture etc.) was described for the other years. There are uncertainties in estimating land use from land cover in 1940, 1986, 1996 and 2001. 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 yields (kgN/ha/yr). The original hydrology calibration of Rutherford et al. (2008) was refined in Rutherford et al. (2009) to incorporate revised aquifer boundaries (White and Rutherford 2009, and Phase 7 GNS results, Paul White, GNS, *pers. comm.*). The 'extra' area which contributes groundwater to the lake was reduced to 44 km^2 from the 60 km^2 reported in Rutherford et al. (2008). The long-term water balance over the period 1950-2008 was found to be satisfactory. Hereafter, the original ROTAN model described in Rutherford et al. (2009) is termed ROTAN-0.

ROTAN scenario modelling

This report, the third in the series, describes how ROTAN was recalibrated using recently collated data for land cover and stream water quality, and then used to predict nitrogen loads to the lake for several scenarios of land use and nitrogen export. Several versions of ROTAN were developed which make different assumptions about key model processes and coefficients – the different versions of the model are termed ROTAN-0, ROTAN-1, ROTAN-2…etc.

This report aims to:

- Quantify the reductions in lake load (hereafter termed 'load reduction') that are likely to be achieved for several scenarios of possible mitigation measures, undertaken on agricultural land.

- Estimate how quickly the lake load is likely to decrease (hereafter termed 'response time') once these mitigation measures are put in place.

‘Response time’ refers to how quickly lake load will decrease following a step change in land use. ‘Response time’ is determined by the physical properties of the catchment, and includes the time taken for nitrogen stores in the soil to readjust following a change in land use, and the time taken for water and nitrogen to make their way to the lake via the various flow pathways that operate in the catchment. ‘Recovery time’ refers to the rate at which the lake load decreases over time, which takes into account not only catchment ‘response time’ but also the way in which land use changes over time.

This report focuses on the required reductions in diffuse sources of nitrogen in the catchment, which are largely on agricultural land. This report does not discuss possible reductions in point source loads – these are included in each of the ROTAN models but do not vary between scenarios. This report is intended to:

- Inform BoPRC managers about what can be achieved in terms of reducing the load of nitrogen entering Lake Rotorua through changing land use or changing the way land is managed.

- Quantify the total area of each current land use that will need to change to meet the lake load target.

- Indicate where in the catchment these land uses currently occur.

- Estimate the likely rate at which the nitrogen load to the lake will decrease after changes are made.

- Help develop effective policy regarding land use and land management.

This report does not set out to identify parcels of land where it would be best to effect change land use in order to reach the target in the least time and/or at least cost – although ROTAN has the potential to be used for that purpose in the future.

2. Methods

2.1 Introduction

BoPRC is considering mitigation actions to reduce nutrient loads to Lake Rotorua in order to improve lake water quality. Two issues of interest to managers are:

- The likely magnitude of the decrease in lake load (load reduction) resulting from proposed mitigations.

- How quickly lake loads are likely to decrease following changes in land use (response time).

This report addresses both issues. It concludes that load reductions can be estimated reliably. Response times are difficult to quantify but likely responses time are discussed.

2.2 Lake load target

The target for nitrogen load to the lake has been set at 435 tN/yr (EBoP 2007, 2009). This is the estimated load to which the lake was subject during the early 1960s, before there was widespread concern about water quality in the main body of the lake (Rutherford et al. 1989). Note that in the early 1960s there was concern about the proliferation of weed growths around the edges of the lake, but not about phytoplankton blooms in the main body of the lake.

There was some confusion about whether the target of 435 tN/yr included contributions from rainfall and/or treated sewage. As part of this study, the original publications which described the derivation of this target were re-examined – see Appendix 2.

It can be confirmed that the target of 435 tN/yr relates to the sum of the nitrogen loads entering the lake from streams and groundwater plus rain plus sewage. Stream and groundwater loads include contributions from forests, farmland, septic tanks, urban runoff, and geothermal sources. The rainfall load averages 30 tN/yr (Hoare 1980b). The 435 tN/yr figure includes an allowance for sewage of 30 tN/yr and the current consent for the Rotorua Land Treatment System (RLTS) allows 30 tN/yr to enter the Puarenga Stream.

In ROTAN, the reported lake load includes inputs from forests, farmland, septic tanks, geothermal areas (Tikitere and Whakarewarewa), urban runoff and drainage from the

RLTS. ROTAN excludes the load from rain falling directly on the lake. Consequently, ROTAN lake loads should be compared with a target load of 405 tN/yr.

2.3 Uncertainty

As discussed in Rutherford et al. (2009), there is uncertainty in estimating lake loads and response times arising from uncertainties in:

- Historic land use and in particular which areas of Pasture were Dairy and DryStock.
- Historic nitrogen export rates from each land use.
- When land use and export rates changed.
- Aquifer boundaries.
- Aquifer parameters (including the proportions of total infiltration that enter the quickflow, slowflow and deep aquifers, and the volume, porosity and conductivity of those aquifers), which determine groundwater lag times.
- Nitrogen attenuation.

2.4 Re-calibration

For this report the ROTAN model was recalibrated using information that recently became available, information used previously but re-analysed, and following consideration of suggestions made by reviewers of a draft report.

The new information comprises:

- Recently obtained information on land cover/use during the 1970s.
- Recently measured flow and concentration data in the major streams during the period 2005-2010.
- Information regarding nitrogen loss from gorse (Mageson and Wang, 2008; Male et al. 2010), and land converted from woody, leguminous vegetation to pasture (Jonanovic et al. 2008).

Re-analysed existing information comprises:

- Nitrogen yields for dairy and drystock farms which have been re-analysed by an 'expert panel' of agricultural consultants, farmers, scientists and BoPRC staff that met in October 2009.
- Agricultural statistics from 1900-2000 which have been re-examined.
- Information regarding the population and areas served by septic tanks, which has been updated from census data.
- Historical N load during the early 1960s which is the target load for lake restoration (EBoP 2007, 2009).

The principal review comments were:

- Sensitivity analysis is desirable to determine the effects of uncertainty in MRT, nitrogen exports, and land use changes.
- The nitrogen species modelled need to be explained and discussed.
- ROTAN assumes a step change in nitrogen export which is unrealistic.
- ROTAN does not consider groundwater flowing directly into the lake.
- There are inconsistencies between internal aquifer boundaries used by GNS and NIWA.
- ROTAN incorrectly links streams and aquifers, notably in the Waingaehe Stream catchment.
- ROTAN is unable to link exports from specific land parcels to the lake, to help inform catchment-scale remediation.

Details of the review comments and responses are given in Appendix 1.

2.5 Alternative models

One way to quantify uncertainty is to run several different models, or several different ‘calibrations’ of the same model, and compare predictions. The latter approach is adopted in this report – several versions of ROTAN using different values for key model coefficients provide estimates of achievable load reductions together with likely upper and lower bounds on the response time. Differences between model runs include:

- Major springs are either fed by a single aquifer or by several separate aquifers.
- The proportion of infiltration that enters deep groundwater is either 70% or 80% – likely upper and lower bounds.
- The location of the internal aquifer boundaries are adjusted to maintain water balances in the nine major streams.
- The proportion of nitrogen that is generated in the soil layer is either 100%, 75% or 50%, with the balance generated in the quickflow aquifer.
- The climate in the years immediately after mitigation measures are put in place is either wet or dry.

Table 1 summarises features of the different versions of the ROTAN model.

Table 1: Features of the different versions of ROTAN used in this study.

Model	Deep aquifers	MRT	Infiltration		N generation [3]		Exports	Climate
			Deep aquifer	Shallow aquifer	Deep aquifer	Shallow aquifer		
ROTAN-0 [1]	Multiple	Morgenstern[2]	70%	30%	53%	47%	Rutherford [4]	Wei Ye [5]
ROTAN-1	Multiple	Morgenstern[2]	70%	30%	53%	47%	Table 6	Wei Ye
ROTAN-2	Single		80%	20%	80%	20%	Table 6	Wei Ye
ROTAN-3	Single		70%	30%	53%	47%	Table 6	Wei Ye
ROTAN-4	Single		70%	30%	35%	65%	Table 6	Wei Ye
ROTAN-8	Single		70%	30%	53%	47%	110% of Table 6	Wei Ye
ROTAN-9	Single		70%	30%	53%	47%	Table 6	Shuffled Wei Ye

[1] Results are detailed in Rutherford et al. (2009).
[2] MRT match published estimates in Morgenstern et al. (2005)
[3] Percentage of the total N generation estimated by Overseer®
[4] Exports are detailed in Rutherford et al. (2009)
[5] Climate change predictions made by Wei Ye, University of Waikato.

2.6 Surface catchments and aquifers

For all versions of ROTAN, the surface catchment boundaries remain unchanged from ROTAN-0 (see Rutherford et al. 2009 for details of ROTAN-0). Streams in catchments outside the surface catchment boundary of the lake catchment (Mamaku, Hiwiroa and Kaharoa) flow to the north or west and do not enter the lake, although deep drainage in these catchments enters groundwater that eventually flows into the lake. The surface catchments and stream flow connections are shown in Figure 1.

For ROTAN-1, internal and external aquifer boundaries remain unchanged from ROTAN-0 (Figure 2). The external aquifer boundaries closely match the GNS Phase 7 external aquifer boundaries, but the internal aquifer boundaries differ slightly from the GNS Phase 7 internal aquifer boundaries (Figure 4). As discussed in Rutherford et al. (2009), it was not possible to achieve water balances in ROTAN-0 for each of the 9 major streams using the "as supplied" GNS-Science Phase 7 boundaries. Therefore, in ROTAN-0, internal aquifer boundaries were adjusted slightly using 'normalised' data[3] – starting in the Hamurana and moving counter-clockwise around the lake – so that average predicted flow in the major streams matched observed average flow over the same time periods.

As part of the GNS-Science Phase 7 study, White et al. (2007) also sized the aquifers that feed the nine major streams to achieve a water balance. They estimated average flow in each stream using data collated from a variety of different sources and covering different time periods (viz., not 'normalised' data), assumed groundwater recharge was 50% of rainfall, and used a rainfall distribution map for the 1970s extrapolated from Hoare (1980a). The internal aquifer boundaries so derived are described in more detail by White and Rutherford (2009).

Because there are differences between the rainfall and stream flow data used by NIWA and GNS-Science, the water balance calculations furnish internal aquifer boundaries that differ slightly. It is highly unlikely that these differences will have a significant effect on predicted load reductions. They may, however, affect predicted response times in some catchments – especially those (e.g., the Waingaehe) where ROTAN assumes a single aquifer but GNS-Science assume two or more aquifers. They will also affect the pathways whereby water and nitrogen is predicted to exit land parcels located near aquifer or surface catchment boundaries.

For ROTAN-2 to ROTAN-9, new internal aquifer boundaries were created (Figure 3) by merging the surface catchments shown in Figure 1. Aquifers feeding the major spring-fed streams (e.g., Hamurana, Awahou, Utuhina and Puarenga) are not sub-

[3] 'Normalised' means that rainfall and flow data cover the same time period.

divided as they were in ROTAN-1 but rather are modelled as single, fully-mixed aquifers. This matches the way the GNS Phase 7 aquifers are drawn (Figures 4-5). Morgenstern et al. (2004), Morgenstern et al. (2005) and Morgenstern and Gordon (2006) assume single, fully-mixed aquifers when they model ‘bomb tritium’ in the nine major streams/springs. They assume that four of the Rotorua aquifers also have a ‘piston flow’ component (viz., a time delay between tritium falling in rain and entering the aquifer) – while ROTAN can include a similar time delay, the simulations reported here do not.

ROTAN-2 to ROTAN-9 are used in this report to assess the sensitivity of predicted load reductions and response times for the lake to key model coefficients. They are not intended to provide accurate predictions for individual catchments. Internal aquifer boundaries coincide with surface catchments boundaries and, as a result, water balances in some major streams are not as good as those in ROTAN-0 or ROTAN-1. While it is highly unlikely that these differences significantly affect predicted lake load reductions, they may have a second-order effect on predicted response times. In this report we use the ROTAN-2 to ROTAN-9 predictions to understand the behaviour of the model (and by inference the groundwater system) to changes in land use. We use the ROTAN-1 model to provide the ‘most likely’ estimates of load reductions and response times. Thus ROTAN-2 to ROTAN-9 are used to make qualitative predictions, and ROTAN-1 is relied upon to make quantitative predictions.

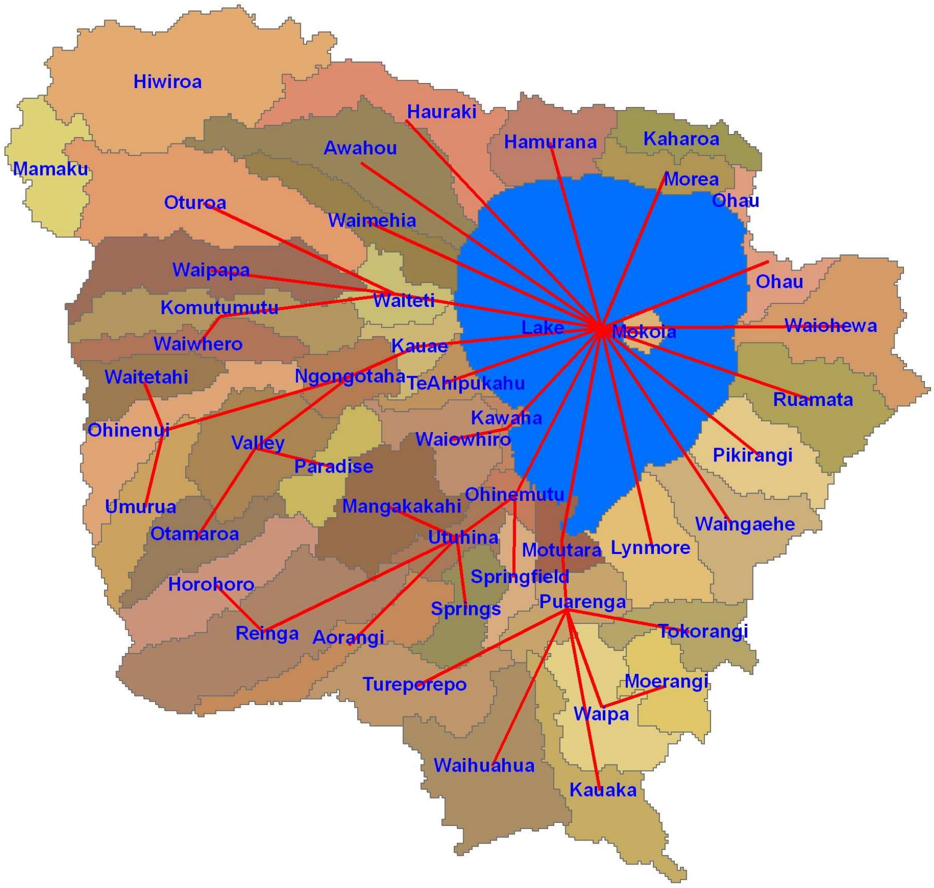


Figure 1: Surface catchments used in all the ROTAN models. Red lines show the surface flow connections. The three catchments without lines (Mamaku, Hiwiroa and Kaharoa) contribute groundwater to the lake but not surface flow.

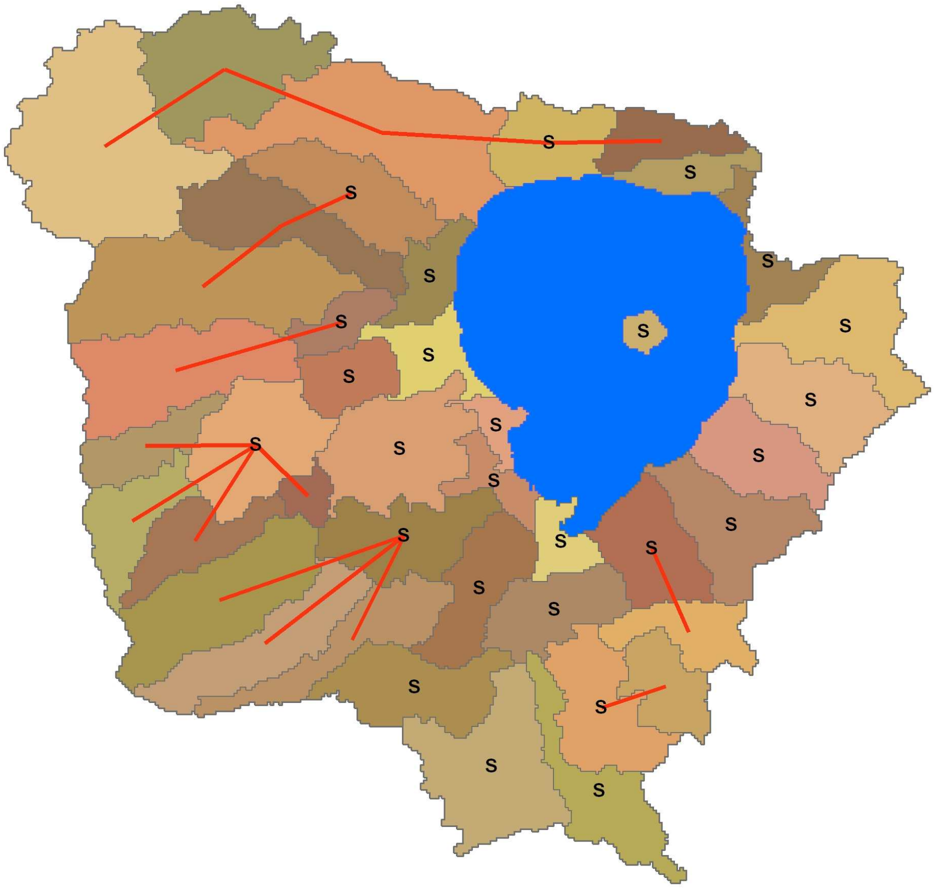


Figure 2: Aquifers used in the ROTAN-1 model. Lines show the groundwater flow connections. ‘S’ denotes where the groundwater emerges as spring-flow which then joins stream flow in the surface catchment (see Figure 1 for the surface catchments).

Figure 3: Aquifers used in the ROTAN-2 to ROTAN-9 models. Groundwater emerges at the lake edge from each aquifer.

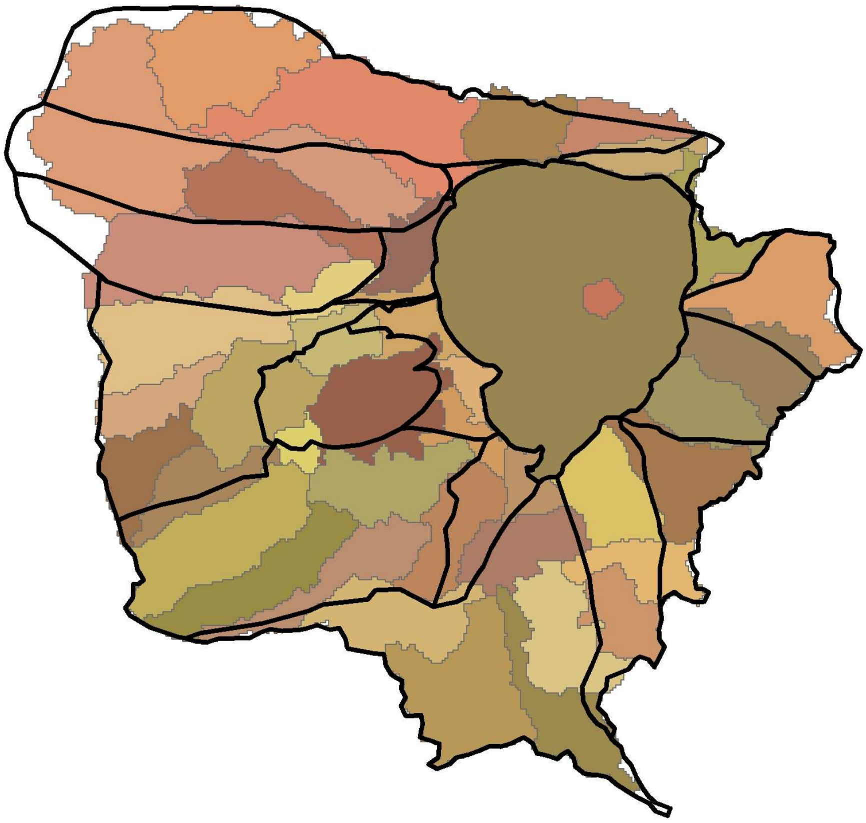


Figure 4: Comparison of aquifer boundaries in the ROTAN-1 model (coloured) with the GNS Phase 7 boundaries (black lines).

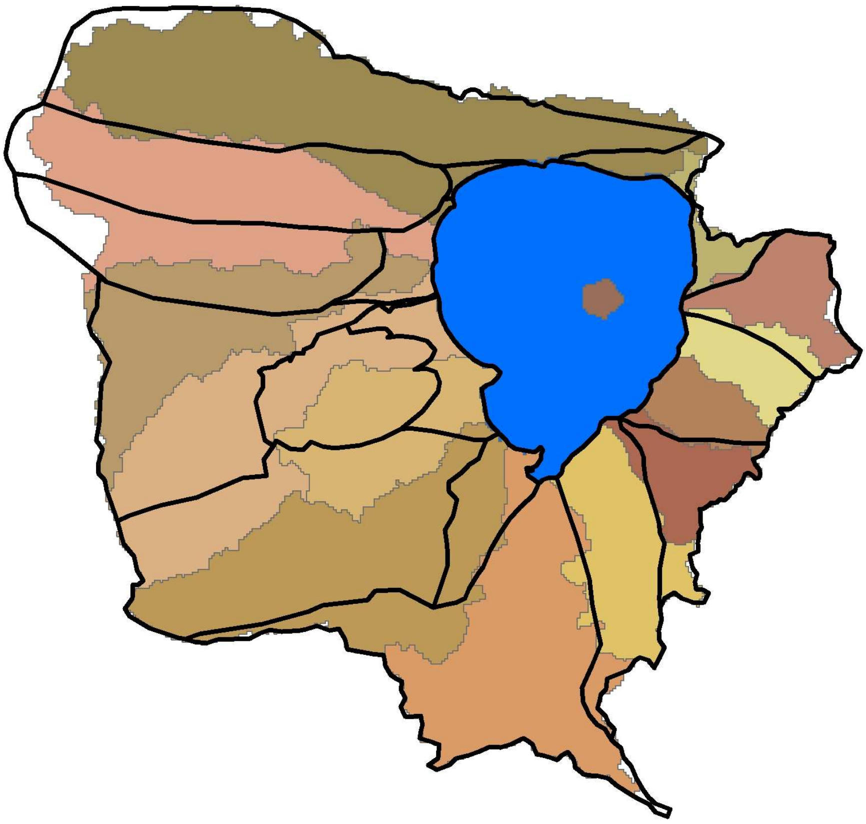


Figure 5: Comparison of aquifer boundaries in the ROTAN-2 to ROTAN-9 models (coloured) with the GNS Phase 7 boundaries (black lines).

2.7 Land use maps

Rutherford et al. (2009) describe six GIS maps (1940, 1958, 1986, 1996, 2001 and 2003) for the Lake Rotorua catchment. These maps quantify land use in 1958 and 2003, and land cover in the other years. For years when only land cover was defined, land use was estimated by interpolation between the available land use maps such that the proportions of each land use matched regional agricultural statistics. For details of how this was done see Rutherford et al. (2009). There is some uncertainty associated with estimating land use in this manner. Furthermore, Rutherford et al. (2009) were unable to locate a GIS map of either land cover or land use for the 1970s – a period of land use intensification.

Four new GIS maps were developed for this report:

- BoPRC provided aerial photographs for 1974 from which NIWA created a GIS land use map. Pasture areas were classified either 'Dairy' or 'DryStock' following discussions with two local farmers (Stuart Morrison and Robert Moore) who have extensive knowledge of land use during this period. The 1958 and 1986 maps were used to help fill gaps in the 1974 map.

- BoPRC provided a GIS land use map for 2005 based on a 2003 aerial photograph of land cover and results from a land use questionnaire sent out to landowners in 2005. This map was dated 2005.

- BoPRC provided a GIS map of the dairy platform[4] created in 2009 based on 2007 aerial photographs and local knowledge. The 2005 map (described above) was copied, adjusted using the dairy platform map, and dated 2010. The most noticeable change was the conversion of land designated 'Dairy' on Wharenui land (on the eastern side of the lake) to 'DryStock' or 'Forest'.

- The 1940 land use map in Rutherford et al. (2009) assumed the same land cover as 1958. Agricultural statistics for Rotorua County in the 1940s indicate, however, that only 13% of land was in pasture compared with 36% in 1958. The 1940 map was 'corrected' by converting pasture areas below 15 ha to forest – such areas were distributed randomly throughout the catchment. After this 'correction', 13% of the catchment was in pasture.

Rotorua District Council (RDC) provided updated information about the changes over time in the population and areas served by septic tanks. Using this information, the

[4] The area that the milking herd graze and produce from (excludes any runoff blocks and land that cannot be grazed, e.g., bush)

areas of land designated ‘SepticTanks’ within the ROTAN land use maps were revised.

2.8 Land use categories

The 20 or so land use categories used in Rutherford et al. (2009) were found to be too numerous to run ROTAN efficiently. In addition, the nitrogen yields for several categories were very similar and/or were uncertain. Therefore, several land use categories[5] were combined.

1. BareGround, Cattle, Cropping, ExtensiveSheep, Grassland, Horticulture, IntensiveSheep, Sheep, SheepBeef and TreesGrazed became DryStock.

2. ExoticForest, IndigenousForest, MixedTrees, Scrub and Wetland became Forest.

The 12 new land use categories are: Dairy, DryStock, Forest, SepticTanks, SewageTreatmentPlant (STP), LifeStyle, NewLifeStyle, Urban, UrbanOpenSpace (UOS), Tikitere, Whakarewarewa (Whaka), and RotoruaLandTreatmentSystem (RLTS).

2.9 Land use areas

Table 2 gives the land use areas and Figures 6-14 show the spatial distribution of the land uses following these adjustments.

[5] Hereafter quote marks around land use categories (e.g., ‘Dairy’, ‘DryStock’ etc.) are omitted for brevity, but they remain capitalised.

Table 2: Land use areas used in ROTAN.

Year	1940	1958	1974	1986	1996	2001	2003	2005	2010
Land use					**Area (ha)**				
Dairy	565	1,073	1,627	2,838	4,742	5,532	5,731	5,412	5,050
DryStock	5,639	15,818	18,716	17,788	17,157	16,842	16,891	14,710	15,072
Forest	37,801	25,447	20,580	20,652	19,039	18,457	18,122	19,594	19,594
ForestPuarenga	1,957	1,957	1,901	1,901	1,599	1,599	1,599	1,588	1,588
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
Whaka	31	31	31	31	31	31	31	31	31
Total land	**46,376**	**46,376**	**46,376**	**46,376**	**46,376**	**46,376**	**46,376**	**46,376**	**46,376**

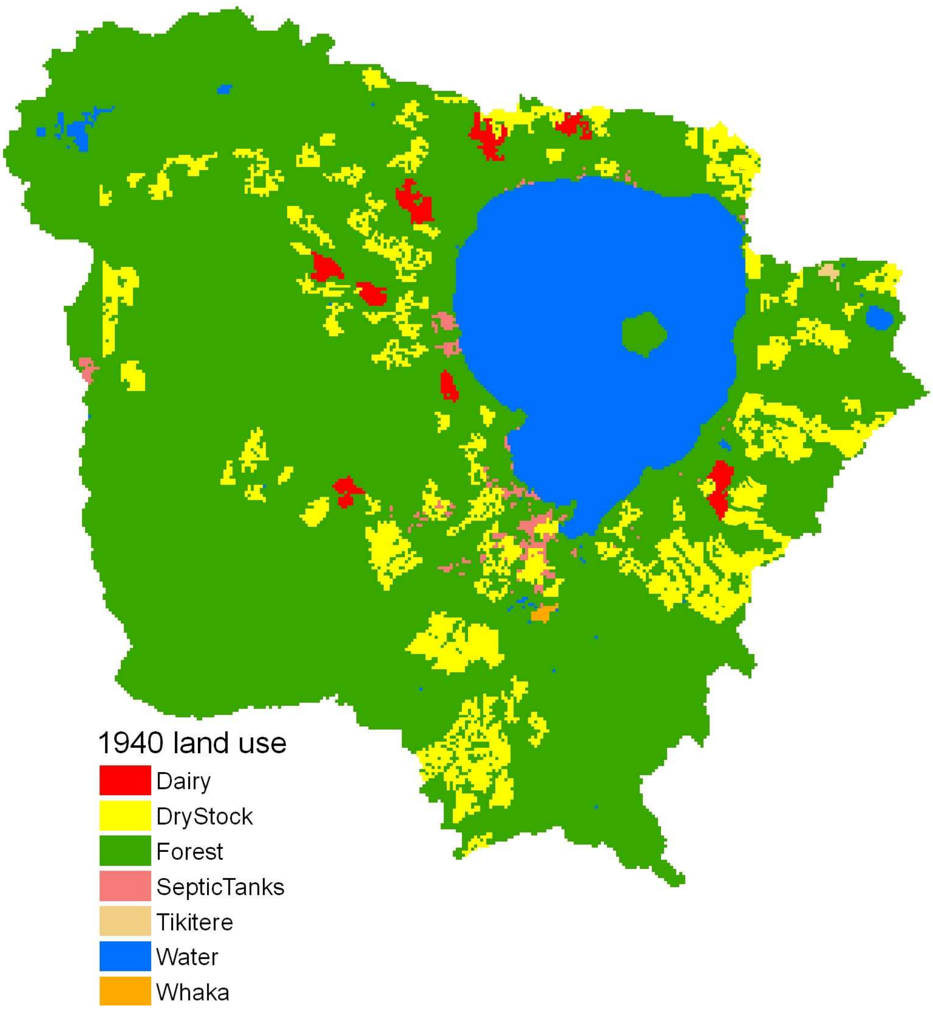


Figure 6: Land use distribution in the Lake Rotorua catchment 1940.

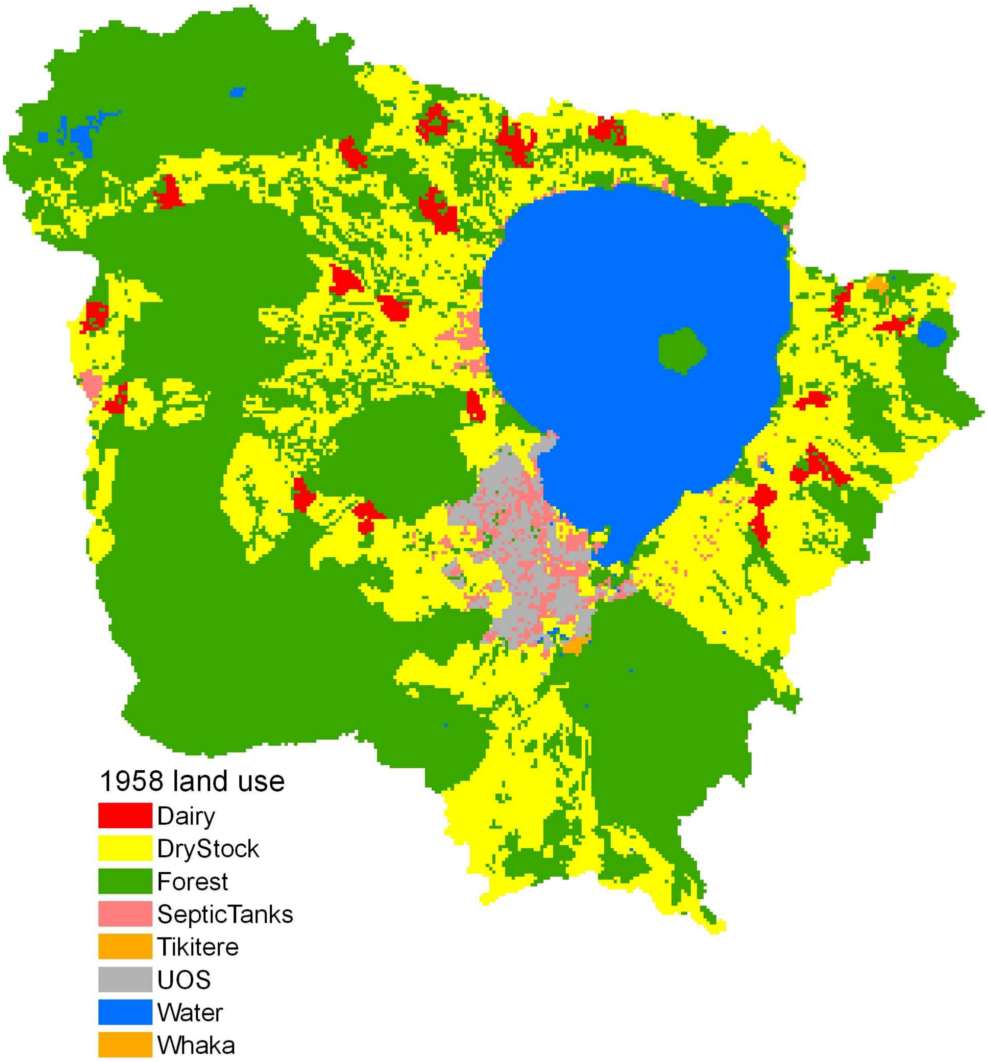


Figure 7: Land use distribution in the Lake Rotorua catchment 1958.

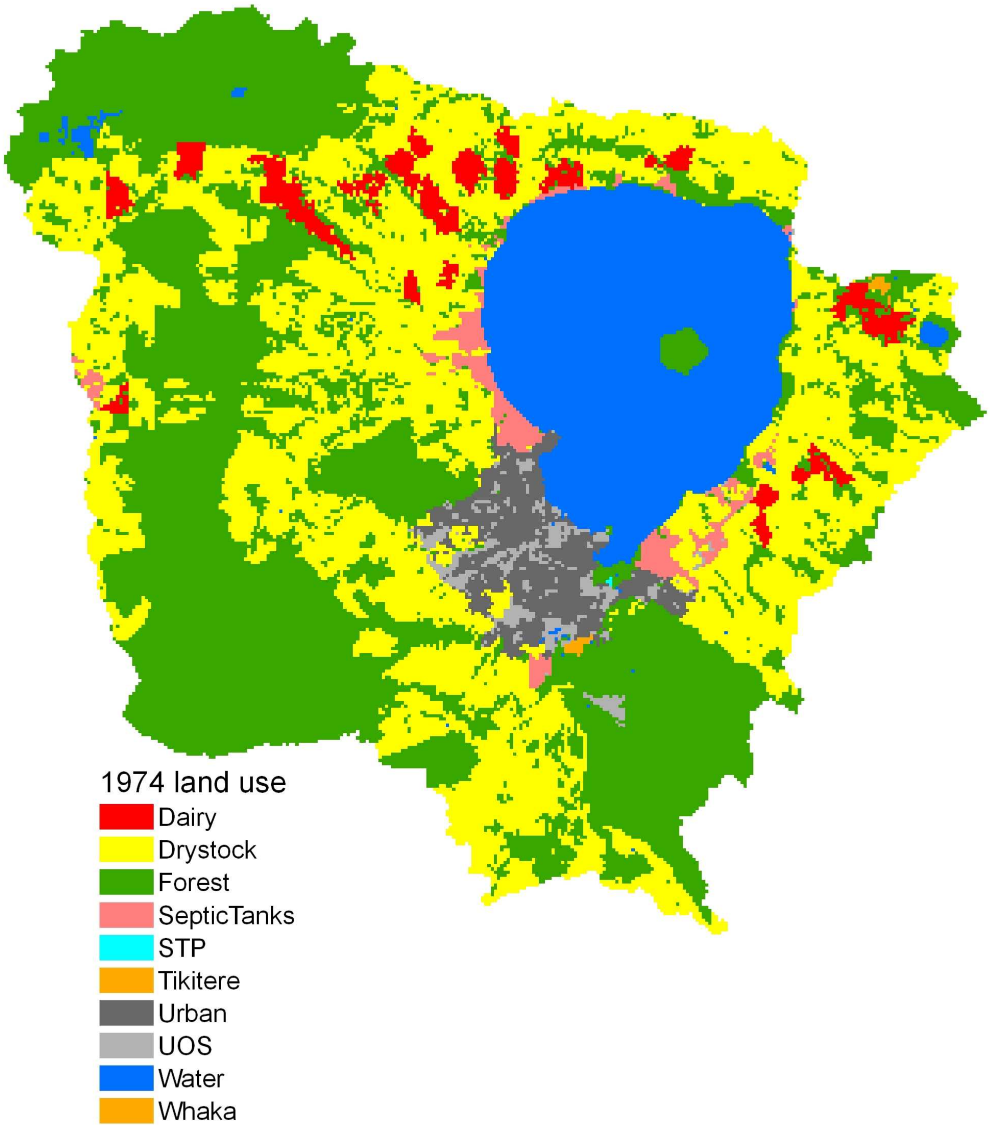


Figure 8: Land use distribution in the Lake Rotorua catchment 1974.

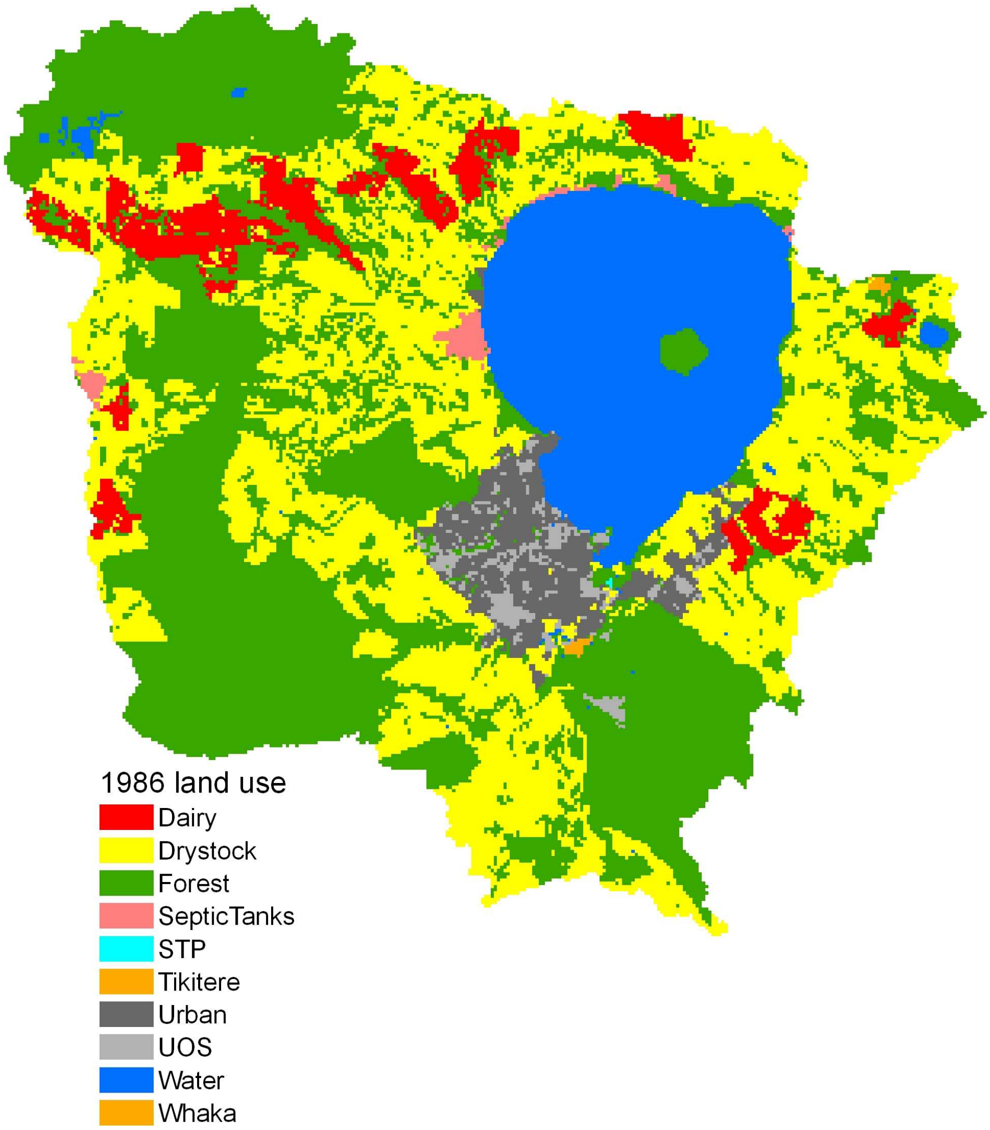


Figure 9: Land use distribution in the Lake Rotorua catchment 1986.

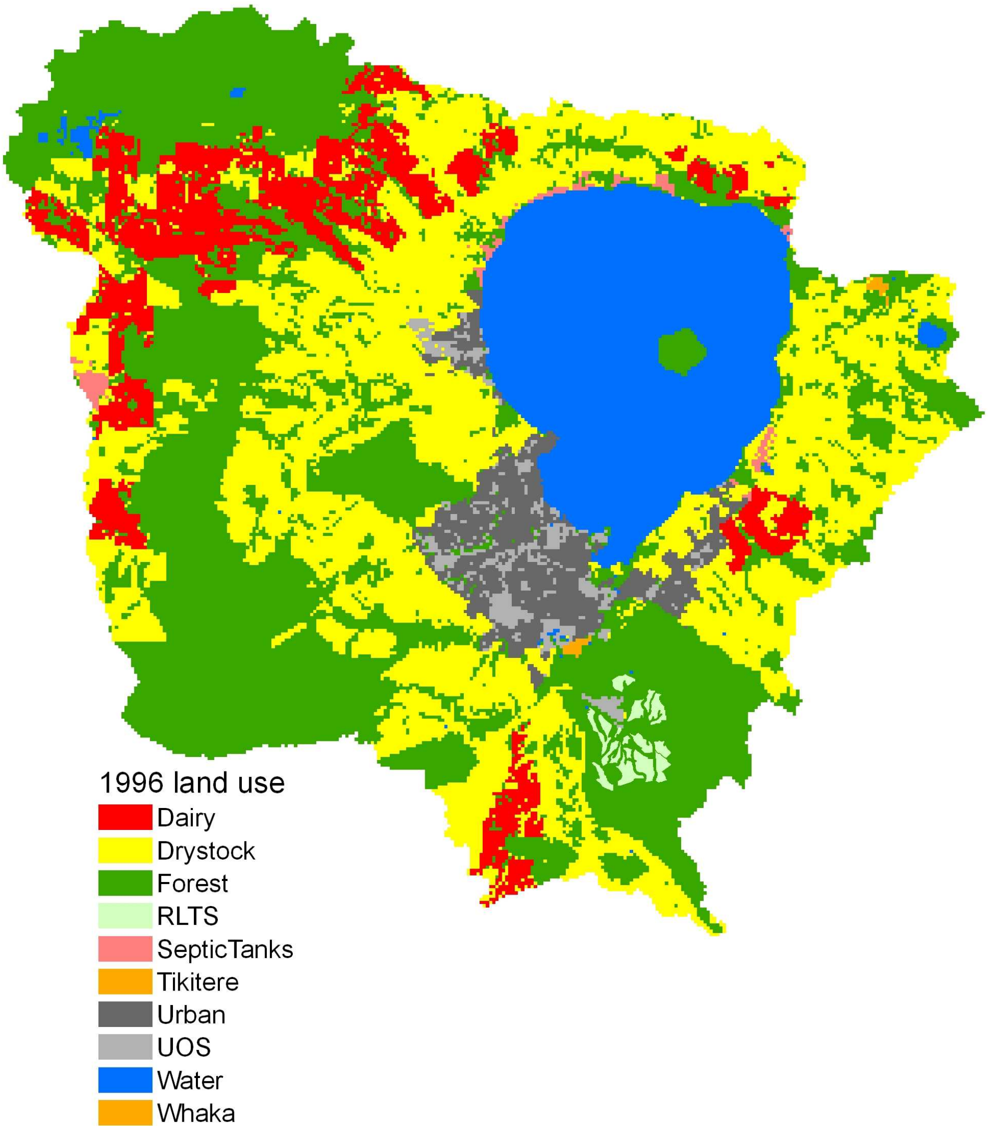


Figure 10: Land use distribution in the Lake Rotorua catchment 1996.

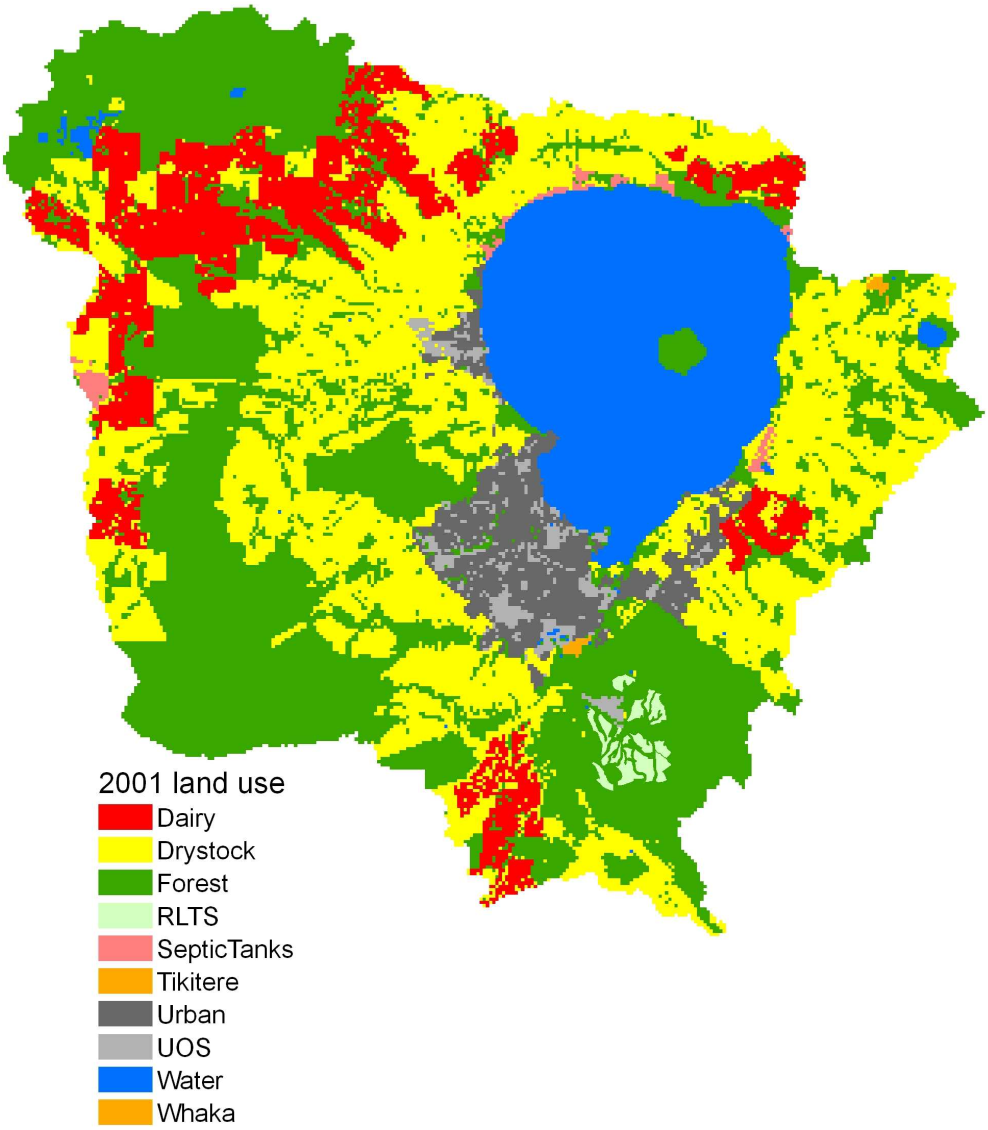


Figure 11: Land use distribution in the Lake Rotorua catchment 2001.

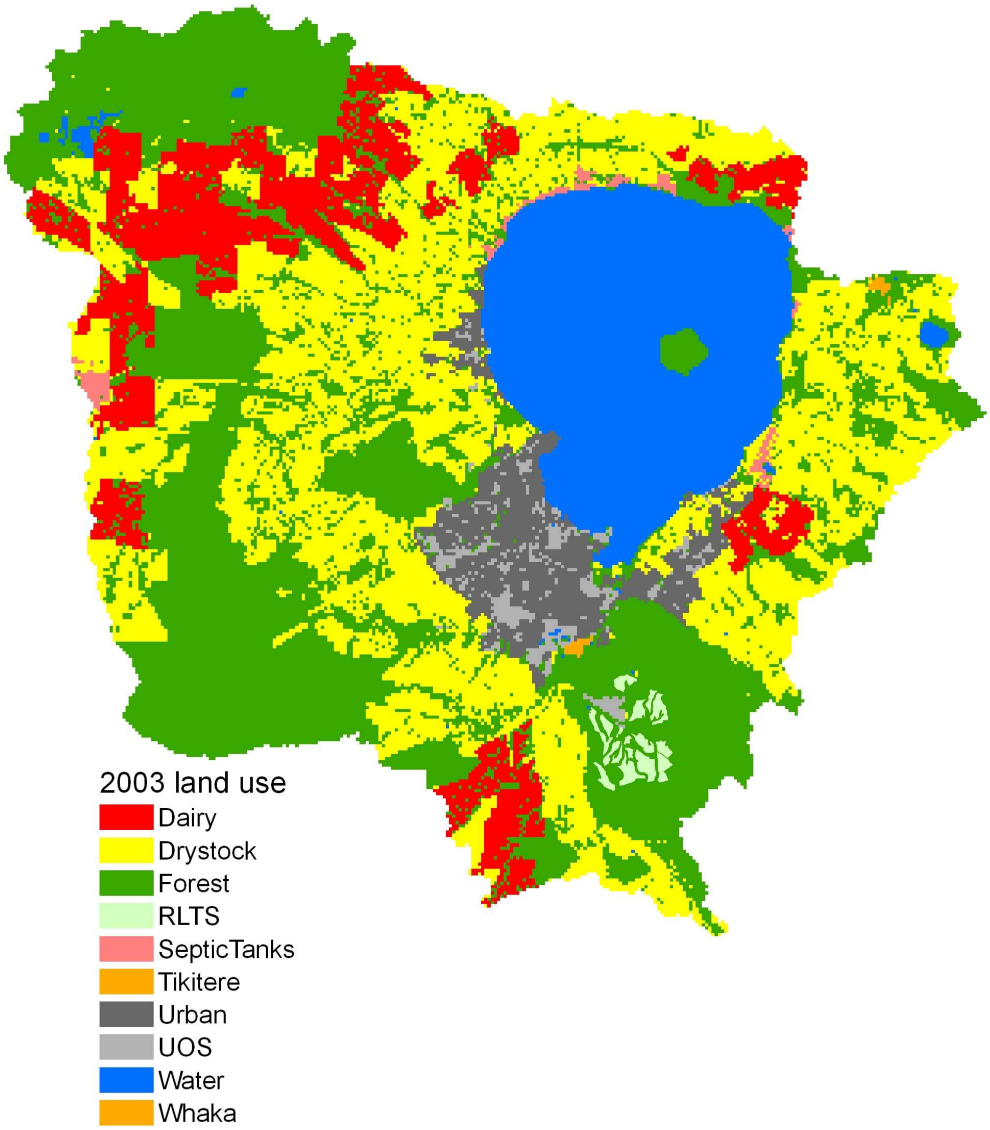


Figure 12: Land use distribution in the Lake Rotorua catchment 2003.

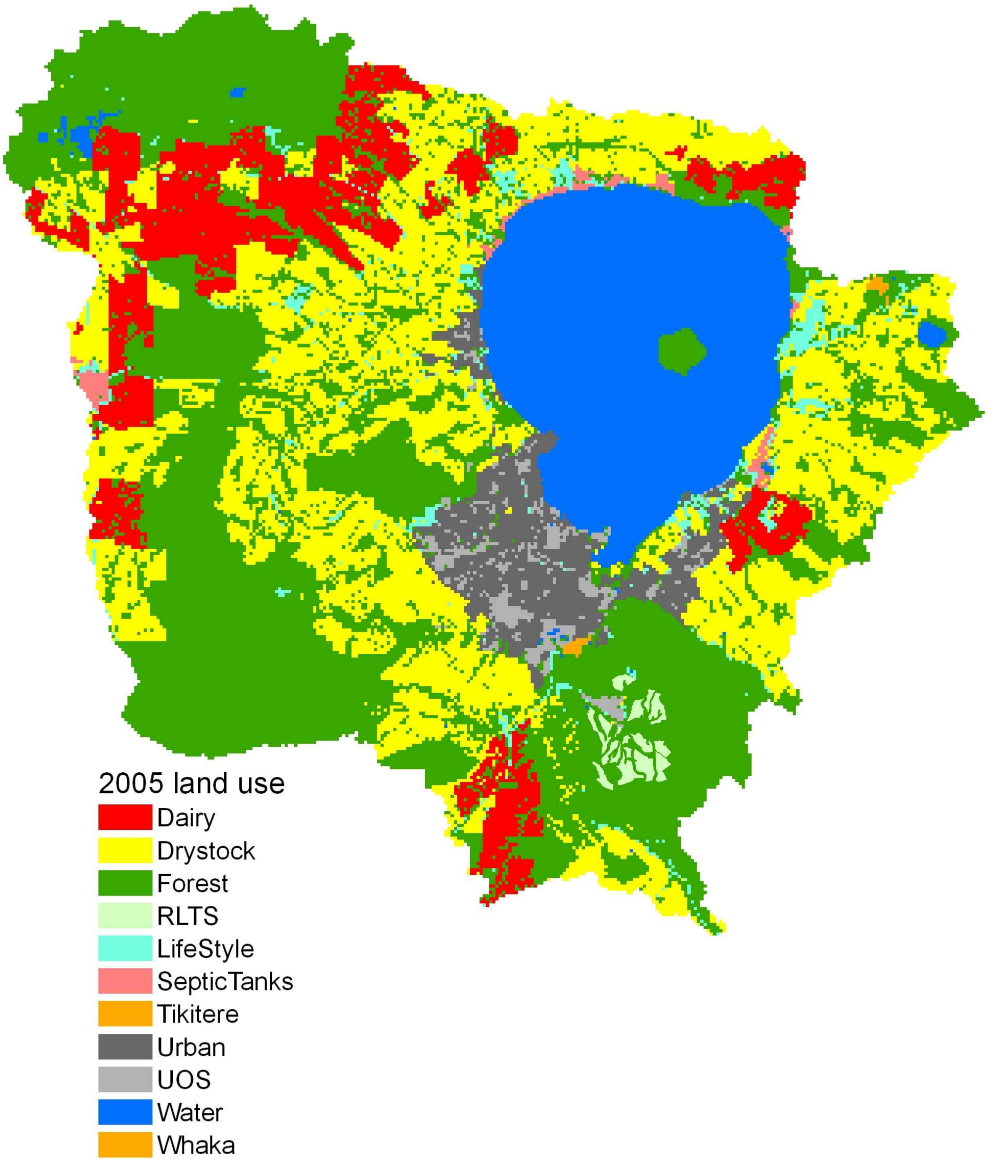


Figure 13: Land use distribution in the Lake Rotorua catchment 2005.

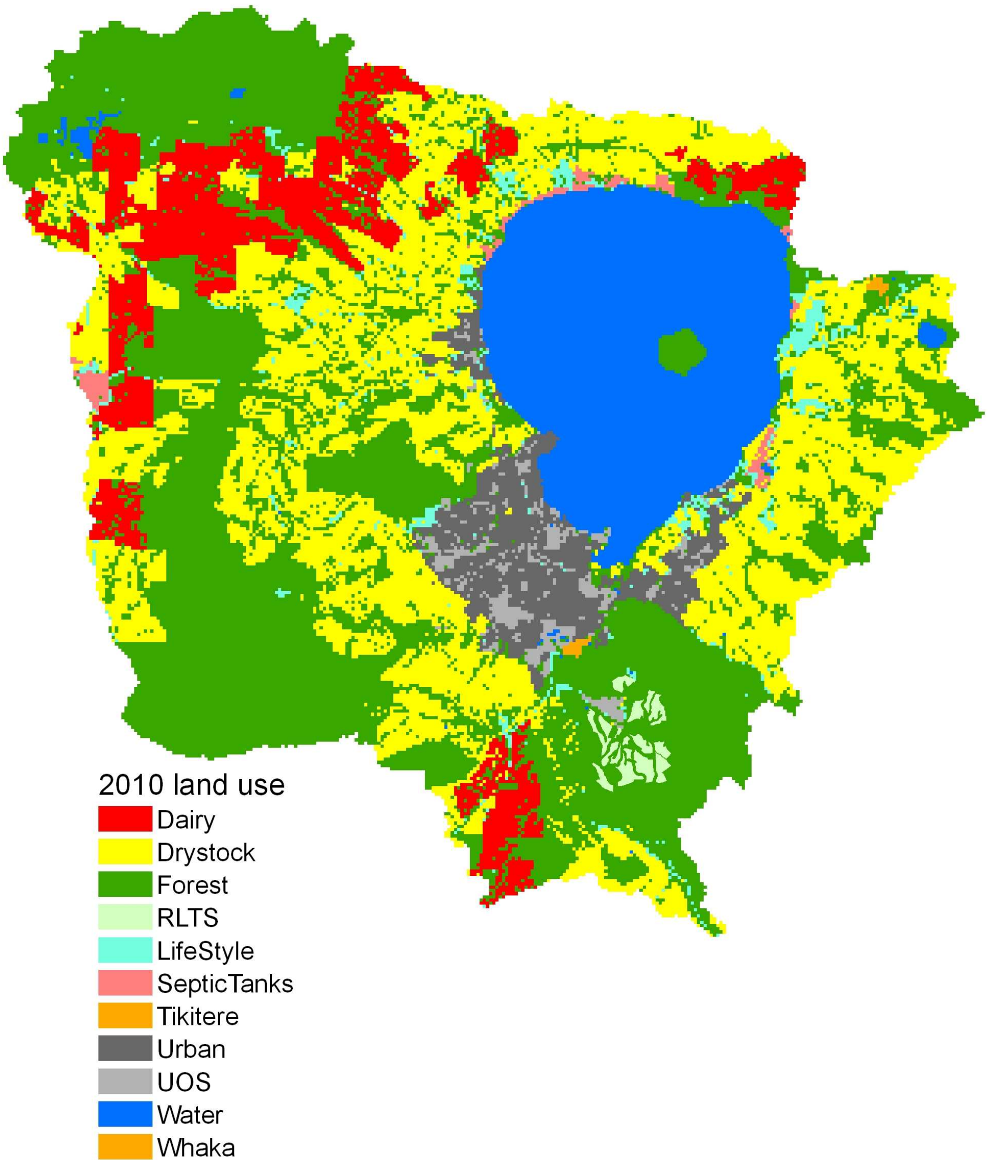


Figure 14: Land use distribution in the Lake Rotorua catchment 2010.

2.10 Nitrogen yields from pasture

Nitrogen yields from pasture were estimated by Rutherford et al. (2009) using stocking rates based on agricultural statistics from 1900-2007, published information on animal weights, and the Overseer® model. An 'expert group' of agriculture consultants, farmers, scientists and BoPRC staff met in October 2009 to review and refine these yields. The group discussed the information available for stocking rates (including valuable but unpublished information from local farmers and farm consultants), together with information derived from model farms, and various published and unpublished Overseer® estimates of nitrogen export. The group concluded that:

- The current (2003-2009) nitrogen yield from dairy farms averages 56 kgN/ha/yr.

- The current (2003-2009) nitrogen yield from drystock farms is 11-18 kgN/ha/yr, with the average being 16 kgN/ha/yr.

- On average, life style and drystock land yield similar amounts of nitrogen at present and in the immediate past.

Subsequently, NIWA re-examined agricultural statistics for 1900-2000 and 'adjusted' earlier estimates of nitrogen export during that period. Stocking rates were re-examined and Overseer® was re-run to calculate nitrogen yields. This re-analysis gave slightly higher yields rates than previously estimated by Rutherford et al. (2009).

2.11 Nitrogen exports during development

Exports for pasture from 1940-1970 were further revised because this was a period during which considerable forest and scrub was converted to pasture. Overseer® predicts the long-term average nitrogen export from established land uses but it does not predict accurately nitrogen export immediately after a land use change (Stewart Ledgard, AgResearch, *pers. comm.*).

In South Africa, Jovanovic et al. (2008) found that when leguminous woody vegetation was converted to pasture there was a significant, short-term release of nitrogen to the groundwater. They reported leaching rates of 380 kgN/ha/yr from converted land compared with 60 kgN/ha/yr from uncleared land. Their yield from uncleared land is comparable with New Zealand estimates of yield from dairy farms (typically 40-50 kgN/ha/yr, Menneer et al. 2004), and significantly higher than yields from New Zealand pine and indigenous forest (4 kgN/ha/yr). However, Mageson and

Wang (2008) and Male et al. (2010) have measured leaching rates that average 50 kgN/ha/yr from gorse and broom in the Rotorua catchment.

The conversion of gorse and broom to pasture in Rotorua during the 1940-1970s may have released significant amounts of nitrogen. Male et al. (2010) estimate there is currently 900 ha of gorse in the Rotorua catchment while LCDB1 and LCDB2 give 600-700 ha of gorse in 1996 and 2001 respectively. Quantitative data regarding the extent of gorse and broom cover in the period 1940-1970 or how much was converted to pasture in that period do not exist.

Alastair MacCormick (BoPRC), has gathered the following anecdotal information from two retired farmers:

- On the western side of the lake:
  - New country was mainly broken in from heavy fern and some native forest.
  - There was very little gorse and broom on the western side of the lake. There was a little more on the northern side, but not as much as the eastern side.
  - Most development on western side occurred in 1940s and earlier.
  - Usually, bush was felled then burned before discing and cropping with either soft turnips or swedes. Usually land was cropped twice before going into pasture to even out the humps and hollows. Every farmer had a crop – roughly about 10% of the farm area. There was more cropping than today.
  - Land was fertilised with potash and super – no urea was used until the 1970s. Without potash they could carry less than a cow to the acre – with potash they could carry up to a cow and a half to the acre.
- On the eastern and southern side of the catchment:
  - Some of the last bush cleared in that part of the catchment would have been on their property around 1965.
  - On their property the steep bush was felled by axe and chainsaw then burnt in January/February. A plane was then used to sow grass seed.

- The lower country was often covered with gorse, broom or lupins. On their property the lower gorse areas were cleared with chainsaws, then the gorse ploughed in and either sown to crop or grass. It was well known that cleared gorse country produced good crops for a number of years.

- Steeper areas of gorse and scrub were sprayed (245-T) or crushed, and then stocked heavily

- General comments about the catchment:

    - A lot of country around Rotorua was cleared in the 1920s then allowed to revert to gorse and scrub. One farmer commented that a block next to his property had been cleared and reverted to gorse six times in his lifetime.

    - One farmer said he could remember significantly more gorse, broom and lupin on the eastern and southern sides of the lake during that period than there is today.

It is not known how much nitrogen is released when scrub, gorse, broom or lupin is converted to pasture, or how long after conversion high release rates persist.

Jovanovic et al. (2008) report a ‘one-off’ release of 380 kgN/ha following the conversion of woody, leguminose vegetation to pasture. Recent studies at Taupo (on similar soils to Rotorua) have shown that ‘development’ results in an increase in nitrogen leaching rate. AgResearch measured a leaching loss of 63 kgN/ha/yr immediately following ‘development’ (spraying, ploughing, cropping, and followed by re-grassing) compared with 10 kgN/ha/yr from ‘undeveloped’ (viz., extensively grazed) pasture. We interpreted this finding as a ‘one-off’ release of an additional 53 kgN/ha immediately after ‘development’.

It is likely that “development” in the Lake Rotorua catchment included various combinations of cutting and burning, giant-disc, aerial seeding, ploughing and cropping. Typically land was cropped twice before being grassed. Taking the Taupo estimate of 53 kgN/ha release after cropping, and assuming land was cropped twice, we estimate a ‘one-off’ release of 100 kgN/ha occurred in the year that land was converted from forest or scrub to pasture. This is termed the ‘land conversion’ release.

The yields used in ROTAN are summarised in Tables 3-4.

2.12 Nitrogen delivery pathways

Nitrogen may be transported from where it is generated to the lake by several different pathways. These include:

- Deep groundwaters, which contain soluble nitrogen, predominantly nitrate (NNN) and dissolved organic nitrogen (DON).

- Shallow groundwaters, which contain soluble nitrogen (predominantly NNN and DON), and occasionally ammonium (NH4N) and fine particulate organic nitrogen (FPON).

- Surface flow (during rainfall events), which contains soluble nitrogen and also fine and coarse particulate-bound organic nitrogen (FPON and CPON).

ROTAN models total nitrogen (TN), which is the sum of NNN + NH4N + DON + PON. The Overseer® model predicts the yield of nitrogen from agricultural land but it does not distinguish between NNN and NH4N, and it is not clear whether it includes DON, FPON and CPON.

Rutherford et al. (2009) used Overseer® in the ROTAN-0 model to estimate nitrogen yield and assumed that 75% of the total yield occurred from the soil layer and 25% from the quickflow aquifer. Nitrogen generation in the soil layer mimics the leaching of NNN and possibly NH4N but it is not clear whether Overseer® quantifies DON leaching. Nitrogen generation in the quickflow aquifer mimics the mobilisation of nitrogen during rainfall events, which includes FPON and CPON. Rutherford et al. (2009) assumed that 70% of infiltration (viz., water leaving the soil layer) entered the deep aquifer, 20% the quickflow aquifer, and 10% the slowflow aquifer. Consequently, 53% of the total nitrogen export entered the deep aquifer, 40% the quickflow aquifer and 7% the slowflow aquifer. In this study, ROTAN-1, ROTAN-3, ROTAN-8 and ROTAN-9 retain these assumptions (Table 1).

ROTAN-4 has the same infiltration as ROTAN-1, but 50% of the total export occurs from the 'soil layer' and 50% from the 'quickflow' aquifer. Therefore 35% of the total nitrogen export enters the 'deep' aquifer, 60% the 'quickflow' aquifer and 5% the 'slowflow' aquifer (Table 1). ROTAN-2 assumes that 100% of nitrogen export is from the 'soil layer' and is transported to the lake via the 'quickflow', 'slowflow' and 'deep' aquifers in proportion to the amount of infiltration that is routed through each of these aquifers, which means that 80% of total N is exported from the 'deep' aquifer and 20% exported from the 'quickflow' aquifer (Table 1).

Table 3: Nitrogen yields for Dairy pasture estimated by Overseer®, revised by the 'expert group', and revised to include effects of 'land conversion'.

Year	1940	1958	1974	1986	1996	2001	2003	2005	2010
Stocking cows/ha	2.1	2.3	2.3	2.3	2.4	2.5	2.6	2.6	2.6
Milksolids kgMS/ha/yr	440	525	600	665	725	750	800	830	830
Breed	J	J	F X J	F X J	F	F	F	F	F
Replacements	On farm	on farm	on farm	on farm	off from 9 mths	off from weaning	off from weaning	off from weaning	off from weaning
Effluent	2 pond + discharge	2 pond + discharge	2 pond + discharge	2 pond + discharge	Spray from sump	Spray from sump	Spray from sump	Spray from sump	Spray from sump
Fertiliser kgN/ha/yr	0	0	50	100	140	160	180	180	180
Yield (kgN/ha/yr)									
Overseer®	30	32	40	46	51	52	57	58	58
Expert group	30	32	40	46	51	52	56	56	56
Land conversion	34.6	34.6	42.1	46	51	53.5	56	56	56

Overseer® Version = 5.4.6.0
Annual PET = 801-950 mm
Topography = rolling

Region = Bay of Plenty
Latitude South = 380
J = Jersey

Distance from coast = 100 km
Altitude = 100 m
F X J = Friesian-Jersey cross

Annual rainfall = 2000 mm
Soil = well drained, pumice

Mean temperature = 13C
Top soil = deep

Table 4: Nitrogen yields from Drystock pasture estimated by the 'expert group', revised using agricultural statistics, and revised to include effects of 'land conversion'.

	1940	1958	1974	1986	1996	2001	2003	2005	2010
Stocking SU/ha[1]	4	6.6	8	8.8	9.2	9.6	12	12	12
					Yield (kg/ha/yr)				
Expert group	7	11	12	13	14	14	16	16	16
Agricultural statistics	12.1	13.4	16.8	17.4	18.5	17	16	16	16
Land conversion	13.8	17.0	17.8	17.4	18.5	17	16	16	16

[1] SU = Stock Units

2.13 Point sources

Geothermal sources

Recent monitoring shows that the nitrogen load from the Tikitere geothermal area averages 30 tN/yr (Paul Dines, Rotorua District Council, *pers. comm.*). This is similar to historic estimates (Williamson and Cooke 1982, White et al. 2004). In ROTAN, Tikitere is modelled as an area of 28 ha with an average export rate of 1,071 kgN/ha/yr.

The nitrogen load from Whakarewarewa geothermal area averages 0.32 tN/yr (Ellis and Mahon 1977, White et al. 2004). In ROTAN Whakarewarewa (Whaka) is defined as an area of 31 ha and assigned a yield of 10 kgN/ha/yr.

Note that the Tikitere and Whakarewarewa geothermal areas have different geochemistry and hence significantly different nitrogen loads (Ellis and Mahon 1977).

Rotorua Sewage Treatment Plant

Prior to the 1970s the central part of Rotorua was served by large municipal septic tanks, while the suburbs were served by small, individual septic tanks. The Rotorua sewage treatment plant (STP) was completed in 1974 and since the early 1970s the population it serves has increased steadily. Outlying suburbs previously served by septic tanks, and more recently, lakeside communities, have been progressively connected to the STP. Nevertheless, some rural communities continue to rely on septic tanks.

The STP discharged treated sewage containing nitrogen and phosphorus to Lake Rotorua via the Puarenga Stream from the early 1970s until 1991. The STP was upgraded several times to cope with increasing volumes of sewage, and to control nutrient loads on the Lake Rotorua. During the 1970s and early 1980s chemical treatment was used to ‘strip’ phosphorus. Chemical treatment proved costly and did not control nitrogen. During the mid-late 1980s biological treatment (the Bardenpho process) was used to remove both phosphorus and nitrogen. There were technical difficulties which meant that effluent did not consistently meet consent limits for N and P load. Commencing in mid-1991 effluent was treated at the STP and then spray irrigated in Whakarewarewa Forest. The Rotorua Land Treatment System (RLTS) has consistently controlled phosphorus but after several years the nitrogen load escaping from the RLTS approached the consented limit of 30 tN/yr. Since 2001 biological treatment has been ‘optimised’ to remove nitrogen prior to spray irrigation, and this combination has reduced the N load that escapes from the RLTS.

STP 1971-1990

In ROTAN the STP is modelled as an area of 4 ha and assigned average nitrogen yields of:

- 0 kg/ha/yr before 1971
- 15,000 kg/ha/yr from 1971-1980
- 30,000 kg/ha/yr from 1981-1990, and
- 0 kg/ha/yr after 1990.

The nitrogen yield of 15,000 kg/ha/yr for 1971-1980 takes into account the municipal septic tanks that operated prior to the STP being completed, and the fact that the reticulated population increased during this period.

RLTS 1991-2010

In ROTAN the RLTS is modelled as an area of 300 ha of pine forest with a uniform leaching rate. The average daily flow applied to the RLTS is 20,000 m3 (Park and Holst 2009) and in ROTAN this amount is added to the rainfall falling on the RLTS.

From 1991-2001 the total nitrogen load applied to the RLTS averaged 80 tN/yr (Park and Holst 2009). ROTAN simulates this as a constant application rate of 267 kgN/ha/yr applied to 300 ha. The STP was upgraded in 2001 to increase nitrogen removal. Since 2001 the total nitrogen applied to the RLTS has averaged 56 tN/yr (Park and Holst 2009) which ROTAN simulates as 187 kgN/ha/yr applied to 300 ha. As discussed below, ROTAN reduces the applied nitrogen loads by 40% to account for attenuation, giving nett yields of 160 and 112 kgN/ha/yr (Table 5).

Septic tanks

Prior to the 1970s all domestic sewage in the Rotorua catchment was discharged to either municipal or household septic tanks. The parcels of land served by septic tanks were identified from land use maps and the population residing within those areas was estimated from census data. Since the STP was completed, unreticulated suburbs and lakeside communities have progressively been connected to the STP, although some rural communities (e.g., Mamaku), lakeside communities (e.g., Hamurana) and isolated dwellings continue to rely on septic tanks. RDC provided updated information about the population served by septic tanks which was used to revise the areas of land designated SepticTanks in the land use maps.

ROTAN modelled SepticTanks as having a constant yield of 85 kgN/ha/yr. Using this value, the total annual load from septic tanks matches the population served by septic tanks times the average per capita yield (3-4 kgN/capita/year, Hoare 1984; RDC unpublished data). The revised yield of 85 kgN/ha/yr lies at the upper end of the range 35-84 kgN/ha/yr estimated by Rutherford et al. (2009) from data in Hoare (1984).

2.14 Timing of historic land use changes

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[6] (see Start and End dates in Table 5). There is some uncertainty about the timing of historic land use changes.

ROTAN-1 was run from 1920-2010 using several different combinations of land use distribution, nitrogen yields, timing of land use changes, and aquifer depth. It was found that predictions were not particularly sensitive to uncertainty in the timing of land use change, but were sensitive to yield and MRT. Slight adjustments were made from the timing of land use change reported in Rutherford et al. (2009).

2.15 Attenuation

As discussed by Rutherford et al. (2009), nitrogen concentrations in the Puarenga Stream are lower than would be expected given the proportions of pasture and forest in the catchment, and the typical nitrogen exports for these land uses. Wetlands are common in the catchment and nitrogen removal (attenuation) in these wetlands may explain the low concentrations observed in streams draining areas of pasture. This led Rutherford et al. (2009) to reduce the nitrogen exports for all pastoral land uses in the Puarenga by 50% which gave an improved match to observed concentrations.

Mageson and Wang (2008) have recently measured low nitrate leaching rates from pine forest in the Rotorua catchment. It is conceivable that the extensive production forest at Whakarewarewa has a lower average yield that the value of 4 kgN/ha/yr which is assumed for native forest, exotic forest, gorse, broom and scrub in the model. In this report ROTAN retains the same nitrogen exports for Dairy and DryStock as elsewhere in the Rotorua catchment, but reduces the nitrogen export for Forest in the Puarenga catchment by 50% (see ForestPuarenga in Table 5). This gave a good match to observed concentrations in the Waipa Stream.

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

The nitrogen loads applied to the RLTS are significantly higher than the measured loads escaping from the RLTS via the Waipa Stream (Park and Holst 2009). This indicates that significant nitrogen attenuation (viz., storage and/or removal) occurs within the RLTS area, most likely within natural wetlands (Peacock et al. 1998) and riparian soils (Rutherford et al. 2000). A satisfactory match was obtained between observed and predicted nitrogen concentrations in the Waipa and Puarenga Streams by assuming that RLTS loads are attenuated by 40% (see RLTS in Table 5).

2.16 Groundwater age

The goodness of fit between observed and predicted stream nitrogen concentrations is strongly influenced by:

- The area of each land use in the catchment.
- The nitrogen yield for each land use.
- The timing of any land use and nitrogen yield changes.

In streams fed by groundwater, the goodness of fit is also strongly affected by 'groundwater lags' which, in the ROTAN model, are determined by:

- The proportions of nitrogen export that enter shallow and deep groundwater.
- The coefficients of the shallow and deep aquifers which determine their mean residence times (MRTs).

Table 5: Nitrogen yields.

LU Map	1940	1958	1974	1986	1996	2003	2010	R-250, 300, 350
Start-End dates	1920–1949	1950–1970	1971–1980	1981–1990	1991–2000	2001–2007	2008–2100	2015–2100
				Yields (kgN/ha/yr)				
Dairy	34.6	34.6	42.1	46.0	51.0	56.0	56.0	40.0
DryStock	13.8	17.0	17.8	17.4	18.5	16	16	14.4
Forest	4	4	4	4	4	4	4	4
ForestPuarenga	2	2	2	2	2	2	2	2
RLTS	NA	NA	NA	NA	160	112	112	112
LifeStyle	NA	NA	NA	NA	NA	NA	16	14.4
NewLifestyle	NA	NA	NA	NA	NA	NA	NA	10
SepticTanks	85	85	85	85	85	85	85	85
STP	NA	NA	15,000	30,000	NA	NA	NA	NA
Tikitere	1,071	1,071	1,071	1,071	1,071	1,071	1,071	1,071
Urban	10	10	10	10	10	10	10	10
UOS	10	10	10	10	10	10	10	10
Water	0	0	0	0	0	0	0	0
Whaka	10	10	10	10	10	10	10	10
Average[1]	**6.7**	**11.4**	**14.7**	**15.8**	**16.6**	**18.3**	**17.2**	

[1] Area-weighted.
'LU Map' denotes the date of the map used to describe the spatial distribution of each land use.
'Start-End' denotes the period for which the land use spatial distribution and the yields apply.
ROTAN-8 uses 110% of the above yields.

Table 6: Historic nitrogen exports for ROTAN-1, 3 and 9.

LU Map	**1940**	**1958**	**1974**	**1986**	**1996**	**2003**	**2010**
Start-End dates	**1920–1949**	**1950–1970**	**1971–1980**	**1981–1990**	**1991–2000**	**2001–2007**	**2008–2100**
			Exports (tN/yr)				
Land use							
Dairy	19.5	37.1	67.4	124	235	309	273
DryStock	76.7	264	325	304	312	266	236
Forest	143	94.8	76	76.2	69.8	66.3	72.2
ForestPuarenga	3.9	3.9	3.8	3.8	3.2	3.2	3.2
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	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	**304**	**518**	**668**	**714**	**752**	**768**	**725**[1]

[1]Total exports are slightly different for ROTAN-2 (737 tN/yr), ROTAN-4 (717 tN/yr) and ROTAN-8 (797 tN/yr).

Rutherford et al. (2009) describe how the coefficients of the aquifers in ROTAN are ‘calibrated’. First, the coefficients of the two shallow aquifers (‘quickflow’ and ‘slowflow’) are adjusted to match the observed short-term variability in flow and nitrogen concentration. Second, the coefficients of the deep aquifer are ‘calibrated’ by setting the initial nitrogen concentration to zero everywhere, the concentration in rainfall to 1,000 g/m3, predicting stream nitrogen concentration, and adjusting the deep aquifer coefficients until the average stream concentrations reaches 50% of the steady state value at the published MRT.

In ROTAN-0 infiltration occurs from the ‘soil’ layer of which:

- 20% enters the ‘quickflow’ aquifers (with MRTs of two weeks for Pasture and four weeks for Forest).

- 10% enters the ‘slowflow’ aquifers (with MRTs of 20 weeks for Pasture and 40 weeks for Forest).

- 70% enters the ‘deep’ aquifers (with MRTs of 16-127 years, Morgenstern et al. 2005).

This approach gave a satisfactory match in ROTAN-0 to observed nitrogen concentrations in seven of the nine major stream inflows. In the Hamurana and Awahou Streams, however, ROTAN-0 under-estimated nitrogen concentrations in the 1970s (see Rutherford et al. 2009 for details).

As part of this study, the coefficients of the deep aquifers in the Awahou were adjusted to reduce the MRTs and thereby improve the match between observed and predicted nitrogen concentrations. Reducing the MRT to 20 years (compared with the published tritium estimate of 61 years) improved the fit to observed nitrogen concentrations. However, 20 years is considered to be an unrealistic MRT for the Awahou and these results are not reported in detail.

In this report, results are presented for the ROTAN-1 model which is almost identical to the original ROTAN-0 model, the only changes being:

- Revised land use maps.

- Higher nitrogen yields.

- A ‘one off’ land conversion release.

- MRTs that match published values (Morgenstern et al. 2005).

ROTAN-1 is the most detailed version of ROTAN developed to date, and provides ‘most likely’ predictions of load reductions and response times.

In order to assess the sensitivity of predictions to key model assumptions, this study also developed versions ROTAN-2 to ROTAN-9. New aquifer boundaries were drawn for these models to better match those supplied by GNS-Science (see Figures 3 and 5). These models enabled us to assess the sensitivity of model predictions to:

- The proportions of water entering the shallow and deep aquifers.

- Aquifer coefficients which, together with the proportions of water, affect MRT.

- The proportions of nitrogen exports entering the shallow and deep aquifers.

In each model ROTAN-2 to ROTAN-9 aquifer coefficients were adjusted so that MRTs matched those reported by Morgenstern et al. (2005). Observed and predicted short-term variability in flow and nitrogen concentration matched for some, but not all, models and catchments.

2.17 Goodness of fit

In this report, goodness of fit is assessed both quantitatively and qualitatively. ROTAN reports mean observed and predicted flows and concentrations, and root mean square differences (RMS) between weekly flows and concentrations. These statistics are only calculated for weeks when both predictions and observations are available. Formal comparisons are discussed between published annual loads to the lake (Hoare 1980b, Rutherford et al. 1989) and total loads predicted by ROTAN, and between predicted and observed average flows.

Formal statistical comparisons between observed and predicted stream concentrations are potentially misleading for two reasons. First, some of the observed concentrations are suspiciously low. The reasons for these outliers need to be identified and the data removed or corrected. Second, as discussed in Rutherford et al. (2008), ROTAN simulates the rainfall pattern across the catchment in a given week by multiplying the weekly rainfall at two reference rain gauges by a ‘scaling factor’ map. The map was derived by spatial extrapolation of annual rainfall measured at several rain gauges. This method gives reliable estimates of the spatial distribution of annual average rainfall. However, it does not give reliable estimates of the spatial distribution of rainfall in any particular week. Consequently, it would be unwise to assess models solely by comparing predictions of flow, nitrogen concentration and nitrogen flux in a particular week with observations in that week (e.g., by calculating the RMS difference between weekly observations and predictions). Better comparisons might involve loads observed and predicted at monthly or annual timesteps. However, reliable estimates of monthly or annual load have yet not been published for individual streams. Further work is required to remove outliers from the observed data, and to apply robust methods for the calculation of loads from the available flow and concentration data.

Table 7: Mean residence times (MRT) for nitrogen in the various ROTAN models and as reported for tritium by Morgenstern et al. (2005).

	Morgenstern	ROTAN-1	ROTAN-2	ROTAN-3 to 9
Catchment	**MRT (years)**			
Hamurana	110	80-100	96-97	106-108
Awahou	61	50-60	56-58	59-65
Waiteti	40	35-45	39-41	35-41
Ngongotaha	15.5	14-15	16	16
Waiowhiro	41.5	39-45	39	39-43
Utuhina	48	45-53	47-48	44-48
Puarenga	37	32-39	39-45	39
Waingaehe	127	100-150	117-123	119-123
Waiohewa	40	33-46	34-38	31-40

3. Future scenarios

3.1 Land use and nitrogen export

This report presents four scenarios of possible land use change (R-0, R-250, R-300 and R-350), aimed at achieving the target nitrogen load to the lake. The focus is on predicting the magnitude (load reduction) and timing (response time) of changes in lake load.

The four scenarios are:

- R-0 in which land use and nitrogen exports remain at their current levels from 2015-2100 (viz., a 'holding' scenario). The total nitrogen export is currently 725 tN/yr for ROTAN-1, 3 and 9 of which 38%, 33% and 10% originates from Dairy, DryStock and Forest respectively, with the balance from lifestyle, point sources, geothermal inflows and sewage. Total nitrogen export is slightly different for ROTAN-2 (737 tN/yr) and ROTAN-4 (717 tN/yr).

- R-250 in which total nitrogen export from land is reduced by 250 tN/yr through a combination of land use change and a reduction in nitrogen yields.

- R-300 in which total nitrogen export from land is reduced by 300 tN/yr through a combination of land use change and a reduction in nitrogen yields.

- R-350 in which total nitrogen export from land is reduced by 350 tN/yr through a combination of land use change and a reduction in nitrogen export. 100% of the Dairy area becomes either LifeStyle or DryStock. In addition, for ROTAN-1, 3 and 9 85% of DryStock becomes either LifeStyle or Forest. Overall Forest increases by 55% and LifeStyle (including NewLifeStyle) by 145% compared with R-0.

The scenarios were selected by an 'expert panel' to assess likely load reductions and response times for three increasing levels of land use change and on-farm mitigation. They are intended to inform managers about the scale of export reductions required to achieve the lake target and to provide an indication of how quickly the lake is likely to recover once exports are reduced.

The land use changes modelled for agricultural land are between Dairy, DryStock, LifeStyle and Forest. It is important to note, however, that the scenarios quantify what happens to lake load when total nitrogen exports remain constant or are reduced by 250, 300 and 350 tN/yr, regardless of how those reductions are achieved. Several different combinations of land use change could achieve the required export reductions. The R-350 scenario assumes that 100% of the Dairy area becomes LifeStyle or DryStock and 85% of DryStock area becomes LifeStyle or Forest. However, it might be possible to achieve the target with some Dairy, less DryStock and more Forest, or with less LifeStyle and more Forest and DryStock etc. It might also be possible to achieve the target with land uses other than those modelled.

If decisions are made about what land use changes will occur, and where in the catchment they will occur, then modelling could be used to estimate the likely effect on lake load. Conversely, more detailed modelling could be used to explore possible alternative spatial distributions of land use change. However, such analysis is best done in the next phase of investigations.

The scenarios assume:

- There is a step change in all land uses in 2015.

- There is an immediate change in nitrogen yield following a given land use change.

All scenarios are run from 1920-2010 with historical land use, nitrogen exports and historical climate data. From 2010 each scenario is run assuming climate change – whose effects are minor as discussed below. Land use changes and export reductions are assumed to occur in 2015.

It is important to appreciate that these scenarios predict 'response time', which are estimates of the time required for lake load to decrease after a theoretical step reduction in nitrogen export. The response time is a property of the catchment which depends on the travel times of the various pathways linking the lake to where nitrogen is generated (viz., deep groundwater, shallow groundwater, springs, surface flow, streams, and groundwater direct). ROTAN simulates this aspect of response time. It also depends on the time it takes nitrogen stores in the soil to adjust to a change in land use, and for nitrogen yields to change to the new steady state. Overseer® does not predict how long this takes, and neither does ROTAN currently. However, ROTAN outputs were 'corrected' by assuming that soil nitrogen stores adjust to new land use at a rate of 10% per year.

Managers are interested in the 'recovery time', which is the time it will take for the lake load to reach the target following land use changes. Land use changes are likely to occur progressively over many years, rather than as a step change in 2015 as simulated in ROTAN. The models could be re-run making assumptions about how quickly land use will change but that was not done in this report. Alternatively, managers can estimate the 'recovery time' as follows. If land use changes are likely to occur over 20-30 years, then given the 'response time' of 35 years, the 'recovery time' will be approximately 60 years.

Table 8: Land use areas used in ROTAN-1, 3 and 9 for the future scenarios.

	2010 [1]	R-250	R-300	R-350
	Area (ha)			
Dairy	5,050	2,525		
DryStock	15,072	9,016	12,668	9,036
Forest	21,182	28,248	27,121	30,753
RLTS	300	300	300	300
LifeStyle	1,053	1,024	1,024	1,024
NewLifeStyle [2]		1,553	1,553	1,553
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
Whaka	31	31	31	31
Total	**46,376**	**46,376**	**46,376**	**46,376**

[1] See Table 2
[2] The NewLifeStyle areas incorporated in R-250, R-300 and R-350 are based on RDC plans for future lifestyle areas as interpreted by Simon Park (Simon Park, *pers. comm*.) (see Table 9). Areas for ROTAN-2, ROTAN-4 and ROTAN-8 for DryStock and Forest are slightly different.

Table 9: Land areas that become NewLifeStyle in scenarios R-250, R-300 and R-350.

	Area of NewLifeStyle (ha)
Dairy	319
DryStock	1,197
LifeStyle	29
SepticTanks	8
Total	**1,553**

Table 10: Annual total nitrogen exports from the land compared with predicted steady state nitrogen loads to the lake.

	Total export from land	Predicted input to lake at steady state
Scenario	Nitrogen (tN/yr)	
R-0	725	724
R-250	475	473
R-300	425	426
R-350	375	380
Target	405	

Exports in the Puarenga and RLTS are nett of attenuation.

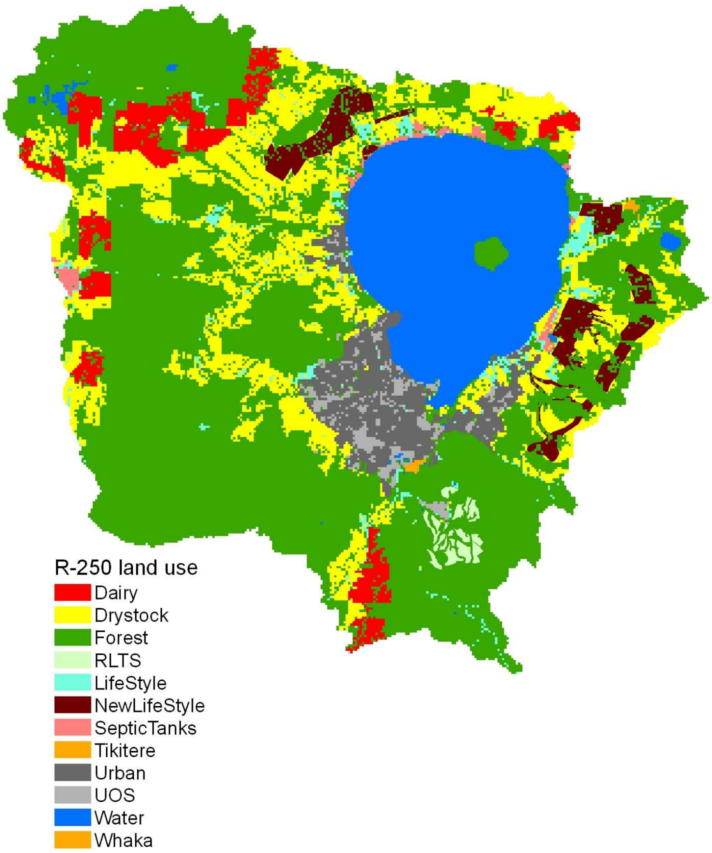


Figure 15: Land use distribution in the Lake Rotorua catchment for scenario R-250.

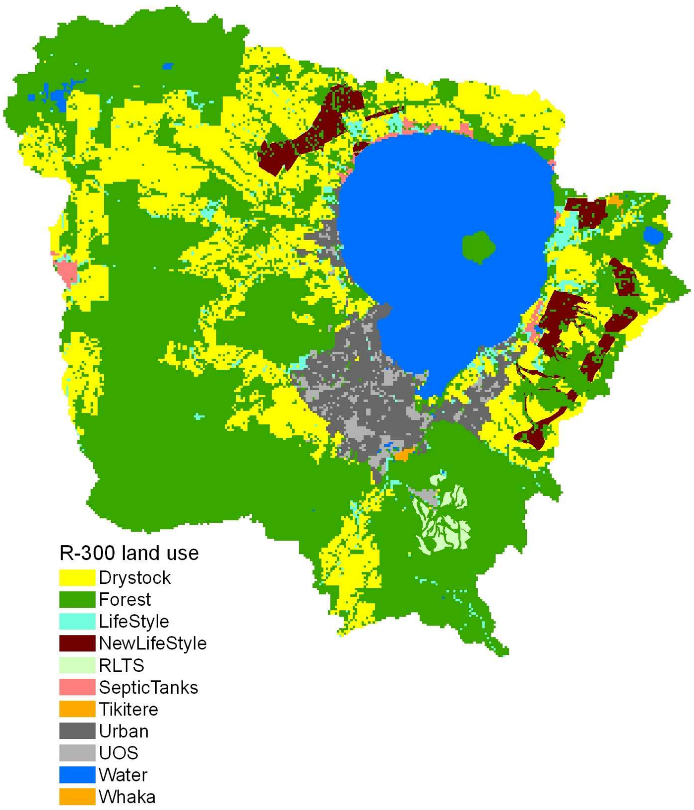


Figure 16: Land use distribution in the Lake Rotorua catchment for scenario R-300.

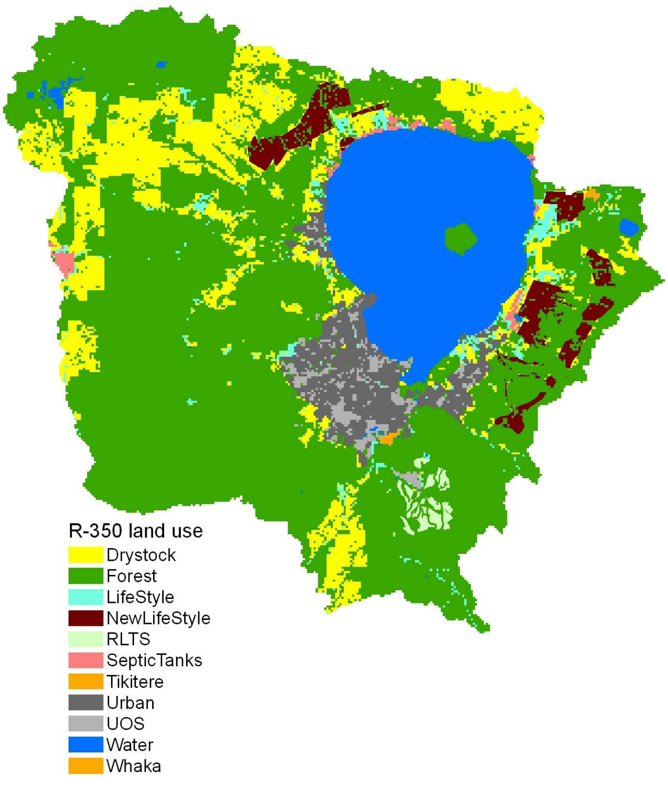


Figure 17: Land use distribution in the Lake Rotorua catchment for scenario R-350.

4. ROTAN-1 calibration

4.1 Introduction

ROTAN-1 differs from the original ROTAN-0 (Rutherford et al. 2009) in that:

- There is less pasture in the 1920-1940s.
- Nitrogen yields are higher.
- There is a pulse of nitrogen during land development in the 1940-1970s.

Key features of ROTAN-1 are:

- Large aquifers are modelled as several well-mixed aquifers, connected in series and/or parallel (see Figure 2).
- 70% of infiltrating water (hereafter termed just 'infiltration') enters deep groundwater.
- 53% of the total nitrogen export (hereafter termed just 'nitrogen') enters deep groundwater.
- 30% of infiltration enters shallow groundwater.
- 47% of nitrogen enters shallow groundwater.
- MRTs for nitrogen match published estimates for tritium (Morgenstern et al. 2005) (see Table 7).

4.2 Mean residence time

In this study MRTs were estimated slightly differently from Rutherford et al. (2009). As previously, the initial nitrogen concentration was set to zero everywhere, nitrogen generation was set to zero, the concentration in rainfall was set to 1,000 g/m3 and stream nitrogen concentrations were predicted for 180 years. The MRT is the time at which stream concentration reached 50% of the steady state value.

One-compartment and two-compartment exponential models were fitted to the weekly predicted concentrations which increased from zero towards a steady state value. The steady state concentration varied slightly between catchments depending on the amount of evapotranspiration. Typically 45% of rainfall is lost through evapotranspiration in the model and this concentrates nitrogen in the soil to a steady state value of about 1,800 g/m3 in these simulations. In some catchments, concentration reached the steady state within the 180 years simulated but in catchments with long MRT a steady state was not reached, making it more difficult to fit the one-compartment and two-compartment exponential models.

The exponential models gave a good fit to ROTAN-1 predictions in catchments where short-term variability in predicted concentration was low, and/or concentrations approached steady state within the period modelled. In such catchments the MRT from the two different models are reported. It was difficult to get a good fit in catchments where short-term variability in concentration was high and/or concentrations did not approach steady state within the period modelled. In these catchments several different models were fitted and the range of MRTs is reported. The aquifer coefficients in ROTAN-1 were adjusted until the model MRTs matched published estimates for tritium (Morgenstern et al. 2005).

Because the one- and two-compartment models were fitted to average concentrations, the MRTs estimated include all the flow pathways that operate in the ROTAN model (viz., deep groundwater, shallow groundwater and surface flow). The same is true for measured tritium provided sampling is conducted over a range of flows. If sampling occurs only during baseflow in a spring fed system then tritium may over-estimate MRT.

4.3 Results

Appendix 3 compares observed and predicted stream flow, total nitrogen concentration (TN) and dissolved inorganic nitrogen concentration (DIN). Table 7 summarises nitrogen MRTs and Table 11 summarises the model fit to observed flows and concentrations. Figure 18 compares observed and predicted total lake loads.

Water balance

The water balances for the lake and each of the nine major streams are within the likely measurement errors (±5-10%) (see Table 11). This indicates that the model successfully quantifies the volumes of water that reach the lake from the catchment and leave the lake via the Ohau Channel. Predicted average flows at the nine gauging sites on major streams total 11.9 m3/s, whereas predicted average total inflow to the lake is 14.0 m3/s. The difference (2.2 m3/s) (hereafter called the ‘ungauged inflow’) is the predicted average flow in catchments without flow recorders (e.g., Hauraki, Ruamata etc.), together with predicted average flow from land downstream of flow recorders on the major streams. Hoare (1980a) reported a lake water balance for 1976-

1977 based on measured stream inflows, measured lake outflow, measured rainfall, estimated evaporation, and measured change in lake volume. He estimated the 'ungauged inflow' to be 2.1 m3/s. This is similar to the value of 2.2 m3/s predicted by ROTAN-1 although a direct comparison is not strictly valid because Hoare (1980a) included in his 'measured inflow' data from several minor streams that are not modelled separately within ROTAN-1.

In ROTAN-1 the groundwater component (70%) of the 'ungauged inflow' is assumed to emerge in springs near the lake edge and to enter the lake as stream flow. The groundwater component of the 'ungauged inflow' may enter the lake directly through the lake bed. ROTAN-1 predicts that 'groundwater direct' is at most 2.2 m3/s (the total 'ungauged inflow') and is most likely 1.5 m3/s (the groundwater component (70%) of the 'ungauged inflow'). GNS-Science estimate 'groundwater direct' at 4.0 m3/s (rounded from their value of 3.97 m3/s, White et al. 2007). This figure is significantly higher than predicted by ROTAN-1, and also significantly higher than the total 'ungauged inflow' (2.1 m3/s) in 1976-1977 (Hoare 1980a). Appendix 1 contains further discussion of 'groundwater direct' inflow to the lake.

Regardless of whether it enters the lake as 'groundwater direct' or surfaces as springflow and enters via streams, all the runoff and the nitrogen it contains is included in the 'lake loads' reported for the ROTAN simulations. Thus, although ROTAN is 'calibrated' by comparing flows and concentrations at gauging sites, the model takes account of runoff from land downstream from the sampling sites and groundwater that by-passes the sampling sites.

Flow variability

In six of the nine major inflows, the observed and predicted short-term flow variability is similar. However, in three streams (Ngongotaha, Utuhina, Puarenga) ROTAN-1 under-estimates short-term flow variability. This indicates that, in these three catchments, the model over-estimates the proportion of infiltration routed to the stream via deep aquifers. As a result, ROTAN-1 over-estimates baseflow in these catchments and under-estimates stormflow. However, in the other six major catchments, ROTAN-1 successfully predicts the observed flow variability.

It would be possible to improve the match to observed short-term flow variability by allowing the proportion of infiltration entering shallow and deep aquifers to vary between sub-catchments. ROTAN-1 assumes that the proportions of water and nitrogen entering shallow and deep groundwater are the same everywhere in the catchment for a given land type (e.g., pasture or forest). There is, however, evidence that these proportions vary spatially – some parts of the catchment have little or no surface flow (indicating that infiltration mostly enters deep groundwater) while other parts of the catchment contain small streams (likely to be fed by shallow groundwater). ROTAN has the capacity to vary the proportions of water and nitrogen that enter shallow and deep groundwater within a catchment, but more work would be required on the spatial heterogeneity of soil drainage properties and stream flow distribution to make this possible. Modelling such spatial heterogeneity would increase model complexity and run-times.

Week-to-week variability of nitrogen concentration

In the Hamurana, Ngongotaha, Utuhina, Waiowhiro and Waingaehe the observed and predicted short-term variability in concentration are similar. This indicates that, in these five catchments, ROTAN-1 successfully quantifies the proportions of water and nitrogen that enter shallow groundwater and find their way to the stream on time-scales of weeks-months. However, in three catchments (Puarenga, Waiteti and Waingaehe), ROTAN-1 over-estimates the variability in concentration. As discussed in the previous paragraph, the proportions of water and nitrogen that enter shallow and deep groundwater may vary spatially (i.e., a higher than average proportion of the total nitrogen export may enter shallow groundwater in some catchments – which would give rise to higher variability). ROTAN has the capacity to vary the proportions of water and nitrogen that enter shallow and deep groundwater between catchments, but further work would be required to make this possible.

Trends in nitrogen concentration

In the Hamurana, Ngongotaha, Utuhina, Waiowhiro and Waingaehe the observed and predicted trends (viz., the timing of increases) in average concentration from 1970-2010 match. This indicates that in these five catchments ROTAN-1 successfully quantifies the timing and magnitude of changes in nitrogen exports (viz., the timing of land use changes and the nitrogen yields from each land use) and the ‘groundwater lags’ for nitrogen.

Concentrations in the Puarenga are affected by exports from the RLTS. There is a mismatch in the timing of concentration changes following commissioning of the RLTS in 1991 – ROTAN-1 predicts that concentrations increase more quickly than was observed. An improved match could be obtained by altering the start time for the RLTS and/or the MRT of the aquifers underlying the RLTS. However, after 2000 ROTAN-1 predicts average concentrations that match observations in the Waipa Stream (which drains the RLTS), indicating that at steady state, the exports from the RLTS are accurately quantified in the model.

In the Awahou Stream the model under-estimates concentrations in the 1970s (i.e., it does not accurately predict the timing of the trend of increasing concentration). This is discussed in detail in the next section.

Average nitrogen concentration

In the Hamurana, Ngongotaha and Utuhina (large inflows) and the Waiowhiro and Waingaehe (smaller inflows), observed and predicted average concentrations match closely. This indicates that in these catchments ROTAN-1 successfully quantifies nitrogen exports (viz., the areas and nitrogen yields for each land use, which both vary over time) and travel times (viz., the proportions of total nitrogen export that enter shallow and deep groundwater, and the MRTs of those aquifers).

In the Puarenga, ROTAN-1 over-estimates the average TN concentration. As discussed in Section 2.15, observed concentrations in the Puarenga are lower than expected for the land uses in the catchment. Wetlands are more numerous in the Puarenga than elsewhere and Rutherford et al. (2009) postulated that attenuation is high in the Puarenga as a result. ROTAN-1 assumes a nitrogen yield from Forest in the Puarenga 50% lower than elsewhere in the Rotorua catchment. An improved match to concentrations in the Puarenga could be achieved by reducing the yields from DryStock and Dairy in the Puarenga as was done for Forest.

In the Awahou (a large inflow), the observed and predicted TN concentrations from 1990-2010 match. However, predicted TN concentrations in the 1970s are lower than observed DIN concentrations, whereas they should be higher. There is a similar mismatch in the Waiohewa (a smaller inflow).

Although the mismatches only occur in two of the nine major streams, it is informative to consider the possible mechanisms that give rise to the mismatches and the implications for the accuracy of predicted load reductions and response times. The mismatch between observed and predicted concentrations in the 1970s indicates that either:

- historic nitrogen yields from 1920-1970 have been underestimated, or
- nitrogen finds its way to the stream from farmland more quickly than predicted using the reported MRTs for tritium.

Rutherford et al. (2009) found that ROTAN-0 also under-estimated concentrations in the Awahou during the 1970s. Historic nitrogen yields in the Awahou catchment are slightly higher in ROTAN-1 than ROTAN-0. Nevertheless, ROTAN-1 still underestimates nitrogen concentrations in the 1970s. There are three possible reasons for the mismatch.

First, ROTAN-1 accurately quantifies nitrogen travel times but there are errors in the historic nitrogen yields. In this case ROTAN-1 can probably be used with confidence to predict load reductions and response times because current and future nitrogen yields can be estimated more accurately. In the Awahou the MRT used to predict nitrogen concentrations (50-60 years) is very close to the MRT estimated by Morgenstern et al. (2005) using tritium (61 years). This suggests that the mismatch is the result of errors in historic nitrogen yields. However, the available historic data has been carefully reviewed and the uncertainty in yields is considered too small to fully explain the mismatch.

Second, historic nitrogen yields are accurate but ROTAN-1 does not quantify nitrogen travel times accurately. In this case ROTAN-1 may not predict response times accurately but, provided yields can be estimated accurately, it can be relied upon to predict load reductions. As discussed above, the MRT for nitrogen in the Awahou is very close to the MRT for tritium. It is possible, however, that the MRTs of tritium and nitrogen are not identical in the Awahou because the spatial distributions of nitrogen and tritium input are not the same. The method used by Morgenstern et al. (2005)[7] assumes a uniform distribution of tritium input across the catchment. Tritium is deposited in rainfall and in the Awahou catchment there is a strong rainfall gradient. Consequently, tritium input is likely to have been highest in the Awahou headwaters and lowest close to the lake. The highest nitrogen inputs occur where land use is intensive. In the 1900-1950s, farming on the western side of Lake Rotorua appears to have been concentrated on land near the lake. Since then, dairying has moved into higher rainfall regions to the west – notably in the upper Ngongotaha, Waiteti and Awahou catchments (see Figures 6-14). We postulate that nitrogen inputs were high close to the lake and the Awahou Stream historically. If so then the MRT for nitrogen could be lower than the MRT for tritium.

Third, there are errors in the historic nitrogen yields and ROTAN-1 does not accurately quantify nitrogen travel times. In this case ROTAN-1 may not predict load reductions or response times accurately. In the Waiteti the model over-estimates both the average TN concentration and the short-term variability in concentration. The mis-match in variability indicates that ROTAN-1 over-estimates the proportion of nitrogen export entering shallow groundwater. This in turn may contribute to the mis-match in average concentration although it is possible that ROTAN-1 over-estimates nitrogen exports in the Waiteti catchment. The same issue arises to a lesser extent in the Waingaehe and Waiohewa.

[7] The so-called EPM (exponential + piston flow model)

As discussed earlier, it might be possible to eliminate these mismatches by allowing the proportions of water and nitrogen entering shallow and deep groundwater to vary spatially. This would require mapping the spatial variability of soil properties and surface flow, and then re-calibrating ROTAN. This might be a worthwhile study in the future. However, uncertainties that result from neglecting spatial variations are not considered to be sufficiently large to invalidate the main findings of this study.

Table 11: ROTAN-1: Observed and predicted mean flows and nitrogen concentrations.

	Mean observed	Mean predicted	RMS error	N	Comment
Stream		**Flow (L/s)**			
Hamurana	2646	2482	312	244	
Awahou	1609	1581	173	405	
Waiteti	1176	1245	349	513	
Ngongotaha	1761	1790	523	1820	Low variability
Waiowhiro	334	411	123	371	
Utuhina	1943	2091	529	1628	Low variability
Puarenga	1772	1644	501	1336	Low variability
Waingaehe	234	291	97	739	
Waiohewa	334	395	107	452	
Ohau Channel	17694	17361	3134	2981	Low variability
	Mean observed	**Mean predicted**	**RMS error**	**N**	**Comment**
Stream		**Concentration (gTN/m3)**			
Hamurana	0.764	0.882	0.270	94	
Awahou	1.275	1.525	0.651	111	Low in 1970s
Waiteti	1.380	3.156	2.841	97	High variability & mean
Ngongotaha	1.008	1.434	0.885	276	
Waiowhiro	1.132	1.204	0.662	122	
Utuhina	0.950	1.068	0.479	149	
Puarenga	1.163	2.812	2.320	215	High mean, high in 1990s
Waingaehe	1.605	2.658	2.620	121	High variability
Waiohewa	3.645	3.272	1.974	119	Low in 1970s

4.4 Groundwater concentrations

Grinsted and Wilson (1978) reported nitrate concentrations in shallow groundwater around Lake Rotorua in the range 1-5 g/m3, with the highest values in bores near cowsheds. Gordon (cited in White et al. 2007) reported an average nitrate concentration of 3.3 g/m3 in shallow (<20m) wells in the Bay of Plenty region. White et al. (2007) reported groundwater concentrations at 169 sites in 2005-2006 (Table 12).

Table 12: Observed total nitrogen (TN) concentrations in groundwater at 169 sites in the Rotorua catchment from 2005-2006. Source: White et al. (2007).

Aquifer	Median conc (gTN/m3)	Aquifer	Median conc (gTN/m3)
Awahou	1.04	Awahou Point	5.96
Hamurana	1.69	Hauraki	2.44
Mission Bay	1.09	Ngongotaha	1.77
Ngongotaha township	2.41	Pohue Bay	2.30
Puarenga	1.52	Rotokawa	1.04
Utuhina	0.41	Waimehia	0.41
Waingaehe	2.74	Waiohewa	0.65
Waiowhiro	0.97	Waitawa	4.43
Waiteti	1.40		

Table 13 compares springflow (viz., groundwater) concentrations predicted by ROTAN-1 for 2005-2006 with values measured by White et al. (2007). The ranges of predicted and observed concentration are similar. In four of the ten catchments, ROTAN-1 predictions match observations. However, in six of the ten catchments concentrations differ by a factor of two or more.

White et al. (2007) report a median TN concentration of 1.60 g/m3 in the Hamurana Spring – significantly higher than the ROTAN prediction of 0.62 g/m3. EBoP measured an average concentration in the Hamurana Stream of 0.76 g/m3 over the same period. Hamurana Stream is dominated by the Hamurana Spring and it is difficult to see why the concentrations should differ. In the Waiohewa, ROTAN-1 predictions are significantly higher than measured values. The likely explanation is that in ROTAN-1 about half of the nitrogen load from Tikitere is assumed to drain into the deep groundwater but this may not be a realistic assumption. The observed concentration of 0.65 g/m3 is consistent with ROTAN predictions in catchments with low-moderate intensity pastoral land use.

In the Utuhina, ROTAN-1 predictions include drainage from suburban areas of Rotorua City which may explain why they are higher than the observations.

In the Waingaehe, White et al. (2007) report a median concentration of 2.74 g/m3 – significantly higher that the ROTAN-1 prediction of 0.44 g/m3. ROTAN-1 assumes that the Waingaehe aquifer is very deep and fully mixed, with a mean residence time of 100-150 years. Consequently, even though there has been intensive land use in the catchment since the 1960s, deep groundwater concentrations have increased only very slowly from the pre-development value[8]. It is conceivable that the reported high concentrations occur in places where pasture drainage is not fully mixed with the deep groundwater. Most Waingaehe groundwater samples are in shallow groundwater (White et al. 2007, Figure 104) and it is conceivable that the reported high concentrations in the Waingaehe are affected by pasture drainage.

In the Ngongotaha and Waimehia, ROTAN-1 predictions are significantly lower than measured values. No explanation for this discrepancy is apparent. In the Waimehia, there is uncertainty about land use and aquifer boundaries which may explain why ROTAN-1 predictions are higher than the observations. Again, it is conceivable that the reported high concentrations occur in places where pasture drainage is not fully mixed with the deep groundwater.

In conclusion:

- The ranges of predicted and observed groundwater concentration overlap.

- There are significant differences between median observed and mean predicted groundwater concentration in six of the 10 catchments.

- Given that groundwater concentration has a high spatial variability and that ROTAN-1 assumes aquifers are completely mixed, some discrepancies are to be expected.

- ROTAN-1 predictions are broadly consistent with measured groundwater concentrations.

[8] ROTAN uses a pre-development nitrogen concentration of 0.40 gN/m3. This is calculated assuming a 'typical' yield from forest of 4 kgN/ha/yr and a groundwater recharge of 1000 mm/year (viz., about 50% of average rainfall). Morgenstern (in EBoP 2007) assumes a pre-development concentration of 0.14 gN/m3 which is the minimum value measured in 'old' groundwater.

Table 13: Comparison between predicted mean springflow and observed nitrogen concentrations.

Aquifer	Concentration (gTN/m3)	
	ROTAN predicted mean	**Measured median**
Hamurana *	0.62	1.69
Waingaehe *	0.44	2.74
Kauae/Ngongotaha *	0.64, 0.55	1.77
Waiteti *	0.53	1.40
Waiohewa *	1.83	0.65
Utuhina *	0.88	0.41
Waimehia *	1.07	0.41
Puarenga	1.03	1.52
Utuhina	0.53	0.41
Awahou	1.10	1.04
Waiowhiro	0.67	0.97
Range	**0.44-1.83**	**0.41-2.74**
Lynmore	1.09	ND
Valley	0.53	ND
Morea	1.51	ND
Kawaha	0.73	ND
Tureporepo	0.60	ND
Pikirangi	1.65	ND
Kauaka	0.58	ND
Ohinemutu	0.55	ND
Waihuahua	0.80	ND
Ruamata	1.06	ND
Motutara	1.49	ND
Waipa	1.66	ND
Ohau	3.33	ND

* Concentrations differ by a factor of 2 or more.

4.5 Trends in lake load

Figure 18 shows that lake loads predicted using ROTAN-1 match published estimates of lake load reasonably well. In the early 1960s, the predicted load slightly over-estimates the target of 405 tN/yr. In the 1920s-1930s the lake load is predicted to have averaged c. 250 tN/yr which is c. 60% of the target load and c. 40% of the current load.

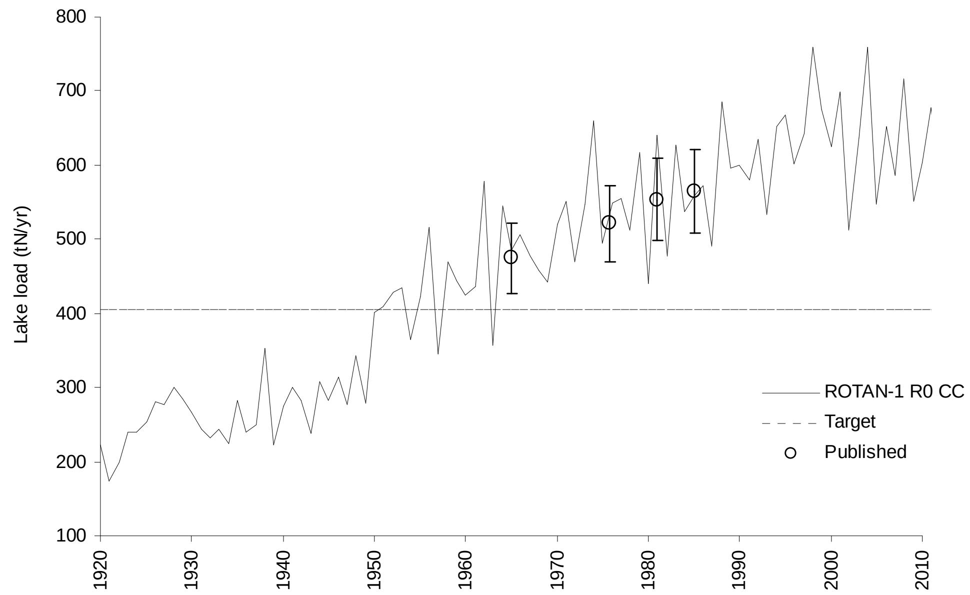


Figure 18: Annual lake loads predicted using ROTAN-1 (solid line). Also shown (circles) are published estimates of lake load, and the target load (dashed line).

4.6 Discussion and conclusions

The main features of the ROTAN-1 model that affect its ability to predict load reductions and response times are:

- Good water balances are achieved for the lake and the nine major streams.
- Annual loads entering the lake from the catchment match published estimates reasonably well.
- Flow variability is reproduced in 6 of the 9 major streams.
- In three major streams, flow variability is under-estimated (viz., baseflow is over-estimated and stormflow under-estimated). Consequently, in these three streams the amount of water and nitrogen that reaches the lake via deep groundwater is over-estimated. This means that ROTAN-1 may over-estimate response times in these three catchments.
- In five of the nine major streams average TN concentrations, short-term variability in TN concentration, and long-term increases in TN concentration are predicted accurately.

- In two streams, average TN concentrations in the 1970s are under-estimated, although from 1990-2010 predictions match. These historic mismatches may be the result of errors in historic nitrogen export estimates rather than a flaw in the model. If so then ROTAN-1 can be used with confidence for prediction.

- The mismatches may, however, arise because the MRT for tritium does not apply to nitrogen – a consequence of the spatial distributions of tritium and nitrogen input being significantly different. If so then the model may, in the future, need to be re-calibrated with a finer spatial resolution in order to predict accurate response times.

- In two streams average TN concentrations are over-estimated. The likely reason is that ROTAN-1 over-estimates nitrogen yields and/or under-estimates attenuation. In the future, it would be worthwhile to re-calibrate export coefficients and/or attenuation in these catchments.

- Several coefficients in ROTAN-1 were estimated by 'calibration' to observed flows and concentrations. This was done for: the proportions of water and nitrogen that infiltrate into shallow and deep aquifers, the MRTs of shallow and deep aquifers, and the amount of attenuation. There are uncertainties in input data including: aquifer boundaries, land use maps, historic nitrogen yields, and the timing of land use changes. Uncertainties in input data make the 'calibration' of model coefficients a difficult task. First, it is a very time consuming exercise given the complexity of the ROTAN model. Second, it is possible to arrive at equally good fits to observations using several different combinations of input data and model coefficients.

- ROTAN-1 does allow spatial variability in key model coefficients (e.g., the proportions of infiltration and nitrogen export that enter shallow and deep groundwater). While ROTAN-1 quantifies the 'catchment-average' delivery of nitrogen, it does not quantify the (possibly subtle) effects of such spatial variability. While ROTAN has the capacity to vary the proportions of water and nitrogen that enter shallow and deep groundwater within a catchment, more work would be required to achieve this, and model complexity and run-times would increase.

- Bay of Plenty Regional Council has a pressing need to make policy decisions and our approach is to 'calibrate' ROTAN-1 as best we can, identify major uncertainties, highlight conclusions that are unlikely to be affected by these uncertainties, and identify where these uncertainties are likely to affect predictions of load reduction and response time. In the next sections we discuss other ROTAN models in which key model coefficients and input data are varied, and the sensitivity of predicted lake loads are examined.

We conclude that:

- ROTAN-1 provides a satisfactory match to key features of observed flows and concentrations.

- Some questions remain about the uniqueness of model calibration and hence the robustness of ROTAN-1 for making predictions.

- ROTAN-1 predictions are considered to be sufficiently reliable to inform policy and management.

- Predicted load reductions are considered to be robust but predicted response times are likely to have a higher uncertainty.

- Follow up modelling can be undertaken if more refined simulations are required.

- Sensitivity analysis using ROTAN-2 to ROTAN-9 (described below) helps quantify the likely robustness of predictions.

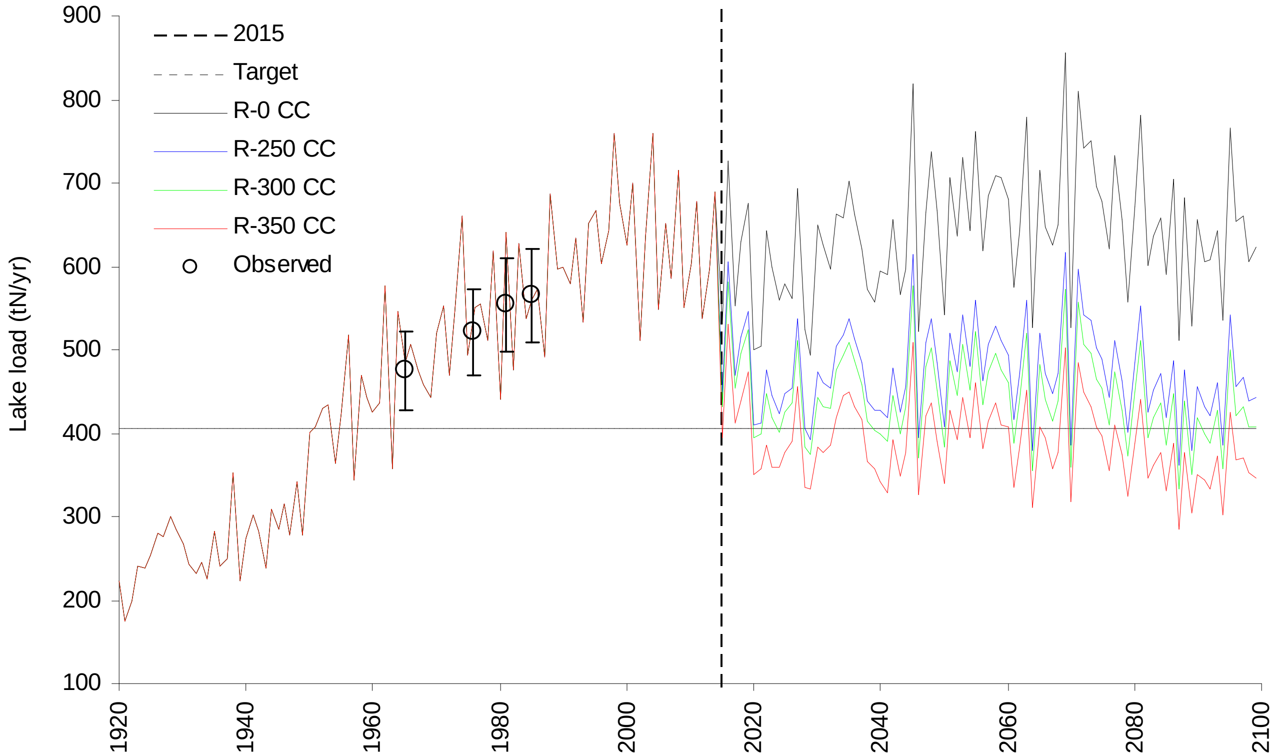


Figure 19: ROTAN-1. Predicted lake loads for current land use (R-0) and three scenarios of land use change (R-250, R-300 and R-350). Simulations assume climate change (CC). Land use change occurs in 2015. The target lake load is 405 tN/yr.

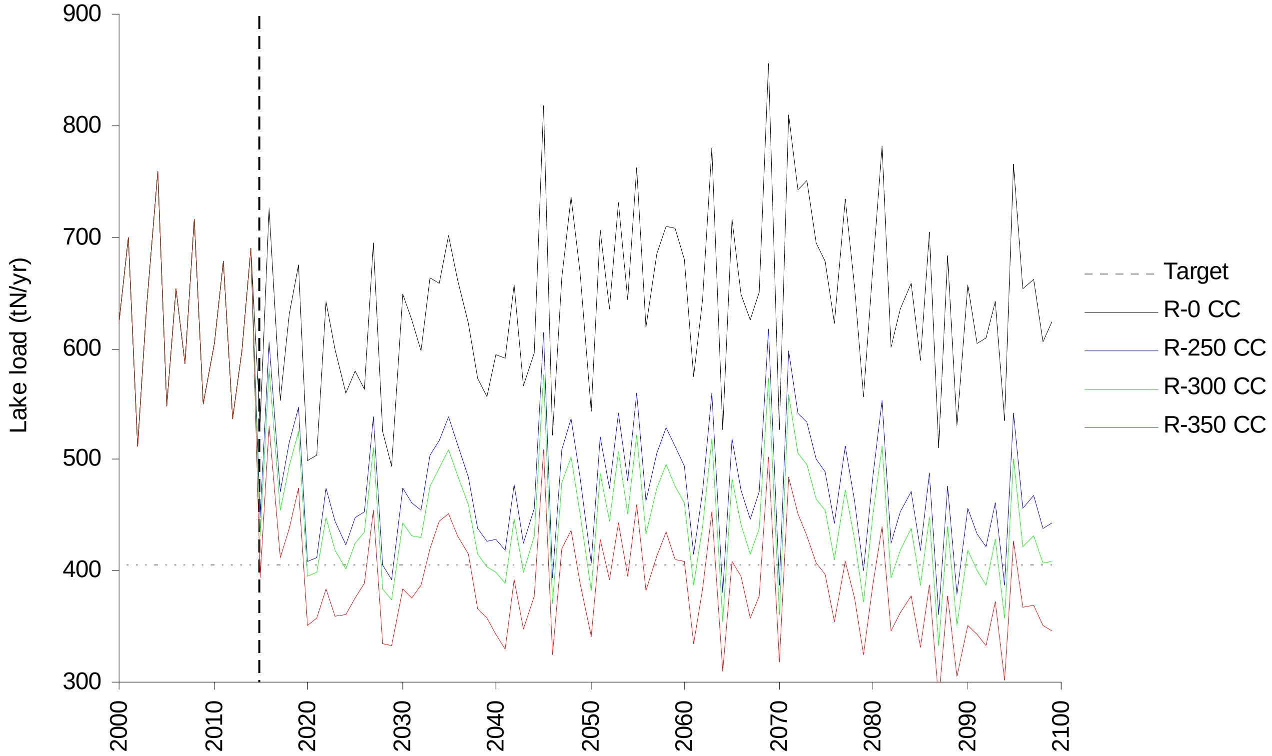


Figure 20: ROTAN-1. Predicted lake loads for three scenarios of land use change (R-250, R-300 and R-350). Simulations assume climate change (CC). Land use change occurs in 2015. The target lake load is 405 tN/yr.

5. ROTAN-1 predictions

Figures 19-20 show predicted annual nitrogen loads to the lake for four scenarios of land use and nitrogen export, including the effects of climate change.

5.1 R-0 scenario

Scenario R-0 assumes that nitrogen yields remain unchanged from 2008-2100 at their current values[9]. This implies that there is not nett intensification (viz., any increase in stocking rate or production per animal is offset by on-farm mitigation, or is offset by changes to less intensive land use elsewhere in the catchment). This simulation provides information about what might happen in a 'holding' or 'do nothing' scenario.

The year-to-year variations in lake load (Figure 21) arise from variations in rainfall and evapotranspiration. In wet years, more nitrogen reaches the lake than in dry years, while in dry years nitrogen accumulates in the soils and aquifers. In these simulations, nitrogen yields do not change after 2008 and the system eventually reaches a 'steady state' (SS) in which the lake load equals the sum of the exports. Table 10 shows that steady state lake loads (predicted by ROTAN) and total exports (the sum of the exports from all land parcels) match closely – demonstrating internal consistency within ROTAN.

In Figure 21 the lake load increases for several years after 2008 even though the yields do not change. This is because it takes years-decades for nitrogen to travel through the groundwater to the lake (especially in catchments like the Hamurana, Awahou and Waingaehe) and for the lake load to reach equilibrium with the exports. From the annual loads it is difficult to determine how long it takes for the lake load to reach steady state. Also shown in Figure 21 is the steady state lake load for the current land use. This was predicted in ROTAN by setting rainfall and PET to their long-term average values (in place of their weekly values), holding nitrogen yields constant at their current values, and running the model to steady state. Figure 21 shows that, if nitrogen exports were to remain unchanged at their current values, the lake load would increase slowly over the next 65 years and approach steady state by about 2080. In Figure 21 the lake load appears to reach steady state at about 2080 before decreasing. This occurs because in these simulations rainfall happens to be below average from 2080-2100 which results in a slight reduction in lake load.

[9] In subsequent scenarios, land use changes in 2015 but current land use is unchanged from 2008-2015 and so effectively Scenario R-0 assumes constant nitrogen exports from 2008-2100.

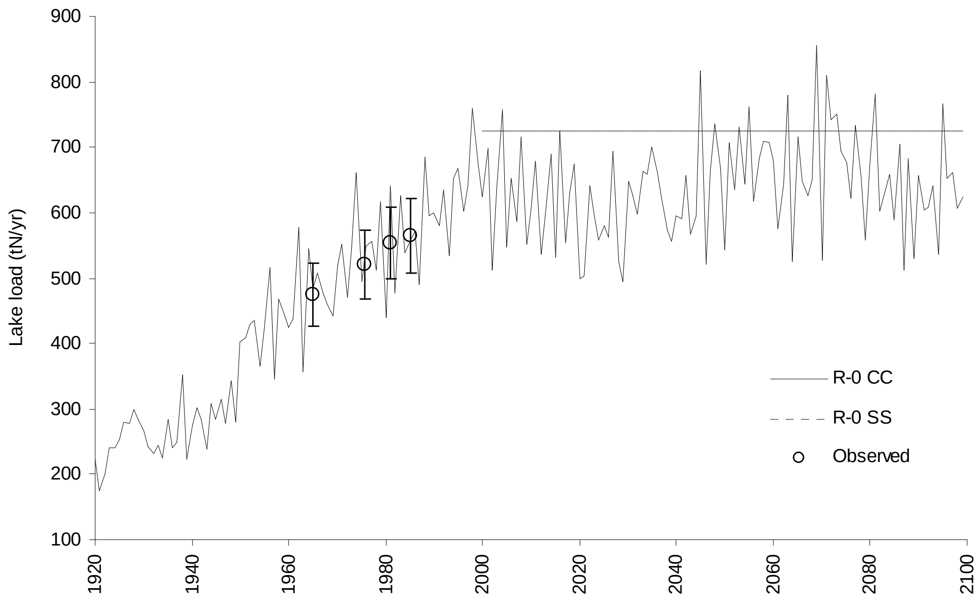


Figure 21: ROTAN-1 Scenario R-0. Annual lake loads predicted assuming historic nitrogen exports from 1920 followed by constant exports at current levels from 2008-2100 (R-0 CC). Also shown (R-0 SS) is the steady state load predicted by ROTAN assuming constant nitrogen exports at current levels (725 tN/yr). The simulations assume climate change (CC).

5.2 R-350 scenario

Figures 22-23 show the predicted annual lake loads for the R-350 scenario which is the largest reduction in nitrogen export modelled. Despite the year to year variations, predicted lake load decreases significantly as a result of the assumed reductions of nitrogen exports in 2015. By 2025 (viz., after 10 years) the predicted lake load has decreased significantly and has occasionally dipped below the steady state load. Note that the horizontal lines in Figures 22-23 are the steady state load for scenario R-350 (375 tN/yr), not the target lake load (405 tN/yr). By 2040 (viz., after 25 years) the average lake load is consistently within 10-15% of the steady state load, although even at 2100 lake load is still not quite at steady state.

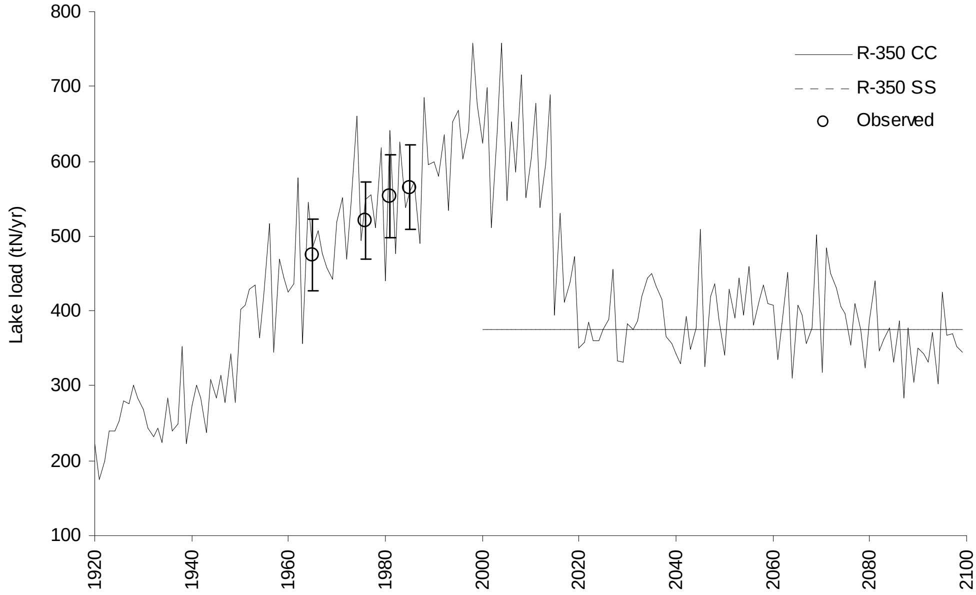


Figure 22: ROTAN-1 Scenario R-350. Annual lake loads predicted assuming historic nitrogen exports from 1920-2015 followed by reduced exports that remain constant from 2015-2100 (R-350 CC). Also shown (R-350 SS) is the steady state load predicted by ROTAN assuming the land use and nitrogen exports for the R-350 scenario (375 tN/yr). Simulations assume climate change (CC).

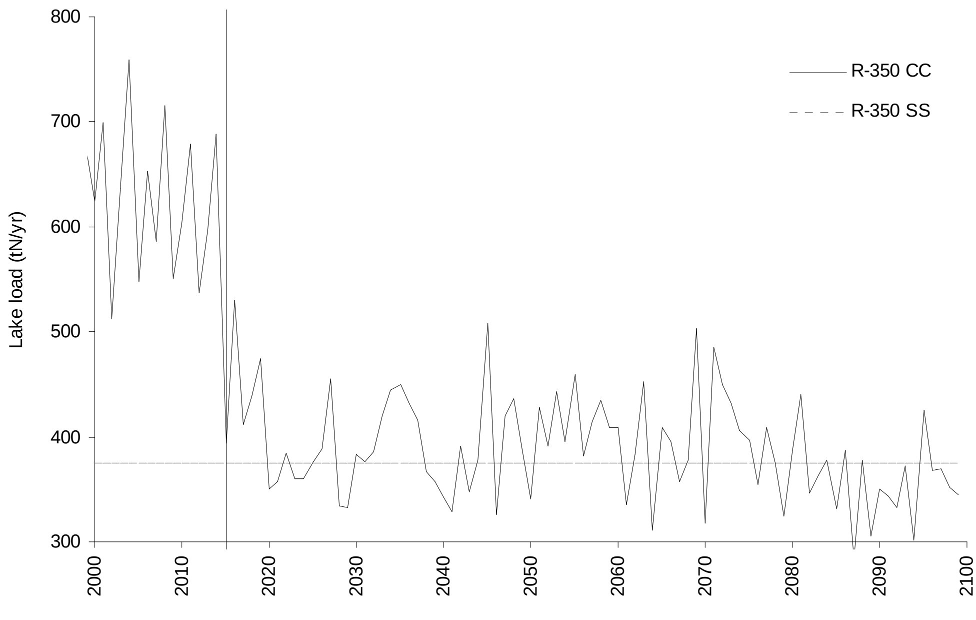


Figure 23: ROTAN-1 Scenario R-350. Annual lake loads predicted assuming reduced exports that remain constant from 2015-2100 (R-350 CC). Also shown (Steady state) is the steady state load predicted by ROTAN assuming the land use and nitrogen exports for the R-350 scenario (375 tN/yr). Simulations assume climate change (CC).

5.3 Load components

Figure 24 shows the components of lake load. ‘Springflow’ is the nitrogen load transported to the lake via deep groundwater, and ‘Quickflow’ is the load transported via surface flow and the two shallow aquifers.

In 2010 the springflow and quickflow loads are similar in magnitude which is consistent with the ROTAN-1 assumption that 53% of nitrogen export is routed to the lake via deep groundwater, while 47% reaches the lake via surface flow and the two shallow aquifers. Following the step change in land use in 2015, the quickflow load decreases very quickly which is consistent with the fact that the response times of the two shallow aquifers are of the order months-years. The springflow load decreases more slowly. The quickflow load reaches its new steady state within about five years. By comparison, the springflow load is not at steady state value in 2100. This is consistent with the long MRTs of deep groundwater.

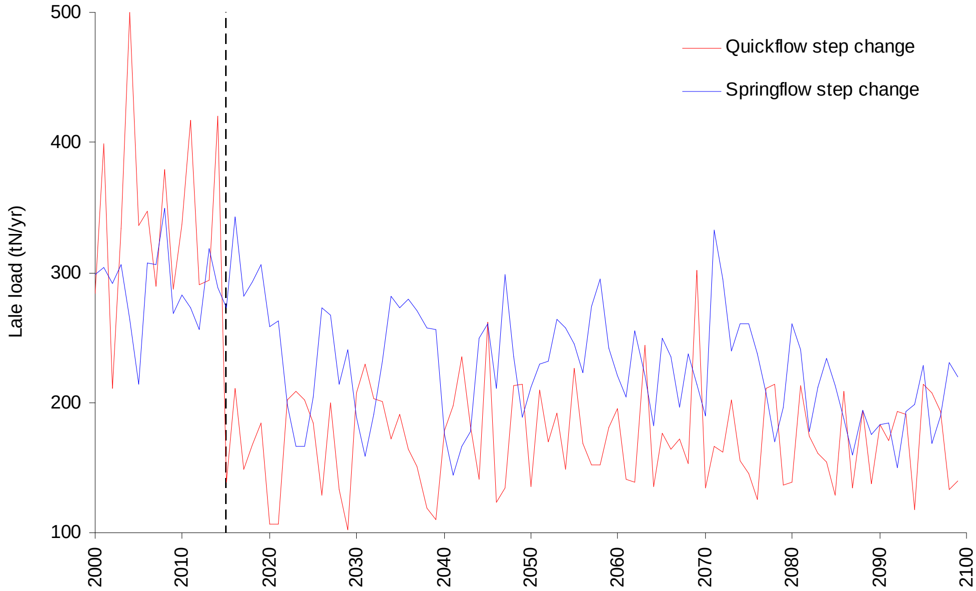


Figure 24: ROTAN-1 Scenario R-350. Components of predicted lake load. A step change in nitrogen exports occurs in 2015.

5.4 Soil lags

ROTAN-1 assumes a step change in nitrogen yield in the year land use changes. In practice it may take several years for nitrogen stores in the soil to be depleted (hereafter termed the 'soil lag'), and for nitrogen exports to decrease to a new steady state value for the changed land use. Overseer® predicts long-term average (viz., steady state) yields but not how quickly yields increase or decrease after a land use change.

There is no reliable information about 'soil lags' in Rotorua soils. However, Figure 25 shows simulations of the springflow and quickflow components of lake load assuming that yields decrease by 10% per year following the land use change in 2015. These results were obtained by applying a 15-term backwards moving average filter to the quickflow and springflow loads output from ROTAN-1[10].

Comparing Figures 24 and 25 it can be seen that 'soil lags' affect quickflow loads more than springflow loads. The reason is that quickflow transports about 50% of the nitrogen exports to the lake within 1-2 years – less time than it takes for the soil stores to adjust to a new steady state. In some catchments, groundwater lags are long compared with soil lags and in these catchments it makes little difference to springflow load whether soil lags are modelled or not. In a few catchments (e.g., Ngongotaha) soil lags are comparable with groundwater lags.

Figure 26 compares predicted lake loads assuming a step change in yield in 2015 with ('soil lag') and without ('step change') soil lags. Neglecting soil lags, lake load is predicted to dip below the steady state in 2020 (after 5 years). Including soil lags, lake load dips close to the steady state in 2030 (15 years) and again near 2050 (35 years), but has not reached steady state by 2070.

These simulations indicate that:

- If nitrogen stores in the soil adjust to new land uses at 10% per year, then the response time of lake load is increased by 10-20 years.

- When soil lags are included, predicted lake load is close to the steady state by about 2050 (after 35 years) although it takes until after 2100 to fully reach steady state.

[10] 'Soil lags' can be modelled within ROTAN. However, this is not done in this study because there is insufficient reliable information about how quickly soil nitrogen stores are likely to adjust following land use change. If such information becomes available, it can be incorporated into ROTAN.

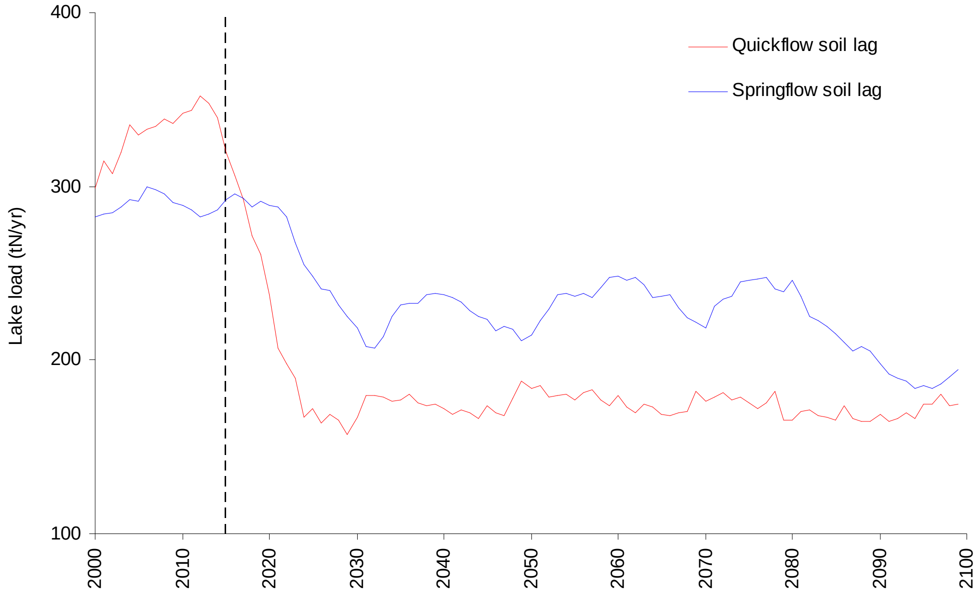


Figure 25: ROTAN-1 Scenario R-350. Predicted components of lake load. A step change in land use occurs in 2015 and nitrogen yields decrease to the new steady state at a rate of 10% per year.

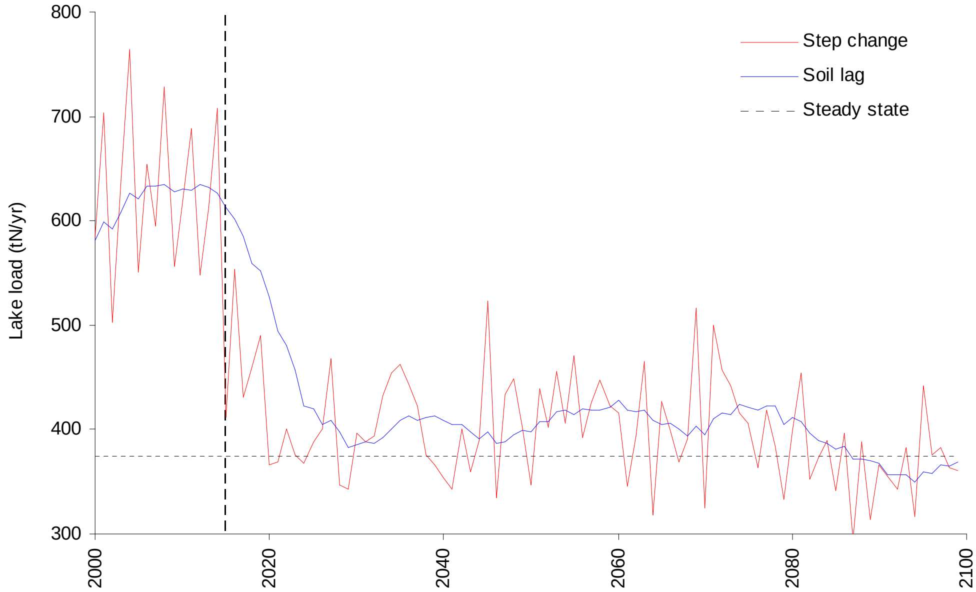


Figure 26: ROTAN-1 Scenario R-350. Predicted lake loads with and without soil lags. A step change in land use occurs in 2015.

5.5 Climate change

The R-0 scenario was run using ROTAN-1 with (CC), and without (NCC) accounting for changes induced by climate change, to assess the effect on lake load. The effects of climate change on lake load were found to be minor (see details below) and so the scenarios R-250, R-300 and R-350 were only run with climate change (CC).

For the NCC scenarios, synthetic rainfall and PET were generated for 2010-2100 by ‘copying and pasting’ historical climate records. For the CC scenarios these rainfall and PET data were ‘adjusted’ for climate change using information supplied by the University of Waikato (UoW) (Wei Ye, UoW, *pers. comm*.). UoW downloaded from NIWA the 12 statistical Global Climate Model (GCM) outputs for New Zealand. The pattern-scaling method was used to generate the relative changes in rainfall and air temperature for each Julian month 2010-2100. The method firstly normalises the downscaled GCM monthly data according to the projected annual global warming trend. Future changes are then calculated from the normalised data and annual global warming projections from IPCC SRES. The relative change for each month is the median value of the 12 GCM ensembles, under IPCC SRES A1B, assuming the mid-range of climate sensitivity.

NIWA use the perturbed air temperature, together with synthetic humidity and wind speed, to re-calculate PET for Forest and Pasture. Details of the PET models used are given in Rutherford et al. (2008). Note that the effects of climate change on wind speed and humidity are unknown and any resulting effects on PET are not included in this report.

Annual rainfall is predicted to decrease as a result of climate change while year-to-year variability is predicted to increase (Figure 27). The changes in the 10-year centred moving average rainfall range from +0.4 mm/yr (0.02%) to -6.4 mm/yr (0.47%), compared with the NCC average rainfall of 1,619 mm/yr. This change has a negligibly small effect on predicted lake inflows. In contrast, annual average PET is predicted to increase substantially (Figure 28). The changes in 10-year moving average PET range from +49 mm/yr (5%) to +302 mm/yr (28%) for Forest and from +141 mm/yr (14%) to +297 mm/yr (30%) for Pasture. As a result ROTAN predicts a significant decrease in runoff from 2010-2100 when climate change is included (Figure 29). Average lake inflow decreases by 2.1 m3/s (14%) from 15.1 to 13.0 m3/s. This is equivalent to a reduction in average runoff from 1,030 mm/yr to 888 mm/yr (142 mm/yr) compared with runoff observed under current average rainfall conditions of 1,619 mm/yr.

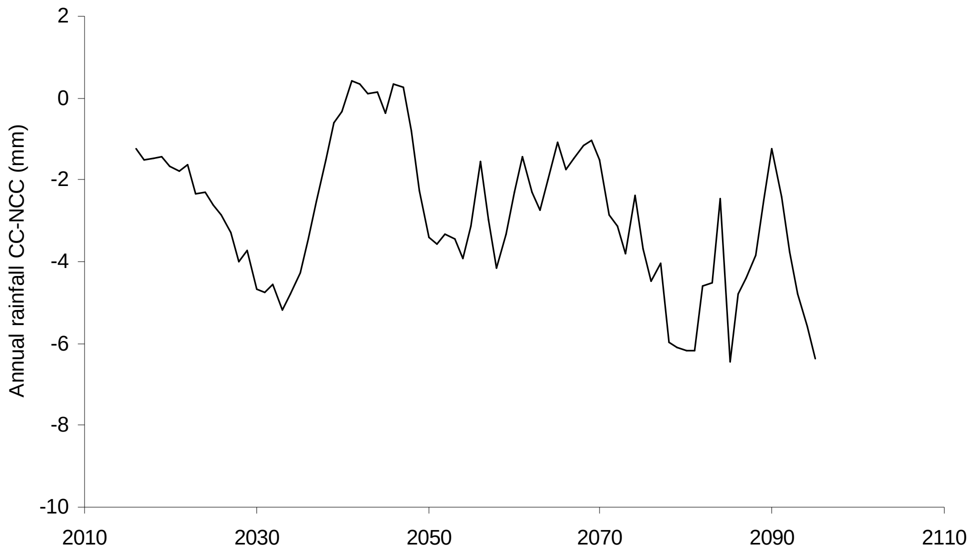


Figure 27: Ten year centred moving average of the difference (CC-NCC) between annual rainfall with climate change (CC) and without climate change (NCC).

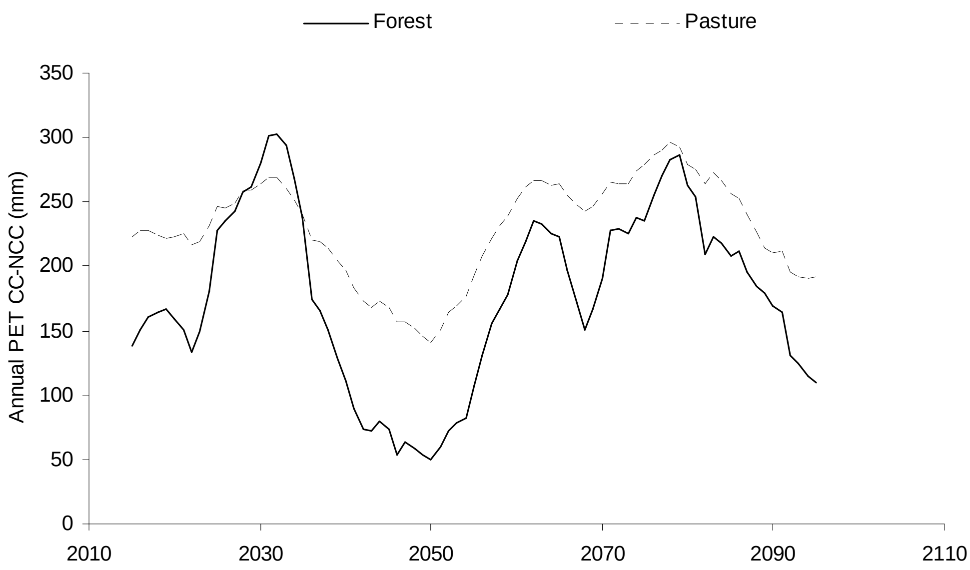


Figure 28: Ten year centred moving average of the difference (CC-NCC) between annual PET with climate change (CC) and without climate change (NCC) for Forest (solid line) and Pasture (dashed line).

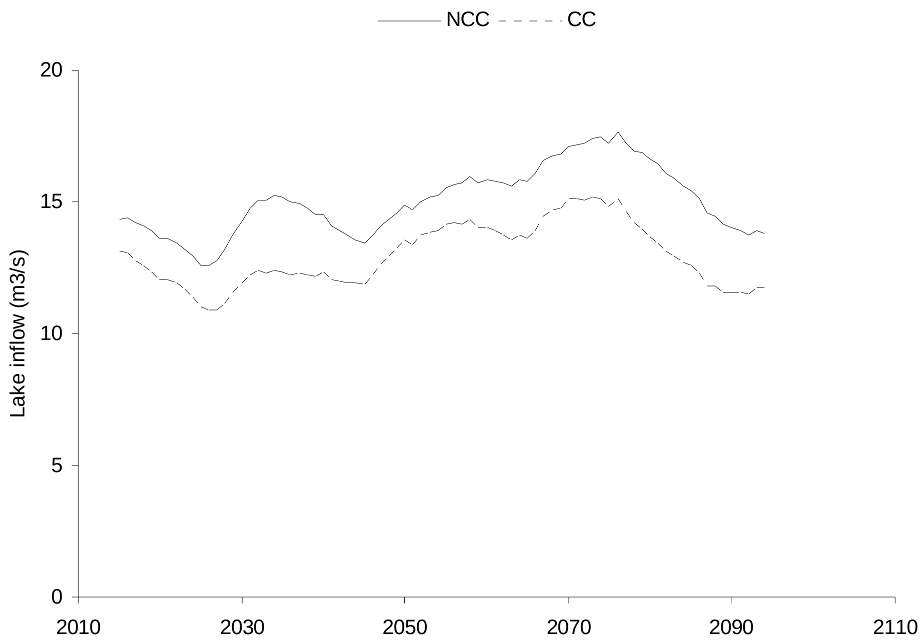


Figure 29: Ten year centred moving average of annual lake inflow with climate change (CC) and without climate change (NCC).

Figure 30 compares loads predicted using ROTAN-1 for scenario R-0 with and without climate change. ROTAN-1 predicts that climate change results in significantly lower lake inflows (Figure 29), but only slightly lower lake loads (Figure 30). Lake loads are lower in dry periods (e.g., 2020, 2030 and 2040) but climate change only reduces the average load to the lake by 2%.

The reason that climate change does not reduce lake load is as follows. ROTAN assumes that climate change does not affect nitrogen yields. Thus for scenario R-0, Dairy is assumed to leach 56 kgN/ha/yr from 2015-2100 regardless of climate change. The effect of climate change is to reduce runoff and hence lake inflows by 2.1 m3/s (14%). However, for constant nitrogen export, this results in higher nitrogen concentrations in groundwater and streams. Lake load (the sum of the products of concentration x stream or spring flow) remains almost unchanged.

It is conceivable that climate change may result in changes to stocking rate, pasture dynamics and/or farming practice. If this is the case, then nitrogen yields may change for a given land use and the effects of climate change may be more significant than those shown in Figure 30. We currently have no information about how climate change may affect nitrogen yields. However, if such information comes to hand then ROTAN could be re-run to estimate the effects on lake load.

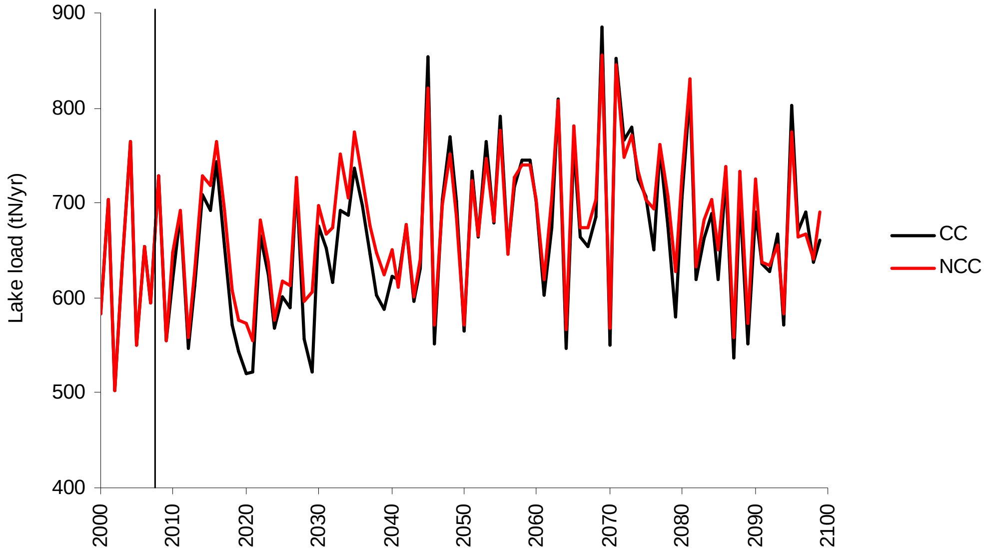


Figure 30: ROTAN-1. Predicted nitrogen loads to the lake for the current land use (R-0) with (CC) and without climate change (NCC).

5.6 Sensitivity analysis

A feature of Figures 19, 20 and 22 is that the lake load seems to approach steady state quickly for scenario R-350. There are three aspects of ROTAN that affect the rate of change of lake load:

1. The fractions of water and nitrogen that enter the lake via shallow and deep groundwater.

2. The depth of the aquifer that determines its mean residence time.

3. The relative size of the surface and groundwater catchments.

The ROTAN model used in this study simulates four layers: soil, quickflow aquifer, slowflow aquifer and deep aquifer. Water and nitrogen enter the shallow and deep aquifers as drainage from the soil layer. Water and nitrogen enter the stream from the quickflow and slowflow aquifers and as springflow that emerges from the deep aquifer. The model coefficients that determine water content and water flux in ROTAN-1 were adjusted so that the variability in predicted weekly streamflow matched the observed flow variability, and the predicted average flow matched the observed average flow. It was found that a satisfactory match was obtained by allowing 70% of drainage from the soil layer to enter the deep aquifer, 20% to enter the quickflow aquifer and 10% to enter the slowflow aquifer. In the model these percentages are averages applied to all land uses across the entire catchment and different land use types. In reality there is spatial variability in soil drainage which probably causes these percentages to vary spatially – such variability is not currently captured in ROTAN.

For given hydrology coefficients, the coefficients that determine nitrogen concentration and flux in ROTAN are the nitrogen generation or removal rates in the soil layer, the quickflow aquifer, the slowflow aquifer and the deep aquifer. In the simulations reported here, there is no removal in the soil, shallow or deep aquifers, or streams.

For each land use category the total generation rate equals the nitrogen yield (kgN/ha/yr) estimated from land use and stocking rate using Overseer®. The majority of nitrogen is generated in the soil layer, but in ROTAN-1 some nitrogen is generated in the quickflow aquifer to simulate the flushing of organic and particulate nitrogen during rainfall events. In the ROTAN-1 model, 75% of nitrogen is generated in the soil layer, 25% in the quickflow aquifer and no nitrogen is generated in the slowflow aquifer or the deep aquifer. This means that 53% of the nitrogen generated enters the deep aquifer via drainage from soil layer 1, and because there is no nitrogen attenuation in deep groundwater, this nitrogen eventually enters the lake via springflow. Forty per cent of the nitrogen generated enters streams via the quickflow aquifer and 7% enters streams via the slowflow aquifer. This apportionment was derived by calibration (Rutherford et al. 2009) and was found to give a tolerably good match between observed and predicted stream nitrogen concentration (see Appendix 3). Note that in the other ROTAN models discussed below, nitrogen is only generated in the soil layer.

5.6.1 Nitrogen generation

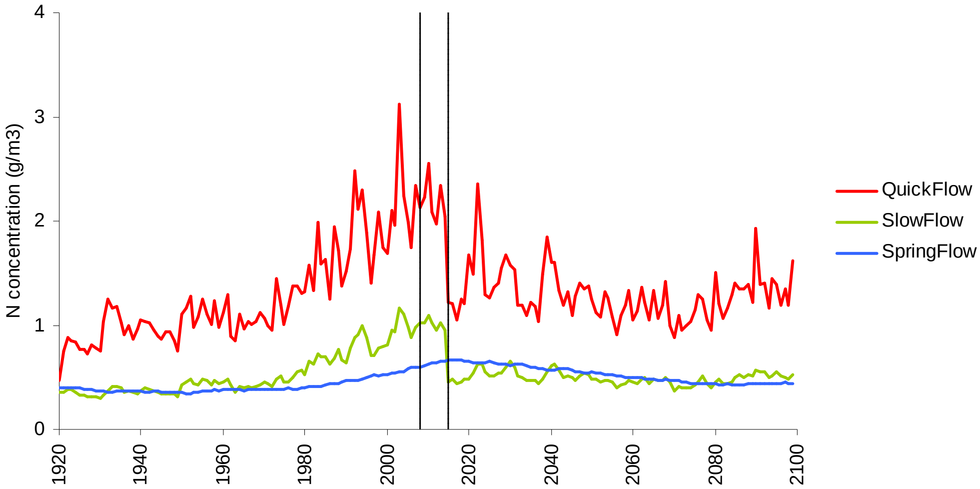
Figure 31 compares annual average nitrogen concentrations predicted in the Ngongotaha Stream, assuming:

a. 75% of nitrogen generation occurs in the soil layer and 25% in the quickflow aquifer (top), and

b. 100% of nitrogen generation occurs in the soil layer (bottom).

For case (a) 25% of the total nitrogen export is generated in the quickflow aquifer, and 20% of the nitrogen generated in the soil layer also drains through the quickflow aquifer. Consequently 40% of the nitrogen export, but only 20% of total runoff, passes through the quickflow aquifer, and quickflow concentrations are high. For case (b) 20% of the nitrogen generated in the soil layer drains through the quickflow aquifer but no nitrogen is generated. Consequently, quickflow concentrations are lower than for case (a). The converse is true for slowflow and springflow – for case (b) a higher proportion of total nitrogen export passes through the slowflow and deep aquifers, the water flow remains unchanged, and consequently nitrogen concentrations are higher than for case (a).

The time scales at which the deep aquifer responds to land use change is similar in both scenarios because drainage and springflow are unchanged. The nitrogen loading changes and as a result nitrogen concentrations differ between scenarios.



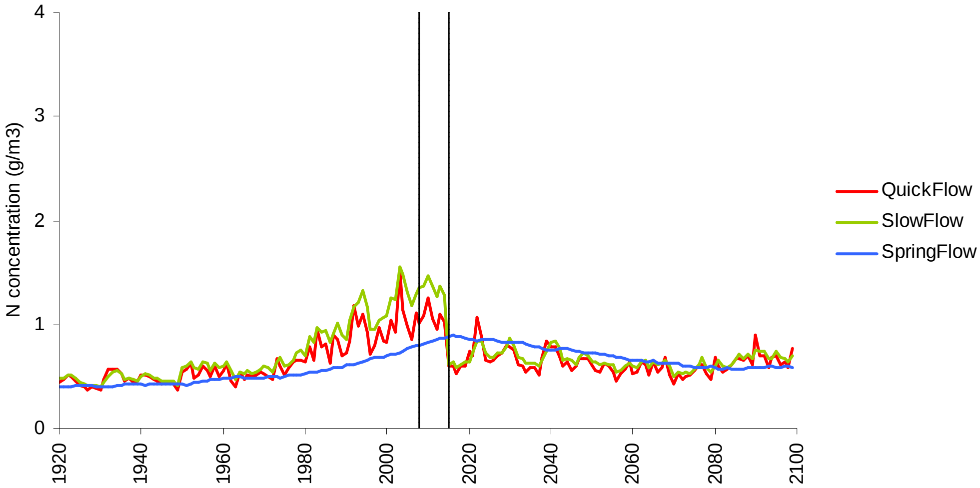


Figure 31: ROTAN-1 Scenario R-350. Predicted annual average nitrogen concentration in the quickflow, slowflow and deep aquifers of the Ngongotaha catchment assuming: 75% of nitrogen is generated in the soil layer and 25% in the quickflow aquifer (top) and 100% of nitrogen is generated in the soil layer (bottom). The vertical lines denote 2008 and 2015 when land use changes occur.

Figure 32 shows that despite significant differences in concentration, the differences in total load (viz., quickflow + slowflow + springflow) are relatively small. Of particular importance is the fact that the rate of change of total load following the land use changes in 2008 and 2015 are not significantly different for cases (a) and (b). In other words, the rate of change of nitrogen load is not strongly influenced by the mechanism of generation.

In ROTAN the proportions of nitrogen export from the land reaching the lake via deep groundwater and via near-surface flow are spatially uniform. There is evidence that more water infiltrates (and hence more nitrogen enters deep groundwater) in some parts of the catchment than others – some parts of the catchment have little or no permanent stream flow (e.g., Hauraki, or Waiteti headwaters etc.). The relative locations of intensive land use and high infiltration soils may affect the response times. Further modelling work would be required to quantify this effect.

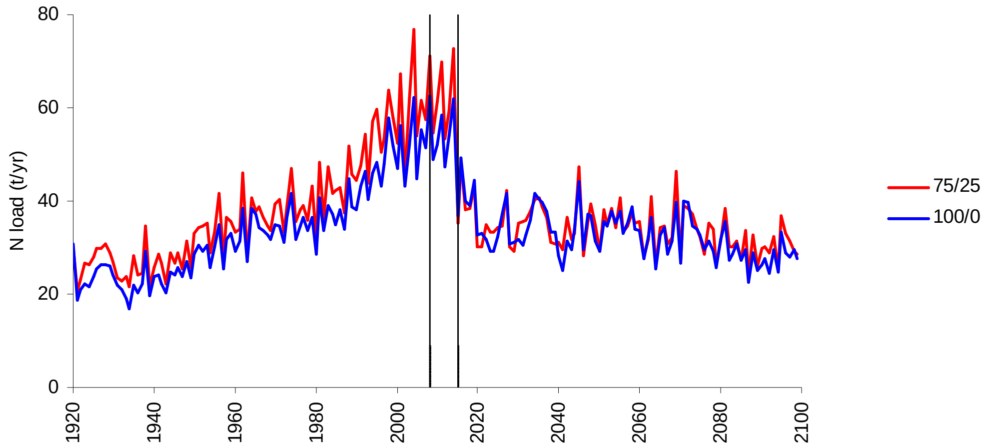


Figure 32: ROTAN-1 Scenario R-350. Predicted annual average total nitrogen load in the Ngongotaha Stream assuming: 75% of nitrogen is generated in soil layer 1 and 25% in the quickflow aquifer (75/25), and 100% of nitrogen is generated in soil layer 1 (100/0).

5.6.2 Aquifer depth

The Ngongotaha aquifer has the shortest groundwater MRT (16 years). Groundwater concentrations increase significantly from 1980-2015 in response to intensive agriculture (Figure 31). Groundwater concentrations also decrease significantly from 2015-2100 in response to the reduced nitrogen exports of scenario R-350. The fairly rapid change in groundwater concentrations is consistent with the short MRT of the Ngongotaha aquifer.

Figures 33-34 show concentration and load predictions for the Waingaehe Stream whose aquifer has a long MRT (127 years). As expected, quickflow concentrations are higher for case (a) (75% generation in soil layer 1 and 25% in the quickflow aquifer) than for case (b) (100% generation in soil layer 1). In contrast, slowflow concentrations are higher for case (b) than case (a) for the reasons discussed previously. The main difference between Figures 31 and 33 is that springflow concentrations (viz., concentrations in the deep aquifers) hardly change over time in the Waingaehe, whereas in the Ngongotaha they change fairly quickly. The muted response of springflow concentration in the Waingaehe is a consequence of its very long MRT. In ROTAN the long MRT was simulated by making the aquifer very deep so that its volume is very large. ROTAN assumes complete mixing within the aquifer. Land use intensification in both the Ngongotaha and the Waingaehe commenced in the 1960s, at which time the nitrogen concentration in drainage increased significantly. However, because the deep aquifer volume in the Waingaehe is large, and it is assumed to be fully mixed, the rate of change of concentration in the deep aquifer is very slow. In the Ngongotaha, however, the deep aquifer volume is small and so the rate of change of concentration is fairly fast.

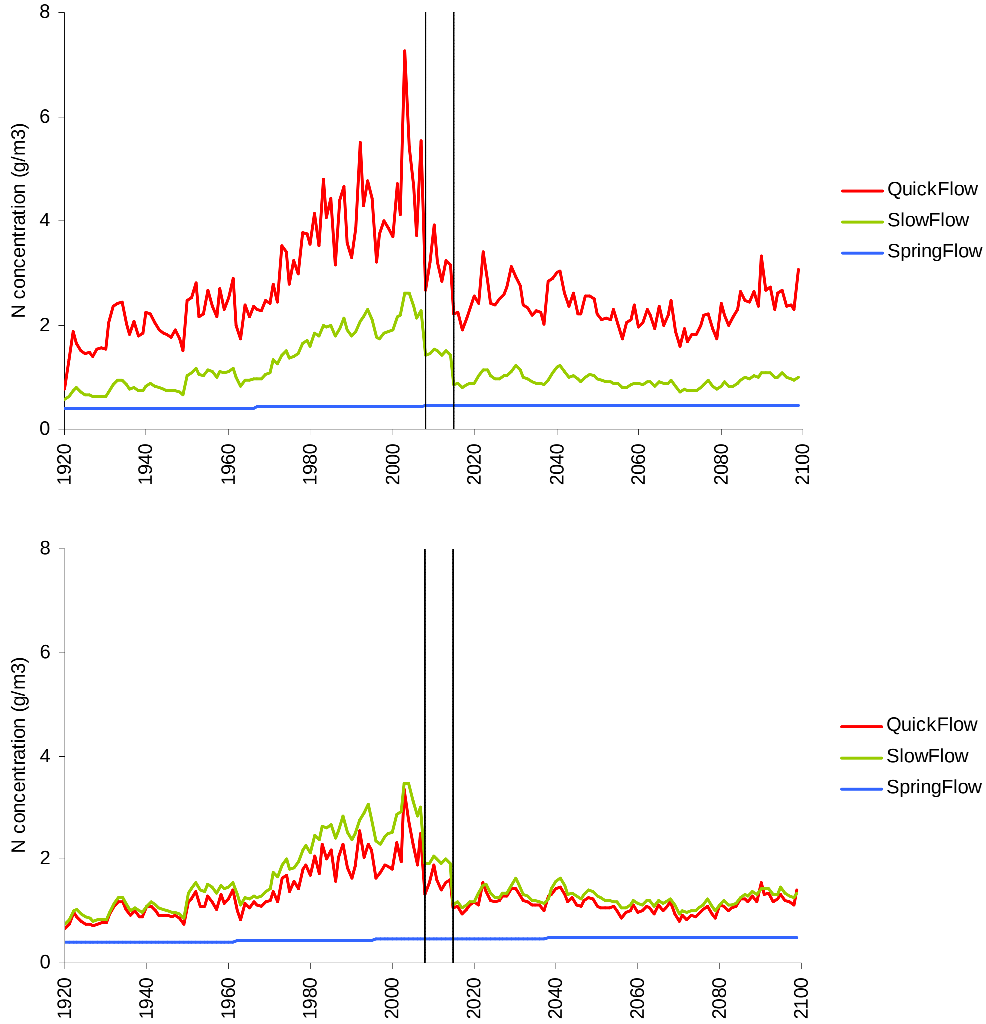


Figure 33: ROTAN-1 Scenario R-350. Predicted annual average nitrogen concentration in the quickflow, slowflow and deep aquifers of the Waingaehe catchment assuming: 75% of nitrogen is generated in soil layer 1 and 25% in the quickflow aquifer (top) and 100% of nitrogen is generated in soil layer 1 (bottom). The vertical lines denote 2008 and 2015 when land use changes occur.

Despite having a large, slow responding aquifer, the nitrogen load in the Waingaehe Stream is predicted to decrease quickly following the land use changes in scenario R-350 (Figure 34). Although the loads in the Ngongotaha and Waingaehe differ in magnitude, the response times following land use change appear to be similar – in both streams, nitrogen load decreases quickly between 2015 and 2030-2040 and, thereafter, do not appear to change. One complicating factor is that in the Waingaehe there was a significant land use change in 2008 when the Wharenui block converted from Dairy to DryStock or Forest – no comparable land use change occurred in 2008 in the Ngongotaha. Nevertheless, Figure 34 indicates that stream nitrogen load in the Waingaehe is predicted to decrease fairly quickly following a reduction in nitrogen export, despite its aquifer having a very long MRT.

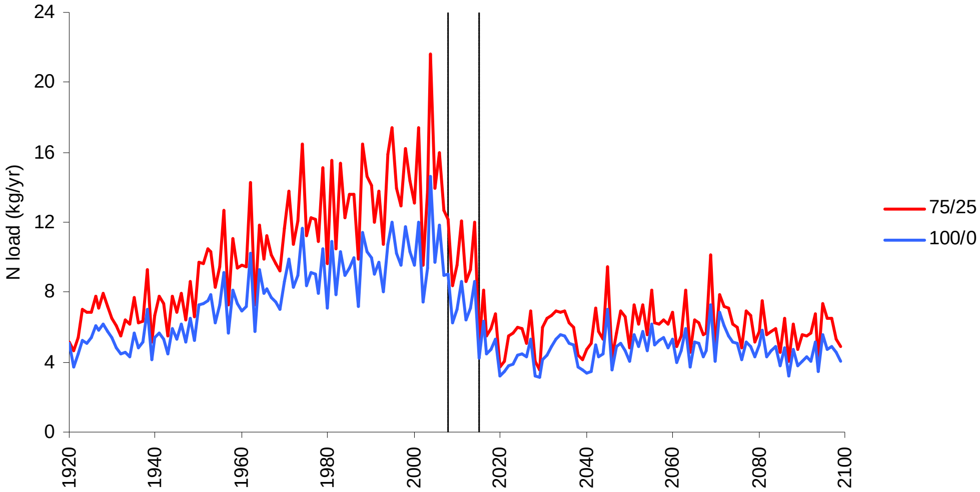


Figure 34: ROTAN-1 Scenario R-350. Predicted annual average total nitrogen load in the Waingaehe Stream assuming: (a) 75% of nitrogen is generated in soil layer 1 and 25% in the quickflow aquifer (75/25) and (b) 100% of nitrogen is generated in soil layer 1 (100/0).

This finding seems counter-intuitive. One might expect catchments with short MRTs to respond to land use change more quickly than catchments with long MRTs. The reasons stream nitrogen load in the Waingaehe is predicted to decrease quickly following land use change include:

Only some of the nitrogen export drains into the deep aquifer to subsequently emerge as springflow. In the ROTAN-1 simulations, 47% of the nitrogen export enters the stream via quickflow or slowflow, while 53% drains to the deep aquifer. Nitrogen that drains into the quickflow and slowflow aquifers reaches the stream within months-years and, therefore, aquifer N concentrations respond quickly to land use change. Thus, in these simulations, about half the nitrogen export responds quickly to land use change.

The other half of the nitrogen export enters the deep aquifer, and responds to land use change more slowly. In the Waingaehe, by 2015 nitrogen concentrations in the deep aquifer have not yet fully responded to the intensive land use of the 1970-2000s. Figure 33 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, discussed above, is that the volume of the deep aquifer in the Waingaehe is very large, and the model assumes the aquifer is completely mixed. The assumption of well-mixed aquifers is commonly made (e.g., Morgenstern et al. 2005). If this assumption is not valid then response times may be longer than predicted.

Consequently, in the Waingaehe Stream in 2015:

- Land use changes reduce exports close to pre-development levels.

- Quickflow and slowflow loads decrease quickly after 2015 to pre-development levels.

- Springflow load hardly changes but springflow load is only slightly higher than it was pre-development.

- Total load decreases quickly soon after 2015 and by 2030-2040 is close to pre-development levels.

By comparison, in the Ngongotaha Stream:

By 2015 nitrogen concentrations in the deep aquifer have increased significantly as a result of land use intensification. 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.

In 2015 when land use changes:

- Quickflow and slowflow loads decrease quickly after 2015 to pre-development levels.

- Springflow load decreases over about 32 years (twice the MRT of 16 years).

- 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.

- Springflow load takes about 32 years to decrease from close to the steady state value for current intensive land use to the steady state for the new land use.

- Consequently, the total load (47% quickflow/slowflow + 53% 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)[11]. However, in the Ngongotaha, springflow concentrations reach a true steady state after about 32 years for constant nitrogen exports – twice the MRT of 16 years. In the Waingaehe, it would take about 254 years (twice the MRT of 127 years) for springflow concentrations to reach a true

[11] Note that these simulations neglect 'soil lags' which are of the order 10 years.

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 catchment or lake load.

The finding that catchments with short and long MRTs have a similar response time is partly dependent on the assumption that groundwater is well-mixed, and partly on the assumed proportions of nitrogen reaching the lake via deep and shallow groundwater. The assumption of well-mixed aquifers is commonly made (e.g., Morgenstern et al. 2005). If this assumption is not valid then response times may be longer than predicted.

5.6.3 Size of the surface and groundwater catchments

The Hamurana Stream is the largest lake inflow (mean flow 2.7 m3/s), but has only a very small surface catchment (Figure 1). The Hamurana Springs are fed by aquifers that lie to the north-west and north-east (White et al. 2007, Morgenstern and Gordon 2006). Because its surface catchment is very small, ROTAN-0[12] predicts that the quickflow and slowflow nitrogen loads in the Hamurana are small compared with the springflow nitrogen load (Figure 35, top). Nitrogen infiltrates into the aquifers underlying the Mamaku, Hiwiroa, Hauraki and Kaharoa surface catchments (Figure 1) and then makes its way to the Hamurana Springs.

The Awahou Stream is adjacent to the Hamurana and is also groundwater dominated. However, in the Awahou the surface catchment contributes a larger proportion of the total nitrogen than does the surface catchment in the Hamurana (Figure 35, bottom). In 2015 predicted springflow and quickflow loads in the Awahou are 55 and 20 tN/yr respectively (ratio 2.75), whereas in the Hamurana they are 50 and 5 tN/yr (ratio 10). In these simulations, the MRT of the Hamurana and Awahou are 40-60 and 20-30 years respectively. Consequently, springflow concentrations increase more slowly from 1920-2015, and decrease more slowly from 2015-2100, in the Hamurana than in the Awahou. Quickflow and slowflow respond quickly in both the Hamurana and the Awahou to the land use change that occurs in 2015. The Hamurana does not reach a new steady state within the period of these simulations. However, the Hamurana is unusual in having such a small surface catchment and being dominated by groundwater from aquifers with long lag times. The total load responds more quickly in the Awahou than in the Hamurana for two reasons (Figure 36). Firstly, the MRT of the aquifer is lower in the Awahou than the Hamurana. Secondly, the proportion of quickflow and slowflow is higher in the Awahou than the Hamurana.

[12] ROTAN-0 has MRTs in the Hamurana and Awahou Streams shorter than ROTAN-1. However, these simulations are sufficiently accurate to illustrate the behaviour of these catchments.

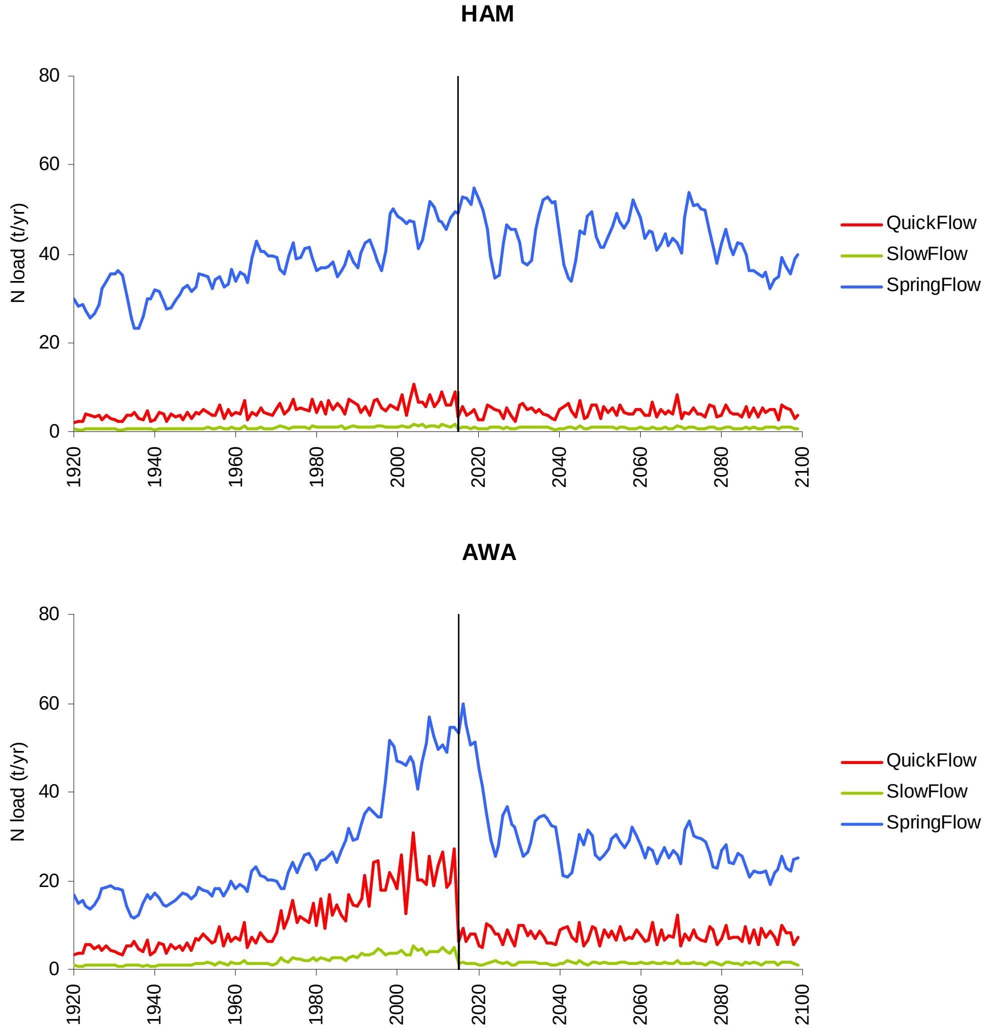


Figure 35: ROTAN-0 Scenario R-350. Predicted annual average nitrogen loads in quickflow, slowflow and springflow in the Hamurana (HAM) and Awahou (AWA) streams.

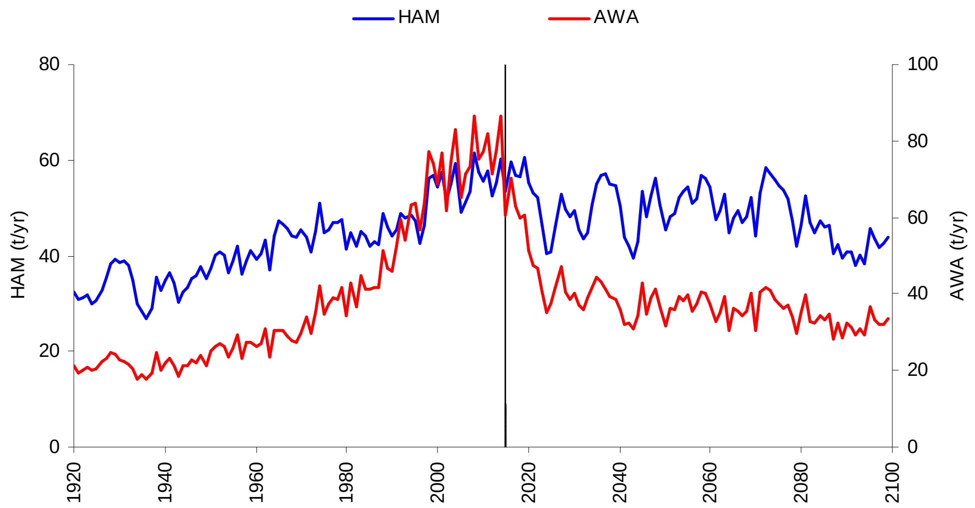


Figure 36: ROTAN-0 Scenario R-350. Predicted annual average total nitrogen load in the Hamurana (HAM) and Awahou (AWA) streams.

6. ROTAN-2

6.1 Calibration

The models ROTAN-2 to ROTAN-9 were developed to assess the sensitivity of model predictions to uncertainties in key model coefficients and input data.

In ROTAN-2 to ROTAN-9, large catchments contain a single, well-mixed aquifer (see Figure 3), whereas in ROTAN-1 large catchments contain several well-mixed aquifers, connected in series and/or parallel (see Figure 2).

ROTAN-2 differs from ROTAN-1 in that:

- 80% of infiltration enters deep groundwater (rather than 70%).
- 80% of nitrogen enters deep groundwater (rather than 53%).
- 20% of infiltration enters shallow groundwater (rather than 30%).
- 20% of nitrogen enters shallow groundwater (rather than 47%).

In other respects ROTAN-2 and ROTAN-1 are identical. Notably:

- MRTs for nitrogen match published values for tritium (see Table 7).
- There is less pasture in the 1920-1940s than in ROTAN-0.
- Nitrogen exports are higher than in ROTAN-0.
- There is a pulse of nitrogen during land development in the 1940-1970s that is not included in ROTAN-0.

Soil lags are not included in the ROTAN-2 to ROTAN-9 models.

6.2 Results

Appendix 4 compares observed and predicted stream flow, TN concentration DIN concentrations. Tables 14 summarises the goodness of fit of the model. Figure 37 compares observed and predicted total lake loads.

The water balance for the lake is good but ROTAN-2 predicts a smaller week-to-week variability in lake outflow than what is observed. Mean predicted and observed flows in the major inflows do not match as well as in ROTAN-1, notably in the Waiowhiro (see Table 15). However, internal aquifer boundaries in ROTAN-2 to ROTAN-9 were not 'fine-tuned' to achieve water balances for individual streams.

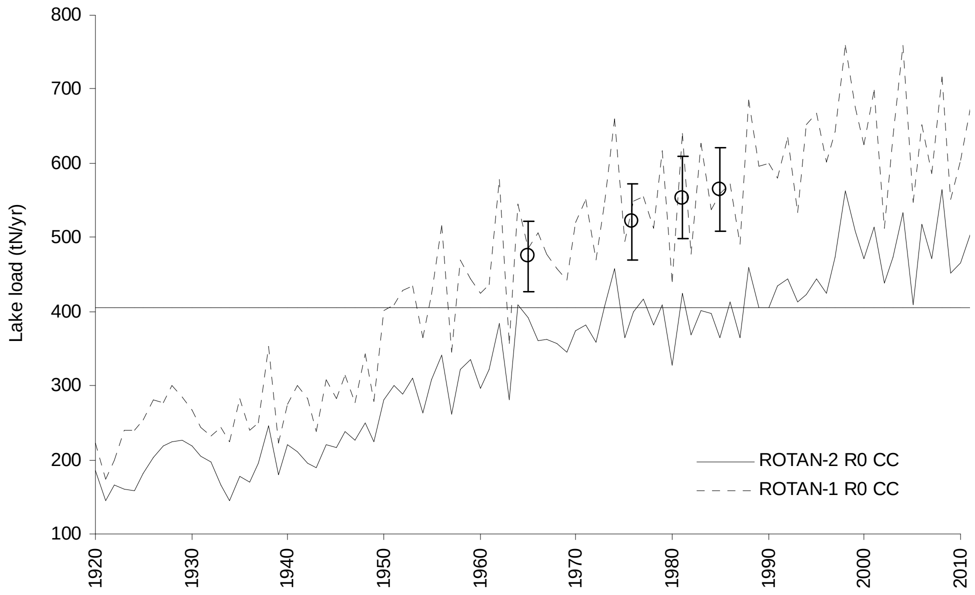


Figure 37: Annual lake loads predicted using ROTAN-2 (solid line) and ROTAN-1 (dashed line). Also shown (circles) are published estimates of historic lake load. The horizontal line is the target load. Soil lags are not modelled.

ROTAN-2 predictions differ in two important respects from ROTAN-1.

- Predicted lake loads under-estimate published load estimates (Figure 37).

- Predicted week-to-week variabilities of flow and concentration in most streams are smaller than those predicted in ROTAN-1 and are smaller than what are observed (Tables 14 and Appendix 4).

The reason for these differences is that a higher proportion of the nitrogen export is routed through the deep groundwater in ROTAN-2 (80%) than in ROTAN-1 (53%). Consequently, in ROTAN-2 a higher proportion of the nitrogen yield experiences a 'groundwater lag' and the lake load takes longer to respond to land use changes.

This may seem strange given that the MRTs in ROTAN-1 and ROTAN-2 are similar, and both match published tritium MRTs (see Table 7). However, in ROTAN-1 a larger proportion (47%) of the nitrogen export is routed through the shallow aquifers with MRTs of weeks-months than in ROTAN-2 (20%). It is not just the mean residence time that determines lake load response time, but the shape of the unit response function[13] (URF).

Week-to-week variability is smaller than observed in most streams. This is because only 20% of infiltration is routed through the shallow aquifers. Variability is high in a few streams (notably Waiteti and Waingaehe). This is because these catchments are predominantly pasture and in ROTAN pasture functional units[14] (FUs) (viz., Dairy, DryStock, Lifestyle, SepticTanks etc.) respond quickly to rainfall. By comparison forest FUs respond quite slowly.

6.3 Discussion

ROTAN-2 consistently under-estimates week-to-week flow variability (viz., over-estimates baseflows and under-estimates stormflows). We conclude, therefore, that the proportion of infiltration entering deep groundwater is less than 80% – the figure assumed in ROTAN-2. Note that the proportions of infiltration entering deep and shallow groundwater do not affect the long-term water balance (viz., annual mean flows still match observations) – only the week-to-week variability in stream flows do not match.

ROTAN-2 under-estimates published estimates of total lake load in the 1960s-1980s, and under-estimates observed concentrations in several major streams. Possible reasons for this are:

- Initial concentrations in the deep aquifers are under-estimated.
- Historic nitrogen exports are under-estimated.
- Land use intensification occurred earlier than the 1940s.
- Too much water and nitrogen is routed into deep groundwater.

The initial concentration in all ROTAN simulations is assumed to be 0.4 g/m3. This is an estimated concentration, assuming a pre-development export of 4 kgN/ha/yr (a ‘typical’ value for forest) and an average infiltration of 1000 mm/year. Morgenstern et al. (2005) estimate a lower initial concentration of 0.14 g/m3 based on observed concentrations in ‘old’ groundwater.

[13] The URF is the distribution over time of lake loads (viz., lake loads (tN/yr) in Years 0, 1, 2, 3...∞) that arise from the export of one unit of nitrogen (e.g., 1 tN) in Year 0.
[14] Functional units are described in detail by Rutherford et al. (2009).

Anecdotal evidence suggests that parts of the catchment were first cleared of native bush in the 1920s and allowed to revert to scrub during the depression (Alastair MacCormack, BoPRC, *pers. comm.*). If so, the initial clearance may have released a pulse of nitrogen into the deep aquifers and 'initial' concentrations in 1920 may have been higher than the 0.4 g/m3 value used in ROTAN. Agricultural statistics do not indicate that large areas were cleared for pasture in the 1920s and in our opinion there is insufficient evidence to support modelling significant land use changes, or a significant increase in nitrogen exports, earlier than the 1940s.

It would be necessary to increase yields by 20-50% in the 1920s-1930s to match the observed loads and this is considered to be unrealistic. However, in ROTAN-8 yields are increased by 10%, in combination with other model coefficient changes, and an improved fit is obtained.

In our opinion the most likely reason ROTAN-2 under-estimates lake loads is that the proportion of nitrogen exports entering deep groundwater is less than 80%.

6.4 Predictions

Notwithstanding the short-comings outlined above, ROTAN-2 was used to model scenario R-350 (Figure 38). An interesting feature of these predictions is that there is very little change in lake load in 2015 when nitrogen exports decrease significantly. The reason is that nitrogen concentrations in deep groundwater are either similar to, or less than, the steady state values for the new land use. Hence, springflow loads do not change much from 2015-2100. The decrease in lake load that does occur in 2015 is the result of the decrease in quickflow load, which is only 20% of the total nitrogen export.

6.5 Conclusions

ROTAN-2 does not match observed lake loads. The most likely reason is that the proportion of nitrogen exports entering deep groundwater is less than 80%. We conclude that ROTAN-2 is not suitable for making predictions about the effects of land use change on load reductions and response times. However, the behaviour of the model helps interpret results from other ROTAN runs. It shows that model predictions are sensitive to the coefficients controlling the proportions of infiltration (water) and export (nitrogen) routed through the shallow and deep aquifers.

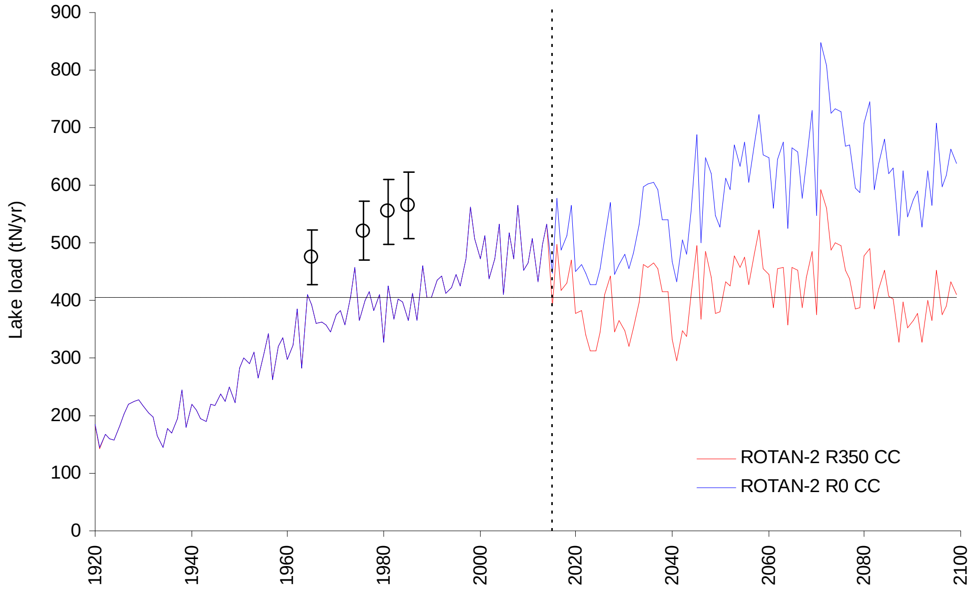


Figure 38: ROTAN-2. Predicted lake loads for the current land use (R-0) and one scenario of land use change (R-350). Also shown is the target load (horizontal line) and published estimates of lake load (circles). Simulations assume climate change (CC). Land use change is assumed to occur in 2015 (vertical line). Soil lags are not modelled.

Table 14: ROTAN-2: Observed and predicted mean flow and nitrogen concentration.

	Mean observed	Mean predicted	RMS error	N	Comment
Stream		**Flow (L/s)**			
Hamurana	2646	2479	359	244	
Awahou	1609	1829	312	405	
Waiteti	1176	1739	646	513	Low variability
Ngongotaha	1761	1947	594	1820	Low variability
Waiowhiro	334	793	481	371	High mean
Utuhina	1943	1961	562	1628	Low variability
Puarenga	1772	1343	640	1336	Low variability
Waingaehe	234	293	91	739	
Waiohewa	334	399	117	452	
Ohau Channel	17694	17574	3275	2981	Low variability
	Mean observed	**Mean predicted**	**RMS error**	**Mean observed**	**Comment**
Stream		**Concentration (gTN/m3)**			
Hamurana	0.764	0.760	0.259	94	
Awahou	1.275	1.118	0.370	209	Low mean 1970s, 1990s
Waiteti	1.380	1.374	0.512	97	
Ngongotaha	1.008	1.133	0.368	276	Low variability
Waiowhiro	1.132	1.170	0.458	122	Low variability
Utuhina	0.950	0.873	0.333	149	Low variability, Low mean 1970s, 1990s
Puarenga	1.163	2.192	1.258	215	High mean
Waingaehe	1.605	1.532	1.000	121	Low variability
Waiohewa	3.645	2.551	1.937	119	Low variability

7. ROTAN-3

7.1 Calibration

The key features of ROTAN-3 compared with ROTAN-2 are:

- 70% of infiltration enters deep groundwater (rather than 80%).
- 53% of nitrogen enters deep groundwater (rather than 80%).
- 30% of infiltration enters shallow groundwater (rather than 20%).
- 47% of nitrogen enters shallow groundwater (rather than 20%).

In other respects, ROTAN-3 and ROTAN-2 are identical.

7.2 Results

Appendix 5 compares observed and predicted stream flow, total nitrogen concentration (TN) and dissolved inorganic nitrogen concentration (DIN). Table 15 summarises the model fit. Figure 39 compares observed and predicted total lake loads.

Predicted and observed mean flows in the Ohau Channel match closely (Table 15), indicating a good water balance for the catchment as a whole. Predicted week-to-week variability in Ohau Channel flow is higher than in ROTAN-2 and better matches observed variability (Appendix 5). The water balances for individual streams are not as good as in ROTAN-1. However, as for ROTAN-2, internal aquifer boundaries were not 'fine-tuned' to achieve water balances for individual streams. Short-term flow variability is higher than in ROTAN-2, but is still lower than observed in three of the nine major streams (see Table 15).

Predicted mean concentrations match observations well in five of the nine major streams (Appendix 5, Table 15). However, in the Awahou, predicted concentrations are smaller than observed TN concentrations in the 1970s and 1990s, while in the Puarenga, Waiteti and Waingaehe predicted concentrations consistently exceed observations. Short-term variability in concentration is higher than in ROTAN-2 and matches observed variability in most catchments (Appendix 5, Table 15). However, predicted variability is higher in the Waiteti, and lower in the Waiowhiro, than is actually observed.

ROTAN-3 predicts annual lake loads that match published estimates fairly well, and are similar to ROTAN-1 loads (Figure 39).

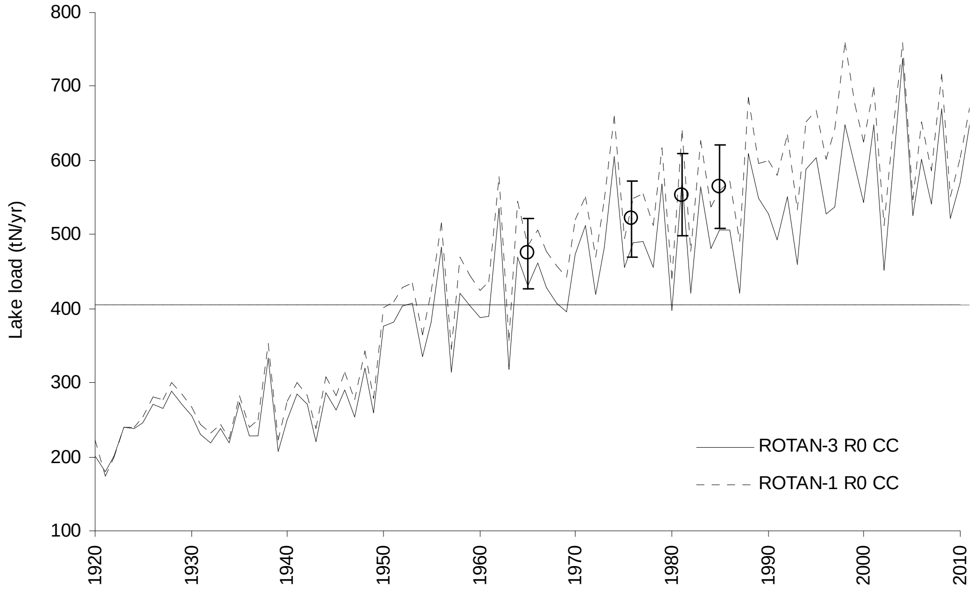


Figure 39: Annual lake loads predicted using ROTAN-3 (solid line) and ROTAN-1 (dashed line). Also shown (circles) are published estimates of lake load. The horizontal line is the target load. Soil lags are not modelled.

7.3 Discussion

ROTAN-3 provides a moderately good fit to observed flows, concentrations and lake loads – similar to ROTAN-1.

However, concentration mismatches remain in the Puarenga and the Awahou, and to a lesser degree in the Waiteti and Waingaehe. As discussed in Section 4.3, an improved match to concentrations in the Puarenga could be achieved by reducing the yields from DryStock and Dairy in that catchment, as was done for Forest.

In the Awahou, ROTAN-3 predicts an increase in concentrations from 1920-2010 but predictions lag observations by 20-30 years (see Appendix 5). There are four possible reasons for this mismatch:

Nitrogen exports may be higher than specified.

There is uncertainty about historic nitrogen exports. However, in other parts of the catchment, the rates estimated from historic stocking rates using Overseer® give a good match between observed and predicted stream nitrogen concentrations. Were nitrogen export rates to be increased across the whole catchment to match concentrations observed in the Awahou, this would result in concentrations being over-estimated in most other catchments.

The initial concentration may be higher than specified.

Because of the long groundwater lag time in the Awahou (61 years), the initial concentration specified in 1920 affects predictions until at least the 1980s. If the concentration in 1920 were set at say 0.75 g/m3, then predicted concentrations in the 1970s and 1990s would increase and better match observations. In the 2000s, predicted concentrations would remain similar because they are less affected by the initial concentration. A higher initial groundwater nitrogen concentration would be justified if, within the Awahou catchment, there was: intensive agriculture in the early 1900s, a high population density (viz., septic tanks) in the early 1900s, and/or a source of geothermal nitrogen. There is no recorded geothermal activity in the Awahou catchment. Population density is known from census statistics. Historic land use is discussed below.

Land use changes may have occurred earlier than specified.

A higher initial concentration in the Awahou aquifer would be justified if there was more intensive agriculture within the Awahou catchment in the early 1900s than is currently modelled. The first reliable land use map is available for 1958. It shows some dairying in the catchment, but it is not clear when this commenced. It is desirable to seek earlier land use or land cover data (e.g., from the 1940 aerial photographic survey of New Zealand).

The MRT of deep groundwater may be shorter than specified.

The MRTs reported by Morgenstern et al. (2005) quantify the average residence time of ‘bomb tritium’ in historic rainfall. There are three potential problems with using tritium to estimate the MRT of nitrogen.

First, nitrogen and tritium may follow different flow pathways. Nitrate plus nitrite (NNN) is highly mobile in the soil and, once generated, follows a similar flow pathway to tritium. Ammoniacal-N (NH4N) is less mobile than nitrate in the soil, and generally does not leach into groundwater at a high rate. However, NH4N can be oxidised to NNN which then gets mobilised. The majority of NNN makes its way to the lake by the same pathways as tritium, so that the MRTs estimated by Morgenstern et al. (2005) apply to NNN. Dissolved organic matter (DON) occurs in stream samples. Very little is known about the rates at which DON is leached from pasture, its bioavailability, and hence its impact on streams and lakes. Particulate organic nitrogen (PON) finds its way into streams and the lake through surface processes (erosion and overland flow). PON travels by different pathways and probably reaches the lake without experiencing ‘groundwater lags’. Neither DON nor PON is included in the nitrogen yields estimated by Overseer®. DON and/or PON exports could be included in ROTAN by increasing Overseer® yields. Soluble DON could be made to follow the same pathway as NNN by specifying its generation in the soil layer. Particulate PON could be made to follow a different pathway by specifying its generation in the quickflow or slowflow aquifers.

Second, the spatial distributions of rainfall and nitrogen export are not co-incident. Rainfall is not distributed uniformly within the Awahou catchment – there is a strong gradient with higher rainfall on the Mamaku Plateau at the head of the catchment than near the lake in the lower parts of the catchment. Prior to the 1960s, agriculture appears to have been concentrated in the lower parts of the Awahou catchment, but from the 1970s onwards, dairying has expanded into the middle and upper parts of the catchment. It is conceivable that much of the historic nitrogen generation occurred close to the Awahou Springs and the lake, rather than being distributed uniformly across the catchment. If so, then the MRT for nitrogen may be lower than the MRT of tritium in rainfall.

Third, there is evidence of localised ‘connections’ or ‘short circuits’ between parts of the land surface and streams or springs. For example, Pang et al. (1996) report evidence of high nitrate concentrations in certain bores, thought to have occurred because of such ‘connections’ to contaminated sites (e.g., offal holes, septic tanks, dairy shed disposal areas etc.). Such small-scale ‘connections’ are not currently modelled within ROTAN which assumes one or more fully-mixed aquifers.

7.4 Predictions

ROTAN-3 predicts a rapid decrease in lake load following land use changes in 2015 (Figure 40). The reasons for this are discussed in detail in connection with ROTAN-1 (see Section 5.2) and are not repeated here.

7.5 Conclusions

ROTAN-3 gives very similar predictions to ROTAN-1. Both assume that similar proportions of infiltration (water) and export (nitrogen) are routed to the lake via deep aquifers, and both have MRTs that match published values. The main difference between the two models is that ROTAN-3 assumes a single well-mixed aquifer in each catchment, whereas ROTAN-1 assumes two or more separate aquifers connected in series and/or parallel. The internal aquifer boundaries in ROTAN-3 have not been ‘fine-tuned’ to achieve a water balance in each of the nine major streams, but this does not adversely affect the water balance for the lake (which is excellent) or alter the total lake load significantly (although it might have a second-order effect on response time).

These simulations indicate that similar response times are predicted assuming a single well-mixed aquifer in each large catchment (as in ROTAN-3) or assuming several, smaller connected aquifers (as in ROTAN-1).

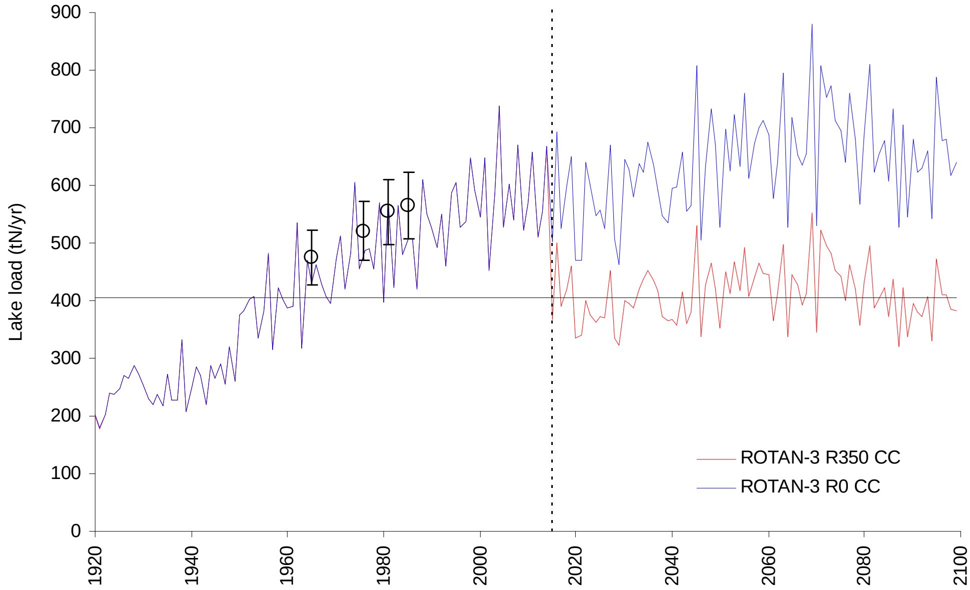


Figure 40: ROTAN-3. Predicted lake loads for the current land use (R-0) and one scenario of land use change (R-350). ROTAN-4 predictions. Soil lags are not modelled.

Table 15: ROTAN-3: Observed and predicted mean flow and nitrogen concentration.

	Mean observed	Mean predicted	RMS error	N	Comment
Stream		**Flow (L/s)**			
Hamurana	2646	2195	539	244	Low mean
Awahou	1609	1641	203	405	
Waiteti	1176	1796	724	513	
Ngongotaha	1761	1965	559	1820	Low variability
Waiowhiro	334	722	409	371	High mean
Utuhina	1943	1980	492	1628	Low variability
Puarenga	1772	1387	577	1336	Low variability
Waingaehe	234	290	96	739	
Waiohewa	334	394	107	452	
Ohau Channel	17694	17356	3112	2981	
	Mean obs conc g/m3	**Mean prd conc g/m3**	**RMS g/m3**	**N**	**Comment**
Hamurana	0.764	0.714	0.256	94	
Awahou	1.275	1.084	0.428	111	Low 1970s-1990s
Waiteti	1.380	2.301	1.720	97	High variability, high mean
Ngongotaha	1.008	1.352	0.753	276	
Waiowhiro	1.132	1.095	0.469	122	Low variability
Utuhina	0.950	1.062	0.485	149	
Puarenga	1.163	2.935	2.363	215	High mean
Waingaehe	1.605	2.760	2.679	121	High mean
Waiohewa	3.645	3.273	1.957	119	

8. ROTAN-4

8.1 Calibration

The key features of ROTAN-4 which differ from ROTAN-3 are:

- 35% of nitrogen enters deep groundwater (rather than 53%).
- 65% of nitrogen enters shallow groundwater (rather than 47%).

In other respects ROTAN-3 and ROTAN-4 are identical. There are no differences in predicted flow.

8.2 Predictions

Appendix 6 compares observed and predicted total nitrogen concentration (TN) and dissolved inorganic nitrogen concentration (DIN). Flows are unchanged from ROTAN-3. Table 16 summarises the model fit for concentration. Figure 41 compares observed and predicted total lake loads.

The week-to-week variability in concentration is higher than in ROTAN-3 because a higher proportion of the total nitrogen export is routed through the shallow aquifers in ROTAN-4 (65%) than in ROTAN-3 (53%). This has two consequences.

First, baseflow concentrations are consistently under-estimated in ROTAN-4 (see Appendix 6 and Table 16). Emerging springflow makes a significant contribution to baseflow. Groundwater concentrations are lower in ROTAN-4 because a smaller proportion of the total nitrogen export (35%) but the same proportion of total infiltration (70%) is routed into the deep aquifers – resulting in lower groundwater concentrations.

Second, response time to land use changes are shorter than in ROTAN-3. This is because a higher proportion of the total nitrogen export is routed to the lake through shallow aquifers which have response times of weeks-months. As a result, predicted concentrations exceed observations in several streams with intensive land use (Table 16).

Annual lake loads are higher than in ROTAN-3 and better match published estimates (Figure 41). This is largely the result of the decrease in response times. Farming intensity and nitrogen exports increased during the 1940s-1970s and the shorter response times resulted in a faster increases in lake load than in ROTAN-3 and hence a better fit to historic loads.

ROTAN-4 gives annual lake loads that match observations more closely than ROTAN-3. However, this does not guarantee that it will provide more accurate predictions. ROTAN-4 predicts a very rapid reduction in lake load following land use changes and export reductions in 2015 (Figure 42). The load target of 405 tN/yr appears to be achieved by 2020 (viz., within c. 5 years).

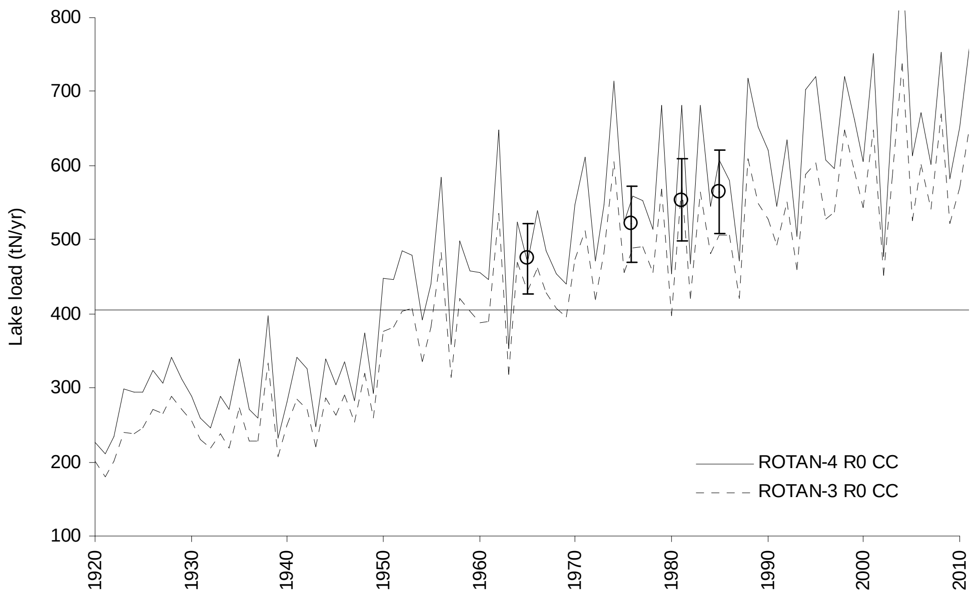


Figure 41: Annual lake loads predicted using ROTAN-4 (solid line) and ROTAN-3 (dashed line). Also shown (circles) are published estimates of lake load. The horizontal line is the target load. Soil lags are not modelled.

8.3 Conclusions

The fact that ROTAN-4 consistently under-estimates baseflow concentrations indicates that it under-estimates the amount of nitrogen finding its way to the lake via the deep aquifers. Were ROTAN-4 used to predict the effects of land use change, it is likely to under-estimate the response time. We conclude from these simulations that a higher proportion of the total nitrogen export enters deep groundwater than the value of 35% used in ROTAN-4.

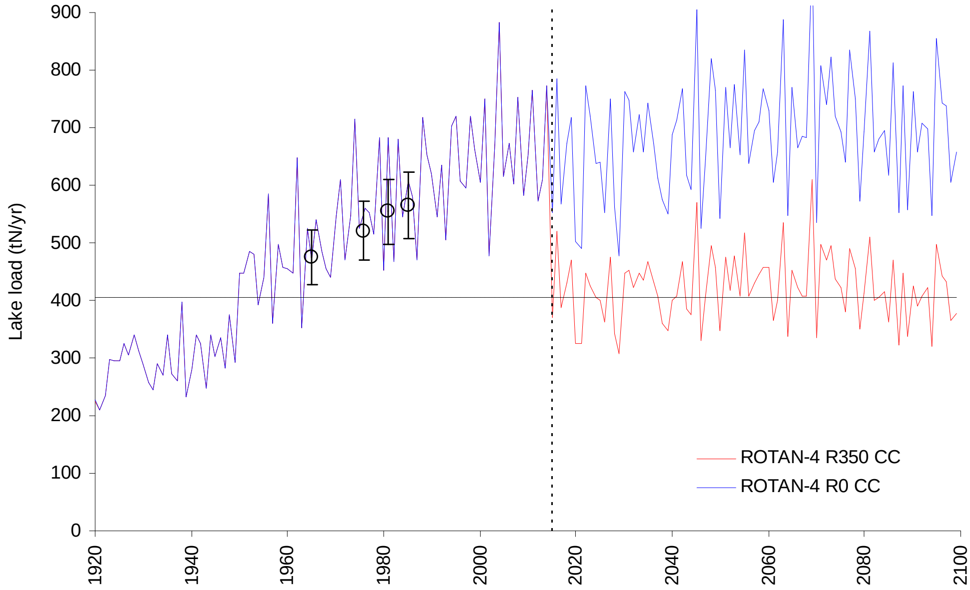


Figure 42: ROTAN-4. Predicted lake loads for the current land use (R-0) and one scenario of land use change (R-350). Soil lags are not modelled.

Table 16: ROTAN-4: Observed and predicted mean TN concentrations.

	Mean obs	Mean prd	RMS error	N	Comment
Stream		**Concentration (gTN/m3)**			
Hamurana	0.764	0.667	0.282	94	Low baseflow
Awahou	1.275	1.035	0.515	111	Low baseflow, low mean
Waiteti	1.380	2.930	2.590	97	High variability, high mean
Ngongotaha	1.008	1.513	1.060	276	
Waiowhiro	1.132	1.014	0.529	122	Low baseflow
Utuhina	0.950	1.212	0.691	149	Low baseflow
Puarenga	1.163	3.507	3.181	215	High variability, high mean
Waingaehe	1.605	3.567	3.953	121	
Waiohewa	3.645	3.774	2.561	119	Low baseflow

9. ROTAN-8

9.1 Predictions

ROTAN-8 is identical to ROTAN-3 except that all nitrogen exports are increased by 10% in all years. This simulation explores whether under-estimation of historic yields could explain mismatches to historic lake loads and stream concentrations.

Appendix 7 compares observed and predicted total nitrogen concentration (TN) and dissolved inorganic nitrogen concentration (DIN). Flows are unchanged from ROTAN-3. Table 17 summarises the model fit for concentration. Figure 43 compares observed and predicted total lake loads.

Compared with ROTAN-3: (1) annual lake loads are higher which gives a better fit to published loads, (2) predicted mean concentrations match better, and (3) short-term variability matches better in most streams. However, in the Awahou, predicted concentrations still under-estimate observed TN concentrations in the 1970s and 1990s, while in the Puarenga they still over-estimate observations.

ROTAN-8 predicts a very rapid decrease in lake load following land use changes in 2015 (Figure 44). The response time is similar to ROTAN-3 and ROTAN-1 for the reasons discussed earlier.

9.2 Conclusions

Scaling was undertaken because of uncertainties in historic yields. After increasing nitrogen yields by 10% ROTAN-8 gives a good fit to historic lake loads, and to stream concentrations in most streams. Current and future yields do not have the same high uncertainty as historic loads. Consequently, ROTAN-8 and ROTAN-3 will give identical predictions of future load reductions and response times for the same land uses and nitrogen yields. Nevertheless, these simulations show that an improved fit to historic lake load and stream concentrations (in all but the Awahou and Puarenga) can be achieved by increasing historic nitrogen yields to values that remain plausible.

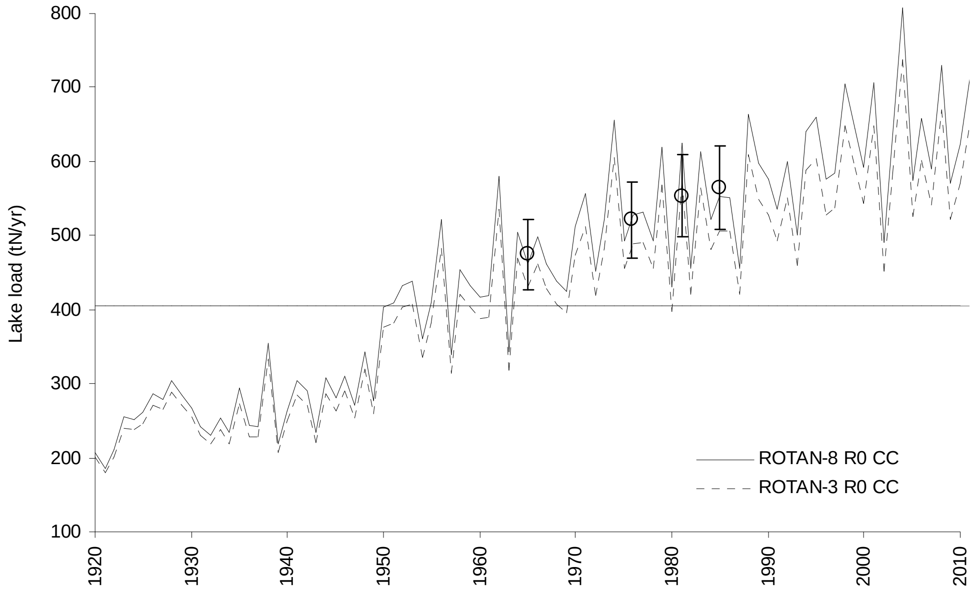


Figure 43: Annual lake loads predicted using ROTAN-8 (solid line) and ROTAN-3 (dashed line). Also shown (circles) are published estimates of lake load. The horizontal line is the target load. Soil lags are not modelled.

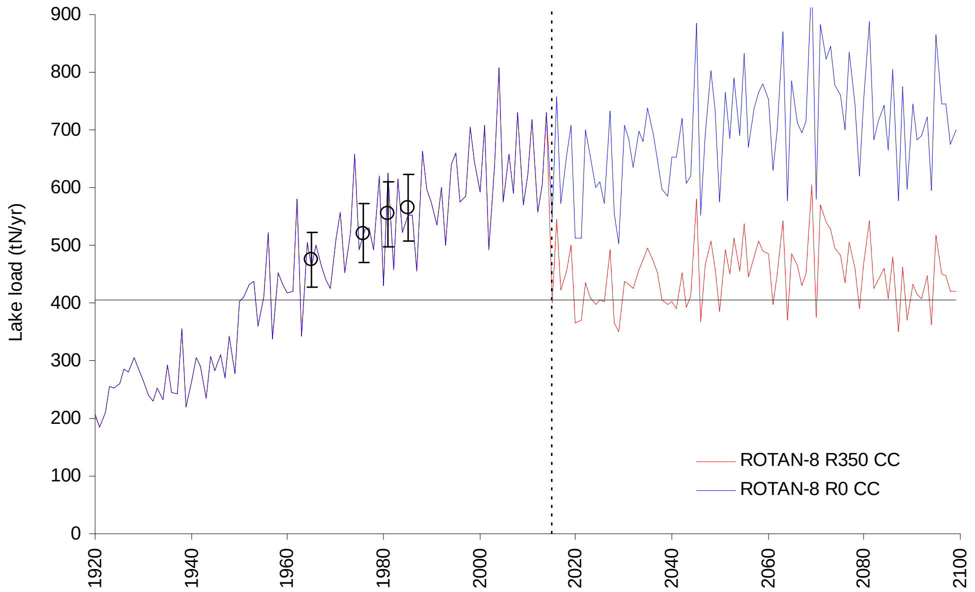


Figure 44: ROTAN-8. Predicted lake loads for the current land use (R-0) and one scenario of land use change (R-350). Soil lags are not modelled.

Table 17: ROTAN-8: Observed and predicted mean TN concentrations.

	Mean obs	Mean prd	RMS error	N	Comment
Stream		**Concentration (gTN/m3)**			
Hamurana	0.764	0.761	0.256	94	
Awahou	1.275	1.173	0.417	111	Low mean
Waiteti	1.380	2.516	1.995	97	High variability
Ngongotaha	1.008	1.484	0.877	276	
Waiowhiro	1.132	1.190	0.496	122	
Utuhina	0.950	1.151	0.594	149	
Puarenga	1.163	3.207	2.667	215	High mean
Waingaehe	1.605	3.004	2.994	121	
Waiohewa	3.645	3.586	2.088	119	

10. ROTAN-9

10.1 Predictions and conclusions

ROTAN-9 is identical to ROTAN-3 except that weekly rainfall and PET in three dry years soon after the land use change (2020-2022) are 'swapped' for rainfall and PET in three wet years (2072-2074). There are no changes to concentrations or lake loads prior to 2015 compared with ROTAN-3.

In 2020-2022 lake loads predicted by ROTAN-3 are lower than those predicted by ROTAN-9 because the former are affected by the below-average rainfall. The converse is true in 2072-2074. In other years, the predicted lake loads are indistinguishable (Figure 45). The effects of a period of low or high rainfall are predicted to be quite transient.

The conclusion from this comparison is that the period of dry weather soon after the land use change in 2015 is not the main cause of the rapid decrease in predicted lake load. Periods of prolonged low or high rainfall do, however, give rise to fluctuations in lake load of the order 100 tN/yr.

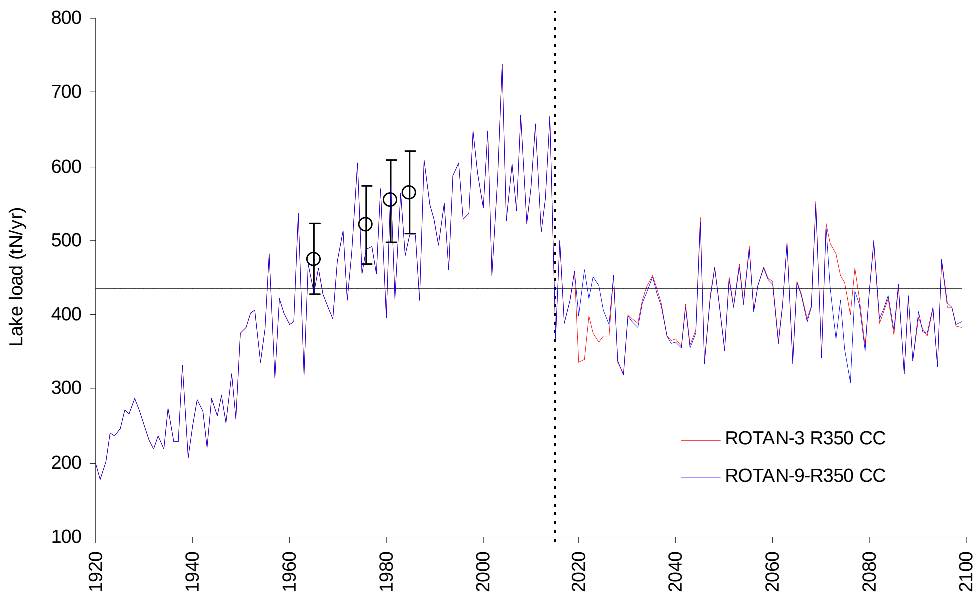


Figure 45: Predicted lake loads assuming 3 dry years (ROTAN-3) and 3 wet years (ROTAN-9) soon after land use change (2020-2022). Also shown is the comparison assuming 3 wet and dry years near steady state (2072-2074). Soil lags are not modelled.

11. Discussion and conclusions

11.1 Soil lags

Currently when modelling land use changes in ROTAN , the nitrogen export rate changes immediately. However, it may 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 (the soil lag). Overseer® is used in ROTAN to estimate nitrogen export rates but it only gives the long-term average export and does not account for soil lags.

Soil lags affect nitrogen exported via shallow aquifers with MRTS of months-years. In these simulations, shallow aquifers carry 47% of the total nitrogen export. The other 53% enters deep groundwater where lags are 16-127 years. In most catchments, groundwater lags are large compared with soil lags although in a few catchments (Ngongotaha) soil lags may be comparable with groundwater lags.

Currently, ROTAN neglects soil lags, which means that simulations furnish a lower bound estimate of the how quickly the lake load responds to land use changes. However, outputs from ROTAN-1 were ‘post processed’ to mimic soil nitrogen stores adjusting to new land uses at a rate of 10% per year. This added 10-20 years to the predicted response time.

Including the effects of soil lags, these simulations indicate that the ‘response time’ of lake load to a step change in land use is of the order 35 years. Here ‘response time’ means that within 35 years the lake load is expected to be within 10-15% of the new total nitrogen export, although it may take up to 100 years for the lake load to fully adjust to the new land use.

No reliable information about soil lags in Rotorua soils exist at present. If such information became available, ROTAN could be modified so that nitrogen exports adjusted over several years after a land use change.

11.2 Land use change

Scenarios R-250, R-300 and R-350 assume that land use changes all occur in 2015 (step change). In practice, land use change is likely to occur progressively over several years or decades. This study did not run scenarios in which land use change occurred over say 10-20 years, although such simulations could be run in the future.

Managers can, however, make rough calculations to estimate the time required for lake load ‘recovery’. If land use were to change over say 15 years, then assuming a response time of 35 years, the lake load would be expected to recover in about 50 years. Here ‘recovery’ means that lake load is expected to be within 10-15% of the new total nitrogen export within about 50 years, although it may take 100 years or more for the lake load to fully adjust to the new land use.

11.3 New land uses

The scenarios consider only a small number of the possible land uses after 2015 (Dairy, DryStock, LifeStyle and Forest). Innovative land uses (e.g., Cut and Carry, Organic Dairy, Tree Crops etc.) are not considered in this report. It is important to note, however, that the scenarios quantify what happens to lake load when total nitrogen exports remain constant or are reduced by 250, 300 and 350 t/yr regardless of how those reductions are achieved. These scenarios enable estimates to be made of:

- export reductions that will be required to meet the lake load target, and
- time delay after the export reductions before the lake load reaches the target.

If land uses other than those modelled are identified as being attractive (e.g., based on economics and nitrogen export), then either estimates of lake load can be made from these simulations, or ROTAN can be re-run to provide more detailed predictions.

11.4 Meeting lake load targets

Figure 20 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. Together with Table 10, this confirms that scenarios R-300 and R-350 ‘bracket’ the lake load target. These simulations indicate that for the catchment export load to match the lake load target of 405 tN/yr, total nitrogen export needs to be reduced from the current value of 725 tN/yr by about 320 tN/yr.

The 405 tN/yr target includes geothermal inputs, septic tanks and sewage. The principal geothermal input is Tikitere (30 tN/yr) and the principal sewage input is drainage from the RLTS (consent limit 30 tN/yr). If the Tikitere nitrogen input were to be reduced (trials are underway) by say 60% (by 20 tN/yr), then reduction by another 300 tN/yr needs to be sought from forests, farmland, septic tanks, and urban runoff.

Note that in Tables 4-5 ‘exports’ are nett of any attenuation. In ROTAN attenuation is only significant in the Puarenga catchment, where it is suspected that wetlands remove or store nitrogen. In the Puarenga catchment, the export from Forest is 50% lower than in the other catchments, and the export from the RLTS is 60% of the applied nitrogen load.

11.5 Response time

ROTAN simulations produce two findings that seem counter-intuitive.

First, when total nitrogen export remains unchanged at its current value (Figure 21), lake load is predicted to increase slowly over the next 70 years, approaching a steady state of 725 tN/yr at about 2070-2080, but does not fully adjust until well after 2100. However, following a step reduction of nitrogen export by 350 tN/yr, lake load is predicted to decrease significantly over a period of about 35 years and approaches a steady state of 375 tN/yr by about 2050 (Figure 22). Thus lake load approaches steady state faster following a step reduction in nitrogen exports than if exports remained constant.

Second, following a step reduction in nitrogen export the stream load leaving a catchment with a short groundwater lag time (Ngongotaha, MRT 16 years) and the stream load leaving a catchment with a long groundwater lag time (Waingaehe, MRT 127 years), both decreases quickly and at a similar rate. Both findings arise from similar mechanisms, which were described in detail, with the aid of simulations in catchments with different aquifer and surface catchment characteristics, in Section 5.

The following concepts are the key to understanding the predicted behaviour.

If the total export is increased and held constant, the predicted lake load will increase gradually and eventually reach a steady state, equal to the total export minus any attenuation. The time it takes for the lake load to reach steady state will depend on the lag times of the shallow and deep aquifers, and the magnitude of the increase in total export.

If the total export is decreased and held constant, the predicted lake load will eventually reach a new steady state equal to the new total export minus any attenuation. If at the time the export is decreased the load is higher than the new steady state, the load will gradually decrease over time. However, if at the time the export is decreased the load is lower than the new steady state, the load will gradually increase over time. The time taken to reach the new steady state depends on: the lag times of the shallow and deep aquifers – as before – and the length of time the export had been at the old level.

In order to reach the lake load target, total nitrogen export nett of any attenuation needs to be reduced to equal the target.

Considering the ROTAN simulations for Lake Rotorua, about half the total nitrogen export enters the shallow groundwater that responds to land use change within months-years in all catchments. The other half enters deep groundwater with lag times of 16-127 years.

In catchments with a short deep groundwater lag time (16 years):

- Deep groundwater nitrogen concentrations increase from 1960-2010 in response to land use intensification and the resulting high nitrogen exports. By 2015, deep groundwater concentrations approach the steady state value for the high nitrogen exports because the groundwater lag time is short.

- In 2015, nitrogen exports drop. It takes about 32 years (twice the lag time of 16 years) for deep groundwater concentrations to approach a new steady state for the lower export rates. During that time the deep groundwater (viz., springflow) load decreases significantly. This accounts for about 50% of the total load.

- The shallow groundwater load decreases very quickly. The sum of the shallow and deep groundwater loads decreases only moderately quickly because of the high initial deep groundwater load.

In catchments with a long deep groundwater lag time (say 127 years):

- Deep groundwater nitrogen concentrations hardly change from 1960-2010 despite land use intensification and high nitrogen exports. This is because it takes about 254 years (twice the lag time of 127 years) for groundwater concentration to reach steady state and land use intensification only commenced in the 1960s.

- In 2015 nitrogen exports drop. However, in 2015 groundwater concentration is not significantly different from pre-development values. Therefore springflow (viz., deep groundwater) load hardly changes.

- The shallow groundwater load decreases very quickly. Hence, the sum of the deep and shallow groundwater loads decreases quite quickly. However, it takes a very long time for the deep groundwater to reach a true steady state.

11.6 Robustness of predicted response time

The ROTAN simulations indicate that if total nitrogen exports are reduced by 320 tN/yr and held constant then the lake load will decrease quite quickly and will approach the target of 405 tN/yr within about 35 years. This is a faster recovery than expected. There is a plausible explanation – discussed earlier – but uncertainty about the response time exists.

The response time of 35 years is a likely lower bound which assumes that:

- On average the proportions of nitrogen export from the land reaching the lake via deep groundwater and near-surface flow are 53% and 47% respectively.

- Deep groundwater is well-mixed.

In ROTAN, the proportions of nitrogen exported from the land reaching the lake via deep groundwater or near-surface flow are spatially uniform. There is evidence that more water infiltrates (and hence more nitrogen enters deep groundwater) in some parts of the catchment than others – some parts of the catchment have little or no permanent stream flow (e.g., Hauraki, or Waiteti headwaters etc.). The relative locations of intensive land use and high infiltration soils may affect the response times. Further modelling work would be required to quantify this effect.

The assumption of well-mixed aquifers is commonly made (e.g., Stewart and Morgenstern 2001). If this assumption is not valid then response times may be longer than predicted by ROTAN. However, ROTAN is calibrated so that the MRTs match published values for tritium (Morgenstern et al. 2005). This ensures that ROTAN matches the 'average' lag time. However, ROTAN may not match the distribution of lag times. The assumption of complete mixing means that when a slug of nitrogen enters the aquifer it immediately mixes and, as a result, outlet concentration increases immediately regardless of where in the catchment the slug entered the groundwater. Concentrations then decreases exponentially over time. In a poorly mixed aquifer, a slug of nitrogen that enters near the outlet may cause outlet concentration to increase almost immediately. However, a slug of nitrogen that enters near the top of the catchment may take a long time to make its way to the outlet. The behaviour of a poorly mixed aquifer may be better captured by a 'streamtube' or 'particle tracking' model, such as the GNS FEFLOW model (Chris Daughney, GNS, pers. comm.).

We note that the published tritium MRTs (Morgenstern et al. 2005) were estimated using the pistonflow-exponential model which assumes well-mixed aquifers, and that the FEFLOW model has been calibrated to match the tritium MRTs. We conclude that the ROTAN assumption of well-mixed aquifers is defensible.

Consequently, the aspects of the current ROTAN simulations that most affect the predicted response time are the proportions of infiltration that enter deep groundwater (53%) and shallow groundwater (47%). In our opinion these proportions (53% and 47%) are defensible estimates of the 'average' proportions – based on the fact that they give a reasonable match to week-to-week variability in flow and concentration. As discussed above, however, these proportions may vary spatially and this may affect the response time. Further modelling work could be done on this topic.

The work done with ROTAN leads us to the conclusion that the lake load is likely to decrease faster than was suggested by other work, using estimates based on published groundwater MRTs. We believe our conclusion is robust even if the estimated response time of 35 years is open to debate.

11.7 Targeting catchments

One might expect catchments with short MRTs to respond to land use change more quickly than catchments with long MRTs. Indeed, discussions about how to achieve a rapid reduction in lake load have tended to assume this will be achieved by focusing mitigation efforts in catchments with short MRTs. However, the simulations presented in this report indicate that this may not be the best strategy.

Before identifying catchments to target for land use change, it is necessary to consider: the lag times of the deep groundwater, as well as: the steady state concentrations in deep groundwater for the historic land use, how close current deep groundwater concentrations are to historic steady state concentrations, and the steady state concentrations in deep groundwater for the proposed new land use.

These four factors determine how quickly land use changes in a given catchment contribute to a reduction in lake load, not just the first factor. These factors are in turn influenced by: the location of aquifer and surface catchment boundaries, the proportion of water infiltration that enters the quickflow, slowflow and deep aquifers, and the proportion of nitrogen export that enters the quickflow, slowflow and deep aquifers.

A closer examination of the results of the existing ROTAN simulations on a catchment by catchment basis, in conjunction with Council staff and stakeholders, could help identify how to achieve the most rapid reduction in lake load. However, it may not be sensible to try and 'optimise' mitigations based solely on achieving the most rapid reduction in lake load. It may be better to focus mitigation measures on land parcels where it is easiest and/or least costly to reduce nitrogen exports regardless of where these lie in the catchment. The simulations done during this study suggest that export reductions in catchments with widely differing characteristics could result in significant lake load reductions within a period of about 35 years.

12. References

Burger, D.F.; Hamilton, D.P.; Hall, J.A.; Ryan, E.F. (2007). Phytoplankton nutrient limitation in a polymictic eutrophic lake: community versus species-specific responses. *Archiv fur Hydrobiologie 169(1)*: 57–68.

Ellis, A.J. ; Mahon, W.A.J. (1977). Chemistry and Geothermal Systems. Academic Press. New York. 392 p.

Environment Bay of Plenty (2007). Proposed Lakes Rotorua & Rotoiti Action Plan written by Environment Bay of Plenty, Rotorua District Council and Te Arawa Lakes Trust. *Environmental Publication 2007/11.*

Environment Bay of Plenty. (2009). Lakes Rotorua & Rotoiti Action Plan written by Environment Bay of Plenty, Rotorua District Council and Te Arawa Lakes Trust. *Environmental Publication 2009/03.*

Grinsted, M.J.; Wilson, A.T. (1978). Nitrate concentrations in groundwater around Lake Rotorua. *NZ Journal of Marine & Freshwater Research 12*: 463–466.

Hoare, R.A. (1980a). Inflows to Lake Rotorua. *Journal of Hydrology NZ 19:* 49–59.

Hoare, R.A. (1980b). The sensitivity to phosphorus and nitrogen of Lake Rotorua, New Zealand. *Progress in Water Technology 12*: 897–904.

Hoare, R.A. (1984). Nitrogen and phosphorus in Rotorua urban streams. *New Zealand Journal of Marine & Freshwater Research 18*: 451–454.

Howard-Williams, C.W.; Rutherford, J.C.; White, E.; McColl, R.H.S.; Vant, W.N. (1986). The significance of phosphorus and nitrogen in the management of Lake Rotorua. NWASCA, Wellington. October 1986.

John, P.; Lock, M.A. (1977). The spatial distribution of groundwater discharge into the littoral zone of a New Zealand lake. *Journal of Hydrology 33*: 391–395.

Jovanovic, N.Z.; Hon, A.; Israel, S.; Le Maitre, D.; Rusinga, F.; Soltau, K.; Tredoux, G.; Fey, M.V.; Rozanov, A.; van der Merwe, N. (2008). Nitrate leaching from soil cleared of alien vegetation. *WRC Report No. 1696/1/08*. Water Research Commission, Cape Town, South Africa.

Mageson, G.N; Wang, H. (2008). Nitrogen leaching from gorse – final report. Scion, Rotorua. February 2008.

Male, C.; Paterson, J.; Magesan, G.N. (2010). Quantification of nitrogen leaching from gorse in the Lake Rotorua catchment. *Bay of Plenty Regional Council. Environmental Publication 2010/03.* ISSN: 1175 9372. March 2010.

Menneer, J.C.; Ledgard, S.F.; Gillingham, A.G. (2004). Land use impacts on nitrogen and phosphorus loss and management options for intervention. *AgResearch Client Report.*

Morgenstern, U.; Gordon, D. (2006). Prediction of Future Nitrogen Loading to Lake Rotorua. *GNS Science Report 2006/10.* Geological & Nuclear Sciences, Lower Hutt.

Morgenstern, U.; Reeves, R.; Daughney, C.; Cameron, S. (2004). Groundwater age, time trends in water chemistry, and future nutrient load in Lake Rotorua and Okareka Area. *Institute of Geological & Nuclear Sciences, Client Report 2004/17.*

Morgenstern, U.; Reeves, R.; Daughney, C.; Cameron, S.; Gordon, D. (2005). Groundwater age and chemistry, and future nutrient loads for selected Rotorua lakes catchments. *GNS Science Report 2005/00.* Geological & Nuclear Sciences, Lower Hutt.

Pang, L.; Close, M.; Sinton, L. (1996). Protection zones of the major water supply springs in the Rotorua district. *ESR Report No. CSC 96/7.* Institute of Environmental Science and Research, Christchurch. 77 p.

Park, S.; Holst, J. (2009). Rotorua District Council Spray Irrigation Compliance Report. *Environment Bay of Plenty Environmental Publication 2009/13.*

Peacock, A.; Tomer, M.D.; Bardsley, E.; Charleson, T. (1998). Water, nitrate and chloride budgets of a wetland receiving land-treated municipal wastewater. Eagleson, K.W. (Ed.). NZ Land Treatment Collective: Proceedings of the Technical Session No. 18.

Rutherford, J.C. (2003). Lake Rotorua Nutrient Load Targets. *NIWA Client Report HAM2003-155.* Hamilton.

Rutherford, J.C. (2008). Nutrient load targets for Lake Rotorua – a revisit. *NIWA Client Report HAM2008-080*. Hamilton. May 2008.

Rutherford, J.C.; Pridmore, R.D.; White, E. (1989). Management of phosphorus and nitrogen inputs to Lake Rotorua, New Zealand. *Journal of Water Resources Planning & Management 115(4)*: 431–439.

Rutherford, J.C.; Nguyen, M.L.; Charleson, T.H. (2000). Nitrogen removal in natural wetlands below the Rotorua Land Treatment System. Proceedings of the New Zealand Water & Wastes Association 42nd Annual Conference, Rotorua 27–29 September 2000.

Rutherford, J.C.; Tait, A.; Palliser, C.C.; Wadhwa, S.; Rucinski, D. (2008). Water balance modelling in the Lake Rotorua catchment. *NIWA Client Report HAM2008-048*. Hamilton.

Rutherford, J.C.; Palliser, C.C.; Wadhwa, S. (2009). Nitrogen exports from the Lake Rotorua catchment – calibration of the ROTAN model. *NIWA Client Report HAM2009-019.* Hamilton.

Stewart, M.K.; Morgenstern, U. (2001). Age and source of groundwater from isotope tracers. *In:* Groundwaters of New Zealand. M.R. Rosen and P.A. White (eds). New Zealand.

White, E.; Law, K.; Payne, G.W.; Pickmere, S. (1977). Nutrient demand and availability among planktonic communities – an attempt to assess nutrient limitation to plant growth in 12 central volcanic plateau lakes. *New Zealand Journal of Marine and Freshwater Research 19*: 49–62.

White, P.A.; Rutherford, J.C. (2009). Groundwater catchment boundaries of Lake Rotorua. *GNS Science report 2009/75LR for Environment Bay of Plenty.*

White, P.A.; Cameron, S.G.; Kilgour, G.; Mroczek, E.; Bignall, G.; Daughney, C.; Reeves, R.R. (2004). Review of groundwater in the Lake Rotorua catchment. *Client Report 2004/130.* August 2004. Geological & Nuclear Sciences, Taupo.

White, P.A.; Zemansky, G.; Kilgour, G.N.; Wall, M.; Hong, T. (2007). Lake Rotorua groundwater and Lake Rotorua nutrients. Phase 3 science programme technical report. *Client Report 2007/220*. September 2007. Geological & Nuclear Sciences, Taupo.

Williamson, R.B.; Cooke, J.G. (1982). Water quality of the Waiohewa Stream, Rotorua. *New Zealand Journal of Marine & Freshwater Research 16*: 327–337.

Williamson, R.B.; Smith, C.M.; Cooper, A.B. (1996). Watershed riparian management and its benefits to a eutrophic lake. *Journal of Water Resources Planning and Management 122:* 24–32.

13. Appendix 1: Review by GNS and responses

Comments on: Prediction of nitrogen loads to Lake Rotorua using the ROTAN model Kit Rutherford et al. NIWA client report Ham2010-134 February 2011

Paul White
Responses by Kit Rutherford & Chris Palliser

Introduction
1.1 Para 2 references White et al. 2004 – should this be White et al. 2007? White 2004 reviews the geology, and is the intended reference.
White et al. 2007 contained a summary of the many springs and spring-fed streams in the Lake Rotorua catchment – is this worth referencing as a development form Pang et al. 1996? Pang is mentioned. I have added reference to White et al. 2007.

1.2 ROTAN is at the catchment scale – I think this is worth mentioning. Done.

Note N species considered in the report (e.g., total? nitrate-nitrogen?) Note added.

Re the ‘two challenges for managers’

- in my opinion the stated challenges ignore direct nutrient export to the lake with groundwater. Our term ‘runoff’ includes both stream and groundwater flow. We have reworded this sentence to separate stream from groundwater flow.

- I presume therefore that ROTAN considers only runoff and does not consider direct nutrient export to the lake with groundwater. Incorrect. ROTAN considers both groundwater and stream flow.

- it is a surprise that ROTAN does not address direct nutrient export to the lake with groundwater as White et al. (2007, their tables 35, 36) estimate significant water and N discharge with direct gw outflow. ROTAN does ‘address’ groundwater water and nitrogen loads to the lake. However, in this report all groundwater generated in sub-catchments adjacent to the lake is assumed to re-emerge as springflow at the lake edge. This assumption has no effect on the total water and nitrogen load entering the lake.

- In the larger catchments (e.g., Ngongotaha), the model assumes small sub-catchments between the flow recorder site and the lake. Infiltration and runoff from these small sub-catchments is assumed to emerge as springflow at the lake edge and flow into the lake as stream flow. It could equally well have been assumed to flow into the lake as ‘groundwater direct’. Either assumption would give the same total water and nitrogen inflow to the lake.

- NIWA notes that the GNS model assumes rainfall recharge of 14.47 m3/s based on their extrapolation of Hoare’s rainfall surface for 1976-1977 assuming 50% of rainfall infiltrates. The approach is sensible and the estimate is plausible. However, there are large uncertainties in estimating catchment-scale rainfall and infiltration, and so in our opinion estimates of recharge should be ascribed an uncertainty of at least 10% and possibly 20-30%. Rutherford et al. 2008 discuss errors in rainfall and AET. We note that White et al. 2009 page 27 give another estimate of recharge – 15.2 m3/s. So from GNS figures, the uncertainty in rainfall recharge is at least 5%.

- White et al. 2009 p22 gives a total streamflow of 12.026 m3/s. On page 75 they state that the model was calibrated to a total streamflow of 11.913 m3/s – for reasons that are not clear to the reader. Hoare (1980a) measured streamflow totalling 13.7 m3/s – higher than either GNS figure. GNS streamflow data are summarised in Table 8 page 23. We note that Table 8 does not use all the available streamflow data. The major sites have flow recorders that operated during 1974-1980, 1990-1995 and 2001-present, if not for longer. GNS seems only to have used published average flows for 1974-1980 plus occasional spot measurements from other periods.

- It is important when doing water balance calculations to attempt to 'normalise' flow and rainfall so that they cover the same period. This is difficult when there are gaps in the time-series. Nevertheless, GNS seems not to have normalised flows and rainfall – which adds to the uncertainty in the water balance.

1) Direct groundwater discharge to Lake Rotorua: approx 3.9 m^3/s.
GNS state (White et al. 2007 Table 35) that there is 3.97 m3/s of water emerging as groundwater direct into the lake. This figure seems to be derived from the GNS groundwater model. GNS notes that this model underestimates stream flow in the Awahou (by 254 L/s 15%) and Ngongotaha (by 734 L/s 27%) catchments (White et al. 2009 Table 26) and overestimates stream flow in the Ngongotaha (217 L/s 13%). Overall, the model underestimates stream flow in the 9 major catchments by 788 L/s (7%). If the model underestimates streamflow, then it presumably compensates by overestimating 'groundwater direct'. Recent GNS modelling may have revised the figure for 'groundwater direct'. We note that Hoare measured total streamflow in 1977 (an average rainfall year) to be 13.7 m3/s. Based on a water balance for the lake, he determined a figure of 2.1 m3/s for the 'missing' or ungauged flow. The 'missing' flow is likely to comprise runoff from the ungauged part of the catchment (viz., land downstream from gauging sites or in ungauged catchments) together with groundwater generated by infiltration within the gauged catchments which by-passes the stream gauging sites (viz., via groundwater flow). Hoare (1980a) estimated that 2.1 m3/s of runoff (either stream or groundwater flow) was plausible based on the area of the ungauged catchment multiplied by the average yield from the gauged catchment. Thus Hoare (1980a) saw no need to invoke a large groundwater flow from the gauged catchment in order to close the water balance. If all the infiltration in the ungauged catchment flowed as groundwater then, based on Hoare's estimates, the 'groundwater direct' could be as large as 2.1 m3/s. This is smaller than the GNS estimate of 3.9 m3/s.

2) Surface water baseflow discharge to Lake Rotorua: 12 m^3/s.
This figure seems plausible for recent years which have been drier than average. We note, however, that Hoare measured total streamflow in 1977 to be 13.7 m3/s and estimated that another 2.1 m3/s of runoff from the ungauged catchment.1977 was an average rainfall year, but it had been preceded by some wet years and springflows may have been higher than in recent years which have been drier than average. For example, Hoare (1980a) reported an average flow in the Hamurana Stream in 1977 of 3,040 L/s whereas the average in recent years has been c. 2,750 L/s – as reported by GNS.

3) Nitrogen discharge to Lake Rotorua with direct groundwater discharge to Lake Rotorua: approx 271 tonnes/year

4) Nitrogen discharge to Lake Rotorua with surface water baseflow: approx 377 tonnes/year

Other estimates include:

Yields (viz., nutrient leaving the land rather than entering the lake)
1. Draft Action Plan page 50 – 783 tN/yr – yields from land, rain and geothermal
2. Rutherford et al. 2001 page 25 – 768 tN/yr in 2003 – yields from land, geothermal, septic tanks and sewage

Discharge to the lake
3. Rutherford et al. 2001 page 42 – 620 tN/yr average 2003-2008 – lake input
4. Draft Action Plan page 51 – 547 tN/yr in 2005 – from streams, lake-side springs and groundwater direct
5. From GNS 3) and 4) above – 648 tN/yr – lake input

So the total load to the lake of 648 tN/yr estimated by GNS is consistent with other estimates. We believe, however, there is considerable uncertainty in what proportions enter in streamflow and groundwater direct.

I note the report does not mention 'complimentarity' with White et al. (2007). The ROTAN model has considered the outside boundary of the lake catchment estimated with White et al. (2007). ROTAN uses the outside boundary provided by GNS in their Phase 7 analysis.

, but I recall ROTAN does not consider proposed White et al. (2007) groundwater catchment boundaries within the Lake Rotorua catchment. Apologies if I am wrong here! You are wrong! Rutherford et al. (2009) used the GNS Phase 7 internal boundaries. Note – the figure you provide below is for the Phase 3 boundaries which GNS subsequently revised.

We used the Phase 7 internal boundaries but were unable to get a satisfactory flow balance at individual streams. Using the Phase 7 internal boundaries as supplied, ROTAN underestimated flow in the Hamurana and Awahou Streams, and overestimated flow in the Waiteti and Ngongotaha Streams. So, working anticlockwise around the lake, we adjusted the internal boundaries until we got enough water in each stream. This mostly affects the Hamurana, Awahou and Waiteti. After that surface and groundwater catchments roughly overlap. Figure 5 (from Rutherford et al. 2009 at page 10, copied below) shows almost exact correspondence to the external boundaries, and a reasonable match in most catchments – except the Hamurana, Awahou and Waiteti.

Omitted for brevity

Figure 5: Comparison of Phase 7 aquifer boundaries estimated by GNS (red) and those used in ROTAN-0 (black). Underlying land use is for 2001. Source: Rutherford et al. 2009.

See Figure 2 where " 'S' denotes where the groundwater emerges as springflow which then joins the stream flow" however groundwater direct to the lake occurs on some catchments on the eastern side of the lake, so groundwater doesn't join stream flow in quite a few of these catchments as streams don't exist. This is a fair comment. We will write some words explaining that, for convenience, we assume all groundwater emerges as springflow. For catchments that adjoin the lake, these springs occur at the lake edge. In reality, the springs may be in the lake bed. However, the catchments where the model is likely to be over-simplistic only contribute a small amount of water and nitrogen. Nevertheless, more detailed modelling may be required further down the track.

So I have an issue with the ability of ROTAN to contribute to linking properties with catchment-scale remediation options. We accept that there is uncertainty about which properties contribute water and nitrogen in streams, groundwater direct and groundwater feed springs – this is mostly an issue for properties that lie near assumed groundwater catchment boundaries. More detailed modelling using the GNS and/or NIWA models may be required in the future to address property issues in particular catchments. However, the main objective of this report is total load to the lake to inform policy.

I have mentioned, at the TAG and to Kit on numerous occasions since White et al. (2007) that the internal catchment boundaries of ROTAN are commonly inconsistent with groundwater catchments developed by White et al. (2007). Yes, we have discussed this issue several times. These comments have fallen on deaf ears! This last statement is incorrect and something of a 'cheap shot'. As explained above, we have only adjusted internal boundaries where we needed to do that to get a good water balance (viz., Hamurana, Awahou, Waiteti and Ngongotaha). The result of the ROTAN catchments not considering some features of groundwater hydrology is that ROTAN catchment-by-catchment calculations of could give an incorrect representation of land use and effects on hydrology. e.g.:

1) Waingaehe Stream catchment gains most flow well before the lake (e.g., '250 L/s point approx 2 km from the lake White et al. 2007, Figure 21). The gw catchment of the inflow is estimated in gw catchment '11' (Figure 1) and Uwe's water date relates to this inflow. I think groundwater direct flow occurs between gw catchment '11' and the lake gw catchment '27' (Figure 1) and therefore land in this area probably doesn't contribute much flow to Waingaehe Stream.

2) ROTAN has all land in the Waingaehe Stream catchment contributing to stream flow, if my understanding is correct. Therefore ROTAN estimates of N in surface flow will significantly overestimate N discharge to Waingaehe Stream and ROTAN N reduction options will significantly overestimate N reductions to the stream. In some catchments (e.g., Waingaehe and Waiohewa) a single aquifer and a single surface catchment are assumed. This is done because: (1) the contribution to the total load from such catchments is fairly small, and (2) we need to reduce the number of aquifers and surface catchments to keep model run times down for 1920-2100 simulations. In the Waingaehe it is conceivable that runoff and infiltration from land 'downstream' from, or 'to one side' of, the recorder site enters the lake directly and is not measured at the recorder. Hence, our assumption could affect model calibration in some of the smaller catchments. It is possible that the calibration of water flow in the Waingaehe and Waiohewa could be improved by sub-dividing the surface and groundwater catchments. There are earlier versions of ROTAN in which the Waingaehe and other catchments are sub-divided into more aquifers and surface catchments than shown in Figures 1 and 2 of this report. These could be used for more detailed modelling in the future if required. However, we do not believe that the simplifications result in major errors in total water or nitrogen load to the lake.

However it looks like the groundwater in the 'Tokorangi' surface catchment (Rutherford et al. 2011, Figure 2) goes to the Lynmore catchment, in agreement with one of the findings of White et al. 2007. Fine.

Also I recall this is the first time (I recall) I have been asked to review a ROTAN report. I recall receiving comments from you on the hydrology and nitrate reports.

Also for introduction I suggest mentioning the components you calculate (Section 4.5.1), with an interpretation of the hydrological feature, e.g.:

- 4 near- surface layers 2 soil layers and 2 near-surface aquifers
- 3 deep aquifers: quickflow = ??; slow flow = ?? spring flow = groundwater flow from deep aquifers??

- this gives some introduction to Section 4. We do direct the reader to our earlier reports which describe the model structure in some detail.

1.2.2 'Mr' Paul White is my correct title. Changed.
There is a report (White and Rutherford 2009) that could be referred to here. Added.
Land uses – use lower case font. Not changed.

2.1 There is also uncertainty surrounding aquifer boundaries. Good point. Comment added.

It seems that ROTAN assumes no uncertainty in aquifer area, i.e., the boundaries in Figure 2 are fixed. Not sure what the point is here.

Does ROTAN consider the urban area with treated sewage? Major changes in the treatment and pathway of treated sewage to the lake have occurred in the past. Yes, these changes are modelled – as explained in the report. Pre-1970s all sewage was to septic tanks, 1970s-1990s – city sewage was to the STP, 1990s onwards – city sewage is to the RLTS. These are all modelled in some detail – see Section 2.13

Figure 2. Rutherford et al. 2011 groundwater catchments (his Figure 2) differ somewhat from Figure 1 (following). We note that Figure 1 below relates to Phase 3 of GNS studies. However, GNS supplied NIWA with Phase 7 aquifer boundaries that are significantly different from Figure 1. NIWA used that Phase 7 boundaries as their starting point, but – as explained above – adjusted some internal boundaries to improve the water balance at individual stream gauging sites.

Figure 1. White et al. 2007, Figure 178. Omitted for the sake of brevity

2.5 and 2.7.2 I see urban/Whaka is covered. Fine.
2.7 Note White et al. 2003 also has a review of geothermal. Added.
2.10. White et al. 2008 (Tables 5.6 and 5.7 following) has measurements of N in rainfall. Not sure how this is relevant to Section 2.10.

2.10, para 2. Residence time: all streams but Awahou and Hamurana match. Correct.
2.10, para 3: a reasonable approach for model calibration. Fine.
It would be good to see a figure comparing N concs for the original with revised. No action.

2.10, para 4. note comments of Chris Daughney via email. Now addressed in the report.

2.10 para 5. Not comment about unique calibration for ROTAN- what does this mean in terms of model predictions. Good question. Now addressed in the text.

A useful statistic may be comparison of: mean residence time (ROTAN); % catchment in intensive land use, e.g., dairy; mean N concs in streams. White at al. 2007 page 59 showed that TN conc in streams were similar regardless of land use. This probably reflects the spatial heterogeneity of land use and the fact that surface catchment and aquifer boundaries do not always coincide. Further work on this type of analysis is unlikely to be productive.

I wonder if some catchments have a similar ROTAN residence time to Awahou and Hamurana but higher N concs in streams. Not sure what point is being made here.

2.11.1 – statistical estimates of the fit would be very useful, rather than an 'eyeball' results. Good point. We fit the hydrology model to annual mean flow based on RMS difference. We considered formal statistical measures of 'goodness of fit' for daily or weekly model predictions. We discussed such measures in Rutherford et al. 2008 and 2009. However, we rejected standard approaches (e.g., RMS error) because we know predictions of daily and weekly rainfall at individual locations are inaccurate. We have not yet identified suitable 'goodness of fit' measures.

- have you looked at the sensitivity to N loading? Another variable (along with residence time) that could explain some of the variability over time. This is a good point. Chris Daughney is of the view that MRT is the most accurate coefficient, and the timing of land use change and the nutrient export rates are the least accurate. I have added discussion of this point to the text.

- fair comment about GNS (Chris Daughney) study

2.11.2 – a fair comparison is to compare gw concentrations in the same 'aquifer' as the ROTAN model. Good.

Some of the gw measurements are in the Huka Formation – a shallow aquifer that probably discharge direct to the lake. I am not sure how to respond to this comment. We compared obs and prd groundwater concentrations in the same catchments. If catchments contain a mix of geology, and geology affects TN concentration, then that is an additional source of uncertainty.

N concs are likely to be higher in shallow groundwater? than in? the deeper aquifer (White et al. 2007, Table 21) and so not representative of spring-fed streams that mainly take water from the deep aquifer. e.g., most Waingaehe groundwater samples are in the zone of direct flow to the lake (White et al. 2007, Figure 104) and so are not so relevant to the ROTAN water flow which I guess relates to the deep aquifer (see notes above). Fine. This supports the statements made on page 58 – further text added.

Future scenarios

3.1. scenario 2: a step change is unlikely in reality as N concs will gradually reduce. We make this point in the report. No action.

- comment on effect of Awahou and Hamurana catchment residence time options and effect of variability of N inflows
- comment on effect of Awahou and Hamurana catchment N inflow from land use and effect of variability of N inflows

Figure 24.
4.1 Re Figure 24 – add another figure with F24 split into major components:
- shallow layers (i.e., soil layer 1, see 4.5.1)?
- deep aquifers

- here we may see the importance of reducing N loading to the near-surface layer (including a soil layer and the quickflow aquifer) v the deep aquifer. i.e., is it the soils that are the cause of the rapid response?

add another figure with F24 split into major components:

- quickflow = near-surface layer aquifer
- slow flow = near-surface layer aquifer
- spring flow = deep aquifer

We have added new Figures 24-25.

- here we may see the importance of reducing N loading to the inflow to the lake via aquifers

Which is most important? Which responds the faster? Why?

Can the N outflow for the whole Lake Rotorua catchment be expressed as two components, not four? Figures 24-25 separate load into 'quick' and 'slow' and reflect on these in following sections

4.3 comment that R-0 means 'capping' of land use intensification

Which is most important? Which responds the faster?
Can the N outflow for the whole Lake Rotorua catchment be expressed as two components, not three? Covered already.

4.4. the decline seems quite rapid compared to the increase (historical data)
- does a step change not represent the record (i.e., gradual increase relating to gradual intensification?) ROTAN simulates the gradual intensification from 1920-2010. The scenarios assume a step change in 2015.

4.5

1. Should this be: 'The fractions of water and nitrogen that enter the lake via quickflow, slow flow and spring flow'? Yes. Changed.

…

3 Should this be: 'The relative size and location of surface and groundwater catchments'? Location has at most a second-order effect. No action.

4.5.1 – some improvements in clarity would be good. You use only four of the layers?
– say this at the start I have reworded this para.

- para 4 How can N be generated in the quickflow aquifer? – needs and explanation. Now explained in the text.

'tolerably good match'? This is quite subjective - best have some stats that show this, I think. Some of the matches (red spots v blue lines) look quite poor to me. See earlier discussion about statistical measures of 'goodness of fit'. There is always room to debate how well a model fits (a) the observed data and (b) the real world.

Would other combinations of…missing text?

- para 5 good.
  - put an 'a' and 'b' against the figure, e.g., one could think that 'soil layer 1 (bottom)' is another unit! Changed text to make it clear.
  - Figure 28 expand with two one more plot (soil v aquifer) – does soil respond faster than aquifers? This would add little to the point being made. The soil layer does not contribute N to the lake, only to the other layers.

- explain why the two aquifers seem to be responding at the same time scale. Comment added.

4.5.2 see my notes about the Waingaehe catchment, earlier. Worth a comment in the ROTAN report. See my responses to these comments.

Figure 31. Likely to be quite wrong as the catchment is wrong e.g., Waingaehe Stream doesn't take all the flow from the Waingaehe catchment (ROTAN figures 1and 2). E.g., dairy land use in the catchment (Figure 10) is mostly over the land area where groundwater goes direct to the lake. I agree that the ROTAN simulations reported probably overestimate flow at the Waingaehe flow recorder because they assume a single catchment. However, they probably estimate the flow to the lake correctly. So the results in Figure 33 are still valid.

4.5.3 I suggest another sub-section 4.5.4 Residence time – compare Hamurana with short (40hrs) and long (Uwe figure) residence times and comment. I think the place to discuss MRT is in the Discussion and Conclusions. However, a note is added.

5.1 para 1 indent text under '1' and '2' so the reader can make the link between assumptions and discussion. Done.
Re discussion under point '2' – why is it impractical to run simulations with soil lags? Because we don't know what these lag times are.
Last sentence. I suggest something like: 'Assumptions 1 and 2 mean that ROTAN calculations provide under-estimates of the timing of lake-load reductions due to land use change. No action.

- discussion on what provides an upper limit? Worth thinking about! Include in final Discussion but not relevant to this section.

I'd suggest a new subsection (between existing 5.3 and 5.4) discussing the importance of soil v the aquifers in reduction in N inflow to the lake. Disagree. I think this topic is well covered already.

5.4 – para 1 – refer back to the new subsection on soil and aquifers and residence time, then reformulate this subsection. I don't see that the suggestion to re-write this section is necessary. Section 11.6 makes the point that '…The ROTAN simulations indicate that if total nitrogen exports were reduced by about 320 tN/yr and held constant at that level then the lake load would decrease quite quickly and would approach the target of 435 tN/yr within about 35 years. This is a faster recovery than expected, but there is a plausible explanation…' The points about soil lags and uncertainty in residence time have been added.

5.5, pg 60.

I would add points:
5. The balance between N flow from soils (a short, but unknown) residence time and N flow in deep groundwater (a longer residence time)
6. Groundwater catchment boundaries including groundwater catchments of streams and groundwater flow directly to the lake.
Added.

7. Water quality indicators for success (e.g., surface monitoring sites that should show the effect of interventions, groundwater monitoring sites that should show the effect of interventions,?lake water quality. While monitoring is important, I don't see its relevance in this section.

I suggest significant revision the last para, and expand

- I'd suggest that that White et al. (2007) can help inform targeting – but you may disagree! I have suggested this quite a few times but it seems to deaf ears.
- State some obvious things:

Are soils the key issue? Key issue for what exactly? My view is that AgResearch or LandCare need to provide input on the response time of soils. There is not time for this to go into our report. It could be a follow up action for BoPRC.

What range do you think in response times? I assume you mean what uncertainty do we put on 35 years. Good point. I have added a rider to this figure where it occurs in the report.

Do you think target catchment with short residence times? Our whole point is that it may not be sensible to target catchments with short MRT. Rather, we consider each catchment on its merits. In practice this may mean that the driver is landowner willingness to act, rather than response time.

Do in–stream processes reduce N. It seems only in the Puarenga. See Rutherford et al. 2009. – so should we focus on direct-gw-to-lake catchments? No.

Do you recommend step changes in land use or will gradual changes do the trick? I have no opinion. See my earlier point about landowner willingness.

Catchment-wide approach or subcatchment approaches? Ditto.

References

White, P.A.; Cameron, S.G.; Kilgour, G.; Mroczek, E.; Bignall, G.; Daughney, C.; Reeves, R.R. (2004). Review of groundwater in the Lake Rotorua catchment. *GNS Client report 2004/130*. 231 p.

White, P.A.; Zemansky, G.; Hong, T.; Kilgour, G.; Wall, M. (2007). Lake Rotorua groundwater and Lake Rotorua nutrients – phase 3 science programme technical report. *GNS Client report 2007/220 to Environment Bay of Plenty*. 402 p.

White, P.A.; Rutherford, K. (2009). Groundwater catchment boundaries of Lake Rotorua. *GNS Science report 2009/75LR for Environment Bay of Plenty.*

White, P.A.; Silvester, W.; Cameron, S.G.; Raiber, M. (2008). Nutrient discharge to groundwater at the Kaharoa rainfall recharge site, Rotorua. *GNS Science report 2008/320 to Environment Bay of Plenty.*

14. Appendix 2: Derivation of the nitrogen target for Lake Rotorua

The lake target of 435 tN/yr originated from meetings in 1986 involving scientists and engineers from the Taupo Research Laboratory, Hamilton Science Centre, Ministry of Works & Development Wellington, National Water & Soil Conservation Authority, Bay of Plenty Regional Council, Rotorua District Council and several engineering consultants. To aid these discussions a position paper was drafted in early 1986, underwent a number of changes and was eventually published by NWASCA in October 1986 (Howard-Williams et al. 1986) and included in a journal paper (Rutherford et al. 1989). This group recommended a limit of 30 tN/yr input from sewage and this is now a consent condition for outflow from the RLTS.

Rutherford (2008) reported that there were 2 typographical errors in the key table of Rutherford et al. (1989). The nitrogen section of the corrected table is included below. The critical numbers, after being corrected, are the target of 405 tN/yr for '…streams + rain…' based on the estimated value in 1965, of 435 tN/yr for '…streams + rain + treated sewage…'.

Table A1: Summary of nitrogen inputs to Lake Rotorua. Adapted from Howard-Williams et al. (1986) and Rutherford et al. (1989).

	1965	**1976-77**	**1981-82**	**1984-85**	**Target**
Population	25,000	50,000	52,600	54,000	-
Nitrogen input					
Raw sewage t y^{-1}	34	100	170	260	-
Treated sewage t y^{-1}	20	66 [b]	134	150	30
Stream + rain t y^{-1} [a]	405 [b]	485	420	415	405
Septic tanks t y^{-1}	50	80	15	10	0
Internal t y^{-1}	ND	0	140	>260	0
Total t y^{-1}	**475**	**558**	**694**	**>825**	**435**

[a] flood flow particulate P and N are excluded.
[b] the original table contains two typographical errors: 455 instead of 405, and 73 instead of 66. Critical numbers are highlighted in grey.
Nitrogen input in rain is 30 tN/yr. The consent limit for nitrogen input to the lake from treated sewage leaving the RLTS is also 30 tN/yr.

Rutherford (2008) also summarised published estimates of nitrogen load for '…streams + rain omitting sewage…'. The nitrogen data are reproduced below (Table A2). This table includes the 1965 estimate of 405 tN/yr from Table A1. McIntosh's estimate of 206 tN/yr in 1900, Fish's estimate of 269 tN/yr for TIN in 1969-70, and White's estimate of 431 tN/yr for 1975 load provide supporting evidence for the 1965 estimate of 405 tN/yr for '…streams + rain…'.

Table A2: Summary of nitrogen inputs to Lake Rotorua. Adapted from Rutherford (2008).

	Year	TIN [a] tN y^{-1}	TN [a] tN y^{-1}
Morgenstern & Gordon 2004	1900	90	
McIntosh in EBoP 2007	1900		206
Rutherford et al. 1989	1965		405
Fish 1975	1969-70	269	
White 1978	1975		431
Hoare 1980a	1976-77	382-407	472-497
Morgenstern & Gordon 2004	2005	449	547
Morgenstern & Gordon 2004	steady state		746
McIntosh in EBoP 2007	exports		783

[a] '…streams + rain omitting sewage…'

Estimates for nitrogen input from rain average 30 tN/yr (Hoare 1980b, Morgenstern & Gordon 2004, EBoP 2007) with a tight range of 29-31 tN/yr. Hence the 1965 estimate of nitrogen input from streams alone is 375 tN/yr. This excludes inputs from septic tanks which in 1965 were estimated to contribute 50 tN/yr to the lake. The 1965 figure of 50 tN/yr includes contributions from the municipal septic tanks operating in Rotorua City at that time and not replaced by the sewage treatment plant (STP) until the late 1970s.

The target of 435 tN/yr in Howard-Williams et al. (1986) and Rutherford et al. (1989) comprises:

Table A3: Components of the target for nitrogen input to Lake Rotorua.

	tN/yr	
Streams	375	
Rain	30	Range 29-31
Sewage	30	Now the consented input for the RLTS
Total	**435**	

It is coincidence that the nitrogen inputs from rain and sewage are both 30 tN/yr.

In the ROTAN simulations, input from the RLTS is included in the Puarenga Stream The reported lake loads do not include rainfall on the lake. The ROTAN simulations include septic tanks, although the number of septic tanks has decreased significantly over time. However, the contribution from septic tanks was included in the recommended limit of 30 tN/yr for sewage when the target was set.

Consequently, ROTAN lake loads (streams + RLTS) need to be compared with a value of 405 tN/yr (total – rain) when assessing whether the target has been met.

15. Appendix 3: Predicted and observed stream flows and nitrogen concentrations for ROTAN-1

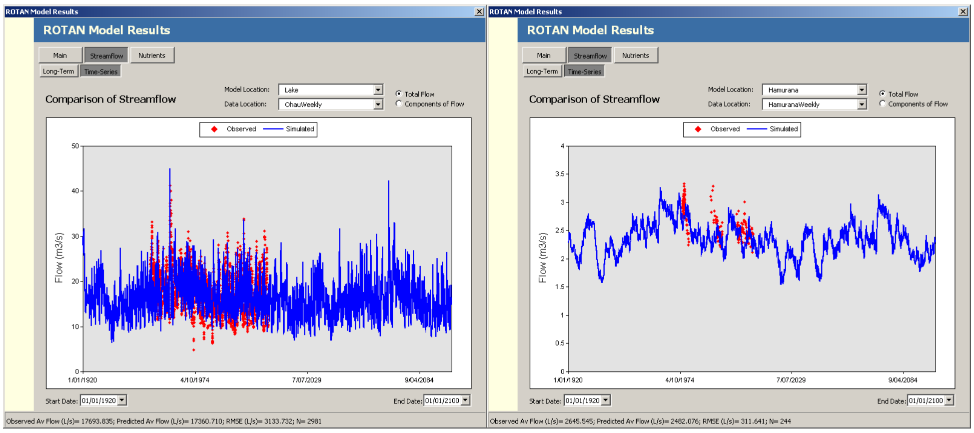


Figure A1: ROTAN-1: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Ohau Channel (left) and Hamurana Stream (right).

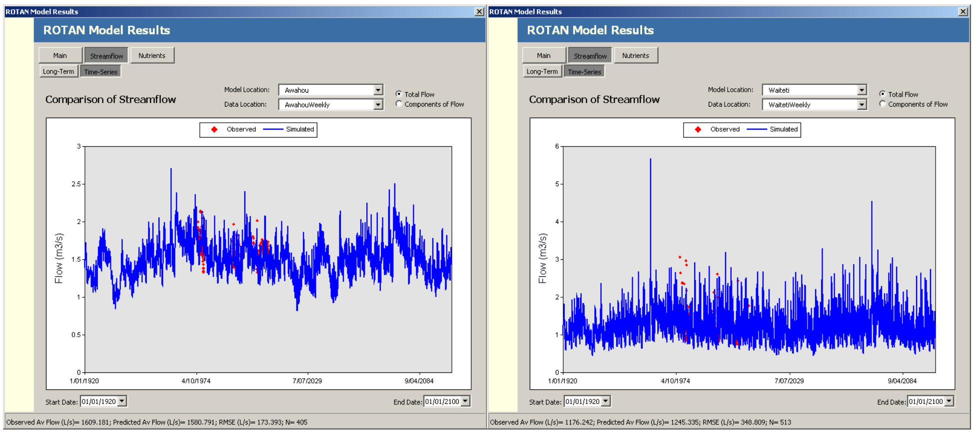


Figure A2: ROTAN-1: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Awahou (left) and Waiteti (right) streams.

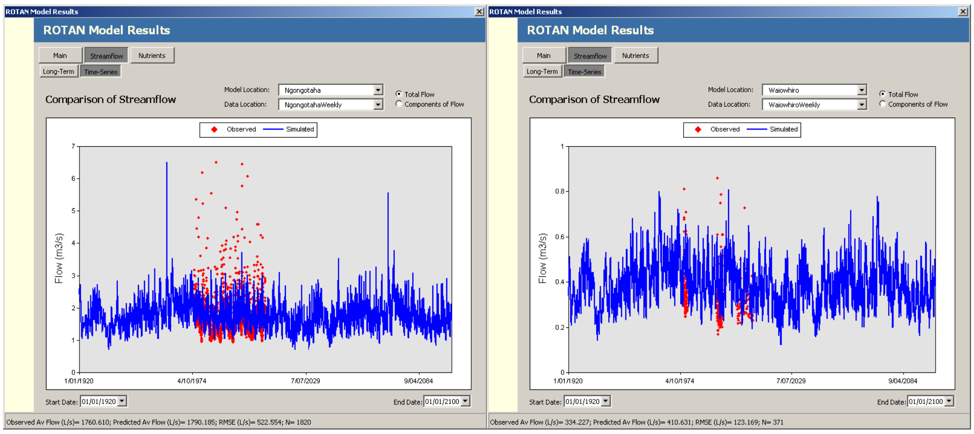


Figure A3: ROTAN-1: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Ngongotaha (left) and Waiowhiro (right) streams.

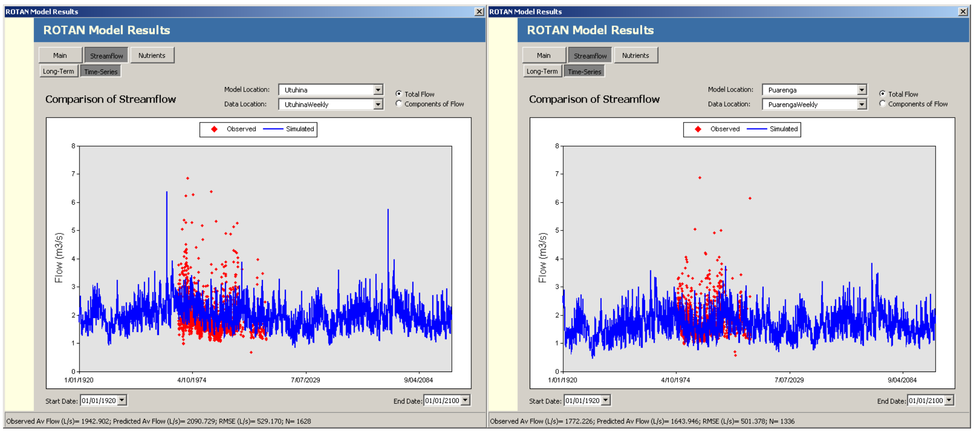


Figure A4: ROTAN-1: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Utuhina (left) and Puarenga (right) streams.

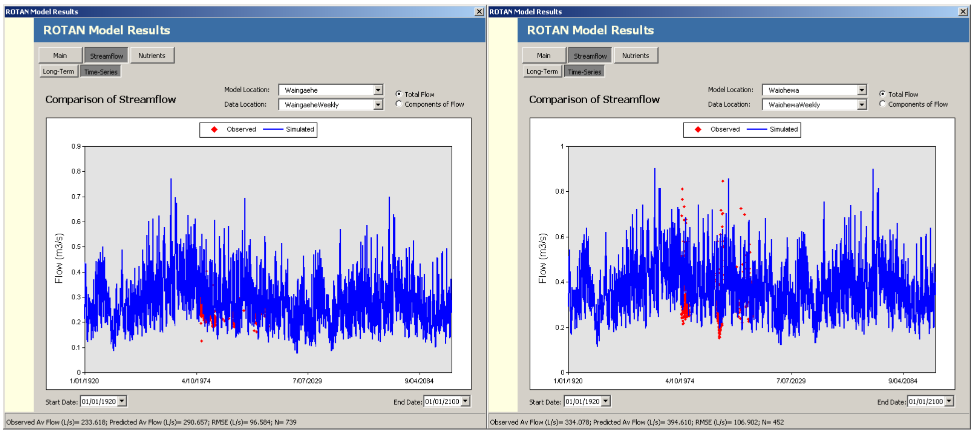


Figure A5: ROTAN-1: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Waingaehe (left) and Waiohewa (right) streams.

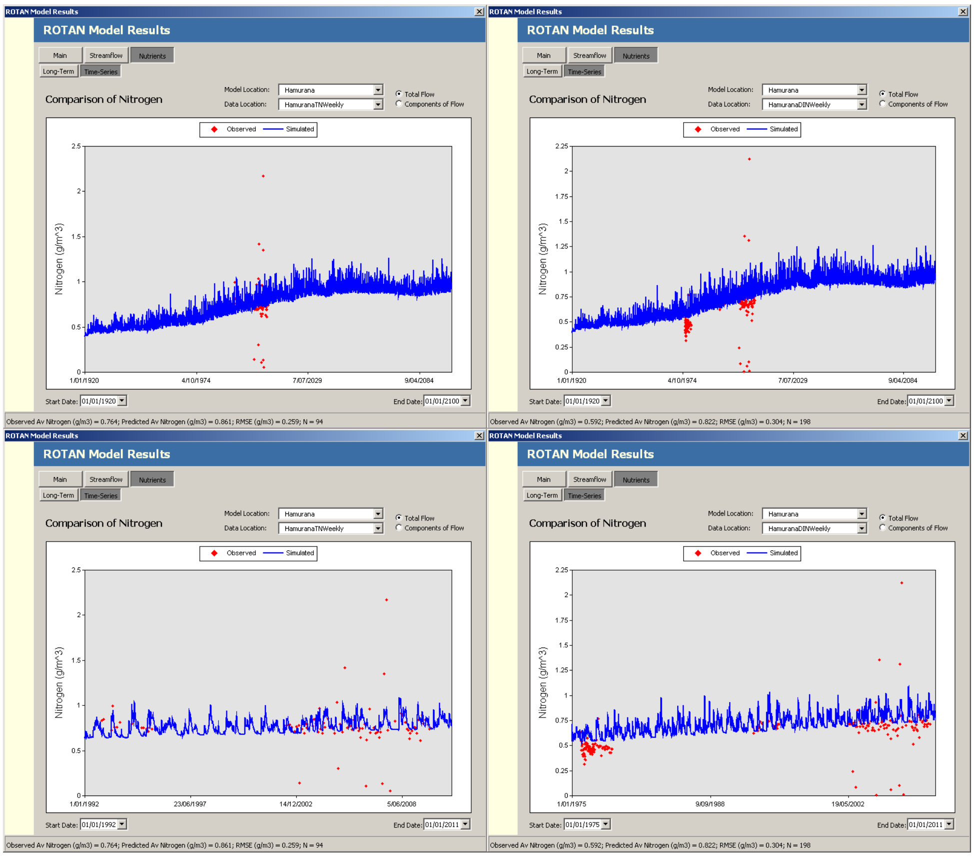


Figure A6: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Hamurana Stream.

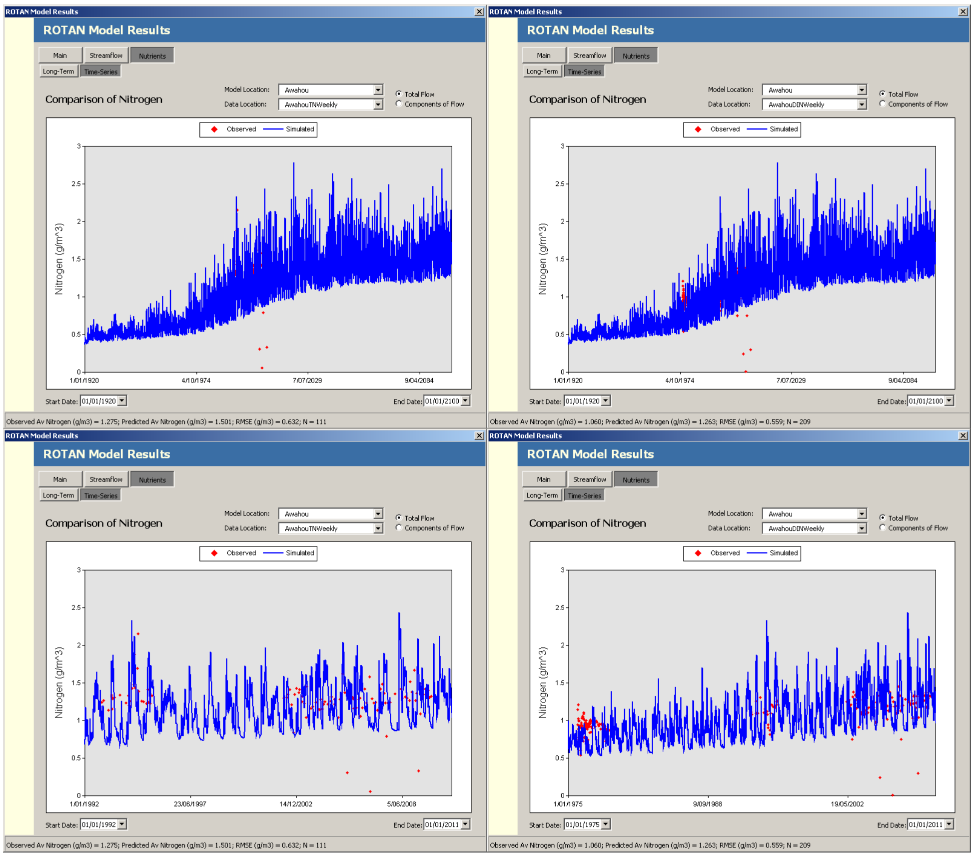


Figure A7: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Awahou Stream.

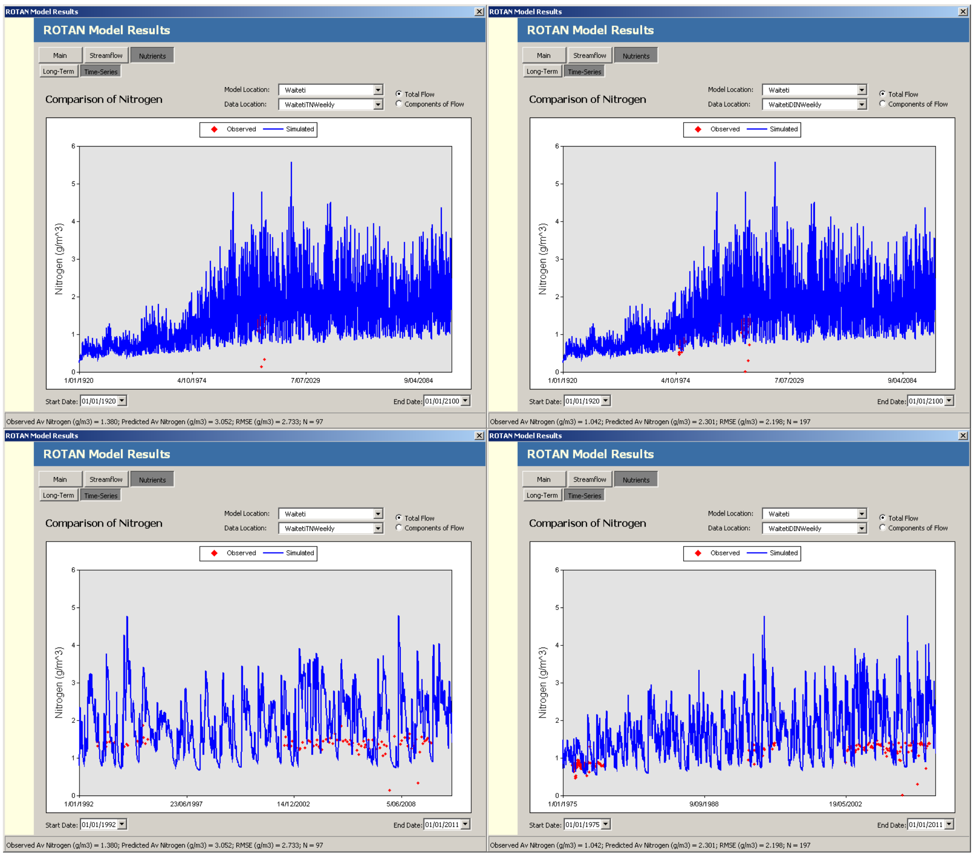


Figure A8: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiteti Stream.

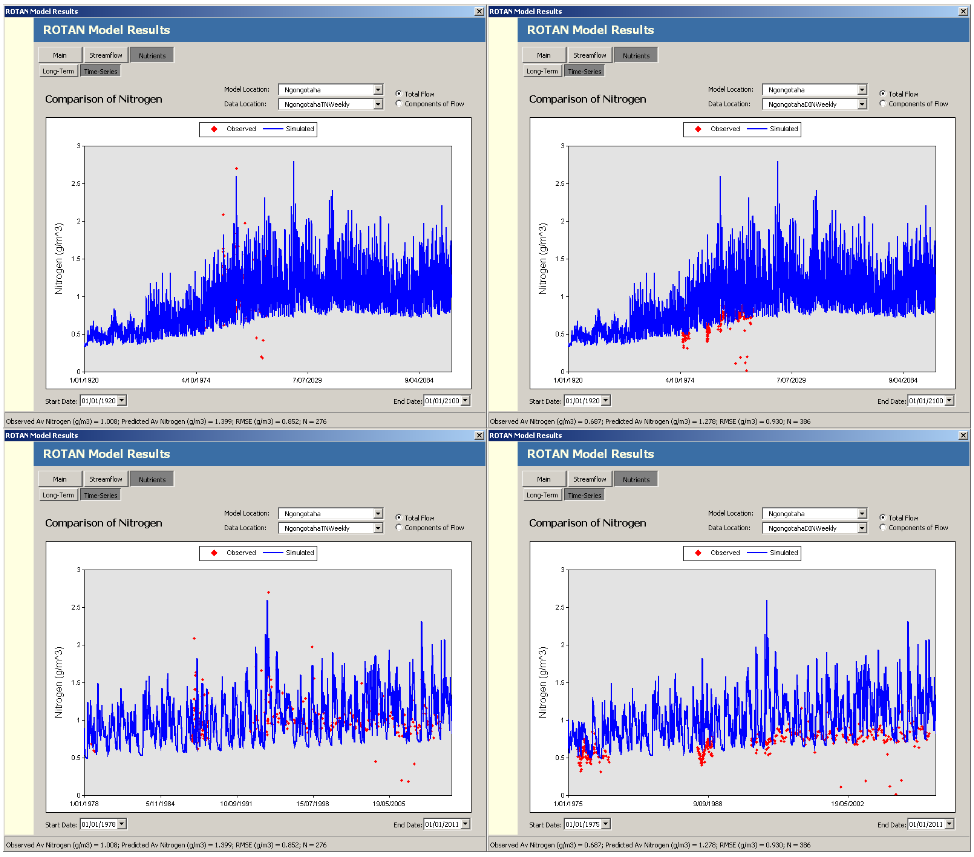


Figure A9: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Ngongotaha Stream.

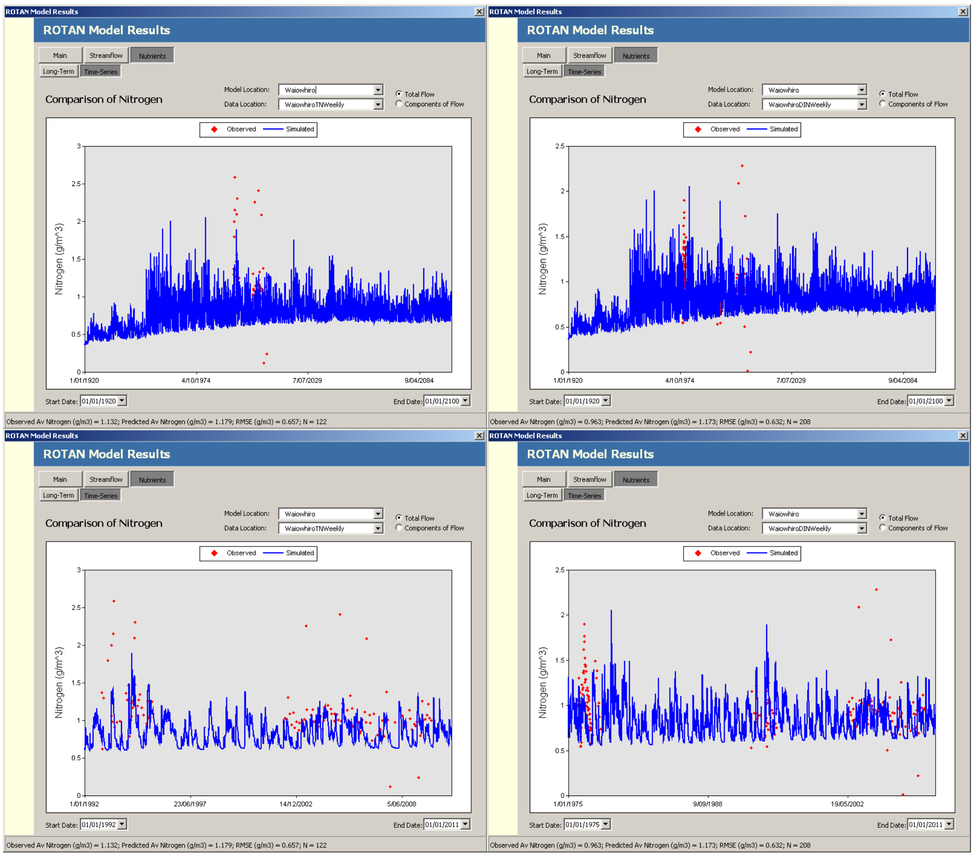


Figure A10: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiowhiro Stream.

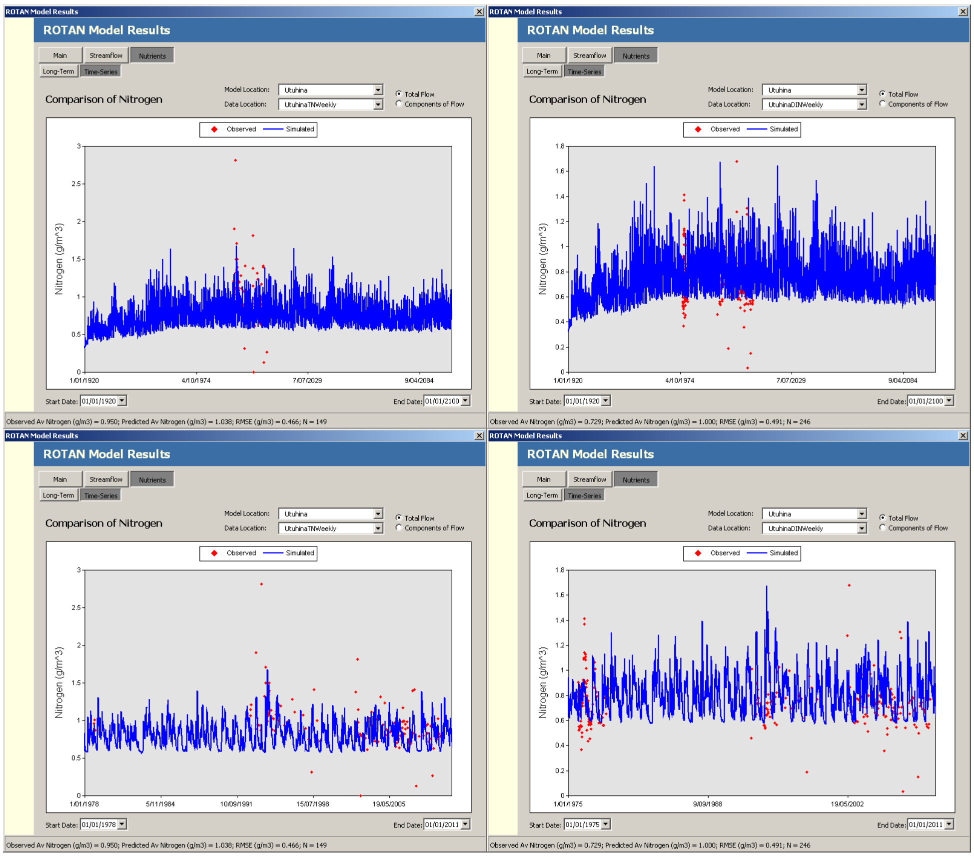


Figure A11: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Utuhina Stream.

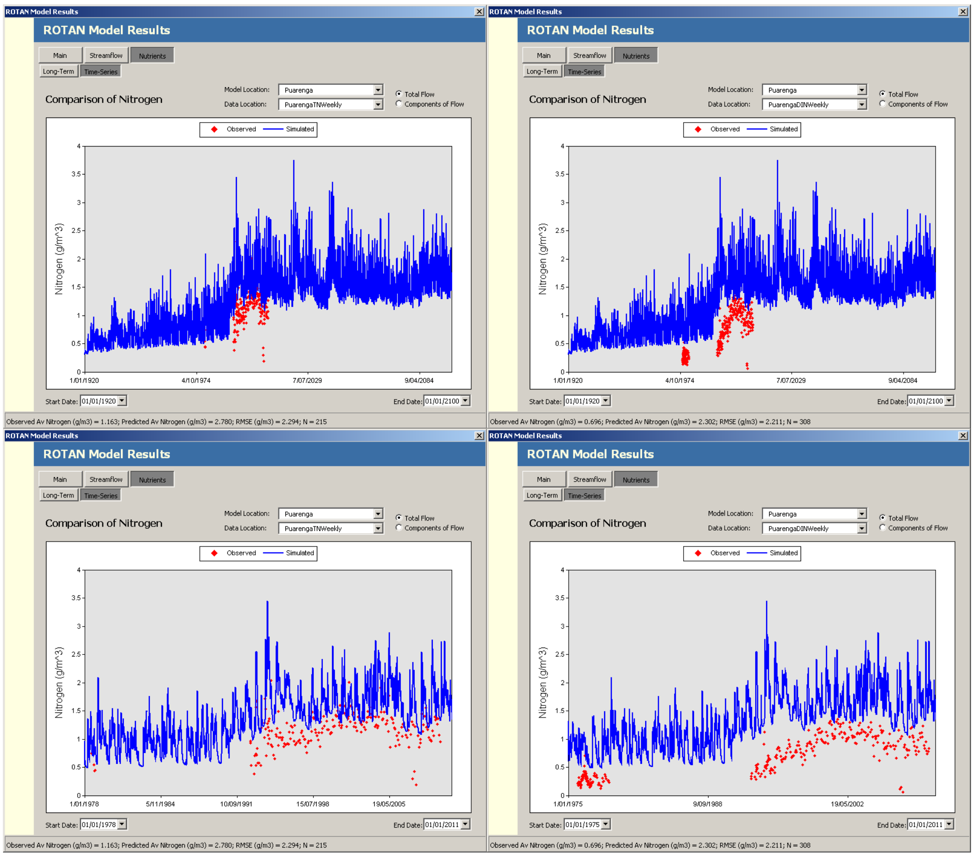


Figure A12: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Puarenga Stream.

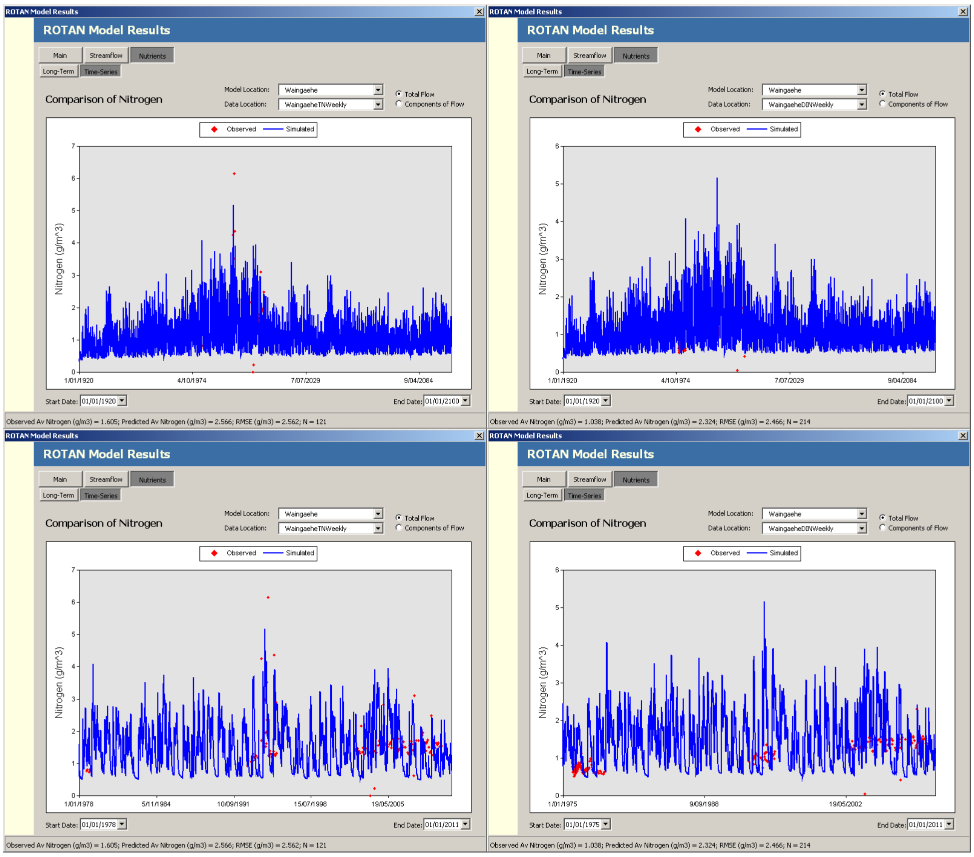


Figure A13: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waingaehe Stream.

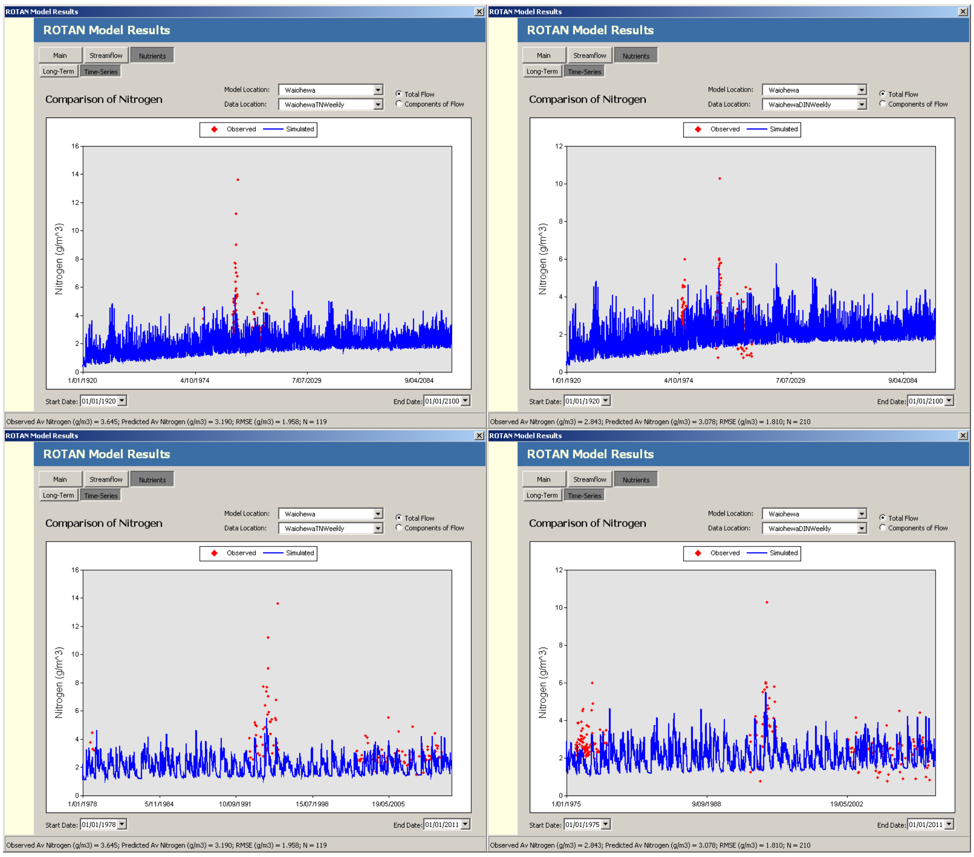


Figure A14: ROTAN-1: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiohewa Stream.

16. Appendix 4: Predicted and observed stream flows and nitrogen concentrations for ROTAN-2

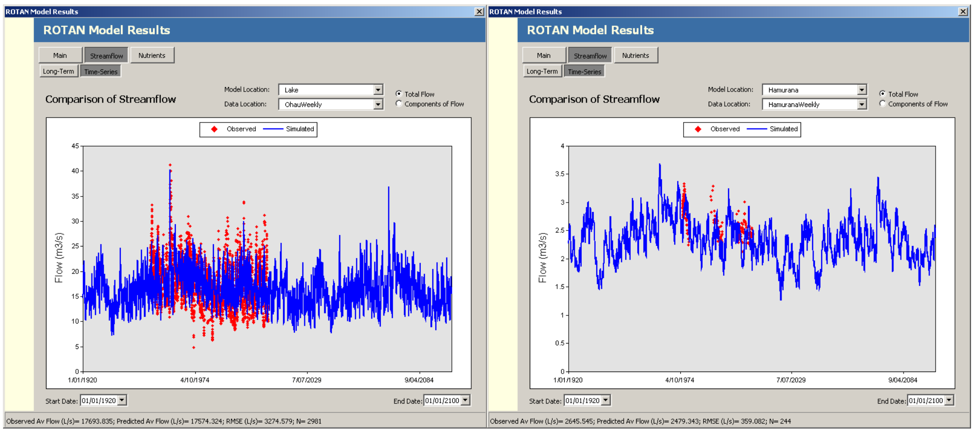


Figure A15: ROTAN-2: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Ohau Channel (left) and Hamurana Stream (right).

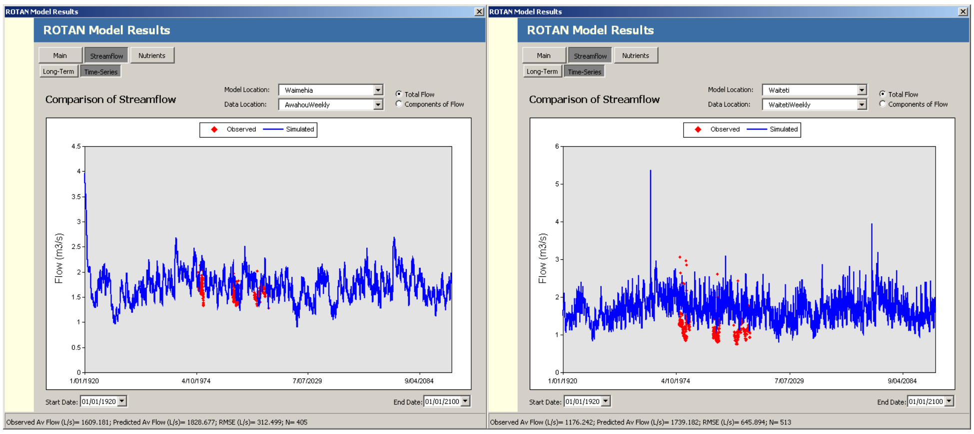


Figure A16: ROTAN-2: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Awahou (left) and Waiteti (right) streams.

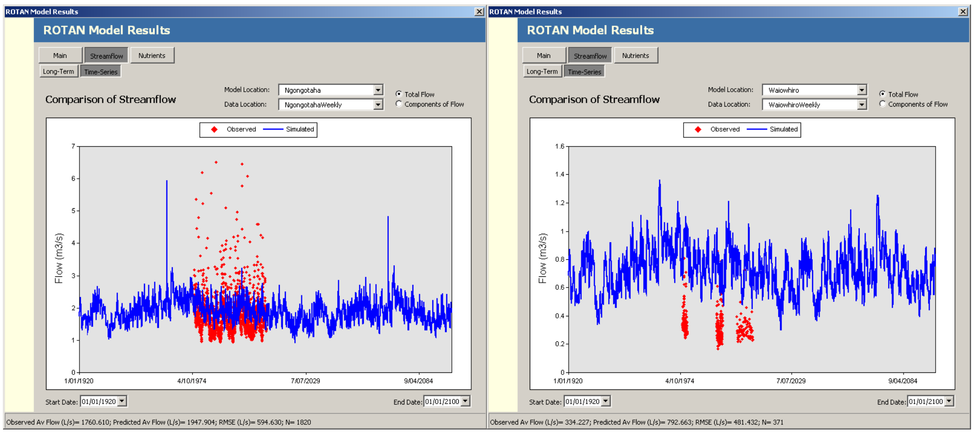


Figure A17: ROTAN-2: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Ngongotaha (left) and Waiowhiro (right) streams.

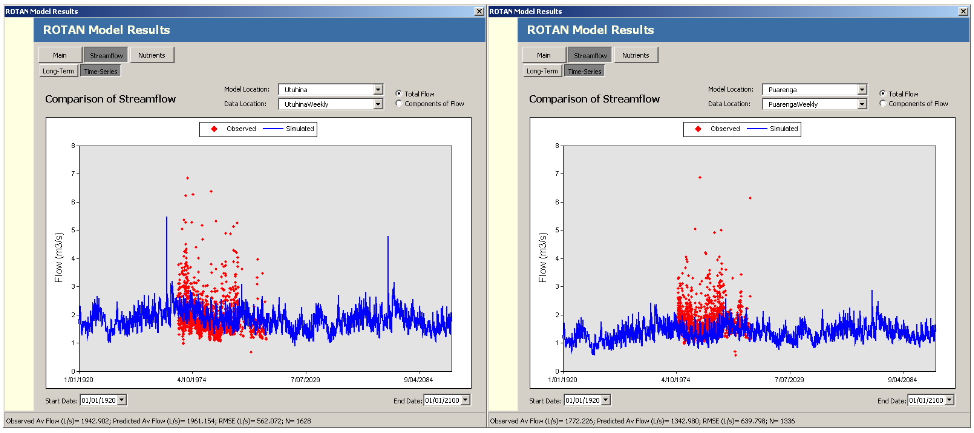


Figure A18: ROTAN-2: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Utuhina (left) and Puarenga (right) streams.

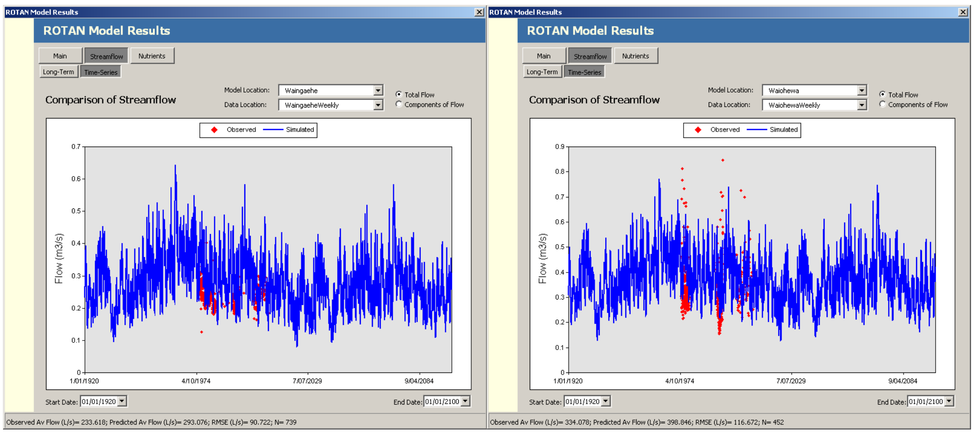


Figure A19: ROTAN-2: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Waingaehe (left) and Waiohewa (right) streams.

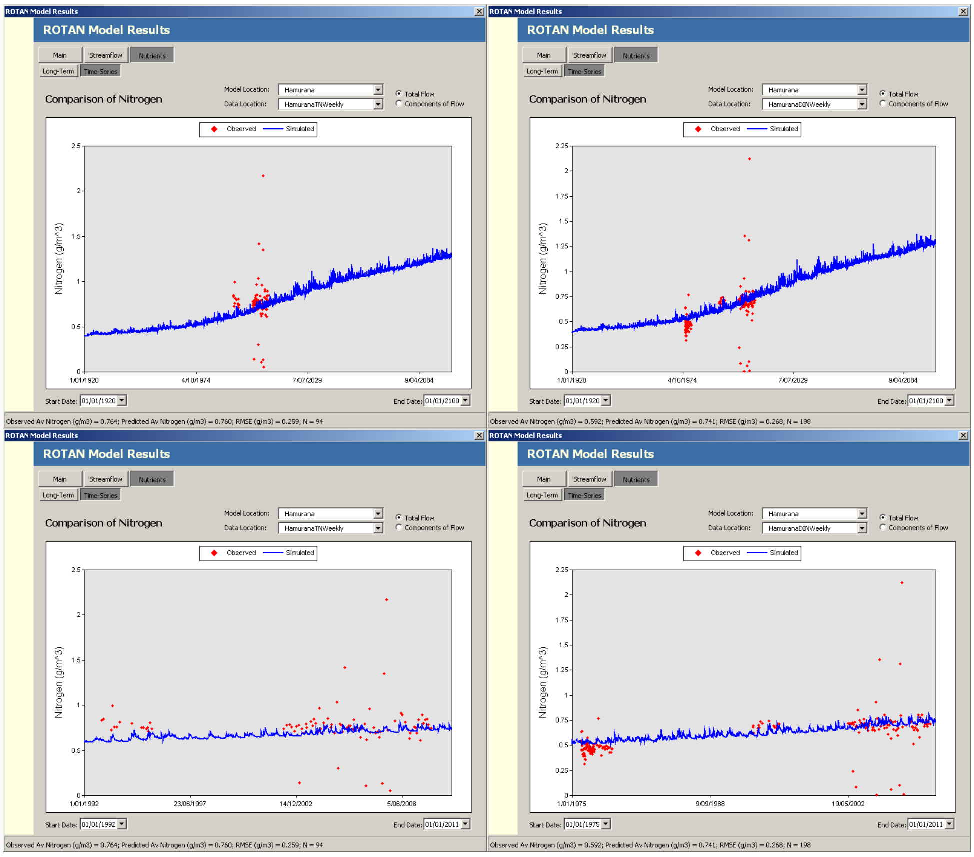


Figure A20: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Hamurana Stream.

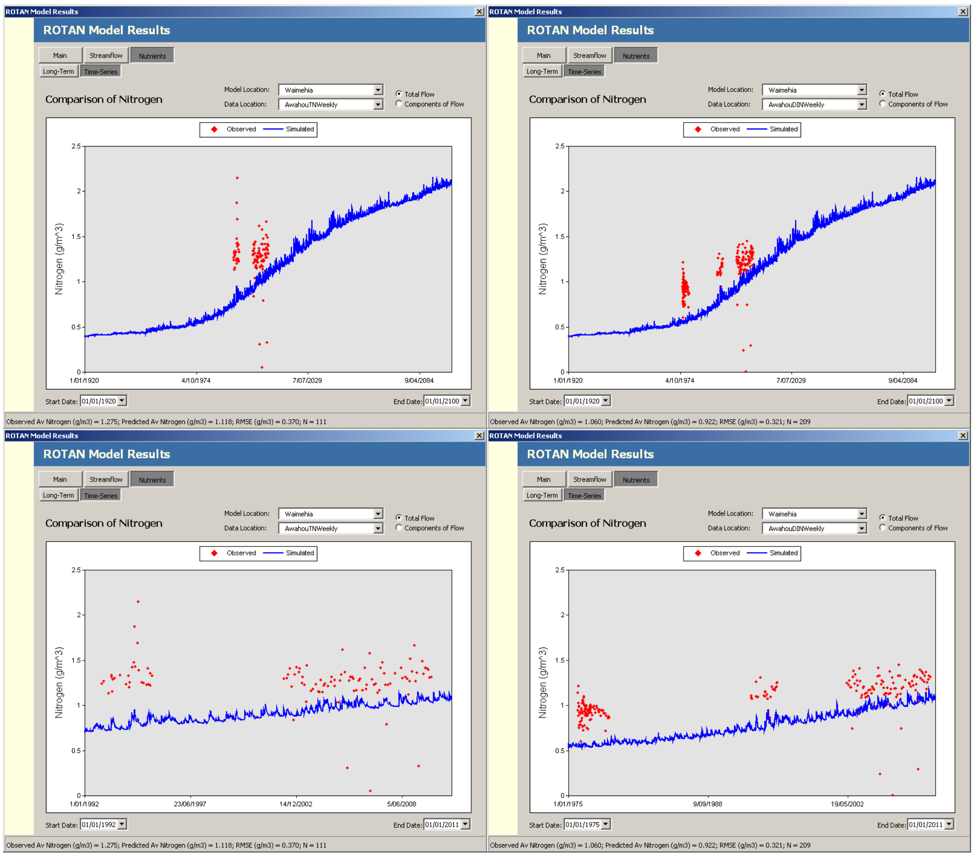


Figure A21: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Awahou Stream.

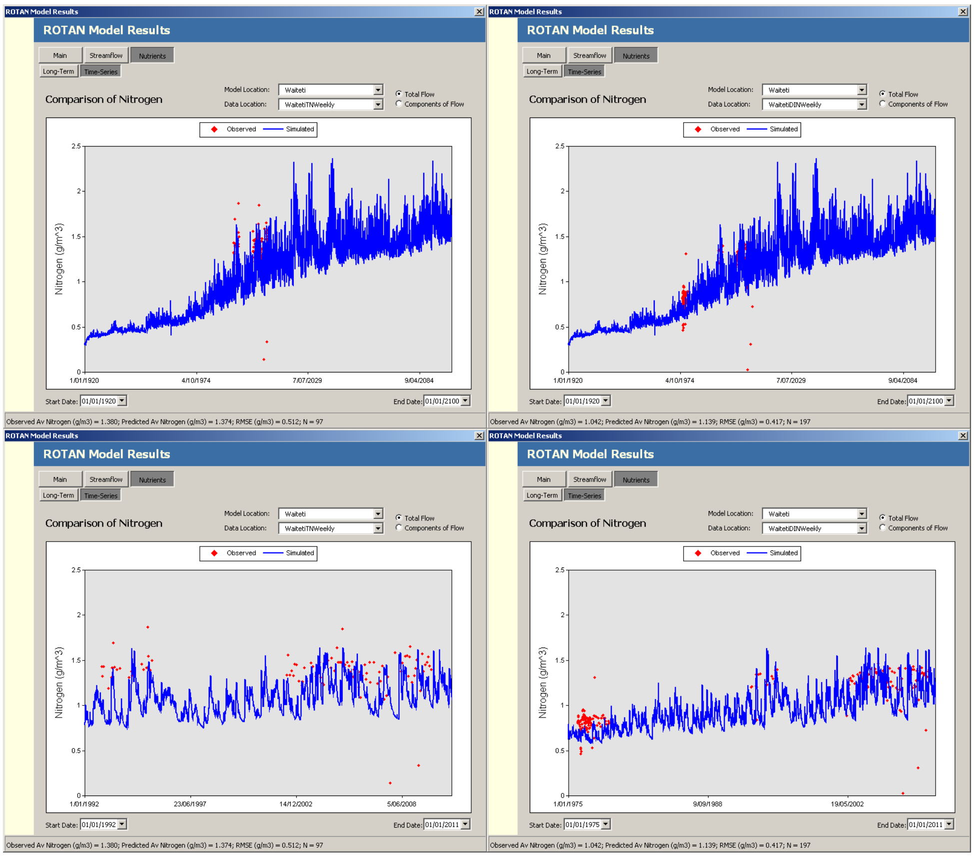


Figure A22: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiteti Stream.

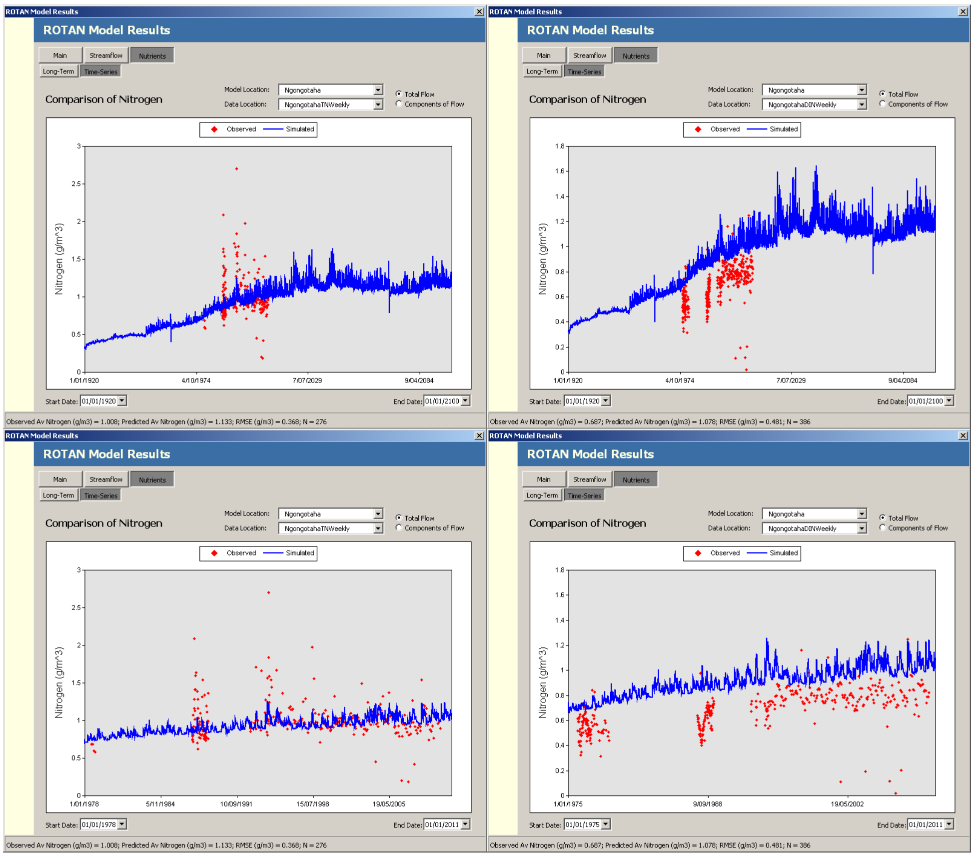


Figure A23: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Ngongotaha Stream.

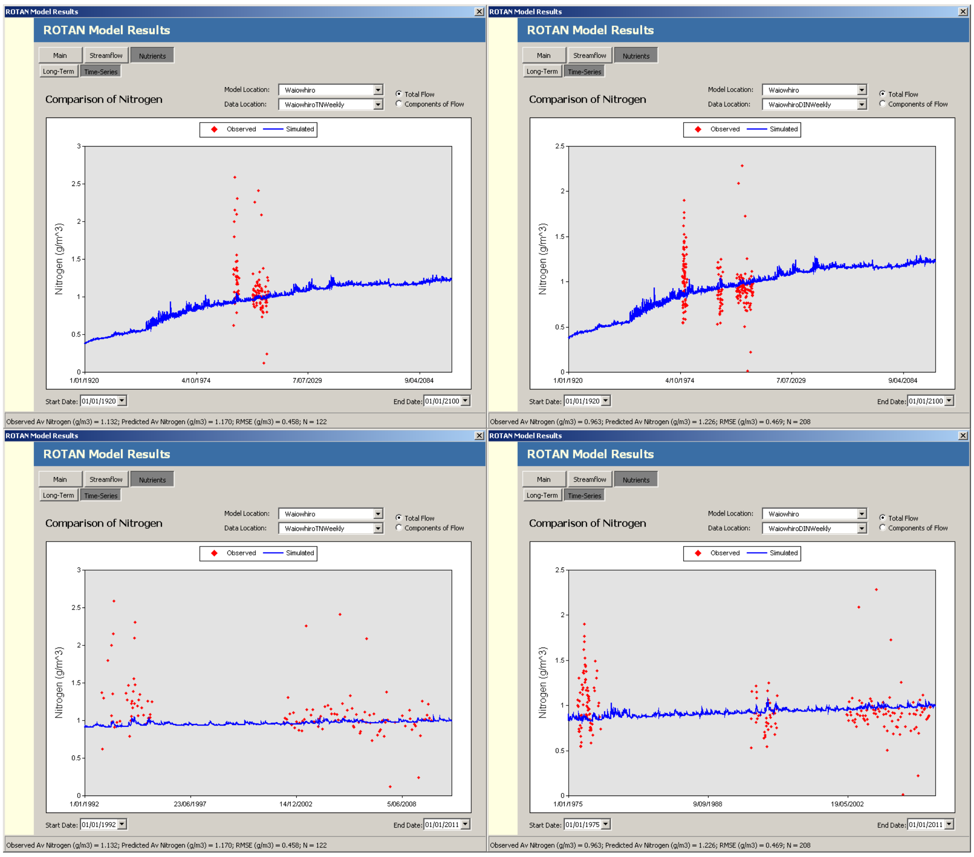


Figure A24: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiowhiro Stream.

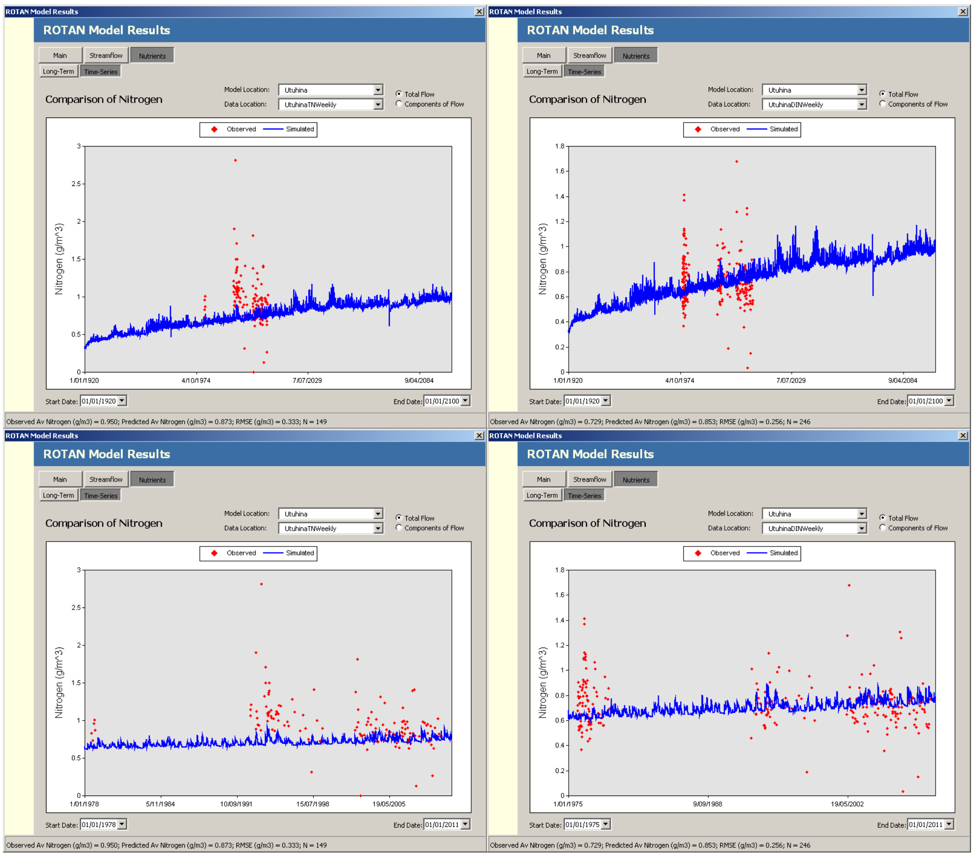


Figure A25: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Utuhina Stream.

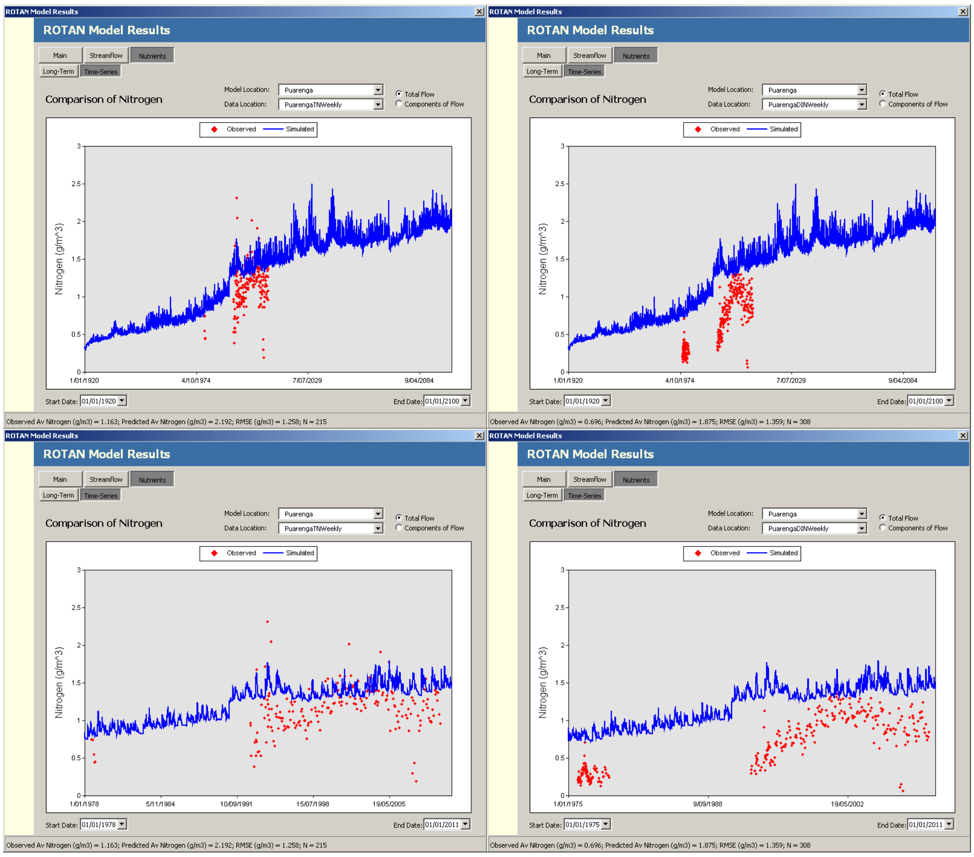


Figure A26: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Puarenga Stream.

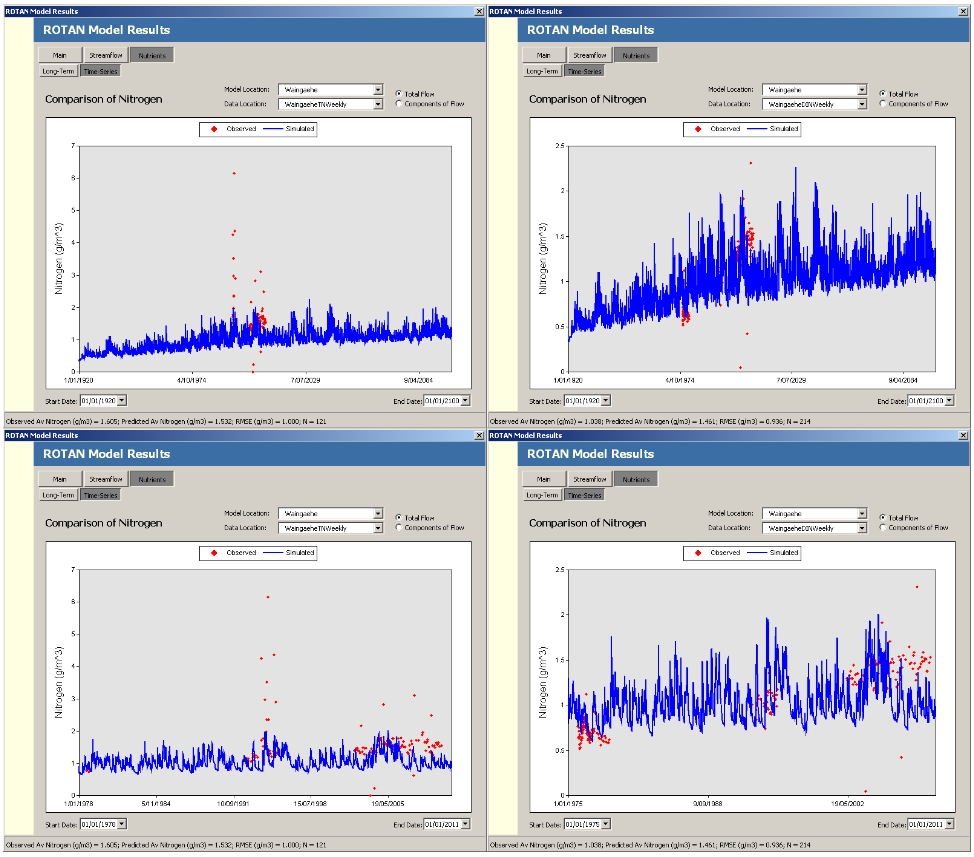


Figure A27: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waingaehe Stream.

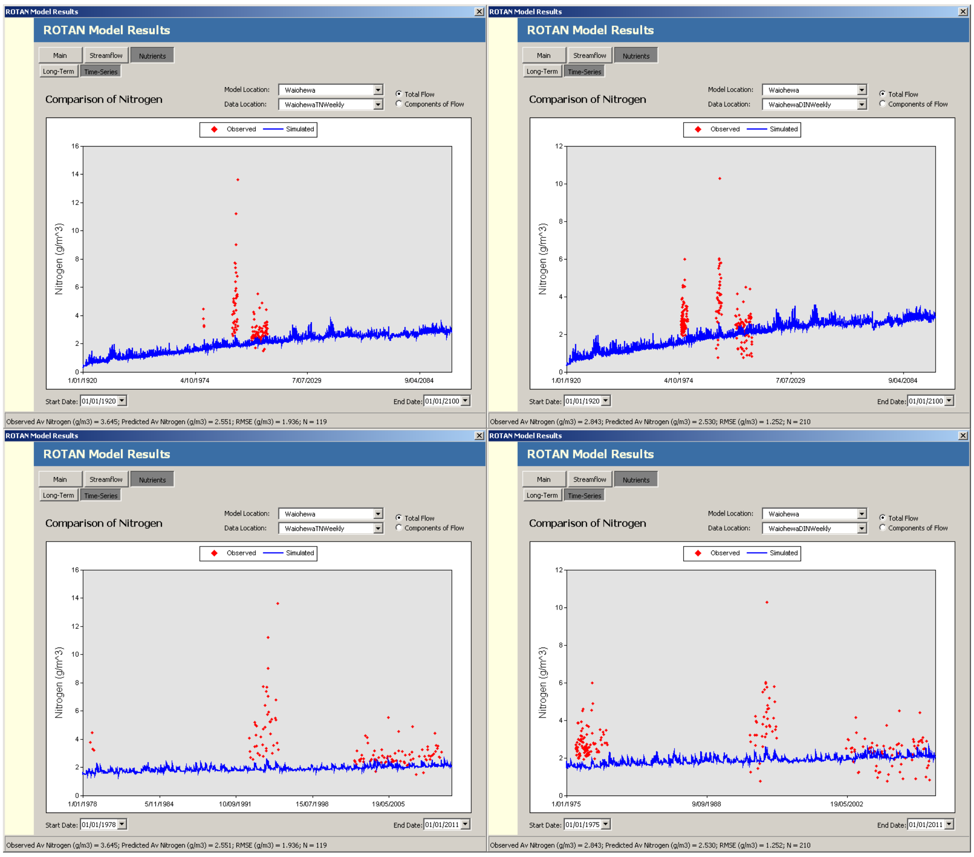


Figure A28: ROTAN-2: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiohewa Stream.

17. Appendix 5: Predicted and observed stream flows and nitrogen concentrations for ROTAN-3

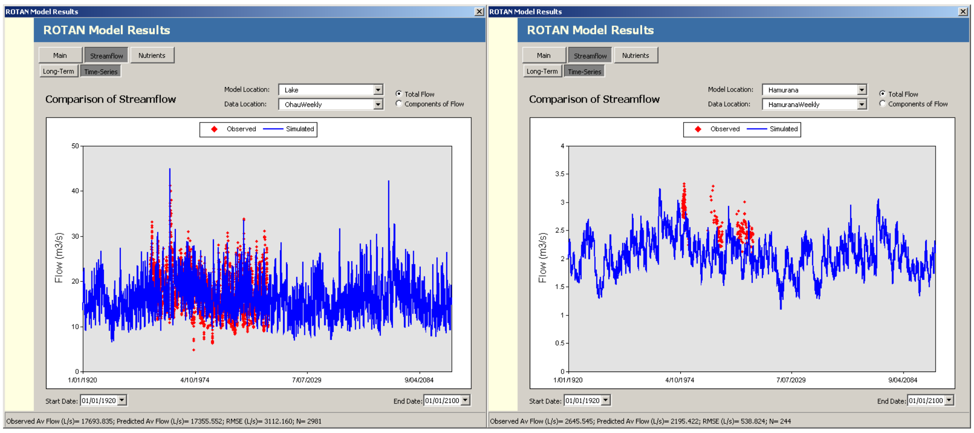


Figure A29: ROTAN-3: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Ohau Channel (left) and Hamurana Stream (right).

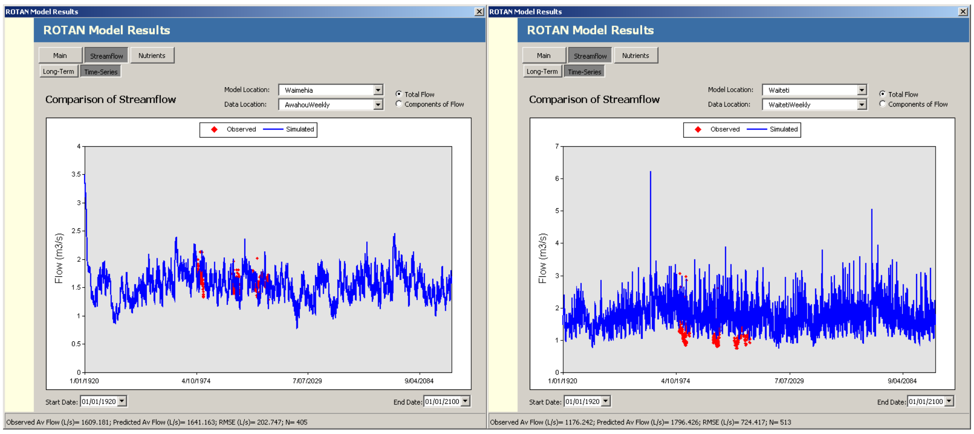


Figure A30: ROTAN-3: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Awahou (left) and Waiteti (right) streams.

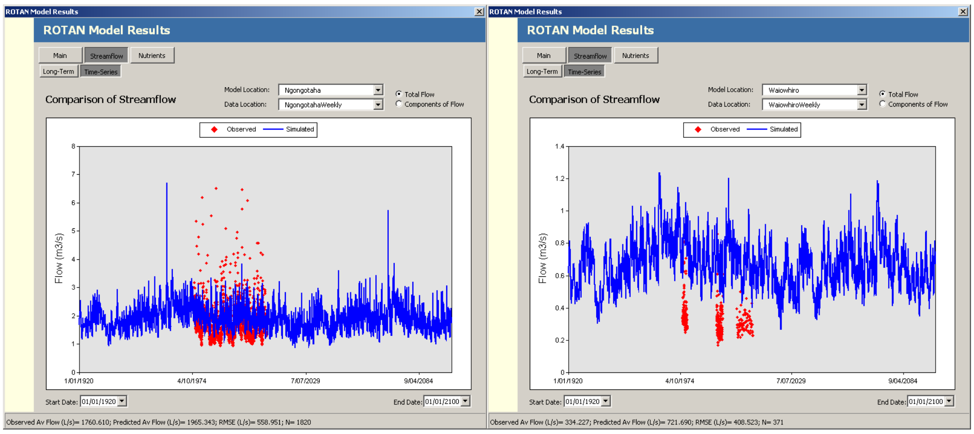


Figure A31: ROTAN-3: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Ngongotaha (left) and Waiowhiro (right) streams.

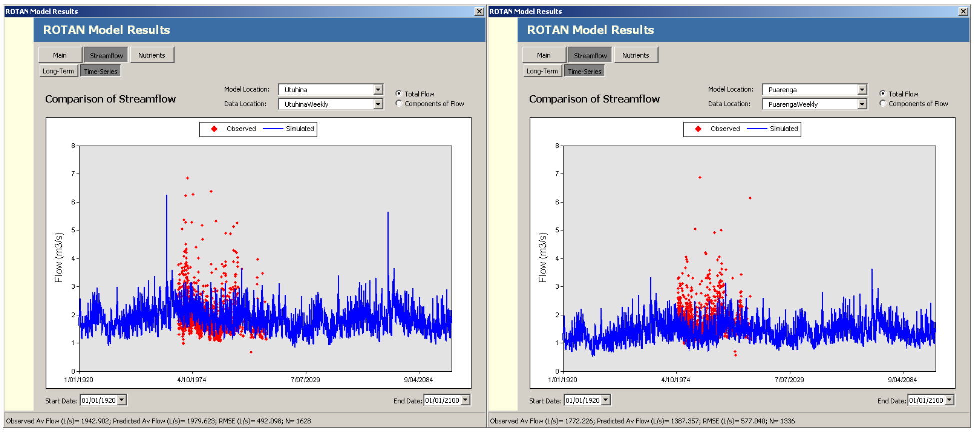


Figure A32: ROTAN-3: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Utuhina (left) and Puarenga (right) streams.

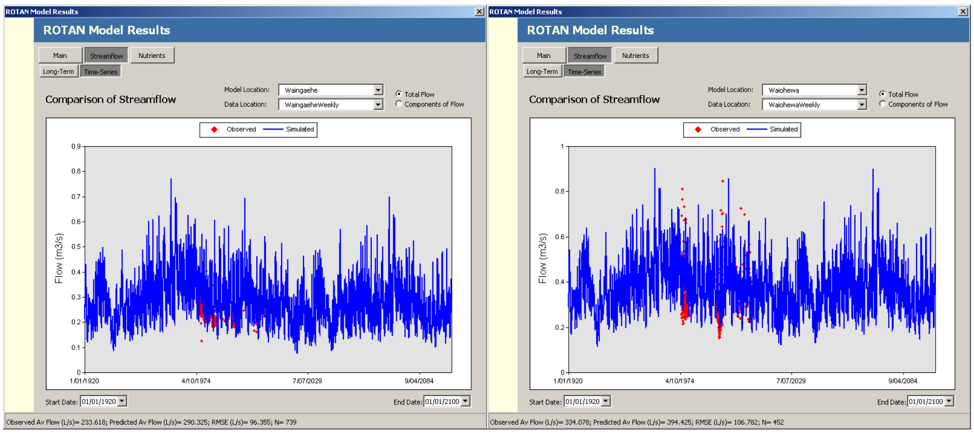


Figure A33: ROTAN-3: Predicted weekly average flow (blue lines) and observed (red circles) weekly average flow in the Waingaehe (left) and Waiohewa (right) streams.

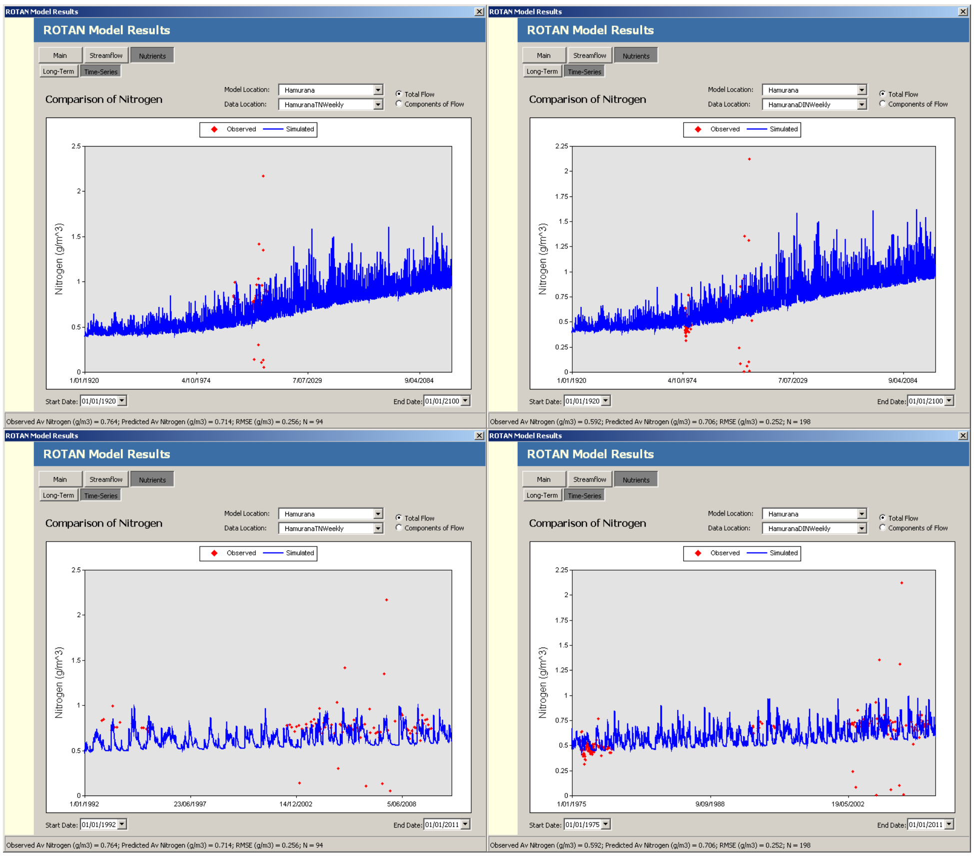


Figure A34: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Hamurana Stream.

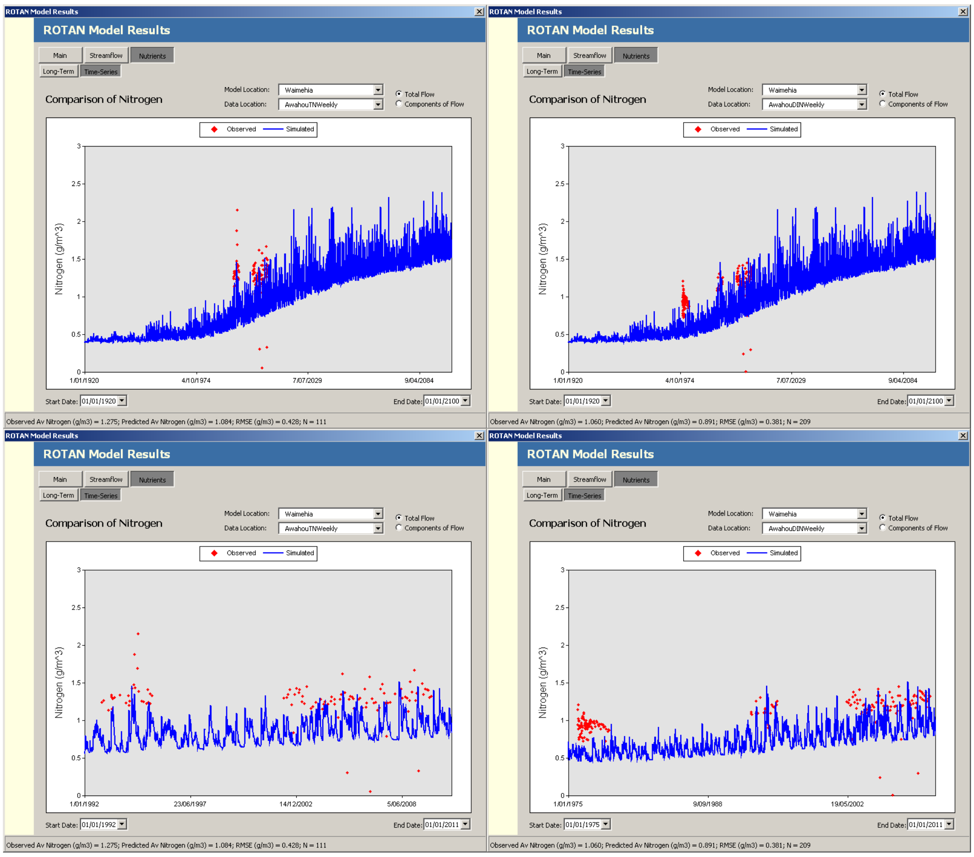


Figure A35: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Awahou Stream.

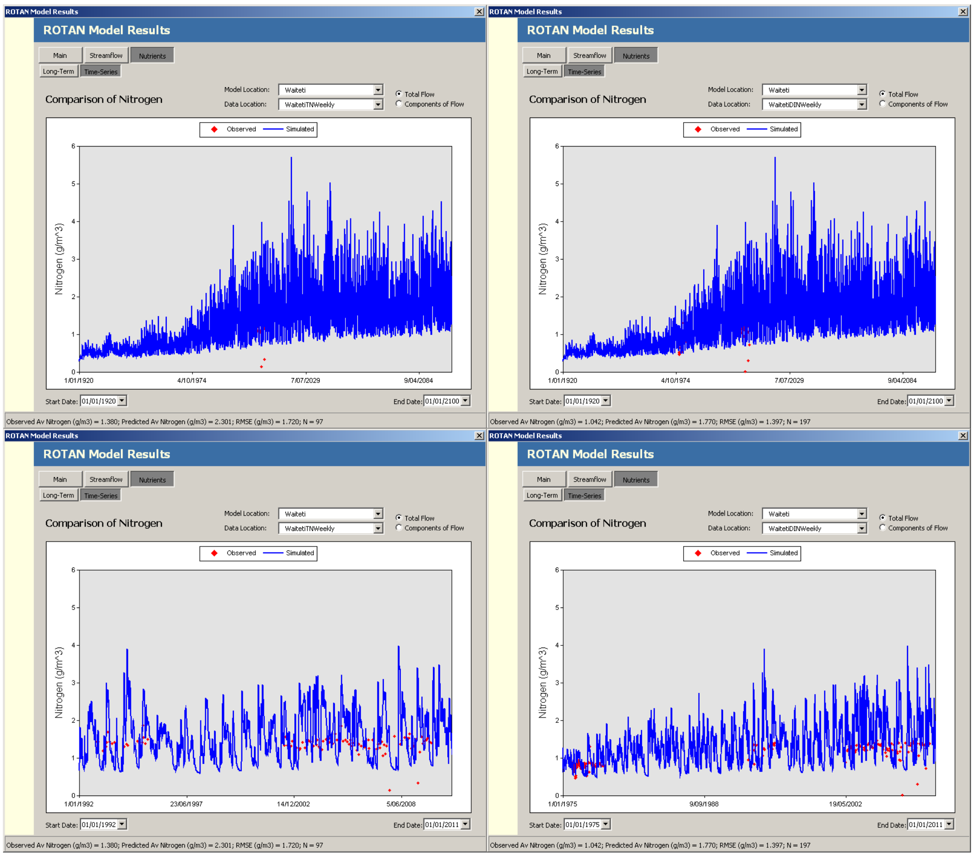


Figure A36: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiteti Stream.

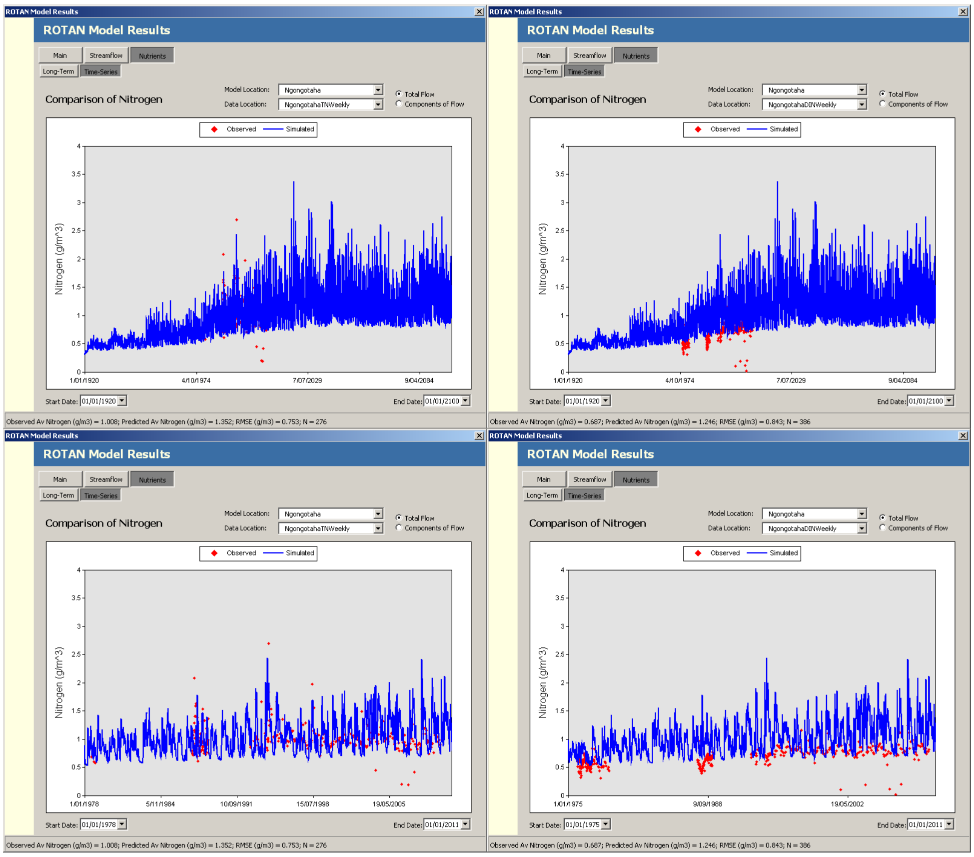


Figure A37: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Ngongotaha Stream.

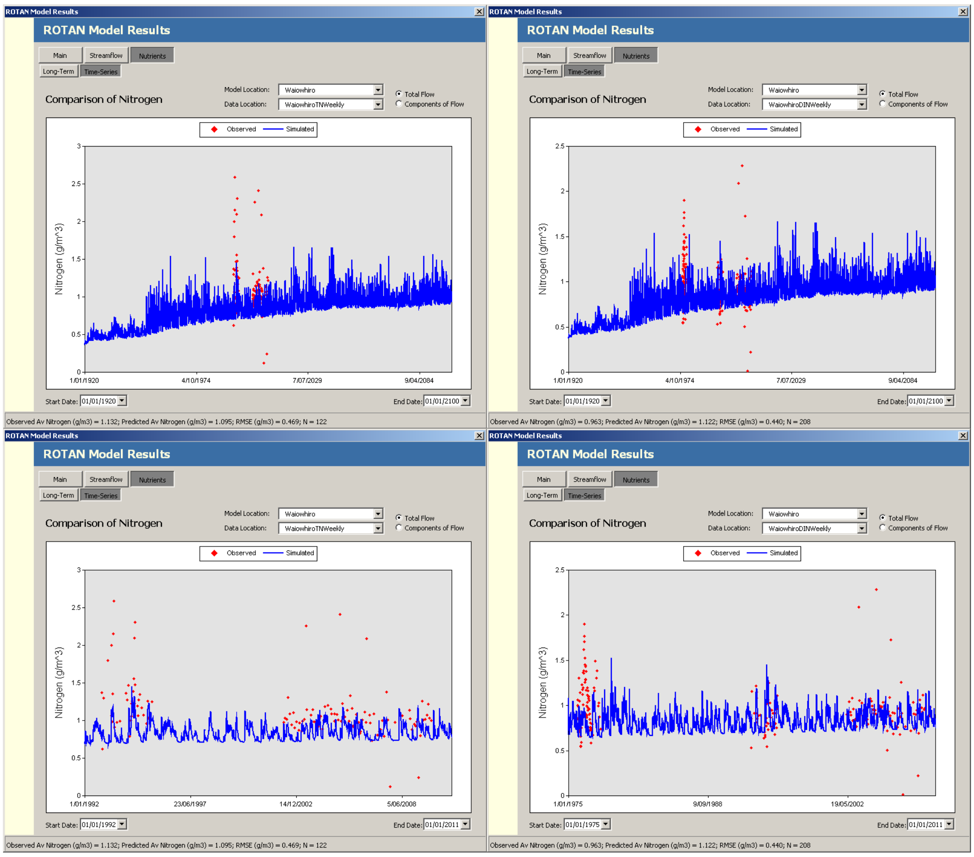


Figure A38: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiowhiro Stream.

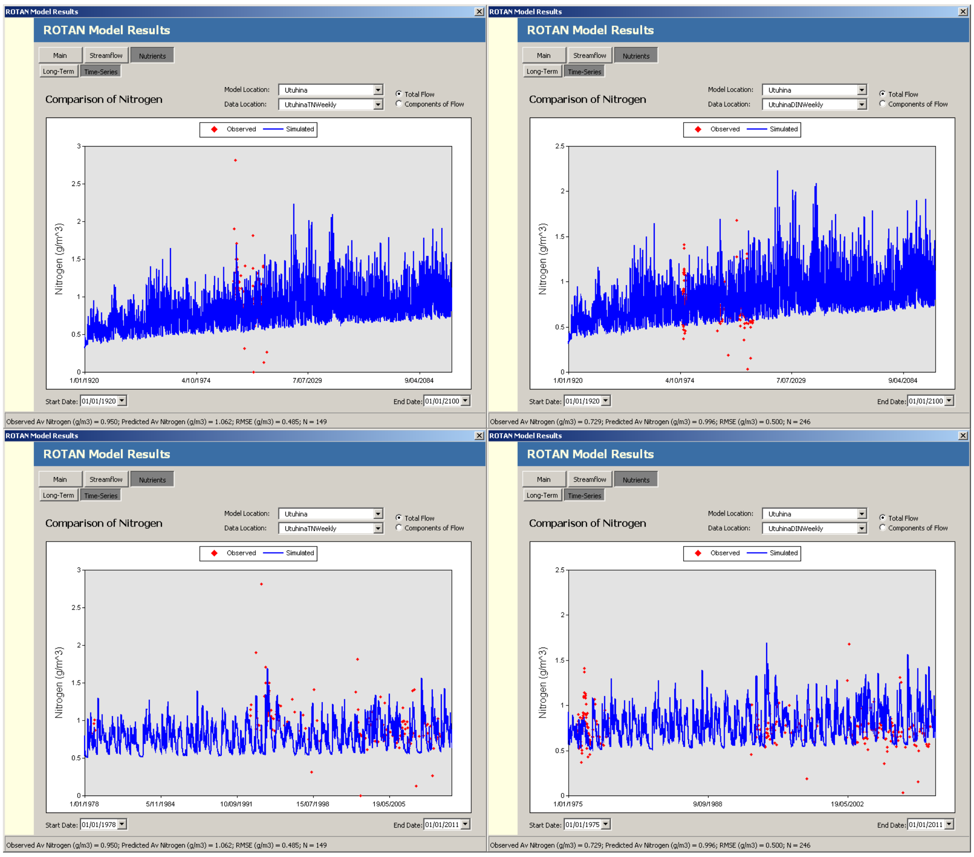


Figure A39: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Utuhina Stream.

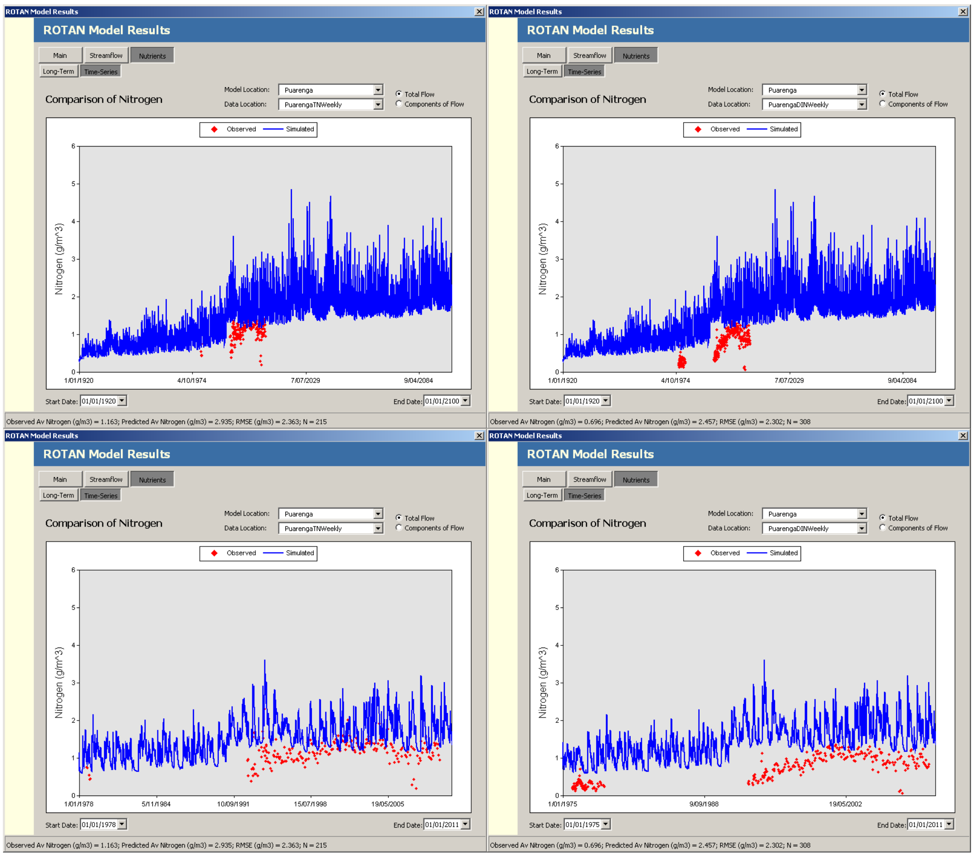


Figure A40: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Puarenga Stream.

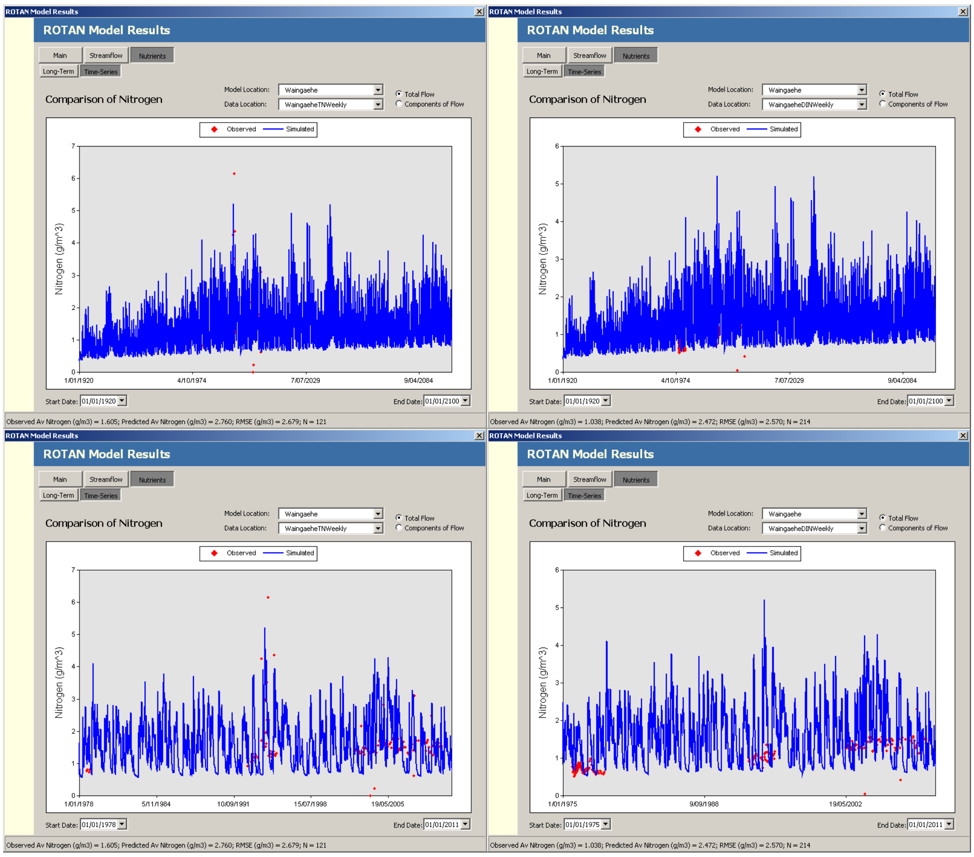


Figure A41: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waingaehe Stream.

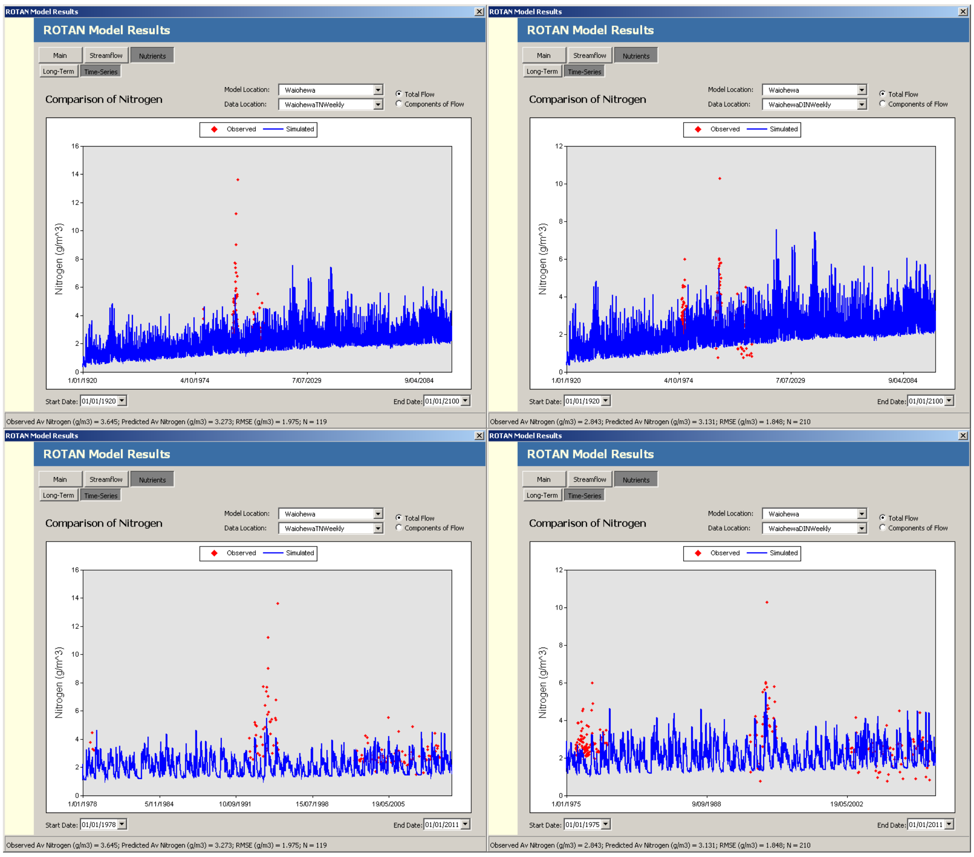


Figure A42: ROTAN-3: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiohewa Stream.

18. Appendix 6: Predicted and observed stream flows and nitrogen concentrations for ROTAN-4

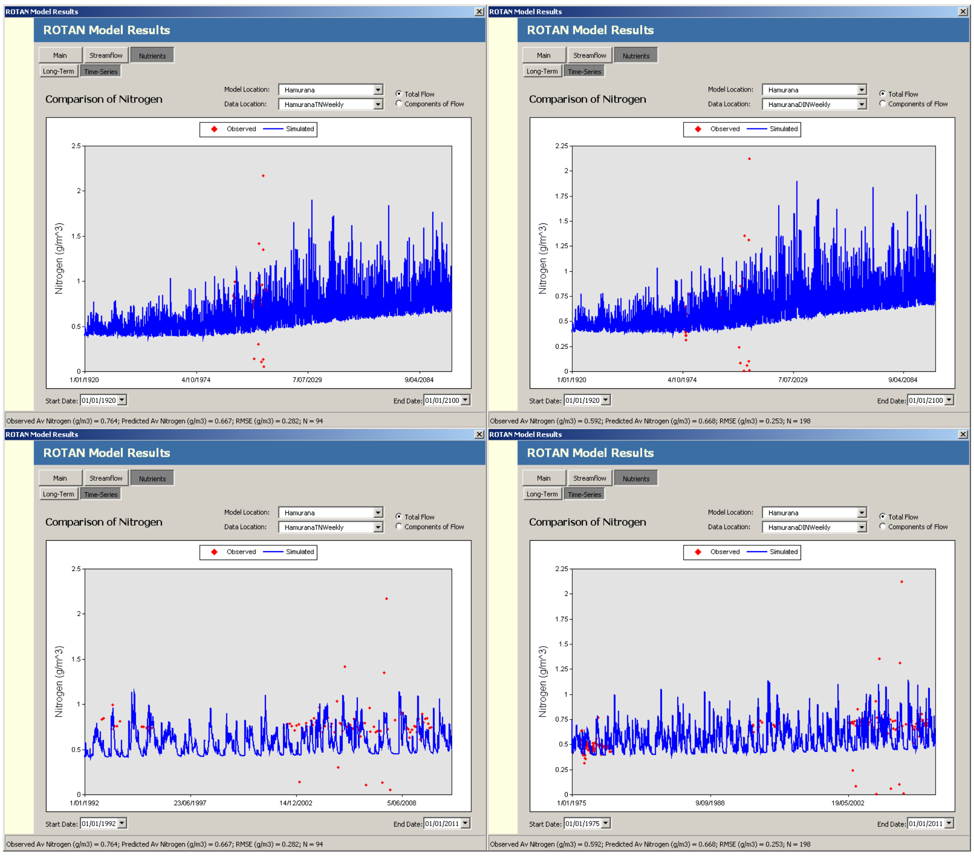


Figure A43: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Hamurana Stream.

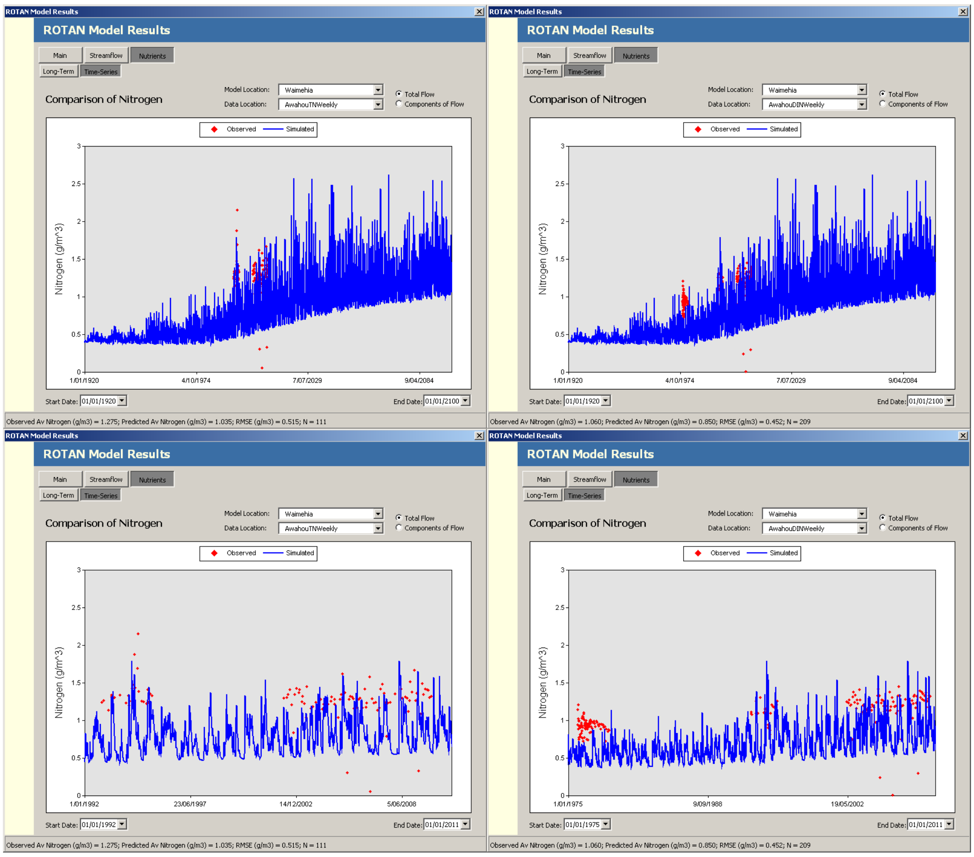


Figure A44: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Awahou Stream.

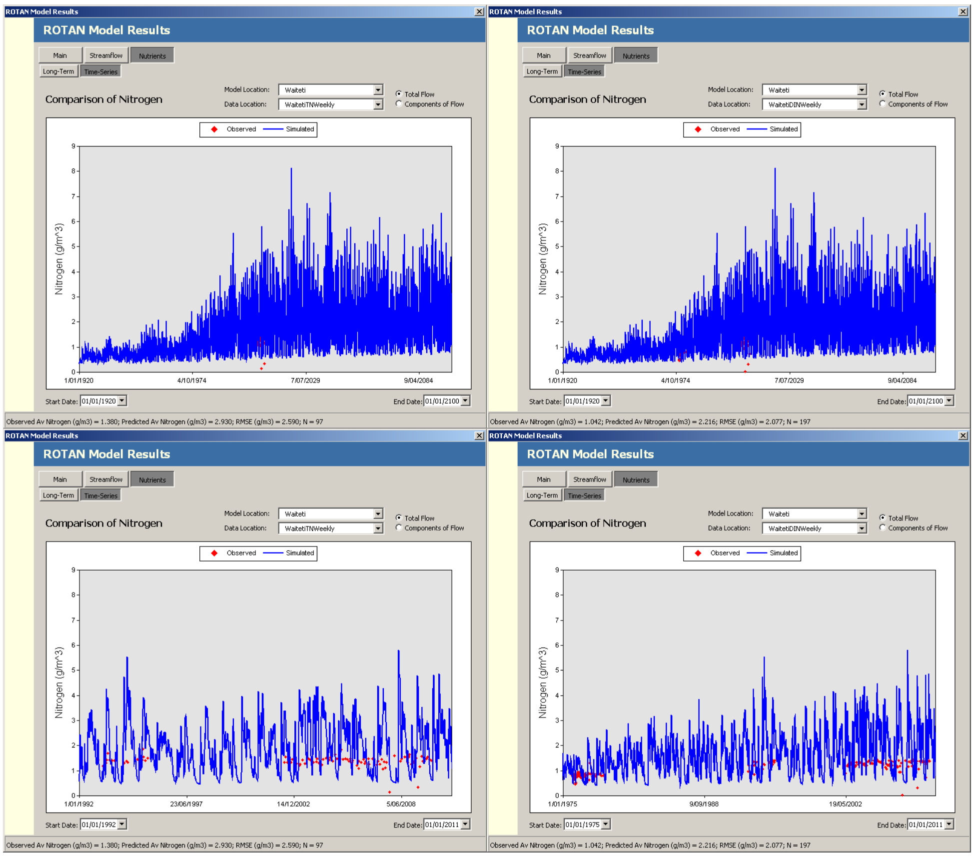


Figure A45: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiteti Stream.

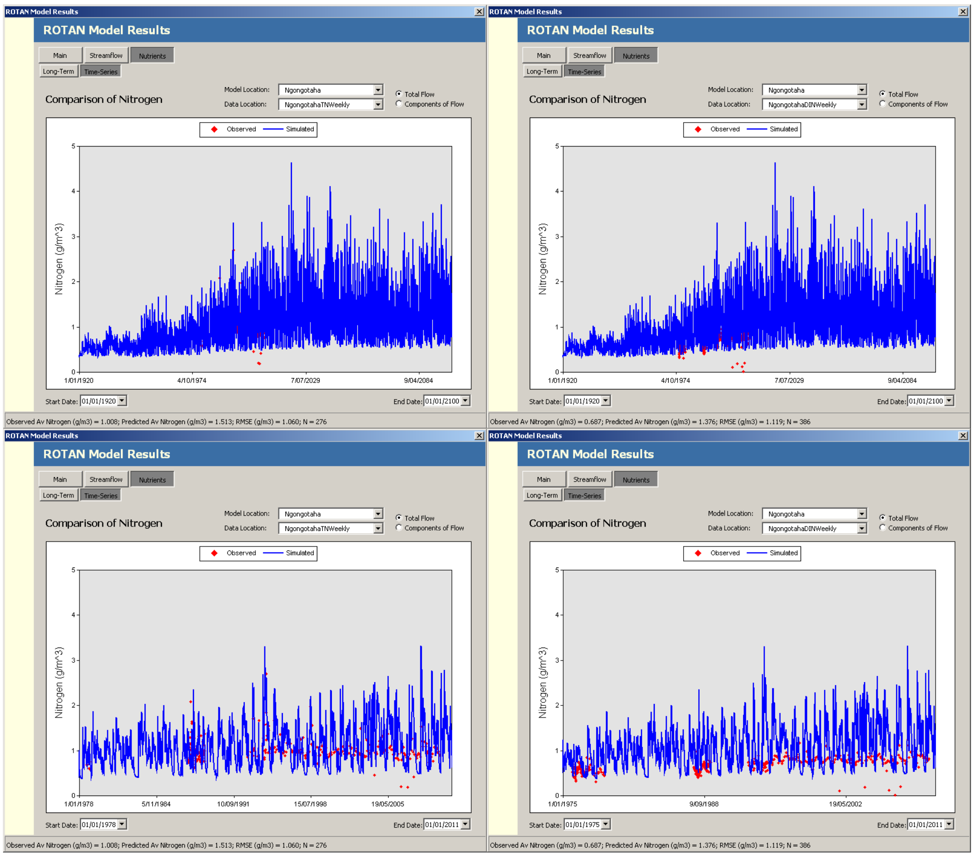


Figure A46: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Ngongotaha Stream.

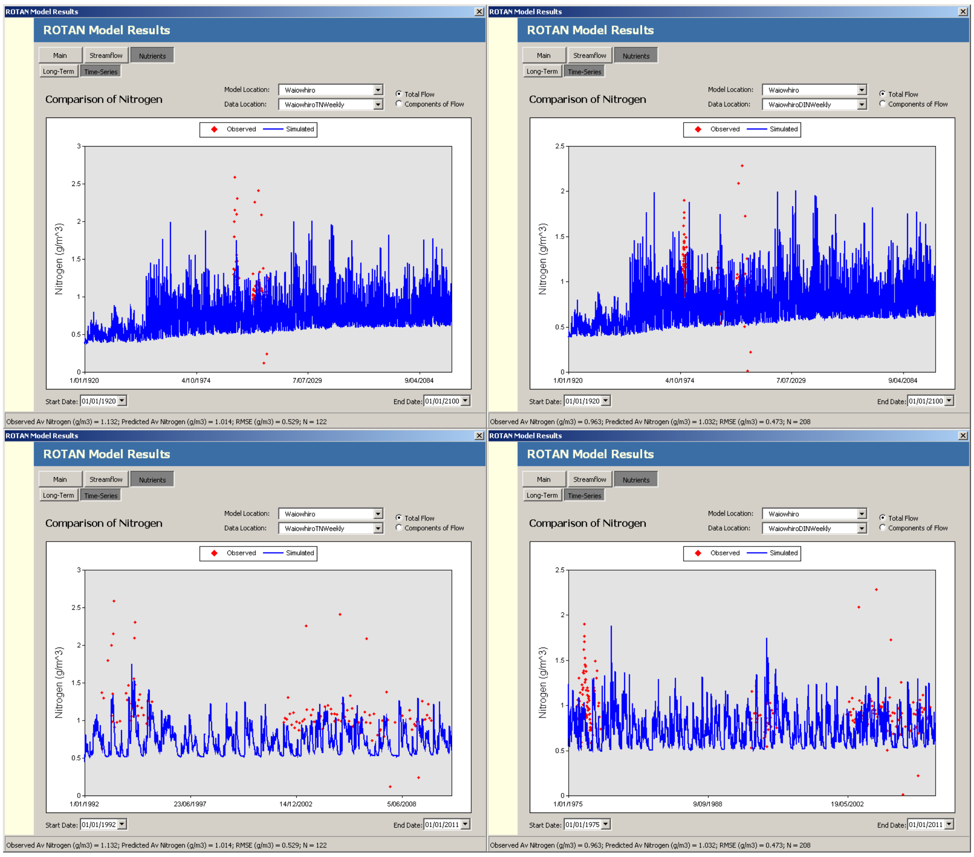


Figure A47: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiowhiro Stream.

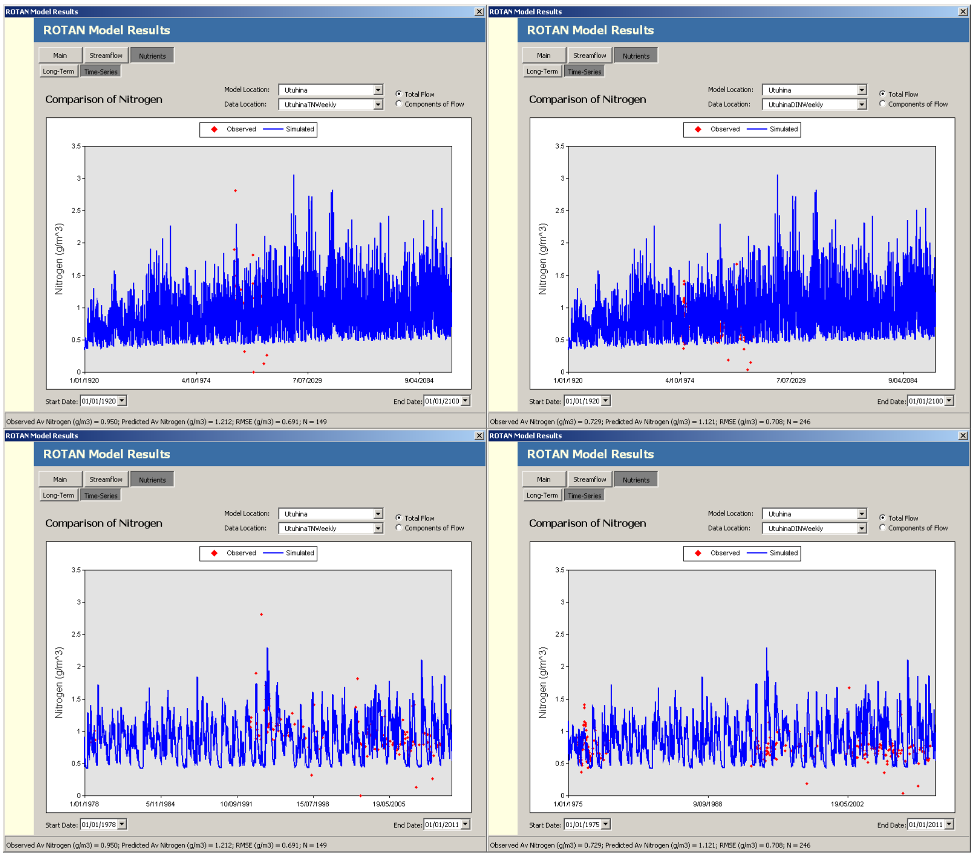


Figure A48: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Utuhina Stream.

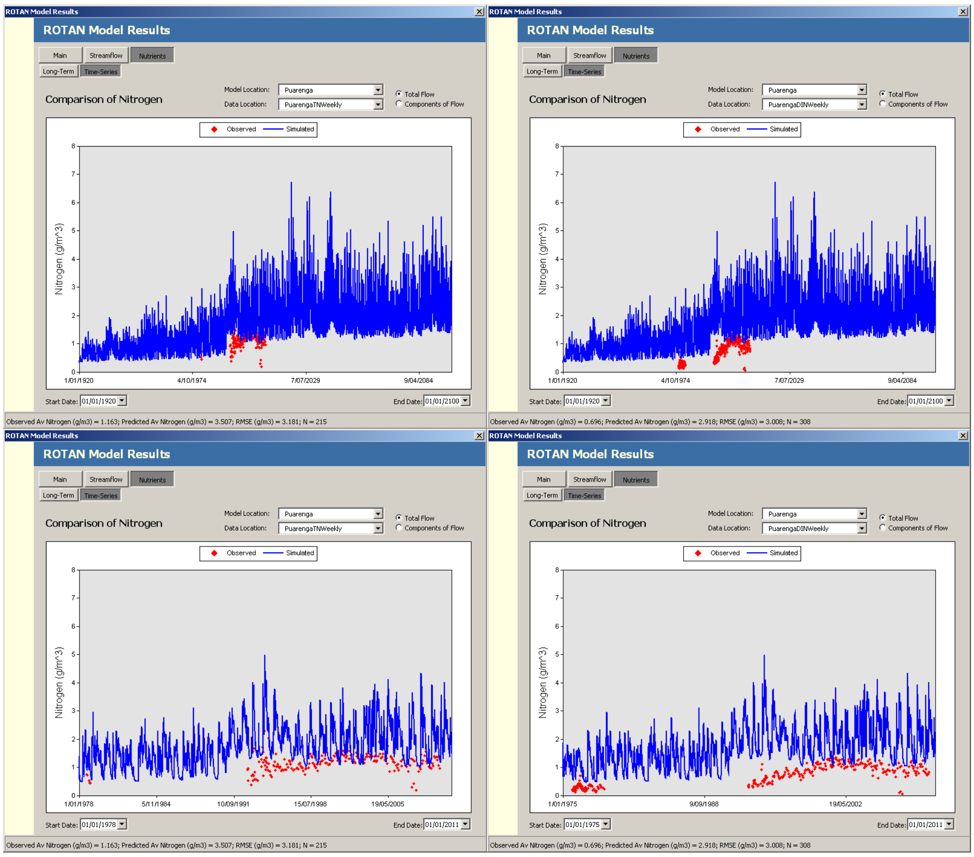


Figure A49: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Puarenga Stream.

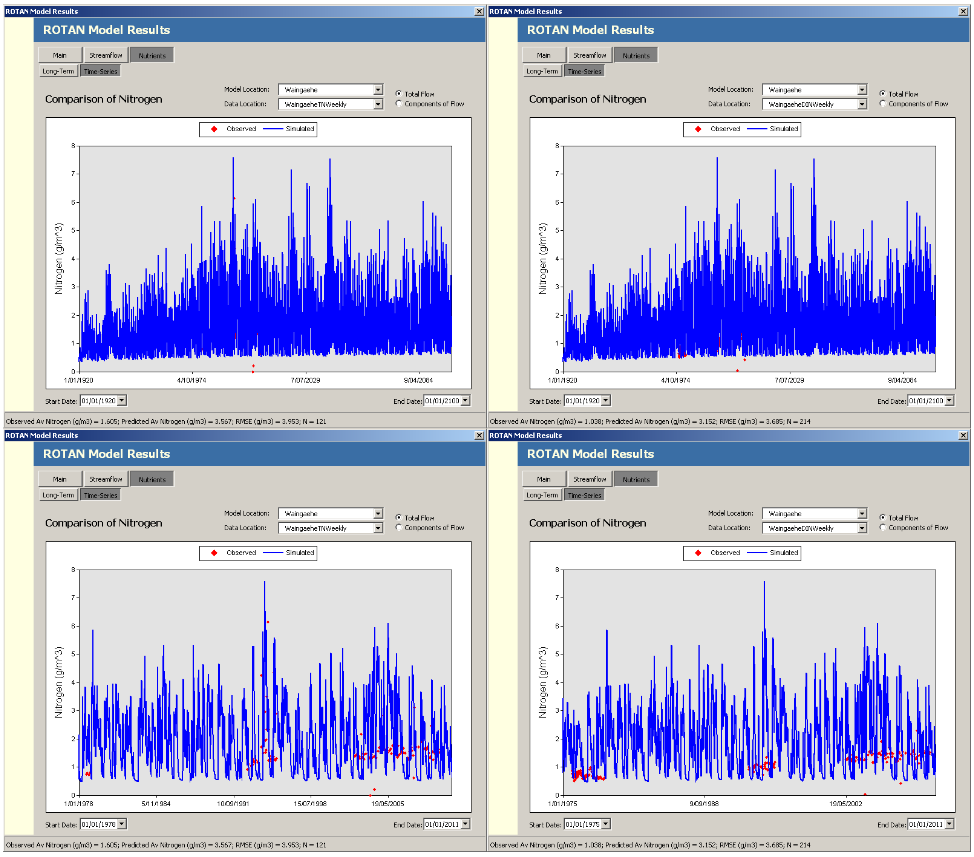


Figure A50: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waingaehe Stream.

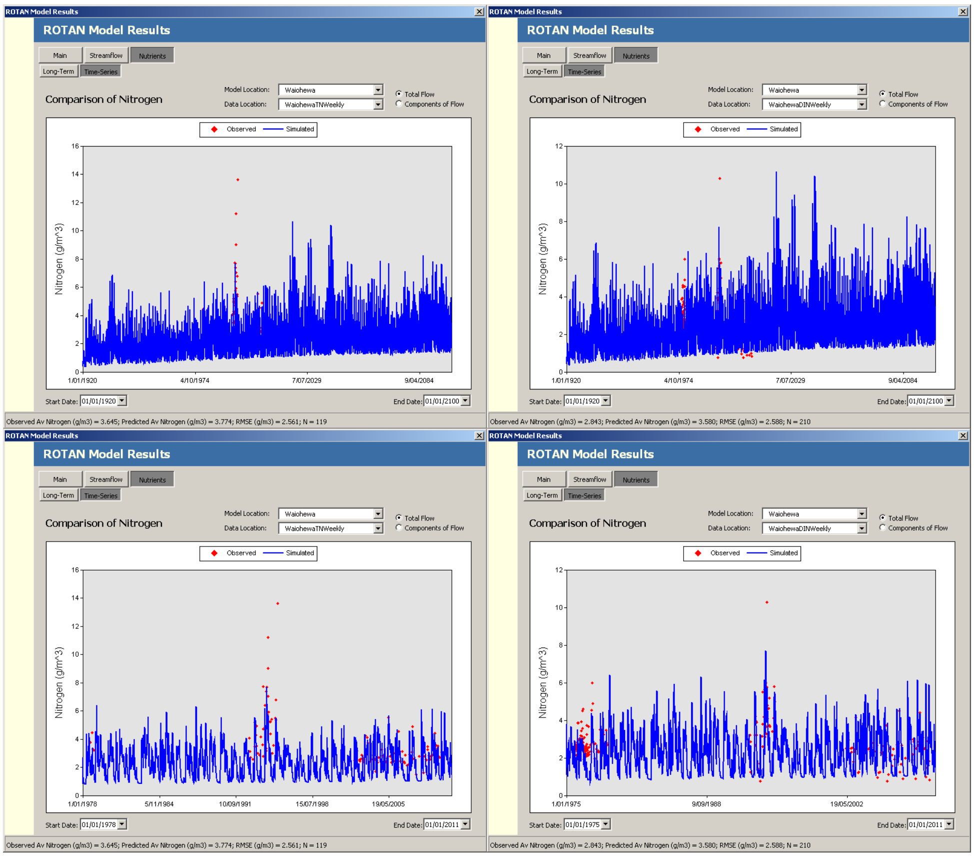


Figure A51: ROTAN-4: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiohewa Stream.

19. Appendix 7: Predicted and observed stream flows and nitrogen concentrations for ROTAN-8

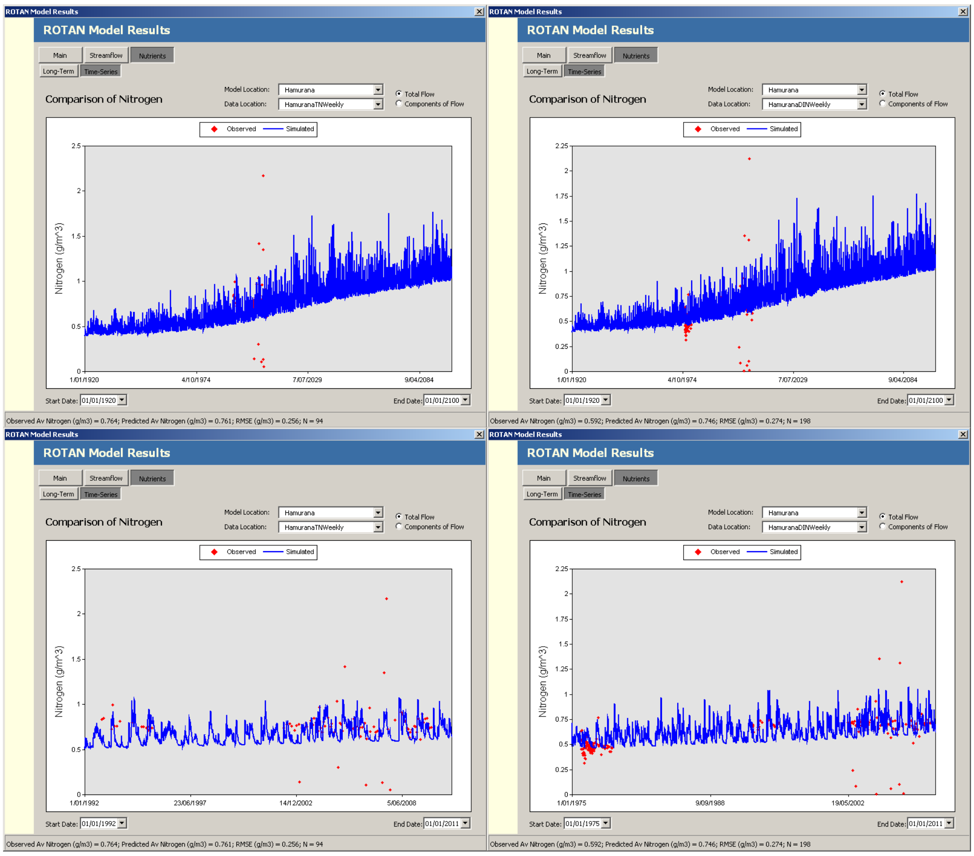


Figure A52: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Hamurana Stream.

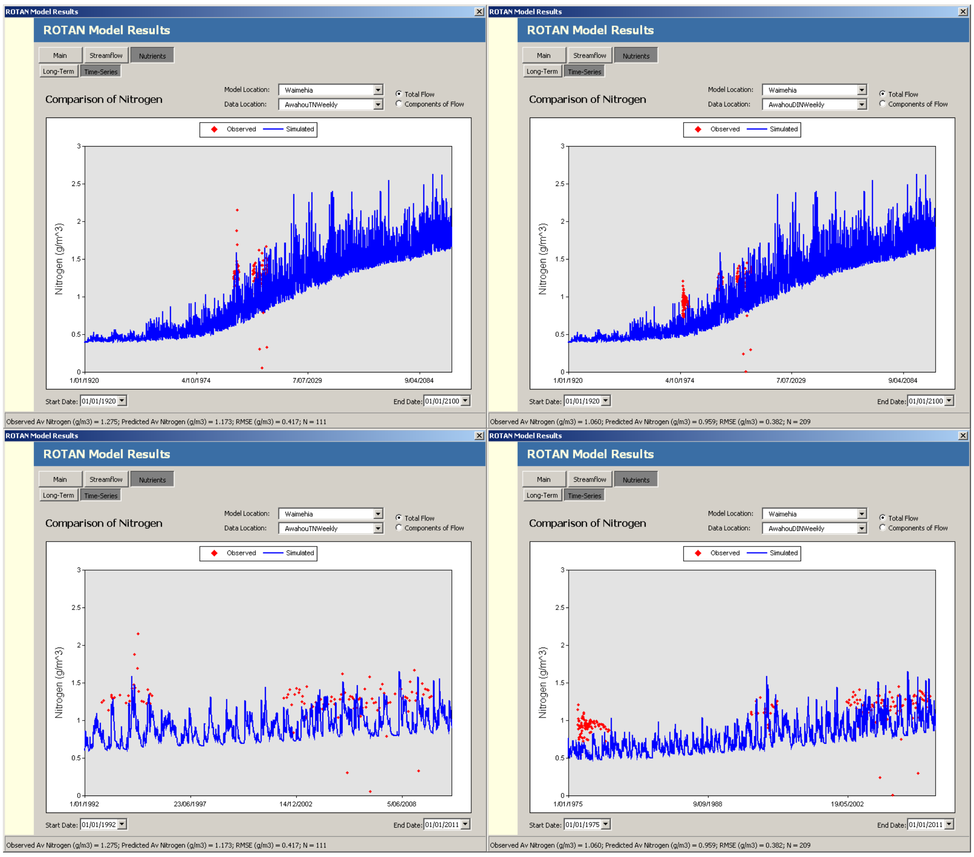


Figure A53: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Awahou Stream.

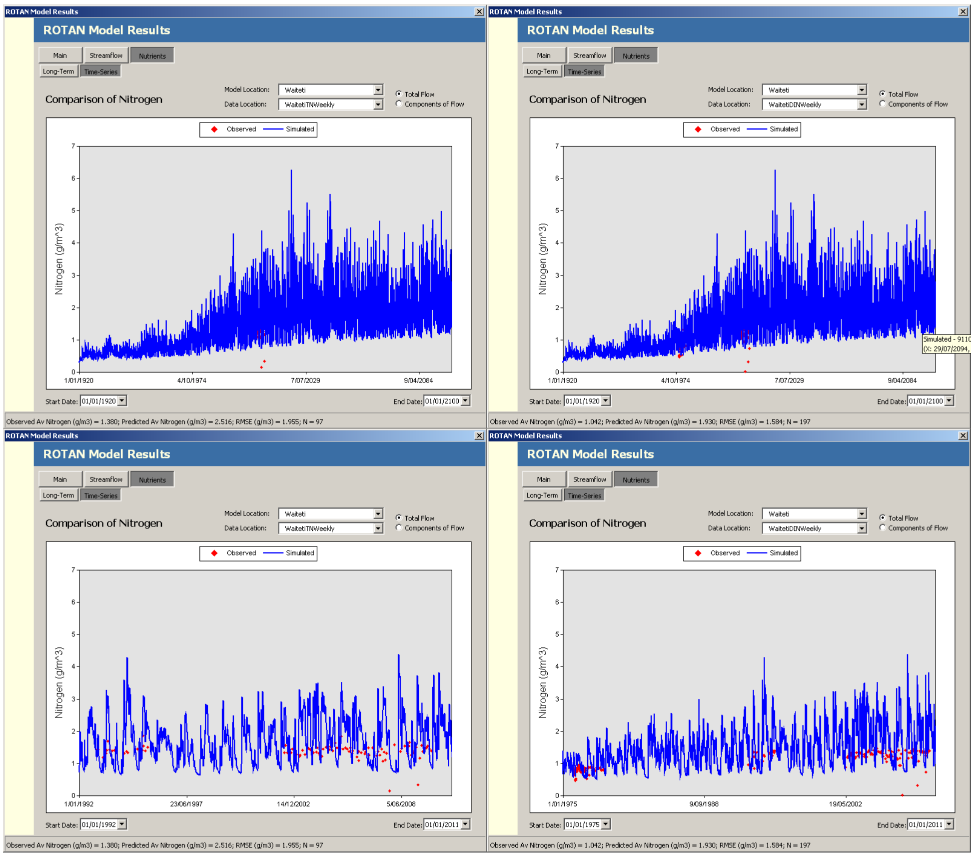


Figure A54: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiteti Stream.

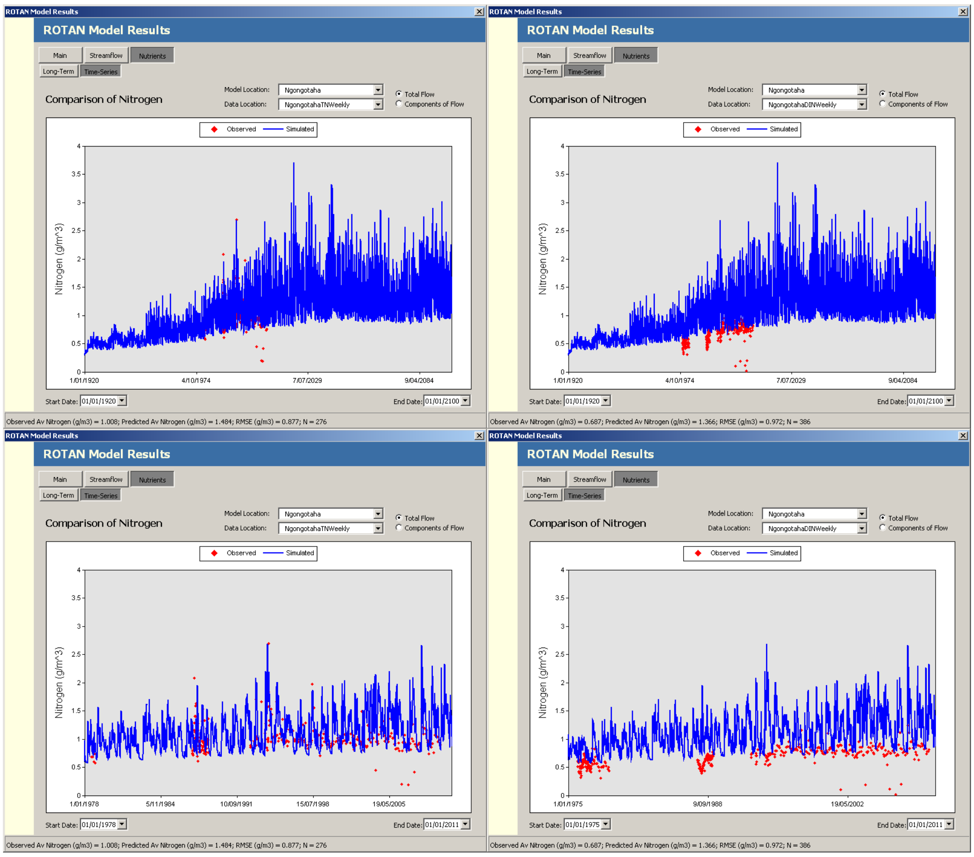


Figure A55: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Ngongotaha Stream.

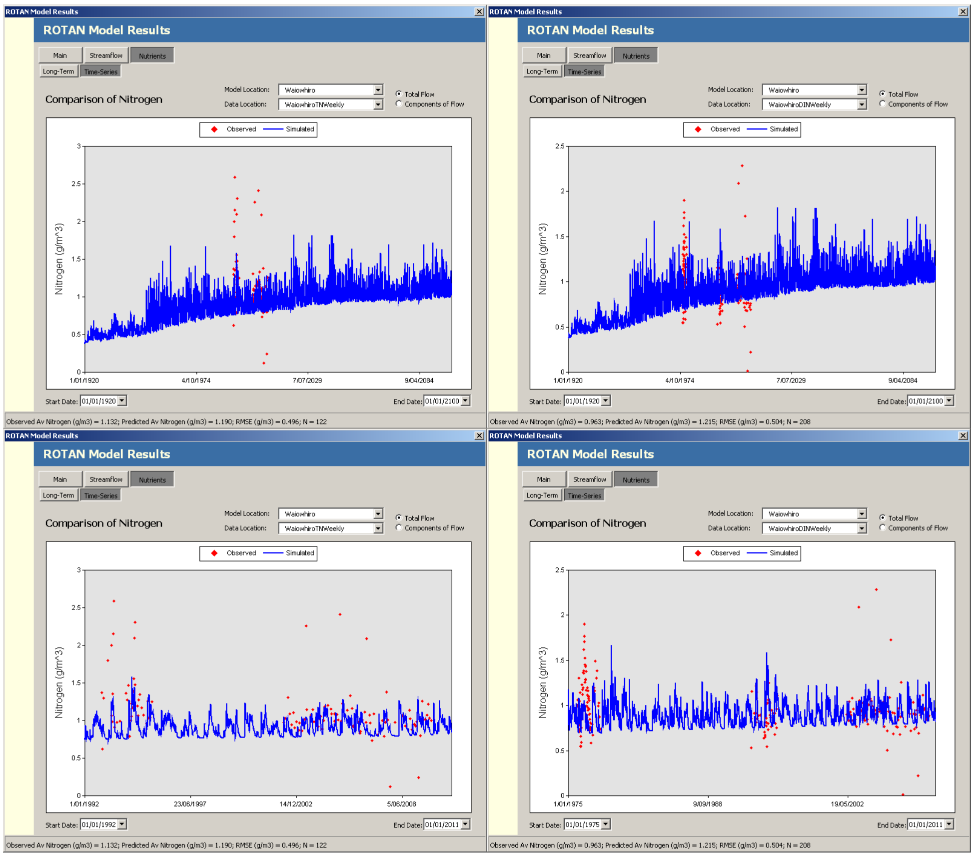


Figure A56: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiowhiro Stream.

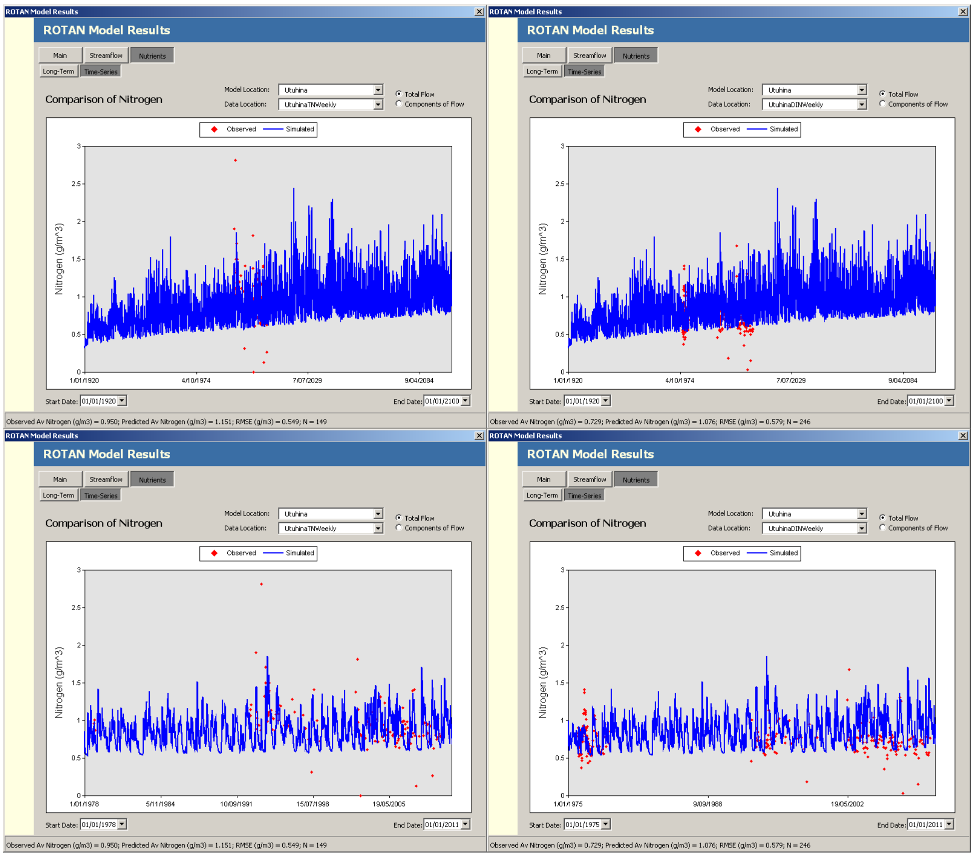


Figure A57: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Utuhina Stream.

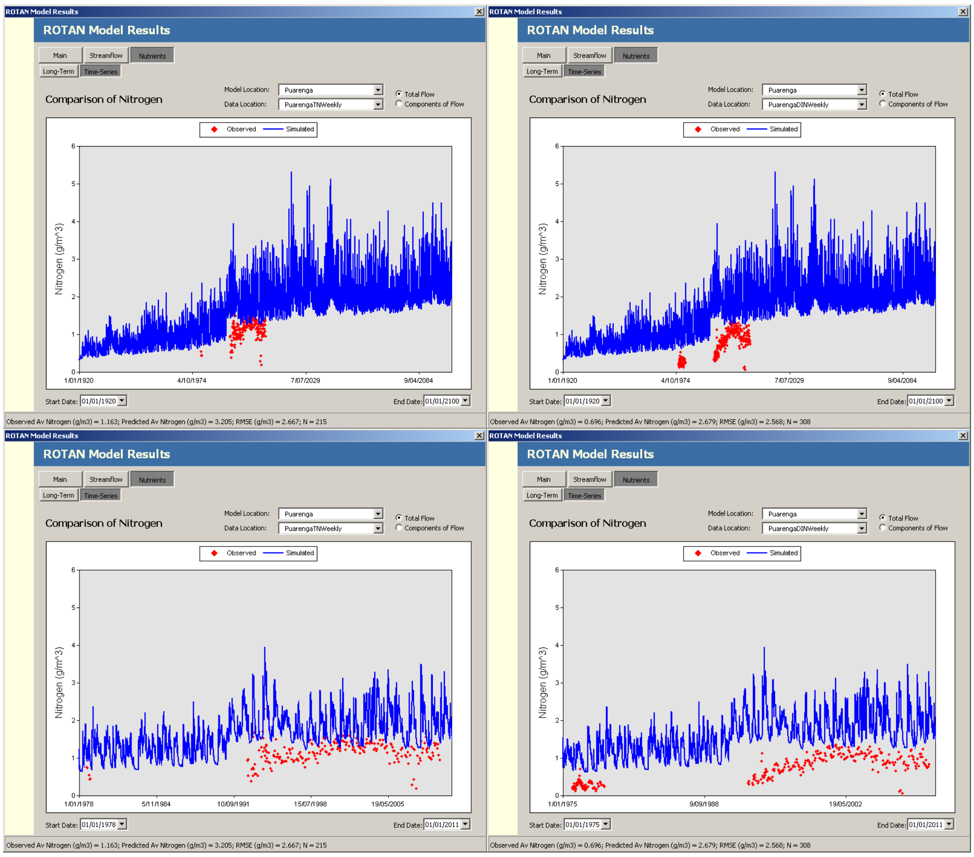


Figure A58: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Puarenga Stream.

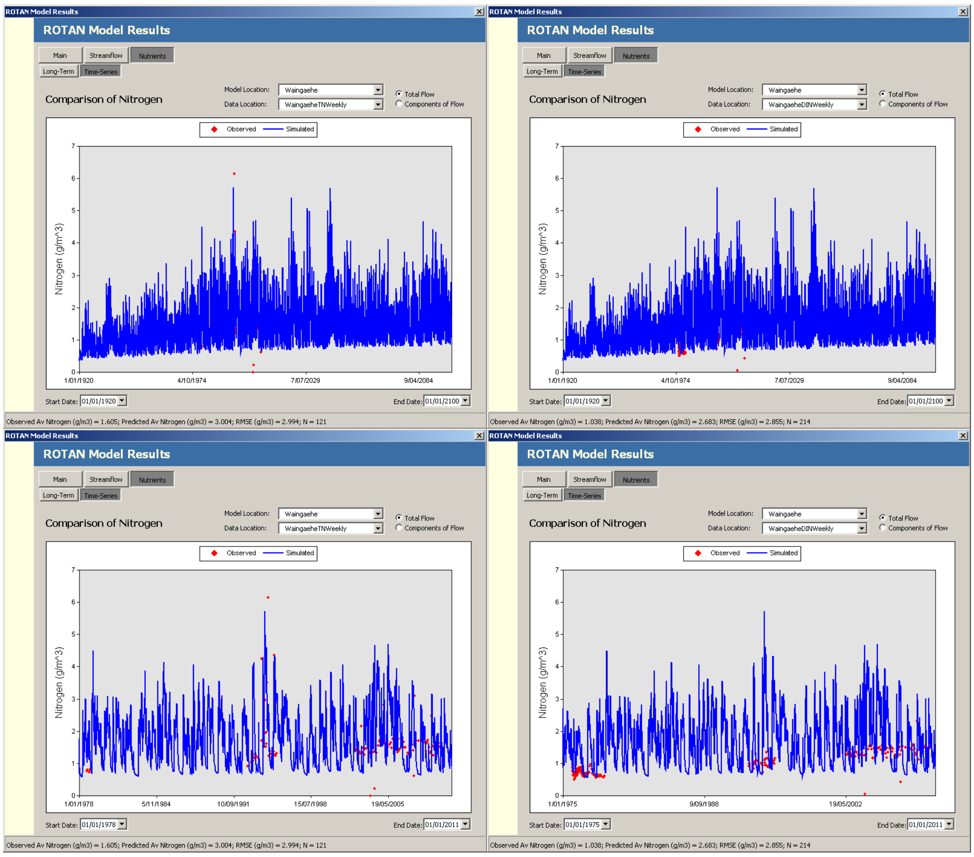


Figure A59: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waingaehe Stream.

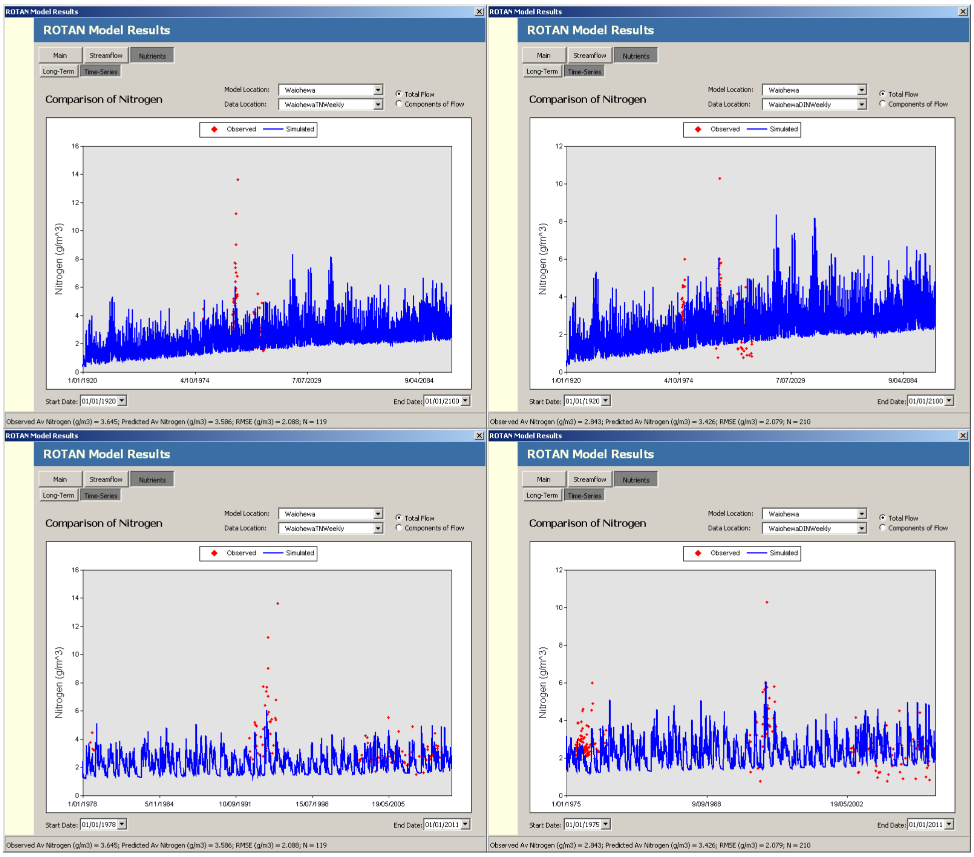


Figure A60: ROTAN-8: Predicted weekly average TN concentration (blue lines) and observed (red circles) weekly average TN (left) and DIN (right) concentration in the Waiohewa Stream.