Summary of ROTAN results

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6.1 Introduction

Bay of Plenty Regional Council (BoPRC) is required by Method M2 in PC10, and the related Science MOU, to review aspects of the science of Lake Rotorua. BoPRC requested that a 'module' covering ROTAN be prepared for the M2 review, with the following brief:

'…No new review is required. A summary (about 2 pages) of the 2011 and 2016 NIWA reports and/or PC10 evidence will suffice, with brief notes on N loss rates, groundwater trends and attenuation rates, including existing sensitivity analyses for ROTAN and OVERSEER inputs…'

6.2 Key Questions

In 2011

- What reductions in nitrogen loss from farmland, forestry and point source discharges are required to meet the lake load target?
- How quickly will the lake load decrease following mitigation?
- Will focusing mitigation on sub-catchments with 'young' groundwater reduces the lake load more quickly than uniform mitigation?

In 2017

- Given that the latest version of OVERSEER estimates higher nitrogen losses than the version used in 2011, are the loss reductions agreed in 2011 (after being adjusted to the new OVERSEER) more than, or less than, required to meet the lake load target?
- What effects do the change in OVERSEER, refinements to the groundwater boundary and stream monitoring since 2011 have on model calibration and predicted lake load?

6.3 Approach

Two versions of the catchment model ROTAN were used to address the key questions posed above. Both versions of ROTAN are conceptual catchment models based on the Scandinavian model HBV-N that routes water and nitrogen losses from farmland through groundwater and streams to the lake, taking account of attenuation and groundwater time lags. Groundwater makes a significant contribution to water and nitrogen loads to Lake Rotorua, and ranges in mean age from 14-170 years. In the ROTAN models, water and nitrogen travel to the lake by three pathways: quickflow (surfaceflow and interflow), slowflow (deep groundwater) and streamflow.

ROTAN-2011 was originally developed in 2008-2009 because none of the models available at the time was capable of incorporating OVERSEER to estimate farm nitrogen losses, and of modelling groundwater using the available information. ROTAN-2011 used OVERSEER v5.4.2 and operated with a weekly timestep.

OVERSEER was upgraded in 2017 and for PC10 BoPRC use v6.2.0, which calculates nitrogen losses at Rotorua 88% higher on average than v5.4.2. A modified model, ROTAN-Annual[1], was developed in 2017 to support PC10 which uses OVERSEER v6.2.0, revised groundwater boundaries and recent stream monitoring data. ROTAN-Annual operates at a yearly time step

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[1] Rutherford, J.C., MacCormick, A. (2016). Predicting nitrogen inputs to Lake Rotorua using ROTAN-Annual. *NIWA Consultancy Report 2016102HN*. Project BOP16201. October 2016.

which is consistent with OVERSEER (which reports annual nutrient loss) and the annual target load for Lake Rotorua.

Land use/cover maps, agricultural statistics and 'expert opinion' from landowners provided input data for OVERSEER v6.2.0 which predicted historic farm losses from 1900-2015 for input into ROTAN-Annual.

Nitrogen removal along each pathway (termed attenuation) is quantified in ROTAN-Annual using three separate coefficients whose values were calibrated to match monitored stream concentrations from 1967-2015 using groundwater residence times[2] and aquifer boundaries[3] published by GNS-Science. It was not feasible to determine the attenuation coefficients directly, and hence they needed to be estimated by model calibration. Calibration relied heavily on measured stream concentrations because there were only limited groundwater concentration data. There is uncertainty about which land parcels drain to each monitoring site and the associated groundwater travel times. There is also uncertainty in the timing of land use intensification, and historic farm nitrogen losses.

6.4 Results and Discussion

The ROTAN-2011 study estimated that the sum of nitrogen export from forests, farmland, geothermal, urban and treated sewage in 2010 was 725 tN y^{-1} and that to meet the lake load target, exports would need to be reduced by about 320 tN y^{-1} (see Table 1). These losses were estimated using OVERSEER v5.4.2. The 2011 modelling concluded that such reductions would result in a significant decrease in lake load within 35 years. Prior to the 2011 modelling, it had been assumed that the best way to reduce the lake load quickly would be to reduce nitrogen losses in catchments with short groundwater lag times. However, modelling indicated that catchments with widely differing groundwater lag times responded at a similar rate in terms of nitrogen export. Two factors contribute to this finding. Firstly, near-surface flow (estimated to supply about half the lake nitrogen load) is 'young' water, whose nitrogen concentrations will respond quickly to any reductions in farm losses. Secondly, 'old' groundwater (estimated to supply the other half of lake nitrogen load) is modelled using large, deep aquifers assumed to be well-mixed. Nitrogen concentrations in 'old' groundwater are low, having not reached equilibrium with the overlying land use. It will take a long time for nitrogen concentrations in 'old' groundwater to reach their final equilibrium values following the proposed reductions in farm losses. Nevertheless, the 2011 modelling predicted that the lake load is likely to decline faster than might be inferred from the published groundwater ages.

A critical factor in determining how quickly lake loads decrease after the proposed N loss reductions is the amount of mixing that occurs in the groundwater. Morgenstern [2] used the exponential-pistonflow model (EPM) to analyse tritium (and other atmospheric tracers) in groundwater. By matching measured tritium concentrations, they infer the proportions of mixing (the exponential E component of the EPM model) and piston flow (the P component). ROTAN-Annual uses a similar EPM modelling approach and for the PC10 study predicted that lake N loads would decrease following the proposed N loss reductions at a similar rate to the ROTAN-2011 predictions.

In 2017 the ROTAN-Annual study used OVERSEER v6.2.0 which estimated nitrogen losses on average 88% higher than those estimated using OVERSEER v5.4.2 and used in the ROTAN-2011

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[2] Morgenstern, U.; Daughney, C.J.; Leonard, G.; Gordon, D.; Donath, F.M.; Reeves, R. (2015). Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand. *Hydrology & Earth Systems Science 19: 803-822.*

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

modelling. A key issue for many stakeholders is the reliability of OVERSEER estimates of N losses from farmland. OVERSEER has been tested at a limited number of sites across New Zealand. The accuracy of N leaching is variously stated to be ±20% and 25-30% [4, 5]. We assumed that the accuracy of OVERSEER predictions of N loss given good input data is ±30%. Soils on many farms at Rotorua (well drained loams and sandy-loams) are like those at Taupo (smap.landcareresearch.co.nz) where OVERSEER has been tested [6]. Rainfall is higher in some parts of the Rotorua catchment than at Taupo. I understand that AgResearch is currently measuring N leaching losses on two farms at Rotorua where soils are permeable and rainfall is high but results were not available for consideration during the ROTAN-Annual modelling. Uncertainty in OVERSEER also stems from inaccuracies in input farming data [7] which is high for historic farming systems. Based on published agricultural statistics, we estimated the uncertainty in historic N losses to be ±50%.

The 88% difference in average N losses between OVERSEER Version 5 and Version 6 raises concerns about the accuracy of the input data used in ROTAN-2011 and ROTAN-Annual. The owners strive to 'improve' OVERSEER as information comes to hand. Updating to Version 6 included changing from an annual to a monthly time step, accounting for seasonal changes in animal numbers, estimating N losses using drainage rather than rainfall, including a wider range of soils/rainfall/drainage classes, and revising the cropping model [8]. The contribution of each of these changes to the overall 88% difference at Rotorua is not clear, but OVERSEER documentation says '…leaching dominates N losses from pastoral systems…' which suggests the model is very sensitivity to the leaching sub-model. There is evidence from our modelling that the OVERSEER Version 6 losses are credible. ROTAN-2011 used OVERSEER Version 5 losses and matched observed stream concentrations with negligible attenuation. This was an unexpected finding because the proportion of N losses reaching the catchment outlet (viz., the proportion attenuated) varied from 39-45% in three Waikato catchments (land area 2,833-4,614 km^2 c.f., 424 km^2 at Rotorua) [9]. Using Version 6 losses, ROTAN-Annual matched observed stream concentrations with an average attenuation of 42% which is a plausible value.

OVERSEER documentation says '…nitrate (NO3N) is the main form of N captured by OVERSEER plus some allowance for dissolved organic nitrogen (DON)…' [5]. DON was found to be 58% of TN leached from Taupo soils, with ranges of 5-70% from other New Zealand studies [6]. It is not clear from the OVERSEER documentation how much DON is included in the estimated losses. OVERSEER includes losses from overland flow, direct deposition in waterways, effluent pond discharges, and septic tanks although its documentation says these losses are small. OVERSEER

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[4] Ledgard S. F., Waller J. E. (2001) Precision of estimates of nitrate leaching in Overseer®. Report to FertResearch. AgResearch Ruakura. 16p.

[5] Watkins, N., Selbie, D. (2015). Technical Description of OVERSEER for Regional Councils. *Report RE500/2015/084*. AgResearch, Hamilton.

[6] Hoogendoorn, C.J., Betteridge, K., Ledgard, S.F., Costall, D.A., Park, Z.A., Theobald, P.W. (2011). Nitrogen leaching from sheep-, cattle- and deer-grazed pastures in the Lake Taupo catchment. *Animal Production Science 51:* 416-425.

[7] Shepherd, M., Wheeler, D. & Power, I. (2009). The scientific and operational challenges of using an OVERSEER® nutrient budget model within a regulatory framework to improve water quality in New Zealand. In: *Proceedings of the 16th Nitrogen Workshop, Turin, Italy, July 2009.* pp 601-602.

[8] OVERSEER Technical Note No. 5 https://www.overseer.org.nz /files/download/ ac9380fbd3fb379

[9] Alexander, R.B., Elliott, A.H., Shankar, U., McBride, G.B. (2002). Estimating the sources and transport of nutrients in the Waikato River Basin, New Zealand, *Water Resources Research 38(12).*

does not model streambank or hillslope erosion [5] and so may underestimate particulate N (PN) losses.

ROTAN-Annual was calibrated to match stream total nitrogen (TN) concentrations (TN is the sum of nitrate, nitrite, ammonium, DON and PN). The rationale for this is that even if N losses occur predominantly as NO3N, some NO3N is likely to be converted to other forms (e.g., DON and PN) before reaching the spring/stream. Effectively we are assuming that OVERSEER estimates TN losses from farms, but that TN is predominantly in the form of NO3N.

ROTAN-Annual is calibrated to flow-weighted annual mean TN concentrations calculated from routine (typically monthly) stream sampling. Routine sampling is likely to have missed floods, although there are some samples in the dataset that were collected during high flows. Hoare [10] sampled floods in Rotorua streams and reported annual TN loads to the lake of 517 and 492 t N y^{-1} for 1976 and 1977 respectively. These loads included floodflow PN (30 t N y^{-1}) which accounted for only 6% of the TN load. Abell [11] conducted high frequency sampling during 17 floods in the Puarenga and Ngongotaha Streams in 2012-2014, and found that omitting the two largest floods only reduced annual TN yields by 6-7%. Thus, not sampling floods is likely to underestimate the annual load but the bias is unlikely to exceed 10%. In the late 1980s the Lake Rotorua Scientific Coordinating Committee agreed that floodflow PN should be omitted when calculating the load of 'bioavailable' N to Lake Rotorua – the rationale being that c. 50% of the load of particulates would settle on the lake bed and not contribute to eutrophication.

OVERSEER probably underestimates N losses during storms because it focuses on leaching, and does not model PN losses from erosion or critical sources areas. In addition, OVERSEER appears not to include DON losses. Nevertheless, OVERSEER provides a quantitative index of the effects of land use. OVERSEER documentation [7] emphasises its strength in quantifying the effects of changes in farm practice. We take this to mean that OVERSEER estimates of the change in N losses with a change in land use are more accurate (including being unbiased) than estimates of actual nitrogen losses. This being so, if OVERSEER underestimates N losses, when ROTAN is calibrated against observed stream and groundwater N concentrations, the resulting attenuation coefficients will be underestimates. However, when the model is used to make predictions following land use change using the calibrated attenuation coefficients, there is a reasonable expectation that predictions will be unbiased.

When ROTAN-Annual was calibrated, several combinations of attenuation coefficients gave equally good fits to stream N concentrations. The slowflow (groundwater) and streamflow attenuation coefficients in ROTAN-Annual were found to strongly influence predicted stream concentrations and were inversely correlated. Thus, an equally good fit was possible using low slowflow/high streamflow attenuation, and high slowflow/low streamflow attenuation. Predictions were insensitive to quickflow attenuation. There were insufficient data available to estimate the slowflow and streamflow attenuation coefficients independently. Morgenstern argues that N attenuation in groundwater at Rotorua is negligibly small [2]. This is based on the finding that oxygen concentrations are high in water >100 years old, implying little microbial activity including denitrification (the principal cause of N loss in groundwaters). When I calibrated ROTAN-Annual, one combination of attenuation coefficients that gave a good fit to observed stream concentrations was negligible groundwater (slowflow) attenuation and high stream attenuation. Thus, the ROTAN modelling is not inconsistent with Morgenstern's suggestion of negligible groundwater attenuation. However, I cannot rule out (based on

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

[11] Abell, J.M., Hamilton, D.P., Rutherford, J.C. (2012). Quantifying temporal and spatial variations in sediment, nitrogen and phosphorus transport in stream inflows to a large eutrophic lake. *Environmental Science Processes & Impacts*. doi: 10.1039/c3em00083d.

ROTAN calibration) the possibility of low but non-zero slowflow attenuation. If groundwater attenuation is negligibly small (as argued by Morgenstern) then most attenuation must be occurring the vadose zone (just below the root zone), in streams, and/or in the riparian zone. We estimate that about half the total nitrogen load is transported to the lake in shallow groundwater and stream flow, with the other half transported in groundwater.

Viner [12] collated data on nutrient removal (streamflow attenuation) rates in New Zealand streams, which were used to constrain streamflow attenuation coefficients during ROTAN-Annual calibration. However, reported nutrient removal rates varied across an order of magnitude and did not allow unique values to be estimated in Rotorua streams. It would be possible to measure streamflow attenuation rates at Rotorua – as discussed below.

The inability to estimate unique values of the three attenuation coefficients indicates that ROTAN is an 'over determined' model. One remedy is to simplify the model and have only one attenuation coefficient. The reason we did not take this approach was that desire to model the effects of groundwater lags and changes over time in N loss with landuse intensification. Water and nitrogen travels to the lake along several different pathways with different travel times, and I see no merit in trying to 'lump' these together. One way to combat 'over determination' in ROTAN would be to conduct experiments that measure directly one or more of the attenuation coefficients – as discussed below.

Although calibration furnished several combinations of attenuation coefficients, these different combinations gave similar predicted lake loads. This is not surprising given that all the combinations of attenuation coefficients identified during calibration matched observed stream concentrations (viz., lake loads). This indicates that not being able to estimate unique attenuation coefficients does not pose a problem when predicting lake load – the focus of the study.

When the model was calibrated assuming that attenuation coefficients were the same in all sub-catchments, it was not possible to obtain a satisfactory match to observed stream concentrations at all 10 monitoring sites. The mismatches may have been the result of uncertainty in model input data, or differences in attenuation between sub-catchments. When the model was calibrated allowing attenuation coefficients to vary between sub-catchments, the goodness of fit to monitored stream concentrations improved slightly. However, there were no obvious reasons for the differences in calibrated attenuation coefficients between sub-catchments. Predicted lake loads were not significantly different assuming homogeneous or variable attenuation coefficients. At the PC10 hearings, submitters were keen to exploit the apparent differences in attenuation between sub-catchments, and to manage each sub-catchment differently. I warned against this because the apparent differences in attenuation may very well be an artefact of uncertainties in the model and/or its input data. Firstly, the boundaries of the recharge zones draining to major springs and stream monitoring sites are uncertain (notably in the Awahou and Hamurana). While the area of the recharge zone can be estimated using a water balance, the complexity of the hydro-geology suggests to me that deciding where the boundaries lie is fraught with difficulty. GNS has estimated boundaries assuming homogeneous porous media but clearly the Mamaku ignimbrites are anything but homogeneous. GNS has developed a groundwater model that could help but few results are available. Secondly, the land use history in each sub-catchment is uncertain (e.g., when exactly did dairy farms come into full operation in the Awahou catchment?). Thirdly, OVERSEER is a steady-state model and there is uncertainty about how long it takes N losses to adjust to a new equilibrium after a significant land use change (e.g., how long after converting a sheep/beef farm to dairy does the N loss rate for the dairy farm apply?).

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[12] Viner, A.B. (Ed). (1987). Nitrogen, phosphorus and oxygen dynamics in rivers. In: *Inland Waters of New Zealand*. DSIR Bulletin 241.

ROTAN-Annual was run using numerous feasible combinations of coefficients (a Monte Carlo simulation). The 'most likely' steady state load for current land (750 t y^{-1}) (range 670-840 t y^{-1}) matches the ROTAN-2011 estimate (725 t y^{-1}) which shows that the results of the 2011 study are still valid even though OVERSEER has changed, new groundwater boundaries have been defined and there are seven years more stream monitoring data. What differs between models is that in ROTAN-2011 (with nitrogen losses estimated using OVERSEER v5.4.2) calibrated attenuation was zero in nine of the ten catchments, whereas in ROTAN-Annual (OVERSEER v6.2.0) attenuation was non-zero in all catchments.

For the loss reductions in PC10, ROTAN-Annual predicted a steady-state lake load of 425 t y^{-1} (390-460 t y^{-1}). This is slightly higher than the target lake load of 405 t y^{-1} but the difference may not be statistically significant. Assuming the distribution of predicted lake loads to be either uniform or normal, with upper and lower bounds of 390 and 460 t y^{-1}, then there is a 21% or 13% probability the steady state lake load will be less than, and a 79% or 87% probability it will be greater than, the target of 405 t y^{-1}. Thus, there is a negligible risk the nitrogen control measures in PC10 will be more than required, but a risk (c. 12-20%) they will be less than required to meet the lake target. ROTAN-Annual predicts that nitrogen reductions specified by BoPRC will reduce lake loads to within 25% of the target within 25 years although steady-state may not be reached until after 2100. The time-scale of recovery is like that predicted by ROTAN-2011.

6.5 Limitations and Gaps in Understanding

When calibrating ROTAN-Annual, it was clear that there were uncertainties in key model input data, notably: historical stocking rates and nitrogen losses; boundaries of the recharge zones feeding the major springs and spring-fed rivers; and hence the flow pathways and travel times between individual farms and springs, streams or the lake.

The majority of stream concentration and flow observations are at sites close to the lake, with few longitudinal surveys of stream flow and concentration. Consequently, stream attenuation coefficients could not be quantified directly. Groundwater concentrations have been monitored at only two sites, although synoptic sampling has been undertaken in nearly 200 bores and springs. Groundwater age measured in several of the major springs and streams, but not at multiple points along streams. These data limitations meant that it was not possible to identify flow pathways, residence times and N concentrations, and hence to estimate groundwater attenuation coefficients directly.

Stream and groundwater attenuation coefficients were estimated by calibration to stream concentrations, with the few available groundwater concentrations helping to constrain calibrated coefficients. However, it was found that unique values for these attenuation coefficients could not be found by calibrating to stream monitoring data. Rather several combinations of (correlated) coefficients gave equally good fits to measured stream concentrations. One consequence is that calibrated coefficients have a high uncertainty, and it was not possible to determine whether attenuation is higher in some sub-catchments than others. The Committee hearing the PC10 noted that evidence '…warned (submitters) against trying to exploit the apparent differences in attenuation between sub-catchments because they are unreliable…' and that '…the expert evidence was not contested...'

6.5 Recommendations for future actions

1. There is little that can be done to refine historical information on stocking rates and nitrogen losses. However, routine monitoring of groundwater at key locations would allow future nitrogen concentration changes over time to be quantified. Initially, concentrations are expected increase as groundwater affected by high nitrogen

drainage from recent land use intensification arrives at the monitoring sites, but as mitigation measures take effect they are expected to decrease.

2. Additional synoptic surveys of groundwater would better quantify the spatial distribution of nitrogen concentration, together with iron, manganese, oxygen, carbon and redox (indicators of the likely groundwater attenuation rate). Routine monitoring of groundwater concentrations would allow the effectiveness of remediation to be tracked over time.
3. Longitudinal surveys of stream flow would indicate where shallow and deep groundwater re-emerges into streams. This would enable refinement of flow pathways and aquifer boundaries – critical in the ROTAN modelling. Measuring water age in longitudinal surveys would help refine current estimates of groundwater flow pathways and residence times. Longitudinal surveys of flow and nitrogen concentration would allow stream attenuation to be calculated, to constrain current estimates based on Viner (1986).
4. In other parts of New Zealand, groundwater models have been used to estimate flow pathways and residence times. The hydro-geology of Rotorua is complex and although GNS-Science has developed a groundwater model, only preliminary results have been sighted to date. Further refinement of the groundwater model would help refine current estimates of groundwater attenuation, aquifer boundaries and the likely response time of lake loads to the mitigation measures proposed under PC10.

Table 1: Historic nitrogen exports for ROTAN-2011. Source: Rutherford et al. (2011).

LU Map Start-End	1940 1920–1949	1958 1950–1970	1974 1971–1980	1986 1981–1990	1996 1991–2000	2003 2001–2007	2010 2008–2100
			Exports (tN y^{-1})				
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

Note: nitrogen losses from farmland was estimated using OVERSEER v5.4.2 (now replaced in PC10 by OVERSEER v6.2.0).