Nutrient load targets for Lake Rotorua – a revisit

NIWA Client Report: HAM2008-080
May 2008

NIWA Project: BOP07223

Nutrient load targets for Lake Rotorua – a revisit

Kit Rutherford

Prepared for

Environment Bay of Plenty

NIWA Client Report: HAM2008-080
May 2008

NIWA Project: BOP07223

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

Contents

Reviewed by:

Chris Palliser

Approved for release by:

Sandy Elliott

Formatting checked

1. Introduction

This report re-examines the technical work that underpins the 'target' nutrient loads for Lake Rotorua set in 1986 and endorsed in 2005. The analysis was requested by the Lake Rotorua Technical Advisory Group at its meeting on the 4th April 2007.

2. Fish study

Dr Geoff Fish measured stream flow and collected grab samples for nutrient analysis at approximately fortnightly intervals between 1968 and 1970 (see Table 1 for sample numbers).

Only summary statistics of these data have been sighted (Fish 1975)[1]. Geoff Fish did not sample storms in as much detail as later studies. However, his average inflow from major sites (13.4 m^3 s^{-1}) is comparable with the average for 1976 (13.3 m^3 s^{-1}) measured by Hoare (1980a) which does include flood flows. Geoff Fish did not measure TP or TKN and so particulate and total nutrient loads cannot be estimated for comparison with later studies. He did not sample the Waiowhiro stream.

As discussed by Hoare (1980a) and Rutherford (1984) Dr Fish's 1968 nitrate data have caused difficulties. The mass load in 1968 given in Fish (1975) and reproduced in Table 3 is ~50% of the loads in 1969 and 1970. It is difficult to explain what could have caused such a large increase in nitrate load in one year. In previous analyses the 1968 data has been neglected and this is done again here.

[1] I have recently made enquiries with Dr Geoff Fish and Dr Max Burnett in an attempt to locate the original field books and/or summaries of the raw concentration and flow data but nothing could be located.

Table 1: Catchment area and flow for 8 major streams flowing into Lake Rotorua, as reported by Fish (1975). ND = no data.

Inflow	Area km^2	Flow $L\ s^{-1}$	SD $L\ s^{-1}$
Waingaehe	11	294	34
Waiohewa	14	479	132
Hamurana		2964	251
Awahou	15.7	1789	19
Waiteti	63	1509	101
Ngongotaha	75.5	2293	422
Utuhina	57	2215	506
Puarenga	77	1919	507
Waiowhiro	4.4	ND	
Catchment total	**317.6**	**13463**	
Sewage		34	1
Rainfall		3944	ND

Table 2: Summary of nutrient concentration in samples collected from 8 major streams flowing into Lake Rotorua, as reported by Fish (1975). Mean concentration. SD = standard deviation, num = number of samples. ND = no data.

Inflow	DRP $mg\ m^{-3}$	SD $mg\ m^{-3}$	num	NO_3N $mg\ m^{-3}$	SD $mg\ m^{-3}$	num	NH_4N $mg\ m^{-3}$	SD $mg\ m^{-3}$	num
Waingaehe	110	28	65	340	162	56	30	21	23
Waiohewa	59	23	62	650	396	55	1500	810	23
Hamurana	81	19	61	310	111	56		5	23
Awahou	66	21	62	640	248	55	10	7	23
Waiteti	40	15	62	490	264	55	20	29	23
Ngongotaha	35	14	62	300	150	56	20	11	23
Utuhina	71	24	62	410	238	56	50	22	23
Puarenga	90	31	62	90	114	56	100	46	23
Waiowhiro	ND			ND			ND		
Sewage	4180	897	64	ND	ND	ND	25770	7750	23
Rainfall	19	22	11	60	111	14	300	158	11

Table 3: Estimated nutrient loads from major streams flowing into Lake Rotorua. Load = mean concentration x mean flow. ND = no data. Recalculated from Fish (1975).

Inflow	DRP t y^{-1}	NH_4N t y^{-1}	TIN[1] t y^{-1}
Waingaehe	1.02	0.3	4.1
Waiohewa	0.89	22.7	35.8
Hamurana	7.58	0.0	33.4
Awahou	3.73	0.6	45.2
Waiteti	1.91	1.0	31.6
Ngongotaha	2.53	1.4	27.8
Utuhina	4.96	3.5	38.6
Puarenga	5.45	6.1	15.4
Waiowhiro	ND	ND	
Streams	**28.1**	**35.5**	**231.9**
Sewage	4.4	27.3	27.3
Rainfall	2.4	37.3	37.3
Streams + rain	**30.5**	**72.8**	**269**

[1] TIN load is the average NH_4N load for 1968-1970 plus the average NO_3N load for 1969-1970. The 1968 NO_3N load is suspect (see Table 4) and is omitted.

Table 4: Estimated nitrate loads from 8 major streams flowing into Lake Rotorua. Load = mean concentration x mean flow. The 1968 loads are significantly lower than the 1969 and 1970 estimates and may be suspect. Recalculated from Fish (1975).

Inflow	NO_3N t y^{-1} 1968	NO_3N t y^{-1} 1969	NO_3N t y^{-1} 1970
Waingaehe	2.3	4.2	3.5
Waiohewa	4.3	13.2	13.1
Hamurana	20.4	33.7	33.2
Awahou	25.7	46.5	42.7
Waiteti	14.8	33.5	27.8
Ngongotaha	14.9	26.4	26.2
Utuhina	17.6	37.2	33.0
Puarenga	2.2	6.4	12.2
Waiowhiro	ND	ND	ND
Catchment load	**102.1**	**201.2**	**191.6**
Sewage	0	0	0
Rainfall		20.4	

3. Hoare study

Dr Ray Hoare conducted detailed nutrient budget measurements during 1976-1977. Results are included in the next section.

4. 1978 Water Right Hearings

At the 1978 water right hearings, nutrient load estimates were presented by Dr Eddie White (Taupo Research Laboratory), Dr Ray Hoare (Hamilton Science Centre) and myself. These estimates were made independently using datasets covering slightly different periods of time. At that time data had been collected by three different agencies (Fisheries Research Division of MAF (Geoff Fish); Ministry of Works & Development (Ray Hoare) and the Taupo Research Laboratory, DSIR (Eddie White)) and a single, common dataset had not been collated. Slightly different assumptions were made by the three authors about nutrient loads in ungauged streams, and about the bioavailability of particulate nutrient, especially that carried in storm flows. Consequently the estimates differ a little from each other.

White's estimate of catchment nitrogen load (streams + rain) in 1975 (431 tN y^{-1}) is lower than Hoare's estimates in 1976-1977 (472-497 tN y^{-1}). Rutherford's estimates for the 1960s (based on Fish and Hoare's stream concentrations (assumed constant) multiplied by measured flows in the 1960s) range from 472-556 tN y^{-1} – comparable with Hoare's 1976-1977 measurements. The most reliable catchment nitrogen loads are those measured by Hoare in 1976-1977 (472-497 tN y^{-1}).

These load estimates do not include sewage loads from the treatment plant. They may include loads from septic tanks where these flowed into stream above the sampling point. There is evidence of nitrate loads from septic tanks entering the Utuhina, Puarenga, Basley and Lynmore Streams above their sampling point (Hoare 1984). For lake-side settlements (e.g., Ngongotaha) septic tank drainage is likely to flow directly into the lake. Nitrate is highly mobile and is likely to reach the lake unless denitrification occurs in reed beds around the lake margins. Phosphorus is less mobile and tends to bind to allophanic material in the soil. It is possible that very little of the phosphorus entering septic tanks reaches the lake (Rutherford 1984).

Hoare (1980a) estimated the total ungauged inflow to the lake (2100 L s^{-1}) from a water balance on the lake. He assumed this had nutrient concentrations typical of the measured streams and hence estimated the load from the ungauged catchments.

Table 5: Estimated catchment loads (1978 water right hearing evidence by White, Hoare & Rutherford) excluding floodflow particulates.

Year	Rain tP y^{-1}	Sewage tP y^{-1}	Streams[1] tP y^{-1}	Streams[1] tP y^{-1}	Total tP y^{-1}	Catchment tP y^{-1}
Phosphorus						
			Hoare (1978)			
1976	1.2	7.5	33.7			35
1977	1.0	8.0	32.6			34
			White (1978)			
1975	ND	ND	ND		ND	ND
			Rutherford (1978)[2]	**Rutherford (1987)[3]**		
1967	1.3	6.8	40		48	41
1968	1.1	6.8	37	38	45	38
1969	1.2	6.8	34	38	42	35
1970	1.6	6.8	35	38	44	37
1971	1.5	8.1	43		52	44
1972	0.9	8.7	43		53	44
1973	0.8	9.8	33		44	34
1974	1.4	9.2	32		43	34
1975	1.2	15.3	37		53	38
1976	1.2	7.5	34		42	35
1977	1.0	8.0	33		42	33
Nitrogen						
Year	**Rain tN y^{-1}**	**Sewage tN y^{-1}**	**Streams tN y^{-1}**	**Streams tN y^{-1}**	**Total tN y^{-1}**	**Catchment tN y^{-1}**
			Hoare (1978)			
1976	31	68	466			497
1977	28	64	444			472
			White (1978)			
1975	31	105	400		536	431
			Rutherford (1978) [2]	**Rutherford (1978) [3]**		
1967	34	46	522		603	556
1968	29	46	482		559	511
1969	33	46	438	370	519	472
1970	41	46	460	349	548	501
1971	39	55	559		654	598
1972	24	59	562		643	587
1973	21	66	431		519	452
1974	37	77	420		533	457
1975	31	133	475		639	506
1976	31	68	446		544	477
1977	28	64	424		515	452

[1] excludes floodflow particulates [2] calculated using data from Hoare [3] calculated using data from Fish

Table 6: Measured catchment nutrient loads in 1969-1970 (Fish) and 1976-1977 (Hoare) and estimated septic tank loads (Rutherford).

		Fish 1969-70 [5]	**Hoare 1976**	**Hoare 1977**
		tP y^{-1}	**tP y^{-1}**	**tP y^{-1}**
DRP	major sites	28.1 [4]	20.5	19.7
DRP	minor sites	ND	0.8	0.8
DRP	unmeasured	ND	3.4	3.3
DRP	rain	2.4	1.2	1
PP+DOP	baseflow	ND	9	8.8
PP+DOP [3]	floods	ND	10	10
catchment	**streams + rain**	**30.4**	**44.9**	**43.6**
TP	sewage	4.4	7.5	8
		tN y^{-1}	**tN y^{-1}**	**tN y^{-1}**
TIN	major	232	295	276
TIN	minor	ND	11	11
TIN	unmeasured	ND	70	67
DON [3]		ND	30	30
TIN	rain	37	31	28
PN	baseflow	ND	60	60
PN [3]	floods	ND	50	50
catchment	**streams + rain**	**269**	**547**	**522**
TN	sewage	27	68	64
		Septic tanks		
TP tP y^{-1}	septic tanks [1]	13.6	14.5	14.5
TN tN y^{-1}	septic tanks [2]		98	98

[1] estimated from unreticulated population assuming 0.5 kgP $capita^{-1}$ y^{-1}. May not reach the lake.
[2] estimated from unreticulated population assuming 3.4 kgN $capita^{-1}$ y^{-1}. Probably reaches the lake.
[3] may not be bioavailable (viz., may not affect lake nutrient concentrations).
[4] Fish did not measure loads in the Waiowhiro which Hoare studied.
[5] 1968 results are omitted because 1968 TIN loads were significantly lower than in 1969 & 1970

5. 1986 Position Statements

During 1986 a number of meetings were held 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 jointly by the Taupo and Hamilton research laboratories (Rutherford et al. 1986) 'The significance of phosphorus and nitrogen in the management of Lake Rotorua'). This draft underwent a number of changes and was eventually published by NWASCA in October 1986 (Howard-Williams et al. 1986). These position papers focused on the issue of sewage nutrients and recommended that:

'…removal of all sewage effluent from the catchment is expected to achieve the nutrient load reduction which is required…'

'…if complete removal proves impracticable, a less satisfactory option is the highest level of reduction that can be achieved for both phosphorus and nitrogen…'

'…any non-zero sewage discharge increases the risk…'

'…the risk of unsatisfactory lake condition is probably low if the sewage inputs are always less than 3 tonnes of phosphorus and 30 tonnes of nitrogen per year…'

The following table was included in the report and in a subsequent journal article (Rutherford et al. 1989)

Table 7: Lake Rotorua nutrient inputs and water quality (Rutherford et al. 1989).

	1965	1976-77	1981-82	1984-85	Target
Population	25,000	50,000	52,600	54,000	-
Phosphorus input					
Raw sewage t y^{-1}	5	18	30	47	-
Treated sewage t y^{-1}	5	7.8	20.6	33.8	3
Stream + rain t y^{-1} [a]	34	34	34	34	34
Internal t y^{-1}	ND	0	20	35	0 [b]
Total t y^{-1}	39	42	75	103	37
Nitrogen input					
Raw sewage t y^{-1}	34	100	170	260	-
Treated sewage t y^{-1}	20	66 [c]	134	150	30
Stream + rain t y^{-1} [a]	405 [c]	485	420	415	405
Septic tanks t y^{-1}	50	80	15	10	0
Internal t y^{-1}	ND	0	140	>260	0 [b]
Total t y^{-1}	475	558	694	>825	435
Average lake quality					
Total phosphorus mg m^{-3}		23.8	47.9	72.6	20
Total nitrogen mg m^{-3}		310	519	530	300
Chlorophyll mg m^{-3}		5.5	37.8	22.6	10
Peak chlorophyll mg m^{-3}		28	62	58	17-24
Secchi disc m	2.5-3	2.3	1.9	1.7	2.5-3
Deoxygenation g m^{-3} d^{-1}		0.4	0.7	0.9	0.25

[a] flood flow particulate P and N are excluded
[b] internal loads may be non-zero even when external loads are reduced
[c] the original table contains two typographical errors: 455 instead of 405, and 73 instead of 66.

6. Vollenweider Modelling

The Vollenweider model was used in 1986 to help set ‘target’ nutrient loads. This model relates annual nutrient input to annual lake concentration and had been previously ‘calibrated’ in Lake Rotorua (Hoare 1980b).

Figure 1 shows observed and predicted lake TN and TP concentrations as a function of total load (streams + rain + sewage) but excluding floodflow particulate loads. Also shown are annual average lake concentrations measured in Rotorua between 1967 and 1986 versus estimated annual load. There is a reasonable agreement between model predictions and observations.

Also shown are lake TN and TP concentrations of 300 mgN m^{-3} and 30 mgP m^{-3}. These concentrations are the generally agreed boundaries between mesotrophic and eutrophic lakes. It is simplistic to think that just above these limits there will be problems with lake water quality and just below the limits water quality will always be acceptable. In the 1986 discussions it was recognised that Rotorua was naturally mesotrophic, because of its shallow nature and large catchment area. For a given nutrient load, shallow lakes (like Rotorua) typically have lower water clarity and higher primary productivity than deeper lakes (Vant 1987). It would be unrealistic to attempt to restore lake water quality to that in deep, oligotrophic lakes like Taupo. It was agreed that ‘target’ lake nutrient concentrations of 30 mgP m^{-3} and 300 mgN m^{-3} were realistic and would avoid many problems associated with nutrient releases from the lake bed and algal ‘blooms’ that occurred during the 1970-1980s.

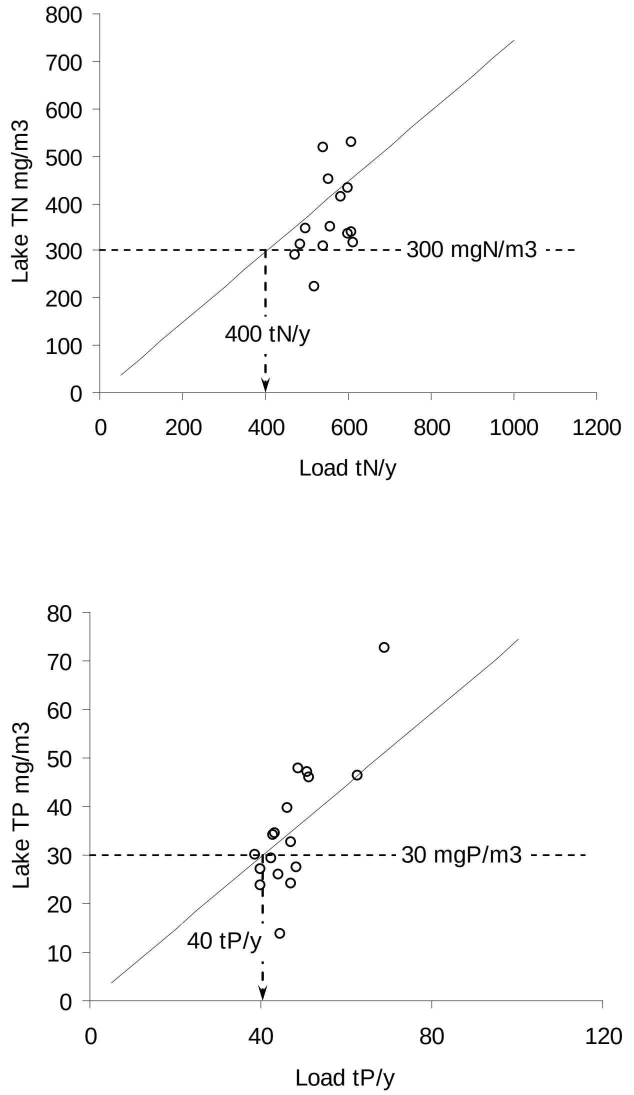

Figure 1: Annual average lake concentrations of TN (top) and TP (bottom) as a function of the annual load of 'available'.

7. 2003 Study

In September 2003 Environment B.o.P commissioned NIWA to:

> '…determine the load of nitrogen and phosphorus from the catchment that will attain a TLI of 4.2 or less in Lake Rotorua…'

A draft report was produced in mid-October 2003 and subsequently the study brief was altered to include the objective:

> '…determine the reduction in catchment loads of nitrogen and phosphorus to attain the target loads of Table 1 in Rutherford et al. (1989)…'

and

> '…estimate the catchment phosphorus load reduction that would result in an N:P ratio of >12 in Lake Rotorua…'

The 2003 study found a linear increasing trend in mean baseflow nitrate concentration in 8 of the 9 major streams from 1968-2002. Some evidence of increasing baseflow nitrate concentrations in the Ngongotaha Stream had been found in an earlier study (Williamson et al. 1996). However, the 2003 report showed that the trend was widespread throughout the Rotorua catchment and had continued.

When the decisions were made in the 1980s to divert sewage away from the lake it was believed that control measures put in place through the Kaituna Catchment Control Scheme would reduce catchment nutrient loads. These control measures have reduced the inputs of sediment, total phosphorus and particulate nitrogen, but have not controlled nitrate inputs. In terms of nitrogen loads to the lake, the benefits from sewage diversion have been negated by subsequent increases in nitrogen load in streams. Part of this increase is associated with 'leakage' from the land disposal site but the majority is associated with increasing nitrate in streams draining agricultural land.

In marked contrast with nitrate, the 2003 study found no evidence of increasing baseflow soluble phosphorus concentration in the major streams. Stream phosphorus loads currently comply with the target load for streams.

Recent work in the Lake Taupo catchment also shows a trend of increasing nitrate concentrations in streams draining catchments on the northern and western sides of the lake. It is believed that nitrate generated 30 – 70 years ago following land clearance may contribute to this increase via deep groundwater. It seems likely that similar land use groundwater linkages operate in the Rotorua catchment. Age data has indicated groundwater feeding the lake and streams in the Rotorua catchment is in the order of 50 – 100 years old. These ages may vary throughout the catchment.

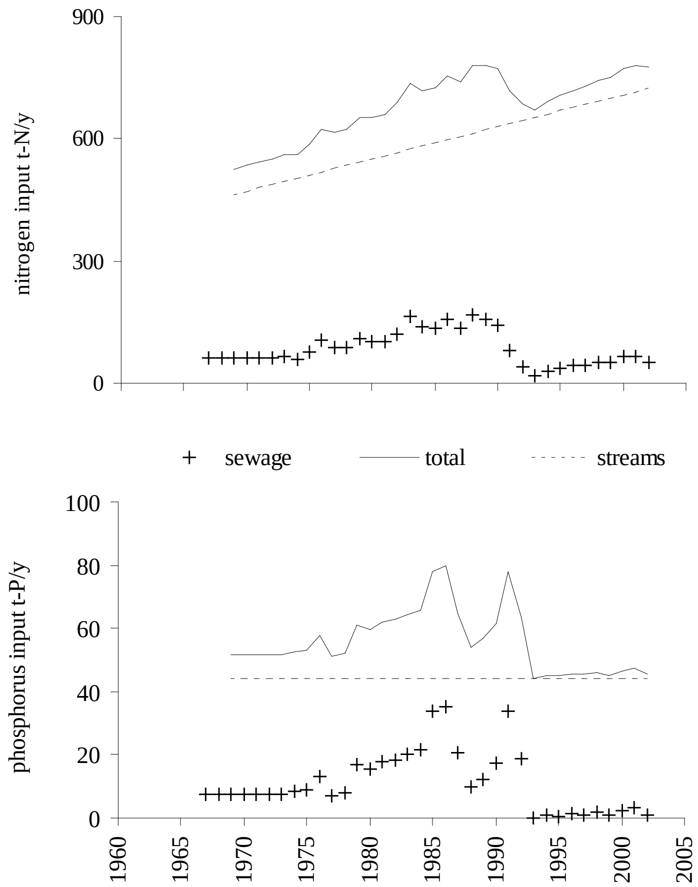

Figure 2: Estimated sewage, stream and total load on nitrogen and phosphorus to Lake Rotorua over the period 1967-2003. For nitrogen both upper and lower bound estimates of stream and total load are shown.

8. GNS Study

Morgenstern & Gordon (2004) summarise work on groundwater age and nitrate concentration, including projections of likely increases in nitrate load. Groundwater residence times range from 15-100 years and high nitrate concentrations associated with land-use intensification in the 1950s are still making their way through the groundwaters and nitrate concentrations are projected to increase in some streams (e.g., Hamurana) for several decades even if land use does not change.

Morgenstern's estimate of load for 2005 of 39 tP y^{-1} and 547 tN y^{-1} (Table 10) include sewage effects on streams (notably the Puarenga which receives nitrogen runoff from the RLTS in Whakarewarewa Forest). The phosphorus load 39 tP y^{-1} is higher than estimates for 1969-1977 of 33-44 tP y^{-1} (Table 8). The nitrogen load 547 tN y^{-1} falls within the range of estimates for 1969-1977 of 431-598 tN y^{-1} (Table 8). The 2003 nitrogen load in Figure 2 for streams plus rain (dashed line) is ~700 tN y^{-1}. This is significantly higher than other estimates and is suspect. The 2003 phosphorus load in Figure 2 for streams plus rain is ~42 tN y^{-1} which is comparable with other estimates.

Morgenstern estimated 'background' stream nitrate concentrations and then calculated the 1900 nitrate stream load to be ~60 tN y^{-1}. Assuming rainfall to have the same N load as is currently measured (29 tN y^{-1}) gives a catchment load (streams + rain) of 90 tN y^{-1}. The total area of catchment is 442.7 km2 and 60 tN y^{-1} is equivalent to a specific yield of 1.35 kgN ha^{-1} y^{-1}. Pine and native forest currently yields 3-4 kgN ha^{-1} y^{-1} on average.

Assuming the entire catchment to be native forest with a yield of 4 kgN ha^{-1} y^{-1} in 1900 gives an estimated 1900 load of 177 tN y^{-1}. Again assuming rainfall load to be 29 tN y^{-1} gives a catchment load (streams + rain) of 200 tN y^{-1}.

This analysis suggests that the nitrate load in 1900 is likely to have been in the range 90-200 tN y^{-1}.

Table 8: Summary of nutrient input estimates from streams plus rain omitting sewage and floodflow particulates. Figures in bold are the targets for streams plus rainfall omitting sewage.

	Year	DRP $tP\ y^{-1}$	TP $tP\ y^{-1}$	TIN $tN\ y^{-1}$	TN $tN\ y^{-1}$
Morgenstern & Gordon 2004	1900	31	38	90	ND
McIntosh 2007	1900		21		206
Fish 1975	1969-70	31		269	
Hoare 1980a	1976-77	25-26	34-35	382-407	472-497
White 1978	1975		ND		431
Rutherford 1978	1967-77		33-44		452-598
Rutherford et al. 1989	1976-77		34		485
Rutherford et al. 1989	**1965**		**34**		**405**
Morgenstern 2004	2005	31	39	449	547
McIntosh 2007	2005				

Table 9: Estimated nutrient loads in 1900 (after McIntosh 2007).

Current land use	Area ha	1900 P loss $kg\ ha^{-1}\ y^{-1}$	1900 P load $t\ y^{-1}$	1900 N loss $kg\ ha^{-1}\ y^{-1}$	1900 N load $t\ y^{-1}$
Native forest & scrub	10,588	0.12	1.3	4	42
Exotic forest	9,463	0.12	1.1	4	38
Cropping	282	0.12	0.0	4	1
Pasture	20,112	0.12	2.4	4	80
Lifestyle	556	0.12	0.1	4	2
Urban	3,267	0.12	0.4	4	13
Rain	8,079	0.16	1.3	3.6	29
Springs			13.0		
Geothermal			1.4		
TOTAL			**21**		**206**

Table 10: Predicted increase in nitrogen loads to Lake Rotorua over time (source: Morgenstern, GNS-Science).

Major streams	**Total nitrate & nitrite loading[2] [t y^{-1}]**							**Total P**	**Average**
	1900	**2005**	**2055**	**2105**	**2155**	**2205**	**Steady State**	**loading [t y^{-1}]**	**Age**
Utuhina	6	31	39	42	43	43	43	2.5	48
Ngongotaha	6	34	35	35	35	35	35	2.2	16
Waiteti	4	40	51	51	52	52	52	1.6	40
Awahou	7	57	85	85	89	91	92	3.3	61
Hamurana	11	53	92	92	102	108	118	6.3	110
Waiohewa	1	13	17	17	17	17	17	0.7	40
Waingaehe	1	10	25	25	28	30	35	0.7	127
Puarenga	5	42	52	52	53	53	53	3.6	37
Waiowhiro	1	8	10	10	10	11	11	0.7	42
Total major streams	**42**	**288**	**406**	**409**	**429**	**440**	**456**	**21.6**	**58[3]**
Minor streams	1	14	17	18	18	18	18	0.8	40
Lake-side springs	1	13	14	15	15	15	15	0.3	27
Groundwater direct	15	104	124	129	130	131	131	7.8	37
Total NO_2/NO_3	**60**	**420**	**532**	**572**	**592**	**602**	**619**	**30.5**	
Organic N, other N & other P[4]	~	98	98	98	98	98	98	7.4	
Rainfall[5]	~	29	29	29	29	29	29	1.2	

[2] Morgenstern & (2004).
[3] Calculated by average age per $m^3 s^{-1}$ flow multiplied by average $m^3 s^{-1}$ flow per stream.
[4] 2002 – 2005 data, calculated by David Burger and Kit Rutherford
[5] pers. comm., Max Gibbs, NIWA.

TOTAL	**~**	**547**	**659**	**699**	**719**	**729**	**746**	**39.1**

9. Summary

For phosphorus, catchment loads (streams + rainfall) estimated by different researchers using different methods and over different periods of time are similar and fall in the range 34-42 tP y^{-1}. The single 'outlier' is the estimate of 21 tP y^{-1} for 1900 (Table 9) made from typical specific yields for native and pine forest. This approach does not accurately quantify groundwater inputs of DRP in the volcanic plateau where 'old' groundwater has high DRP concentrations as a result of dissolution.

The recommended 'target' load for catchment (streams + rain) is 34 tP y^{-1}. Note that this target neglects floodflow particulate phosphorus which is considered to be unavailable to lake phytoplankton.

There is an additional allowance of 3 tP y^{-1} from sewage given a total 'target' load for the lake of 37 tP y^{-1}.

The catchment 'target' of 34 tP y^{-1} matches the value measured by Hoare for TP in 1976-77. Fish measured a DRP load of 30.4 tP y^{-1} in 1969-70 and adding Hoare's estimate of TP load from the Waiowhiro plus Hoare's value of 9 tP y^{-1} for PP + DOP in baseflow brings Fish's catchment TP load to 38 tP y^{-1} – slightly higher than the target of 34 tP y^{-1}.

For nitrogen the recommended 'target' load for the catchment (streams + rainfall) is 405 tN y^{-1}. Note that this target neglects floodflow particulate nitrogen which is considered to be unavailable to lake phytoplankton but includes dissolved organic nitrogen. There is an additional allowance of 30 tN y^{-1} from sewage giving a total 'target' load of 435 tN y^{-1}.

The target N load is higher than the estimated load pre-development (90-206 tN y^{-1}). Note that the pre-development load estimates have a very large uncertainty and are not considered to be reliable. It is not realistic to try and reduce nutrient loads to pre-development levels because this may not be achievable given the current population density and catchment development.

The catchment target N load (405 tN y^{-1}) is lower than catchment loads (streams + rain) measured by Hoare (1980a) in 1976-77 (range 472-497 tN y^{-1}). There were water quality problems during this period – notably blue-green algal blooms in the early 1970s. The consensus at the time was that these problems arose principally as a result of sewage nutrients. Nevertheless, the target catchment load was set below the estimated catchment loads at the time water quality problems occurred.

The boundary between mesotrophic and eutrophic lakes is generally accepted to lie at annual average lake concentrations of 30 mgP m^{-3} and 300 mgN m^{-3}. The Vollenweider model was used to demonstrate that total loads (streams + rain + sewage) of 40 tP y^{-1} and 400 tN y^{-1} would achieve these 'target' lake concentrations in most years.

It was recognized that during prolonged periods of hot, windless weather the lake was likely to stratify and the bottom waters to de-oxygenate even after reducing nutrient loads. When prolonged stratification occurs, high concentrations of nutrients build up in the bottom waters and these stimulate algal growth when the lake re-mixes, possibly contributing to nuisance 'blooms'. However, reducing nutrient loads was expected to reduce de-oxygenation rates meaning that only in prolonged periods of calm, warm weather (>10 days) was the lake likely to de-oxygenate. 'Capping' of sediments (e.g., using flocculants) is currently being trialled in lake Okaro and, depending on the results of those trials, may prove to be a suitable albeit expensive method for quickly improving water quality in Lake Rotorua.

When the catchment 'target' of 405 tN y^{-1} was set in 1986 it was assumed that measures put in place by the Kaituna Catchment Control Scheme would maintain or reduce stream nutrient loads at 1970s levels. This has proved not to be the case. Morgenstern & Gordon (2004) have shown that groundwater residence times range from 15-170 years and high nitrate concentrations associated with land-use intensification in the 1950s are still making their way through the aquifers.

The current nitrogen load of 547 tN y^{-1} (Morgenstern, Table 10) exceeds the 'target' of 435 tN y^{-1} by more than 100 tN y^{-1} and the predicted steady-state load of 746 tN y^{-1} (Table 10) exceeds the 'target' by more than 300 tN y^{-1}.

10. References

Fish, G.R. (1975). Lakes Rotorua and Rotoiti, North Island, New Zealand: their trophic status and studies for a nutrient budget. Fisheries Research Division, Wellington.

Hoare, R.A. (1978). Evidence presented to the Water Right Hearings on the disposal of treated sewage to Lake Rotorua from the Rotorua sewage treatment plant. May 1978.

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

Hoare, R.A. (1980b). Inflows to Lake Rotorua. *Journal of Hydrology (New Zealand) 19(1):* 49-59.

Hoare, R.A. (1984). Nitrogen and phosphorus in Rotorua urban streams. *New Zealand Journal of Marine and Freshwater Research 18:* 451-455.

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.

McIntosh, J.J. (2007). In: A programme of adaptive management for the long-term protection and restoration of Lakes Rotorua and Rotoiti. Environment B.o.P. May 2007.

Morgenstern, U.; Gordon, D. (2004). *Prediction of Future Nitrogen Loading to Lake Rotorua.* GNS Science Consultancy Report 2006/10.

Rutherford, J.C. (1978). Evidence presented to the Water Right Hearings on the disposal of treated sewage to Lake Rotorua from the Rotorua sewage treatment plant. May 1978.

Rutherford, J.C. (1984). Trends in Lake Rotorua water quality. *New Zealand Journal of Marine and Freshwater Research 18:* 355-365.

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.; Pridmore, R.D.; White, E. (1986). The significance of phosphorus and nitrogen in the management of Lake Rotorua. NWASCA, Wellington. March 1986.

Vant, W.N. (Ed). (1987). Lake Manager's Handbook. *Water & Soil Miscellaneous Publication No. 103*, NWSCO, Wellington.

White, E. (1978). Evidence presented to the Water Right Hearings on the disposal of treated sewage to Lake Rotorua from the Rotorua sewage treatment plant. May 1978.

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.