Environment Waikato Technical Report 2002/18R

Inflows to Lake Taupo—nutrients and water ages

Environment Waikato
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Nutrient concentrations and water ages in 11 streams flowing into Lake Taupo (Revised)

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Summary

During 2001–02 water samples were collected from near the mouths of 11 streams flowing into Lake Taupo at summer low flow. All 11 streams contain reasonably large areas of pasture in their catchments, and between them they contain about half of the area of pasture in the lake's catchment. Samples were analysed for forms of the plant nutrients nitrogen and phosphorus, and for tritium (a radioactive isotope of hydrogen). The tritium results were used to determine the average age of the water in each stream. They were also used to determine the fraction of the water that is likely to have been affected by the development of the land for pasture that has occurred since about the 1950s.

The stream waters tended to be cool, reflecting their groundwater origins. In most cases, dissolved inorganic forms of nitrogen and phosphorus predominated, and typically comprised about 80% or more of the total nitrogen and phosphorus. Concentrations of dissolved phosphorus tended to be higher in streams where the average age was higher, possibly because greater time underground means there is more chance that phosphorus will be dissolved from the volcanic deposits.

The average age of the baseflow waters ranged from <30 years to 80 years. The oldest water was found in three streams in the northern part of the catchment (Kawakawa, Mapara and Whangamata). In these streams only a small fraction (6–40%) of the water was young enough to have been affected by the pasture development over the past 35–45 years. In the other streams, however, up to 80–95% of the water was young.

Measurements made since the early 1970s show that nitrogen concentrations in the streams containing older water have steadily increased. In two of these (Mapara and Whangamata), concentrations of inorganic nitrogen are now 2–4 times higher than in the 1970s. In streams where the water is younger, the increases have been smaller, as the water is more likely to have already adjusted to the previous land development.

The water age and nitrogen results were used to make approximate estimates of the load of nitrogen that is yet to appear in the streams. These calculations indicate that at steady-state the combined load of nitrogen from areas of pasture in the catchments of the 11 streams will be between about 20% and 80% higher than the current load. Generalising these results to the areas of pasture in the catchment of the lake as a whole, it appears there will be a further moderately-large increase in the load of nitrogen from pasture areas in the future as a result of the land development that has occurred during the past 35–45 years.

Contents

1 Introduction

Historically, the 2800 km^2 catchment of Lake Taupo was mostly covered in native forest and tussock grassland (Leathwick et al. 1995). Low fertility of the volcanic soils, and the nature of land tenure meant that prior to the 1950s this part of the North Island was largely undeveloped (Environment Waikato 1998). By 1955, about 160 km^2 of land at the southern end of the lake had been developed for farming (Ward 1955). In 1970, the Crown- and Maori-owned land in the catchment was largely covered in low growing indigenous vegetation, comprising cut over forest and scrub (Environment Waikato 1998). However, from 1970 onwards, increasing areas of land—mainly in the north and west—were developed under major development schemes, so that by 1973 an area of about 470 km^2 was in pasture (Waikato Valley Authority 1973). A high-resolution satellite image of the catchment taken in January 2002 showed a total area 524 km^2 in pasture (or about 19% of the catchment area).[1] Much of the development of the land into pasture has thus occurred within the past 35–45 years.

The water quality of several streams draining pasture sub-catchments was measured in the 1970s (White & Downes 1977, Schouten et al. 1981), and then again in the period since 1997 (Vant 2000, Elliott et al. 2002). In several cases, average nitrogen levels in recent years have been considerably higher than in the 1970s. By contrast, concentrations in streams draining areas of pine or native forest are lower, and have generally not changed since the 1970s. These results suggest that development of the land has resulted in increased loads of nitrogen entering the lake via streams draining areas of pasture—as had been anticipated by White et al. (1983).

A recent investigation of the hydrogeology of the catchment has shown that the average age of the groundwater ranges from 20 to 75 years (Hadfield et al. 2001). At the older end of this range, appreciable proportions of the groundwater are unlikely to have been affected by the development of the land for pasture that has occurred within the last 35–45 years. Nitrogen levels in some pasture streams can therefore be expected to continue to increase for some time to come as older, uncontaminated water in the aquifers that feed them is progressively replaced by newer water that has been affected by past land development. Any additional intensification of land use in the future can be expected to further increase the nitrogen load from these areas (Vant & Huser 2000, Elliott & Stroud 2001).

During the summer of 2000/01, water samples were collected from the mouth of the Mapara Stream in a preliminary study of stream water age.[2] Following this, a more comprehensive study was undertaken in the summer of 2001/02, with samples being collected from sites close to the mouths of a total of eleven streams (Figure 1, Table 1). In this report we describe the results of both studies.[3] We use the results to make approximate estimates of the amount of development-related nitrogen that is stored underground, and is yet to enter the streams (and thus the lake). In this context, water age is used as a measure of the (underground) storage of the water feeding the streams that flow into Lake Taupo. It thus provides an indication of the delays between activities that introduce contaminants to streams, and the transport of these contaminants into the lake.

[1] EW Enhanced Land Cover Database: EW DOCS #813824 and #813012.

[2] The results of this preliminary investigation were described in an unpublished report from the Institute of Geological and Nuclear Sciences (IGNS) to Environment Waikato in July 2001 (see DOCS #688043).

[3] This report was originally published in December 2002. However, in October 2003 IGNS advised they wished to re-consider their interpretation of the results for two of the eleven streams. This has now been done (see Addendum on p. 21), and the results of this re-assessment are included in this revised report. We have also taken the opportunity to use the enhanced land cover information from the January 2002 satellite image, rather than that from the 1996 image that was used in the original report.

Figure 1: Location of the 11 streams in the northern and western areas of the Lake Taupo catchment that were sampled during 2001/02.

Table 1: Map references for 11 stream mouth sites. Catchment areas and the proportion of each catchment in pasture are also shown.

Site*	Map reference†	Catchment area (km^2)	Percent pasture
Mapara (504.2)	681 750	22	88
Whangamata (1300.2)	636 786	31	74
Otaketake (680.3)	627 787	28	64
Omoho (1502.1)	577 787	20	50
Kawakawa (1501.1)‡	566 783	11	55
Waihora (1121.1)	528 772	60	52
Waihaha (1106.3)	490 722	155	13
Whanganui (1301.1)	473 653	65	34
Whareroa (1318.4)	515 568	59	73
Kuratau (282.5)	502 536	194	39
Omori (645.4)§	483 517	27	56

*in each case the number in brackets is the EW Hydrol database code for the site

†NZMS 260, sheet T18

‡no name given on NZMS 260, T18; referred to as Kawakawa in EW Taupo sub-catchments analysis (e.g. DOCS #662637), and apparently referred to locally as “Chinamans”

§site is about 1 km upstream from the lake edge (i.e. upstream of the wastewater spray irrigation area)

The 11 streams surveyed were all located in the northern or western parts of the Lake Taupo catchment. The streams drain a combined area of 673 km^2, or about 24% of the land draining to the lake. Of this, 283 km^2 (42%) is in pasture (EW Enhanced Land Cover Database). These sub-catchments contain about half (54%) of the area in pasture in the Lake Taupo catchment as a whole. Most of the remaining area of pasture in the lake's catchment is spread between about 30 other sub-catchments (see EW DOCS #835232).[4]

Information on the hydrology of most of the streams was obtained as part of a major study in the late 1970s, and is summarised in Table 2. The streams vary widely in size, with mean flow rates ranging from less than 0.1 m^3/s to 7 m^3/s. The specific water yields of the catchments also varied markedly, from 3–7 L/s/km^2 in four streams in the northern area, to 16–42 L/s/km^2 in the others (Table 2). The corresponding surface runoff rates were 100–220 mm/yr and 775–1312 mm/yr, respectively (Table 2).

The streams also differed in the way in which flows varied with time (Table 2). In the Omori and Whareroa Streams high flows (5 percentile, or q5) were just 2–3 times greater than low flows (95 percentile, or q95). At the other end of the range, high flows were eight times greater than low flows in the Whanganui River. Streams showing less flow variability carried a somewhat greater proportion (c. 90%) of their annual water load during baseflow than did those showing more variability (82–83%). Schouten et al. (1981) found that low flow variability in the Lake Taupo catchment was a feature of streams that were fed by groundwater springs in areas of thick, recent volcanic deposits.

Table 2: Previous information on the hydrology of ten of the streams sampled in this study (from Schouten et al. 1981). Information in italics is for three sites located some distance upstream* of those in this study; otherwise the sites sampled in this study were at or near Schouten's sites. "q5/q95" = ratio of high flow (5 percentile) to low flow (95 percentile).

Site†	Mean flow (m^3/s)	Specific water yield (L/s/km^2)	Runoff (mm/yr)	q5/q95	% of output as baseflow
Mapara (331)	0.085	4	125	–	90
Whangamata (321)	0.11‡	3	110	–	90
Otaketake @ weir (301)	*0.135*	*7*	*220*	*3.8*	*88*
Omoho (291)	0.06	3	100	–	90
Waihora (271)	1.9	29	900	–	90
Waihaha @ SH32 (261)	*5.53*	*42*	*1312*	*7.3*	*82*
Whanganui @ SH32 (231)	*1.23*	*39*	*1250*	*8.1*	*83*
Whareroa (210)	0.944§	16	775	2.6	89
Kuratau (182)	7.0	36	1135	4.4	86
Omori (171)	0.56	21	650	2.2	91

*catchment areas (in km^2) for these sites were as follows: Otaketake, 19; Waihaha, 133; and Whanganui, 31

†in each case the number in brackets is the "Water Quality site number" in Schouten et al. (1981)

‡the average of measurements made during 1995–2003 is 0.10 m^3/s (n = 37; Howard-Williams & Pickmere 2003)

§EW reinstalled a recorder at this site in 2002; the average flow during the 22-month period 8/5/02 to 8/3/04 was 0.94 m^3/s, very similar to that measured in the 1970s

[4] Altogether 47 sub-catchments contain areas of pasture that total more than 1 km^2. The Kuratau (75 km^2 of pasture) and Whareroa (43 km^2) sub-catchments contain the largest areas (see also Table 1, and DOCS #660307).

2 Methods

Samples were collected from sites at or near the mouth of each stream, mostly during the summer of 2001/02 (Table 3). There is no road access to several of the sites (Otaketake, Omoho, Kawakawa, Waihora and Waihaha), so a boat was used to visit and sample these. For convenience, the Whangamata and Whanganui sites were also usually visited by boat.

Wastewater treatment and disposal systems are present near three of the streams (Omori, Whangamata and Whareroa). However, existing information from stream sites upstream and downstream of each treatment system indicates that wastewater disposal has thus far had little, if any, effect on the nitrogen concentrations in these streams (see Appendix 1). This means the results of this study are unlikely to have been affected by the presence and operation of the wastewater systems. Furthermore, in one case (Omori), the site sampled in this study was actually *upstream* of the wastewater spray-irrigation area (Table 1).

Most of the sampling occasions followed a period of fine weather, with the streams thus being at baseflow (Table 3). However, conditions were wetter at the time of the January 2002 sampling, and stream flows were above average (Table 3). The water level of Lake Taupo was also particularly high at this time (Table 3). At certain sites this meant the sampling location had to shift upstream somewhat to ensure the samples collected were of inflowing stream water. At Waihaha, the re-located site was thus several hundred metres upstream of the lake.

At each site water temperature was measured, and samples were collected for analysis for various forms of nitrogen and phosphorus (Hills Laboratories, Hamilton) and tritium (IGNS, Lower Hutt). In both cases existing protocols for sample collection were followed. For the tritium samples, this included the following steps: (1) ensure no luminous watches are being worn, (2) use a one litre Nalgene bottle (as supplied by IGNS), (3) fill and rinse the sample bottle three times, (4) completely submerge the bottle, fill and cap tightly, and (5) check tightness of the cap after several hours.

The methods used for the analysis of nitrogen and phosphorus are summarised in Table 4. Concentrations of dissolved inorganic nitrogen (DIN) were calculated as the sum of nitrate (NNN) and ammonia (amm-N); and those of total nitrogen (TN) as the sum of total Kjeldahl nitrogen (TKN) and NNN.

Table 3: Cumulative rainfall and average river flows in the fortnight prior to each sampling occasion. The average level of Lake Taupo on the day of each survey is also shown.

Survey date	Rainfall (Reids Farm) in previous fortnight (mm)	Mean flow (Kuratau @ SH41) in previous fortnight (percent of summer* average)	Daily average Lake Taupo level (m above minimum control level†)
First summer (Mapara only)			
24 January 2001	18	84	0.77
23 March 2001	40	65	0.56
Second summer (11 streams)			
18 October 2001	38	74	0.17
17 January 2002	120	156	1.26
18 February 2002	31	92	1.16
19 March 2002	33	65	1.06

*December-March; record covering period from December 1978 to March 2002

†355.85 m above sea level

Table 4: Methods used to analyse stream water samples for nitrogen and phosphorus.

Variable	Method
Ammoniacal-nitrogen (amm-N)	Phenol/hypochlorite colorimetry, APHA 4500-NH3 G
Nitrate and nitrite nitrogen* (NNN)	Automated cadmium reduction, APHA 4500-$NO3^-$ F
Total Kjeldahl nitrogen (TKN)	Kjeldahl digestion, then ammoniacal-N (see above)
Dissolved reactive phosphorus† (DRP)	Molybdenum blue colorimetry, APHA 4500-P F
Total phosphorus† (TP)	Persulphate digestion, colorimetry. NWASCO method 8
Water temperature (Temp)	Ebro TFX392 thermistor

*hereafter referred to as "nitrate"

†at times the reported value of dissolved reactive phosphorus exceeded the corresponding value for total phosphorus, but the analyst commented that such discrepancies were "within the experimental variation of these methods" (see relevant laboratory reports)

The IGNS measurement technique for tritium at the low levels found in waters in New Zealand involves electrolytic enrichment prior to counting via ultra low-level liquid scintillation spectrometry (Taylor 1994). Results are expressed as "tritium ratios" (TR), where TR = 1 corresponds to a tritium:hydrogen ratio of 1×10^{-18}.

3 Results and Discussion

3.1 Field and laboratory results

All of the nutrient and tritium concentrations are listed in Appendix 2. The full report from IGNS on the analysis and interpretation of the tritium values is included as Appendix 3. Tables 5 and 6 summarise the summer baseflow results for nutrients and water ages, respectively.

Water temperatures were generally low (Table 5). Apart from that for Kuratau (16.4°C), average temperatures in these otherwise warm summer months were generally between 10 and 13°C. These low water temperatures are consistent with the streams being fed by (cold) groundwater springs. The Kuratau River is impounded further upstream to form a small hydroelectric reservoir (Lake Kuratau), so its waters are more exposed to solar heating.[5]

In most cases, dissolved inorganic forms of nitrogen and phosphorus predominated in the baseflow waters. About 70–80% or more of the total nitrogen was DIN, while a similar proportion of the total phosphorus was DRP. The exceptions to this were (1) the Omoho Stream where DIN comprised just 7–17% of the TN, and DRP comprised 40–48% of the TP; (2) the Waihaha River where DIN comprised 50–76% of the TN; and (3) the Whareroa Stream where DRP comprised 46–75% of the TP.

Average nutrient concentrations varied several-fold between sites (Table 5). Average values of TP differed by up to a factor of ten, from 0.018 g/m^3 (Kuratau River) to 0.185 g/m^3 (Mapara Stream). Furthermore, TP and DRP concentrations tended to be highest in the northern streams, and lowest in the south-west. Average concentrations of TN were somewhat less variable, with values for most streams being between about 0.5 g/m^3 and 1.0 g/m^3, although concentrations in the Omoho (0.26 g/m^3), Waihaha (0.29 g/m^3) and Waihora (0.37 g/m^3) were lower than this.

[5] Surface water temperatures in Lake Taupo are typically 18–20°C at this time of year as a result of solar heating: Gibbs et al. (2002, fig. 1A).

Table 5: Average stream water quality at summer baseflow (i.e. excluding January 2002 results). Water temperatures are in °C, and nutrient concentrations in g/m^3. See Appendix 2 for the complete set of results.

Site	Temp	TN	DIN	TP	DRP
Mapara, 1st summer	12.5	0.72	0.65*	0.181*	0.135*
Mapara, 2nd summer	10.9	0.95	0.77	0.185	0.151
Whangamata	10.5	1.05	0.79	0.079	0.057
Otaketake	10.6	0.74	0.63	0.062	0.057
Omoho	10.5	0.26	0.04	0.076	0.034
Kawakawa	10.7	0.73	0.63	0.099	0.096
Waihora	11.8	0.37	0.28	0.075	0.068
Waihaha	12.6	0.29	0.16	0.040	0.039
Whanganui	11.5	0.50	0.39	0.019	0.018
Whareroa	13.1	0.62	0.48	0.044	0.026
Kuratau	16.4	0.54	0.38	0.018	0.010
Omori	12.4	0.92	0.82	0.022	0.022

*from EW regional rivers routine monitoring values for Jan & Mar 2001—see Appendix 2

Table 6: Average tritium ratios (TR, range in brackets), mean residence time (MRT, years) and percent younger than 35 and 45 years for samples collected at summer baseflow (i.e. excluding January 2002 results). In some cases potentially ambiguous age interpretations were possible. The values shown here are those recommended for use by the IGNS analyst (see Appendix 3 for the complete set of results). Values in italics result from the April 2004 re-assessment by IGNS: see Addendum to Appendix 3.

Site	TR	MRT	%yf (<35 yr)	%yf (<45 yr)
Mapara, 1st summer	0.98 (0.94–1.02)	72	13	31
Mapara, 2nd summer	0.94 (0.92–0.96)	73	12	30
Whangamata	0.74 (0.71–0.78)	80	6	24
Otaketake	1.73 (1.69–1.81)	36	61	78
Omoho	2.09	38	55	76
Kawakawa	1.25 (1.13–1.34)	60	15	39
Waihora	1.42 (1.37–1.48)	55	24	47
Waihaha	1.75 (1.72–1.77)	34	67	82
Whanganui	1.76 (1.71–1.82)	34	67	82
Whareroa	1.63 (1.57–1.68)	35	64	79
Kuratau	1.90 (1.86–1.93)	*1 and 30**	*90*	*95*
Omori	2.05 (2.00–2.08)	*1 and 30**	*90*	*95*

*Values of MRT corresponding to waters originating in areas with (1) andesitic and (2) rhyolitic geology, respectively

Average values of the tritium ratio at baseflow tended to be low, with most values being less than 2 (Table 6). Apart from the Otaketake Stream with an average value of 1.73 and the Omoho (2.09), tritium ratios tended to be lower (0.7–1.4) in the northern streams (i.e. Waihora to Mapara), with values progressively increasing through the west (1.6–1.8) to the south-west (1.9–2.1). Lowest values occurred in the Whangamata (0.74) and Mapara (about 0.9–1.0) Streams.

The January survey followed a wetter period than the other surveys, with flows being generally higher (e.g. Table 3). This was reflected in the tritium ratios for this month (Appendices 2 and 3), which were mostly somewhat higher (5–20%) than the corresponding baseflow averages. The additional water was presumably largely young water from the recent rainfall, so its higher tritium ratio tended to raise the overall value for the stream. The exception was the Omori Stream where the tritium ratio in January was actually about 12% lower than the average for the other months. However, flows vary the least in this stream (Table 2), so in this case conditions in January were probably less affected by recent surface runoff.

Table 6 also lists the mean residence time or average age of the baseflow water at each of the sites. The low water storage of the andesitic volcanics in the south-west of the catchment meant that the Kuratau River and the Omori Stream both contained

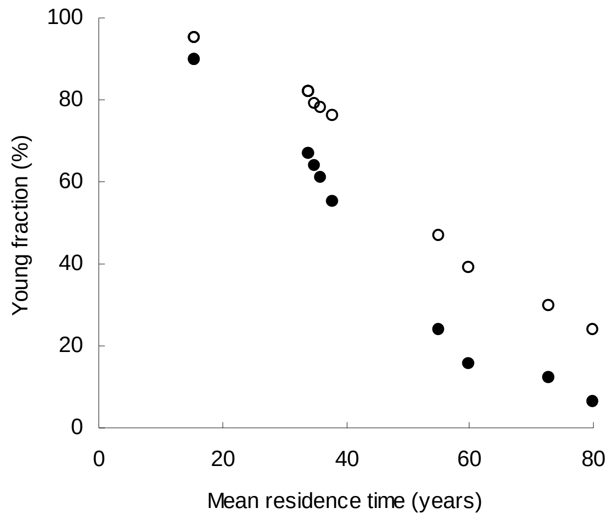

Figure 2: Water age results for 11 streams in the northern and western parts of the catchment of Lake Taupo: percent of sample younger than 35 years (solid circles) and 45 years (open circles) versus average age. Two ages were obtained for the Kuratau River and Omori Stream (Table 6); in each case the value plotted is the average of these (namely 15.5 years).

a mixture of young and older water. For the other nine streams, average ages ranged from 34 years (Waihaha and Whanganui) to 60–80 years (Kawakawa, Mapara and Whangamata). The oldest water (MRT > 50 years) was found in four streams in the northern part of the catchment.

Figure 2 shows how the average ages and young fractions covaried. Streams with higher average ages had smaller fractions of young water, and vice versa. In the Whangamata Stream for example, the average age was 80 years, with only 24% of the water being younger than 45 years, and just 6% being younger than 35 years. In this stream, much of the water was therefore too old to have been affected by the development of the catchment for pasture, most of which has occurred during the past 35–45 years. Conversely, 67% and 82% of the water in the Waihaha and Whanganui Streams was younger than 35 and 45 years, respectively. That is, in these streams much of the water was young enough to have been affected by land development, as was most of the water in the Kuratau River and Omori Stream.

3.2 Dissolved phosphorus

Figure 3 shows that DRP concentrations tended to be considerably higher in streams with older water, and vice versa (correlation coefficient r = 0.77, p-value <1%). Timperley (1983) showed that DRP concentrations are often high in streams in the Central Volcanic Plateau that are fed by coldwater springs. This occurs because of dissolution of phosphorus from the volcanic deposits. The results in Figure 3 may suggest that this process occurs to a greater extent in systems where water is stored underground for a considerable period. That is, an extended period of underground storage apparently enhances the extent to which phosphorus is dissolved from volcanic deposits. Alternatively, the geology of the northern area may mean that dissolution rates are higher there.

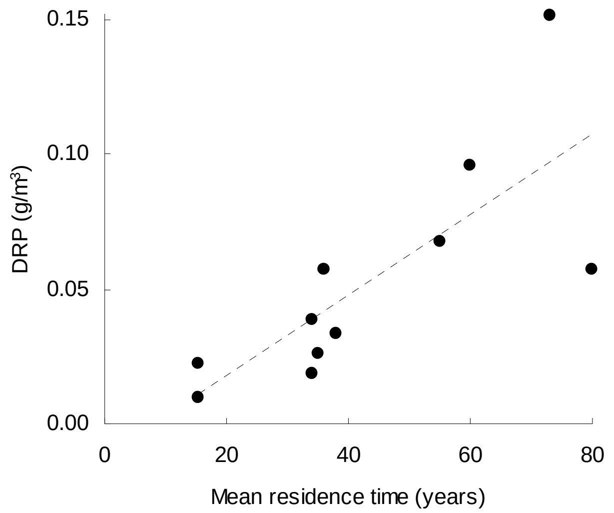

Figure 3: Average concentration of DRP and average water age in 11 streams in the northern and western parts of the catchment of Lake Taupo. Two ages were obtained for the Kuratau River and Omori Stream (Table 6); in each case the value plotted is the average of these (namely 15.5 years).

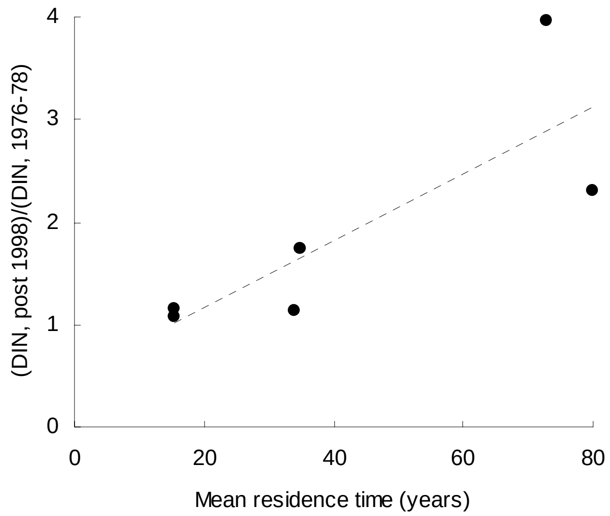

Figure 4: Change in average DIN concentration since the 1970s and average water age in six streams in the northern and western parts of the catchment of Lake Taupo (see Table 7). Two ages were obtained for the Kuratau River and Omori Stream (Table 6); in each case the value plotted is the average of these (namely 15.5 years).

Table 7: Historic and recent* average nitrogen concentrations (g/m^3) in streams in the northern and western part of the Lake Taupo catchment that contain moderately-large areas of pasture. Where information for total N is not available, the corresponding result for DIN is used to provide a lower bound (values in brackets).

	Average DIN			**Average TN**	
	1973–74	**1976–78**	**Post-1998***	**1976–78**	**Post-1998***
Mapara	no data	0.18	0.73	(>0.18)	0.93
Whangamata, upper	0.37†	0.50	1.15	0.75	(>1.15)
Whangamata, lower	0.33	0.32	1.10	0.61	(>1.10)
Whanganui	0.22	0.36	*0.41*	0.51	*0.51*
Whareroa	0.24	0.35	*0.60*	0.48	*0.77*
Kuratau	0.30	0.43	*0.49*	0.59	*0.62*
Omori	0.51	0.74	0.80	0.95	1.01

*values in plain type for 1998–2002 (four sites); values in italics for 2001–2003 (three sites)
†value for NNN—see DOCS #714408 (from NIWA)

3.3 Changes in nitrogen

For six of the streams, some information is available on nutrient concentrations in the past (Elliott et al. 2002; see also DOCS #641326).[6] Table 7 lists the average concentrations of DIN and TN measured in two separate studies in the 1970s. It also shows the corresponding concentrations in recent years. In most cases DIN concentrations during the late 1970s (i.e. 1976–78) were somewhat higher than in the early 1970s (1973–74). Furthermore, since 1998 average concentrations in all six streams have been higher than those in the late 1970s. In the Mapara and Whangamata Streams concentrations have been substantially higher (2–4 fold),[7] but, in the Omori Stream they increased by less than 10%.

The ratio of the average DIN concentration since 1998 to that in 1976–78 is a simple measure of the extent to which concentrations have increased over the past 2–3 decades. Figure 4 shows that this ratio tended to be higher in the streams containing older water (r = 0.82, p-value <5%). That is, streams that have shown the smallest increase in DIN concentrations since the 1970s tend to be those where the water is younger—namely the Kuratau, Omori and Whanganui Streams. In these streams much of the increase in nitrogen concentrations resulting from conversion of the catchment to pasture has probably already occurred. Conversely, where streams contain a large fraction of older (i.e. pre-1960) water that is less likely to have been affected by the pasture conversion, DIN concentrations at present tend to be considerably higher than those seen in the 1970s. Furthermore, in these latter streams DIN concentrations can be expected to continue to increase in the future as pre-1960, low-N water is progressively replaced by post-1960 water that has been affected by the land development that has occurred during the past 35–45 years.

3.4 Nitrogen load to come

The information from this study can be used to provide *approximate estimates* of the extent to which the nitrogen loads to the lake from previous land development will continue to increase in the future. The calculations are straightforward, being based on linear extrapolation of part of the measured nitrogen concentrations in each stream, taking account of the current young fraction. They involve several key assumptions as outlined in the following steps:

1 Baseflow loads currently carried by the streams can be *approximately* estimated as the product of mean flow (Table 2) and mean total N concentration at baseflow (Table 6).[8] Note that flood flows are ignored in this assessment as floodwater is likely to largely be surface runoff of a very young age, so underground storage is irrelevant in this situation. Note also that flood flows in these streams represent a small proportion (10–20%) of the overall water yield (see Table 2).

2 The "background" concentration of total N—i.e. the concentration that would be seen in the streams regardless of land development—is in the range 0.1 to 0.2 g/m^3 (i.e. similar to the concentrations currently found in the Hinemaiaia, Tauranga-Taupo and Tongariro Rivers, all of which drain largely non-pasture areas of the lake's catchment). The background load can be estimated as the product of mean flow (Table 2) and the background concentration of total N.

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[6] For one of these—Whangamata Stream—information is available for two sites (called "upper" and "lower" here).

[7] For the Whangamata Stream a near-continuous record of annual average DIN is available for the period 1973–2003 (Howard-Williams & Pickmere 1999, 2003; and NIWA unpublished results). This record shows a reasonably steady rise in DIN concentrations over this period, particularly at the more upstream of the two monitored sites.

[8] The average flow for the Kawakawa stream was calculated from the catchment area (Table 1), assuming a specific water yield of 5 $L/s/km^2$ (being the average of the yields for the nearby Mapara, Whangamata and Otaketake catchments: see Table 2).
For the Otaketake, Waihaha and Whanganui streams the mean flows shown in Table 2 (in italics) are for sites some distance upstream of those sampled in this survey. To take account of the additional area between the flow sites and the stream mouth sites, the relevant mean flows in Table 2 were multiplied by the following ratios of areas: Otaketake, 1.43 (= 28/19); Waihaha, 1.17 (= 155/133); and Whanganui, 2.10 (= 65/31).

3 In each stream the current load due to past development of the catchment can be calculated as the difference between the current total load (step 1 above) and the background load (step 2).
4 At some time in the future, nitrogen concentrations in all water draining areas of pasture will reach steady-state. That is, a time will come when no pre-1950, low-N water will remain, so that all water draining areas of pasture will be affected by the development that has occurred to date.
5 At steady-state, the load resulting from development of the catchment can be estimated as the current load due to development (step 3) divided by the current fraction younger than 45 years (Table 6). (This implies that all water currently older than 45 years is assumed to be unaffected by development, and that the effect of development has been—and will be in the future—the same for all affected parcels of water.)
6 At steady-state, the total load in each stream can be estimated as the sum of the background load (step 2) and the steady-state load due to development (step 5).
7 The load due to catchment development that is yet to appear in the streams can be calculated as the difference between the total load at steady-state (step 6) and the total load at present (step 1).
8 By taking account of the combined area in the 11 catchments that is in pasture (283 km^2), the additional load can be expressed as an increase in the load from this land use.
9 The calculations in steps 5–8 were also done using the fraction of water younger than 35 years (i.e. assuming all water currently older than 35 years is unaffected by development).

Table 8 shows the results of these calculations for water younger than 45 years, assuming a background N concentration of 0.2 g/m^3. The estimated combined load of nitrogen at baseflow from the 11 streams at present is 288 t/yr. The combined background or “natural” load is calculated to be 126 t/yr. Given the assumptions described above, the background load is not expected to change in the future. The remaining 162 t/yr is therefore the extra load due to development of the land over the past 45 years that has thus far worked its way through the groundwater system and entered the streams. This fraction of the load is expected to increase in the future as the remaining older, low-N water in the aquifers is progressively replaced by newer, high-N water.

Table 8: Approximate estimates of the current and future baseflow loads of nitrogen (t/yr) in 11 streams in the northern and western parts of the catchment of Lake Taupo, assuming (1) a background concentration of 0.2 g/m^3, and (2) water younger than 45 years draining from pasture areas has been affected. See text for details.

	Current N load			**Future N load**		
	Background	**Developed**	**Total**	**Developed**	**Total**	**Additional***
Mapara	0.5	2.0	2.5	6.7	7.2	4.7 (10)
Whangamata	0.7	2.9	3.6	12.2	12.9	9.3 (21)
Otaketake	1.2	3.3	4.5	4.2	5.4	0.9 (2)
Omoho	0.4	0.1	0.5	0.2	0.5	<0.1 (<1)
Kawakawa	0.3	0.9	1.3	2.3	2.7	1.4 (3)
Waihora	12.0	9.9	21.9	21.1	33.1	11.2 (25)
Waihaha	40.7	17.7	58.4	21.6	62.3	3.9 (9)
Whanganui	16.3	24.8	41.1	30.2	46.5	5.4 (12)
Whareroa	6.0	12.6	18.6	16.0	22.0	3.4 (8)
Kuratau	44.2	75.1	119.2	79.0	123.2	4.0 (9)
Omori	3.5	12.7	16.2	13.4	16.9	0.7 (1)
Sum	**126**	**162**	**288**	**207**	**333**	**45 (100)**

*values in brackets are the percent of the combined additional load from the 11 streams, namely 45 t/yr

The eventual nitrogen load resulting from the land development that has occurred to date is expected to increase markedly in the streams containing older water (Mapara, Whangamata, Kawakawa), but to a small extent in others (Table 8). The combined load resulting from land development to date from all 11 streams is calculated to increase by 45 t/yr to 207 t/yr at steady-state. The combined load of nitrogen from these streams is thus calculated to increase to 333 t/yr.

As it happens, the three streams that have the greatest proportion of old, uncontaminated water—Mapara, Whangamata, Kawakawa—are relatively small (Tables 1 and 2). Together they contribute no more than 3% of the estimated current combined load of nitrogen from the 11 streams in this study (Table 8). Although the calculations show that the combined load from these streams will increase 3-fold in the future, their small size means that together they represent only a minor proportion of the combined load to come (namely 34% of the load shown in Table 8). Conversely, the Waihaha and Kuratau Rivers contribute much of the current combined load to the lake—simply because they drain larger catchments. But as it happens, they both contain water that is mostly young, so they are less likely to show marked increases in the future. The Waihora Stream is intermediate in both size and water age, and as a result is calculated to contribute the single greatest proportion of the combined load to come (namely 25%).

The N loads can also be expressed as specific yields (i.e. in kg/ha/yr). From Table 8, the current yield of nitrogen from the 11 catchments combined is about 4.3 kg/ha/yr (based on a load of 288 t/yr and an area of 673 km^2). If we assume the undeveloped areas in these catchments export 1–2 kg/ha/yr (Elliott & Stroud, 2001; see also DOCS #686262), this implies the current nitrogen yield from the pasture areas is about 7–9 kg/ha/yr (based on 42% of the land in the 11 catchments being in pasture, and the remainder being undeveloped). This compares well with the yield of 7.3 kg/ha/yr calculated by Elliott & Stroud (2001, p. 43) for areas of sheep and beef pasture in the Lake Taupo catchment as a whole. At steady-state, the yield from the areas of pasture is calculated to increase to about 10 kg/ha/yr.

Table 9 shows the results of calculations based on alternative values for both (1) the fraction of water likely to have been affected by pasture development (<45 years cf. <35 years), and (2) the background concentration of N (0.2 g/m^3 cf. 0.1 g/m^3). It is clear that the different sets of assumptions produce markedly different outcomes, with the calculations being most sensitive to the estimate of the young fraction (i.e. to the assumptions about the history of land development). The combined load of N from the 11 catchments in the future is calculated to be between 333 t/yr and 470 t/yr. The load from the undeveloped areas is not expected to change, so all of the increase will come from the 283 km^2 of pasture in the catchments. At steady-state

Table 9: Approximate estimates of the combined current and future baseflow loads of nitrogen from the 11 streams considered in this study for four different sets of assumptions. The estimated total loads in the future are also expressed as specific N yields from the combined area of pasture in the 11 catchments; these yields can be compared with the current yield from the pasture. "[N_B]" = background N concentration, "B'ground" = background, "Devel" = developed, "% incr" = percent increase in yield from pasture

Scenarios		**Current**		**Future**			
Fraction	**[N_B] (g/m^3)**	**B'ground (t/yr)**	**Devel (t/yr)**	**Devel (t/yr)**	**Total (t/yr)**	**Pasture yield* (kg/ha/yr)**	**% incr**
<45 years	0.2	126	162	207	333	9.7	20
<45 years	0.1	63	225	287	350	10.3	27
<35 years	0.2	126	162	298	424	12.9	59
<35 years	0.1	63	225	407	470	14.5	79

*calculated assuming the yield from the undeveloped areas is 1.5 kg/ha/yr (see text) the N yield from pasture is calculated to increase to between 9.7 to 14.5 kg/ha/yr (Table 9), values that are 20% to 79% higher than the current pasture yield (namely 8.1 kg/ha/yr, assuming the undeveloped areas yield 1.5 kg/ha/yr).

In some cases these calculations produce what seem to be extreme outcomes. In particular in streams with the oldest water, where the fraction of water affected by pasture development is low, the predicted steady-state nitrogen concentrations are very high. For example, steady-state nitrogen concentrations in the Whangamata Stream are predicted to be in the range 4–16 g/m^3. Values at the higher end of this range seem barely credible, and suggest that this assessment has over-simplified the true situation. It may be that processes that have not been considered here will prevent steady-state concentrations from reaching these extreme values. As noted above, however, the streams with the oldest water tend to be small, so the overall loads to come from the 11 streams as listed in Table 9 are not unduly sensitive to the results for one or two extreme cases.

4 Conclusions

The following conclusions can be drawn from the information available at present:

1. The average age of baseflow water in streams draining areas of pasture in the catchment of Lake Taupo ranges from <30 years to 80 years. The oldest water is found in three streams in the northern part of the catchment. These streams also have considerably lower specific water yields than do those in the western part of the catchment. It is likely that both features reflect the geology of the northern area.

2. Much of the pastoral development has occurred within the past 35–45 years. The fraction of water that is younger than this—and thus which has probably been affected by development—varies, depending on average water age. Tritium dating indicates that in three northern streams, a minority (6–39%) of the water is young enough to have been affected by development, whereas in the other streams up to 80–95% of the water is young.

3. Nitrogen concentrations in streams draining areas of pasture are higher than in those draining undeveloped parts of the lake’s catchment. In some pasture streams, concentrations have shown a steady increase since measurements were first made in the early 1970s. It is now clear that these streams tend to contain older water. In streams where the average water age is younger, the rate of increase appears to be slowing.

4. By making several assumptions, it is possible to calculate the load of nitrogen that is still to appear as the streams approach steady-state. The yield from the areas of pasture in the streams’ catchments is calculated to be between about 20% and 80% higher than the current load. There is thus considerable uncertainty in these estimates of the amount of nitrogen that is yet to come.

5. The streams in this study drain about half the area of pasture in the lake’s catchment. If we assume they are broadly representative of streams draining areas of pasture in general, we can conclude that there will be a moderately-large increase in the nitrogen load from areas of pasture in the future as the older, uncontaminated water in the groundwater feeding the streams is replaced by water that has been affected by pasture development.

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Appendix 1: Nitrogen concentrations upstream and downstream of wastewater treatment systems near three streams flowing into Lake Taupo.

Wastewater treatment and disposal systems are present near the mouths of three of the streams (Omori, Whangamata and Whareroa). In each case, information is available on nitrogen concentrations at sites located upstream and downstream of the wastewater disposal areas (see Table A1.1).

Table A1.2 shows the average concentrations of both DIN and TN at the upstream and downstream sites. In each case upstream and downstream concentrations were similar, with average values differing by less than 5 percent. At both Omori and Whangamata the upstream and downstream average DIN values were significantly different (*p*-value <0.1%; paired *t*-test). None of the other differences were significant.

The average concentration of DIN at the downstream Omori site was 3–4% higher than the upstream value, possibly because of leaching from the wastewater spray-irrigation area. However, the site sampled in this study was *upstream* of this area, and was thus unlikely to have been affected by it. (The upstream and downstream concentrations of TN hardly differed at all.)

The average concentration of DIN at the downstream Whangamata site was 4–5% *lower* than the upstream value. There was thus no evidence of an effect of the nearby wastewater system on nitrogen concentrations in this stream. The increases in both DIN and TN at the Whareroa sites were small, and can probably be ignored. (They may simply be due to the area of pasture between the sites.)

We may therefore conclude that the wastewater treatment systems near these three streams have probably not contaminated the samples collected in this stream nutrient and water age study.[9]

Table A1.1: Site location and period of record for stream samples. Sources of information as follows: Omori, Taupo District Council consent monitoring information (for its sites “1” and “2”); Whangamata, NIWA (Howard-Williams & Pickmere 1999, 2002); Whareroa, Environment Waikato (Smith 2002, and unpublished results). “MR” = map reference (for NZMS 260, sheet T18)

Stream	Period	Upstream MR	Downstream MR
Omori	Oct 1996 to July 2002	483 517*	487 519
Whangamata	May 1995 to Sep 2002	648 805	640 787
Whareroa	Dec 2000 to Oct 2002	483 583	515 568*

*site sampled in this nutrient and water age study as well

Table A1.2: Average nitrogen concentrations (g/m^3) at sites upstream and downstream of wastewater disposal areas near three streams.

Stream*	Upstream	Downstream	Difference (%)
DIN			
Omori (*n* = 40)	0.770	0.798	3.6
Whangamata (*n* = 34)	1.189	1.138	–4.3
Whareroa (*n* = 23)	0.629	0.632	0.5
TN[†]			
Omori (*n* = 39)	0.996	0.989	–0.1
Whareroa (*n* = 23)	0.813	0.826	1.6

*value in brackets is the number of sampling occasions
[†]no TN results for the Whangamata sites

[9] Note, however, that the wastewater disposal systems may be contaminating the associated groundwaters, and that stream nutrient concentrations may show the effects of this at some time in the future.

Appendix 2: Water quality of eleven streams flowing into Lake Taupo, January 2001 to March 2002. "NZST" = New Zealand Standard Time (hh:mm), "sigTR" = one sigma standard measurement error. Values in italics for Mapara are from EW's routine regional rivers monitoring programme (Smith 2002).

Date	NZST	Temp	TKN	NNN	NH4	TN	DIN	TP	DRP	TR	sigTR
Mapara											
24/1/01	13:30	12.8	<0.1	0.53	–	0.53	–	–	–	1.02	0.04
31/1/01	*07:02*	*12.2*	*0.14*	*0.670*	*<0.01*	*0.81*	*0.675*	*0.177*	*0.137*	–	–
23/3/01	15:18	12.3	0.2	0.66	–	0.66	–	–	–	0.943	0.035
28/3/01	*08:15*	*12.5*	*0.19*	*0.610*	*0.01*	*0.80*	*0.620*	*0.185*	*0.133*	–	–
24/10/01	*06:55*	*10.6*	*0.15*	*0.867*	*0.01*	*1.017*	*0.877*	*0.174*	*0.140*	–	–
17/1/02	07:10	11.6	0.18	0.778	<0.01	0.958	0.783	0.188	0.158	1.02	0.04
18/2/02	07:05	11.3	0.13	0.732	<0.01	0.862	0.737	0.195	0.163	0.961	0.035
19/3/02	08:20	10.7	0.26	0.697	<0.01	0.957	0.702	0.187	0.151	0.916	0.034
Whangamata											
18/10/01	08:20	–	0.33	1.110	0.03	1.440	1.140	0.131	0.082	0.78	0.038
17/1/02	08:06	11.4	0.21	0.593	<0.01	0.803	0.598	0.050	0.046	0.802	0.033
18/2/02	07:58	11.3	0.18	0.568	<0.01	0.748	0.573	0.041	0.045	0.705	0.030
19/3/02	09:10	9.6	0.31	0.637	0.02	0.947	0.657	0.066	0.044	0.722	0.028
Otaketake											
18/10/01	08:30	–	0.12	0.682	0.01	0.802	0.692	0.065	0.056	1.81	0.06
17/1/02	08:17	11.6	0.11	0.570	<0.01	0.680	0.575	0.056	0.047	1.88	0.04
18/2/02	08:05	11.3	0.10	0.582	<0.01	0.682	0.587	0.054	0.058	1.69	0.05
19/3/02	09:20	9.9	0.13	0.595	0.01	0.725	0.605	0.066	0.058	1.70	0.05
Omoho											
17/1/02	09:05	12.5	0.23	0.012	<0.01	0.242	0.017	0.044	0.020	–	–
18/2/02	08:25	11.7	0.27	0.027	0.02	0.297	0.047	0.084	0.040	–	–
19/3/02	09:43	9.3	0.21	0.018	0.02	0.228	0.038	0.068	0.027	2.09	0.04
Kawakawa											
18/10/01	09:10	–	0.21	0.665	<0.01	0.875	0.670	0.099	0.098	1.34	0.04
17/1/02	08:47	12.0	0.11	0.604	0.03	0.714	0.634	0.093	0.082	1.44	0.04
18/2/02	08:38	11.7	<0.05	0.565	0.01	0.590	0.575	0.096	0.096	1.29	0.05
19/3/02	09:50	9.7	0.07	0.649	0.01	0.719	0.659	0.102	0.094	1.13	0.04
Waihora											
18/10/01	09:35	–	0.11	0.291	<0.01	0.401	0.296	0.071	0.064	1.48	0.05
17/1/02	09:35	12.5	0.44	0.241	0.03	0.681	0.271	0.057	0.048	1.69	0.05
18/2/02	08:55	12.3	0.07	0.254	<0.01	0.324	0.259	0.074	0.071	1.37	0.04
19/3/02	10:10	11.2	0.10	0.271	0.01	0.371	0.281	0.080	0.068	1.40	0.04
Waihaha											
18/10/01	10:15	–	0.17	0.162	<0.01	0.332	0.167	0.039	0.037	1.77	0.06
17/1/02	10:02	12.3	0.07	0.137	0.02	0.207	0.157	0.032	0.025	2.03	0.08
18/2/02	09:18	13.3	0.09	0.128	0.01	0.218	0.138	0.039	0.042	1.72	0.06
19/3/02	10:32	11.8	0.17	0.141	0.02	0.311	0.161	0.042	0.037	1.76	0.05
Whanganui											
18/10/01	10:45	–	0.08	0.389	<0.01	0.469	0.394	0.017	0.016	1.71	0.06
17/1/02	10:32	12.8	0.12	0.486	0.03	0.606	0.516	0.028	0.012	1.88	0.07
18/2/02	09:40	11.8	0.13	0.389	<0.01	0.519	0.394	0.019	0.021	1.82	0.06
19/3/02	12:50	11.2	0.17	0.355	0.02	0.525	0.375	0.022	0.018	1.75	0.07
Whareroa											
18/10/01	13:20	–	0.12	0.527	<0.01	0.647	0.532	0.040	0.030	1.64	0.05
17/1/02	13:25	14.4	0.45	0.646	0.02	1.096	0.666	0.128	0.017	1.78	0.05
18/2/02	12:20	13.7	0.14	0.449	<0.01	0.589	0.454	0.043	0.025	1.68	0.06
19/3/02	13:34	12.5	0.19	0.448	<0.01	0.638	0.453	0.050	0.023	1.57	0.06
Kuratau											
18/10/01	13:55	–	0.15	0.462	<0.01	0.612	0.467	0.017	0.008	1.90	0.06
17/1/02	14:00	17.6	0.15	0.383	0.01	0.533	0.393	0.020	0.007	2.13	0.05
18/2/02	12:51	17.5	0.13	0.317	<0.01	0.447	0.322	0.017	0.014	1.93	0.05
19/3/02	14:10	15.3	0.21	0.351	0.01	0.561	0.361	0.021	0.008	1.86	0.05
Omori											
18/10/01	14:20	–	0.09	0.842	<0.01	0.932	0.847	0.022	0.020	2.08	0.06
17/1/02	14:30	14.0	0.14	0.949	0.02	1.089	0.969	0.024	0.018	2.02	0.06
18/2/02	13:15	12.8	0.09	0.785	<0.01	0.875	0.790	0.019	0.025	2.07	0.06
19/3/02	14:30	12.0	0.15	0.803	<0.01	0.953	0.808	0.023	0.022	2.00	0.05

Appendix 3: Report on tritium analyses and interpretation. The report from IGNS is reproduced below, together with its attachment (see also DOCS #788272).

Age interpretation of Lake Taupo catchment streams

Uwe Morgenstern, 31 October 2002

Age interpretation of groundwater is affected by mixing processes. Waters with different age contribute to the mixture in the aquifer or stream. Very little is known about mixing processes for stream waters in general and in particular for the Taupo catchment. As a consequence, stream water age interpretation is extremely difficult. To narrow the possible range of mixing processes any evidence must be taken into account, and with increasing data sets (temporal and spatial) the picture becomes clearer.

A standard tool for groundwater dating is the tritium method (see Attachment A). Stream waters retain their tritium ratios relatively well because exchange with atmospheric moisture takes a long time compared to the residence time in the stream. Therefore, the tritium method was applied at this stage. The tritium method is, however, in some age ranges ambiguous due to the “bomb” tritium in the early 1960s. On the other hand, this “bomb” tritium gives in many cases the possibility to identify mixing processes if several data are available over time.

Tritium samples were taken at various stream mouths at Lake Taupo over 5 months at baseflow (driest period in March 2002) and at slightly wetter periods. See results below in Table 1 and Figure 1.

Trip 3 (March) driest			
site	TT No.	**TR**	SigTR
3/1	512	**0.916**	0.034
3/2	513	**0.722**	0.028
3/3	514	**1.70**	0.05
3/4	522	**2.09**	0.04
3/5	515	**1.40**	0.04
3/6	516	**1.76**	0.05
3/7	517	**1.75**	0.07
3/8	518	**1.57**	0.06
3/9	519	**1.86**	0.05
3/10	520	**2.00**	0.05
3/11	521	**1.13**	0.04

Trip R (Oct) little wet			
Site	TT No.	**TR**	sigTR
R/2	523	**0.78**	0.038
R/3	524	**1.81**	0.06
R/5	525	**1.48**	0.05
R/6	526	**1.77**	0.06
R/7	527	**1.71**	0.06
R/8	528	**1.64**	0.05
R/9	529	**1.90**	0.06
R/10	530	**2.08**	0.06
R/11	531	**1.34**	0.04

Trip 2 (Feb) wetter			
site	TT No.	**TR**	sigTR
2/1	502	**0.961**	0.035
2/2	503	**0.705**	0.030
2/3	504	**1.69**	0.05
2/5	505	**1.37**	0.04
2/6	506	**1.72**	0.06
2/7	507	**1.82**	0.06
2/8	508	**1.68**	0.06
2/9	509	**1.93**	0.05
2/10	510	**2.07**	0.06
2/11	511	**1.29**	0.05

Trip 1 (Jan) wettest			
site	TT No.	**TR**	sigTR
1/1	532	**1.02**	0.04
1/2	533	**0.802**	0.033
1/3	534	**1.88**	0.04
1/5	535	**1.69**	0.05
1/6	536	**2.03**	0.08
1/7	537	**1.88**	0.07
1/8	538	**1.78**	0.05
1/9	539	**2.13**	0.05
1/10	540	**2.02**	0.06
1/11	541	**1.44**	0.04

Table 1: Tritium results (see figure 1 for site codes)

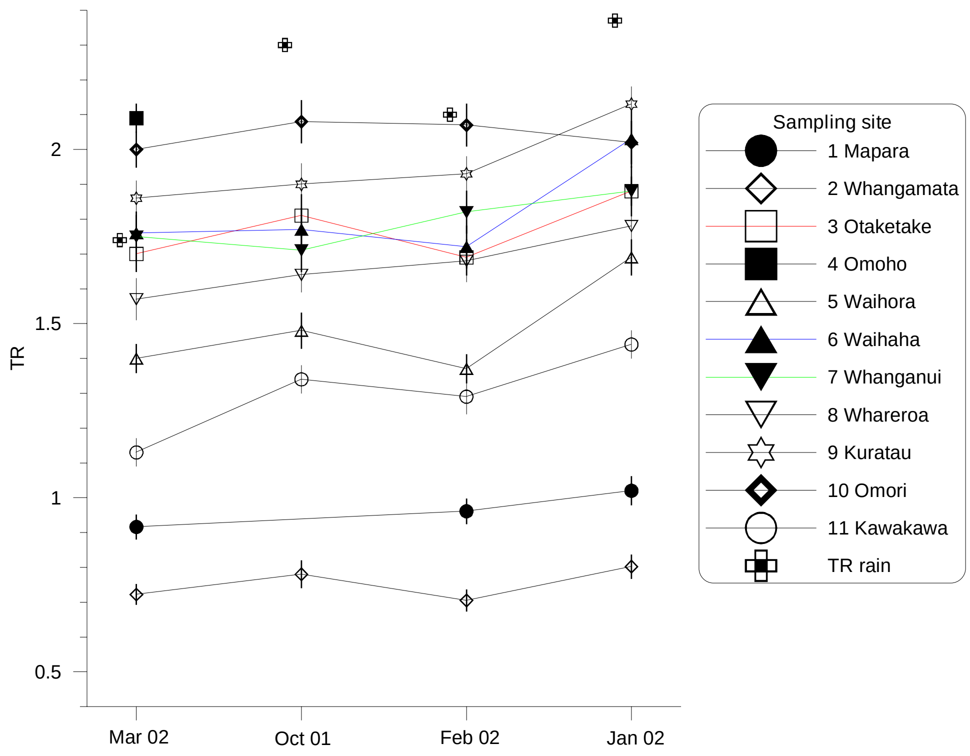

Fig. 1: Tritium ratios in Lake Taupo streams. March 02 is the driest period, and toward the right streams flow was increasingly higher due to previous rain (in mid January flow was significantly higher, and Whanganui and Whareroa were turbid). 'TR rain' is the mean TR for the rain (Kaitoke) two months previous to sampling.

Despite a visible change in streamflow, the tritium data are very consistent and show only slightly the trend that the TRs are shifted toward recent rain water with increasing water flow. At all 4 flow conditions, the age of the water is not significantly different and represents base flow conditions. However, as a conservative approach, the results from January '02 have been excluded from the calculation of the average. Stream flow in January was significantly higher, but is only slightly changed in age structure. Therefore, by using Mar '02, Oct '01 and Feb '02 results only, it is guaranteed that the average TR represents baseflow conditions.

Findings:

1. The stream water data over 5 months do not show the seasonal tritium variability of rain water (1.4-2.5TR). Therefore, all stream waters are older than 3 years.

2. TR below 1.3 can easily be identified as old water (>45 years). TR's above 1.3 are ambiguous in age interpretation with theoretically a possibility of very young water (<3 years). However, this very young age interpretation can be excluded because of (a) constancy in TR over time (see finding 1), and (b) hydrogeology is uniform over the whole study area and therefore MRTs cannot vary over such wide range of 50 years to less than 3 years.

3. Mixing: No hydrogeological information in respect of mixing processes is available. The first intuitive approach was to use between 50 and 90% mixed flow for the streams, with 70% as a mean. However, the tritium data show clear evidence of much less mixing. Tritium ratios above 1.8 are possible only for

mixed flow less than 50%. Four streams show clear evidence of mixing less than 50%: Otaketake, Omoho, Omori, and Kuratau. On the other hand, the tritium data of Mapara stream from 2 consecutive years show no increase during that time and therefore do indicate a mixed flow fraction of more than 50%. From these observations it is concluded that the mixed flow fraction is near 50%. With a relative uniform hydrogeology (rhyolitic volcanics), the mixed flow fraction is assumed to have a relatively narrow range. The uniformity of flow characteristics is supported by the fact that stream waters at different locations within one catchment have very similar ages (where identifiable by non-ambiguous dating). For age interpretation, 40% is used for Otaketake, Omoho, Omori and Kuratau, 60% for the northern streams with Taupo ignimbrite cover (Mapara and Whangamata), and 50% for all other streams. As a comparison, 10-20% mixed flow was found in the Hutt Valley artesian aquifers. This hydrologic system with 2 months residence time of the water in the Hutt River catchment and recharge from the river into the confined aquifers represents probably the minimum mixing (most ideal piston flow) for natural groundwater flow situations.

Age interpretation:

Mean residence times (MRT) for different mixing ratios are listed in Table 2. Three streams (Mapara, Whangamata, Kawakawa) allow for unambiguous age interpretation. In case of ambiguous age results (due to bomb tritium), it was searched for the fraction of mixed flow where the bomb-peak maximum is equal to the measured tritium ratio (called ‘Adjusted to centre of bomb peak). This solution gives a mean between the 2 ambiguous solutions (rather than using the arithmetic mean between the 2 solutions). The preferred values are in bold. For Waihora the ambiguity cannot be resolved at this stage. However, the older age (MRT 55 years) is more likely because of 2 reasons: (a) the higher tritium value at Waihora #1 (1.78 TR) indicates that MRT 11 years is unlikely, and (b) Waihora has also significant Taupo ignimbrite cover.

				EM% 40			EM% 50			EM% 60			Adjusted to centre of bomb peak			
Site	Stream	TR	sigTR	mrt	yf (35y)	yf (45y)	mrt	yf (35y)	yf (45y)	mrt	yf (35y)	yf (45y)	EM%	MRT	yf (35y)	yf(45y)
1	Mapara	0.94	0.030							**73**	**12.4**	**30**	not appl.			
2	Whangamata	0.74	0.025							**80**	**6.1**	**24**	not appl.			
3	Otaketake	1.73	0.04	50 / 27	22 / 83	53 / 93							**50**	**36**	**61**	**78**
4	Omoho	2.09	0.04	40	50	73							**37**	**38**	**55**	**76**
5	Waihora	1.42	0.04				**55** / 11	**24** / 100	**47** / 100				not appl.			
6	Waihaha	1.75	0.04				36	61	78				**47**	**34**	**67**	**82**
7	Whanganui	1.76	0.05				36	61	78				**47**	**34**	**67**	**82**
8	Whareroa	1.63	0.05				45 / 28	43 / 79	63 / 90				**54**	**35**	**64**	**79**
9	Kuratau	1.90	0.04	45 / 33	36 / 68	63 / 85							**42**	**42**	**47**	**70**
10	Omori	2.05	0.04	40	50	73							**38**	**39**	**53**	**76**
11	Kawakawa	1.25	0.03				**60**	**15.4**	**39**				not appl.			

Table 2: Age interpretation. TR is the average of the Mar ‘02, Oct ‘01 and Feb ‘02 results (see above).

ATTACHMENT A: TRITIUM AND CFC/SF_6 AGE DATING OF WATER

Groundwater Age Dating

Tritium is naturally produced in the atmosphere by cosmic rays, but large amounts were also released into the atmosphere in the early 1960s during nuclear bomb tests, giving rain and surface water high tritium concentration (Figure 1). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground, and the tritium concentration in the groundwater then decreases over time due to radioactive decay. The tritium concentration in the groundwater is therefore a function of the time the water has been underground. Additionally, detection of superimposed bomb tritium can identify water recharged between 1960 and 1975. Groundwater dating via tritium is described in more detail in *Cook & Herczeg 1999* and *Stewart & Morgenstern 2001.*

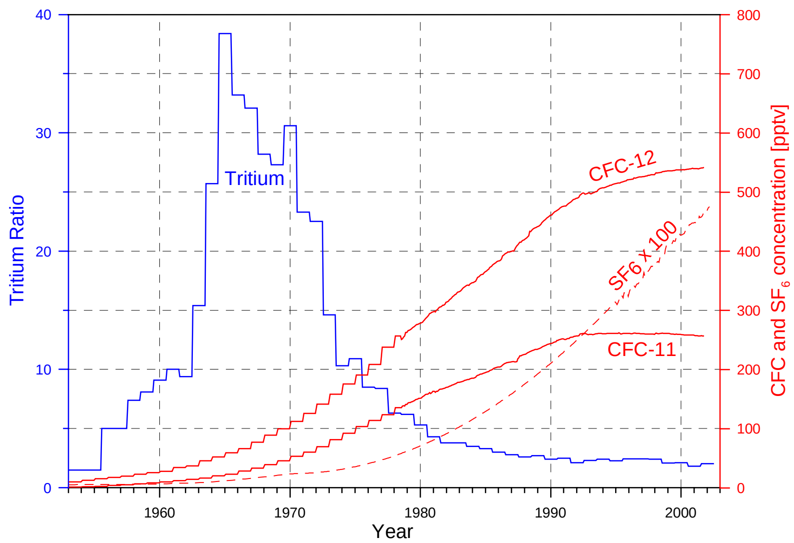

Figure 1: Tritium in rain from Kaitoke, 40km North of Wellington (yearly averages) and CFC and SF_6 concentrations in Southern Hemispheric air. Tritium one TR represents a $^3H/^1H$ ratio 10^{-18}, and 1 pptv is one part per trillion by volume of CFC and SF_6 in air, or 10^{-12}. Pre-1978 CFC data are reconstructed according to *Plummer and Busenberg 1999* and scaling to Southern Hemisphere by factor 0.83 (CFC-11) and factor 0.9 (CFC-12). Post-1978 CFC data are from Tasmania. Pre 1970 SF_6 data are reconstructed (USGS Reston), 1970-1995 data are from *Maiss and Brenninkmeijer 1998*, and post 1995 data measured in Tasmania.

As a result of the superimposed atmospheric tritium "bomb" peak in the 60s, ambiguous ages can occur with single tritium determinations in the age range 15-40 years (i.e. the tritium concentration can indicate any of several possible groundwater ages). This ambiguity can be overcome by using a second tritium determination after about 2-3 years, or combined age interpretation of tritium data and data from an independent dating method, for example CFCs or SF_6. CFC and SF_6 concentrations in the atmosphere have risen monotonously over that time.

Chlorofluorocarbons (CFCs) are entirely man-made contaminants. They were used for refrigeration and pressurising aerosol cans, and concentrations in the atmosphere have gradually increased (Figure 1). CFCs are relatively long-lived and slightly soluble in water and therefore enter the groundwater systems during recharge. Their concentrations in groundwater record the atmospheric concentrations when the water was recharged, allowing determination of the recharge date of the water. CFCs are now being phased out of industrial use because of their destructive effects on the ozone layer. Thus rates of increase of atmospheric CFC concentrations slowed greatly in the 1990s, meaning that CFCs are not as effective for dating water recharged after 1990.

Sulphur hexafluoride (SF_6) is primarily anthropogenic in origin, but can also occur in some volcanic and igneous fluids. Significant production of SF_6 began in the 1960s for use in high-voltage electrical switches. The residence time of SF_6 in the atmosphere is extremely long (800-3200 years). It holds considerable promise as a dating tool for post-1990s groundwater, because unlike CFCs, atmospheric concentrations of SF_6 are expected to continue increasing for some time (Busenberg and Plummer, 1997).

Tritium is a conservative tracer in groundwater. It is not affected by chemical or microbial processes, or by reactions between the groundwater, soil sediment and aquifer material. Tritium is a component of the water molecule and age information is therefore not distorted by any processes occurring underground. In CFC age interpretation, however, care has to be taken. A number of factors can modify CFC concentrations in the aquifer, including microbial degradation of CFCs in anaerobic environments (CFC-11 is more susceptible then CFC-12), and CFC contamination from local anthropogenic sources (CFC-12 is more susceptible to this). See Plummer and Busenburg (1999) for more information. CFC-11 has been found in New Zealand to be less susceptible to local contamination and agrees relatively well with tritium data. Note that CFC ages do not take into account of travel time through unsaturated zones.

Due to the large tritium input during 1965-1975 the tritium method is very sensitive to the flow (mixing) model. If time series of tritium data, or additional CFC and SF_6 data are available, age ambiguity can be resolved. Therefore, both groundwater age and age distribution can be obtained.

Groundwater mixing models

Groundwater comprises a mixture of water of different ages due to mixing processes underground. Therefore, the groundwater doesn't have a discrete age but has an age distribution or spectrum. Various mixing models with different age distributions describe different hydrogeological situations (Maloszewski and Zuber, 1982). The piston-flow model describes systems with little mixing (such as confined aquifers and river recharge), while the exponential model describes fully mixed systems (more like unconfined aquifers and local rain recharge). Real systems, which are partially mixed, lie between these two extremes. They can be described by a combination of the exponential and piston-flow models representing the recharge and flow parts of a groundwater system respectively. The output tracer concentration can be calculated by solving the convolution integral, and the mean residence time (MRT) can be obtained from the tracer output that gives the best match to the measured data. If the second parameter in the age distribution function, the fraction of mixed flow, can not be estimated from hydrogeologic information, two independent tracers (tritium and CFC) or two measurements over time are necessary.

References*:*

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Addendum (April 2004): Revised interpretation of results for Kuratau and Omori

Since this age interpretation was first made (in October 2002), we have become aware of two additional pieces of information, as follows:

1. The fact that the geology in the southern part of the study area is a transition zone between rhyolitic volcanics and andesitic volcanics (see Geological Map of New Zealand 1:250,000, Sheet 8 Taupo), and
2. Several determinations of tritium ratios in water from the Kuratau River that were made during the 1960s (unpublished data in IGNS files)

This additional information alters the interpretation of the tritium results for the two southern-most streams studied, namely Kuratau and Omori.

The water storage capacity of andesitic volcanics is considerably smaller than that of rhyolitic volcanics. This means that much younger water is likely to be present in andesitic areas. Both andesitic and rhyolitic volcanics are likely to be present in the Kuratau and Omori catchments. Furthermore, the 1960s measurements for the Kuratau River clearly show the contribution of young water from the andesitic areas. The historic and recent tritium results can be accurately simulated by running parallel models for the andesitic and rhyolitic areas of the catchment. These models have mean residence times of 1 year and 30 years, respectively.

Table A shows the original and revised age interpretations for the Kuratau and Omori sites.

Stream	TR	SigTR	MRT	yf (35 y)	yf (45 y)
Original (October 2002)					
Kuratau	1.90	0.04	42	47	70
Omori	2.05	0.04	39	53	76
Revised (April 2004)					
Kuratau	1.90	0.04	1 / 30	90	95
Omori	2.05	0.04	1 / 30	90	95

Table A: Age interpretations for Kuratau and Omori sites.