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Lake Taupo Streams : Water Age Distribution, Fraction of Landuse Impacted Water, and Future Nitrogen Load

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Lake Taupo streams – Water age distribution, fraction of landuse impacted water, and future nitrogen load

Uwe Morgenstern

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EXECUTIVE SUMMARY

The near pristine water of Lake Taupo has begun to deteriorate, mainly as a result of delayed arrival of nitrate from farming. Nitrogen travels from farms to the lake mostly via groundwater, entering the lake via groundwater-fed streams, and directly by groundwater seepage via the lake bed. To quantify the delayed arrival of nitrogen from landuse into the lake via the streams, the age of the water was measured in all the larger streams in the northern and western parts of the Lake Taupo catchment. These parts of the catchment contain the largest area of farming. Age distribution of the water allows for identification of future arrival of landuse-impacted water, and for prediction of future nitrogen mass loading to Lake Taupo from current landuse practises.

Tritium dating is the only applicable method for determining the water age in streams, but was also the method of choice. It was known from two earlier measurements in Mapara Stream that water ages up to more than 50 years can be expected, which allows unambiguous pre-bomb tritium to be identified. For younger waters, tritium time-series normally can resolve ambiguous results which are caused by the fact that a high tritium concentration could indicate either very young water, or water with several decades residence time containing remaining bomb-tritium.

In the previous study in 2002 and 2004, only short time series tritium data were available to measure the age distribution of the stream waters. While the northern catchment streams had mostly unambiguously old mean ages (>50 years), the western catchment stream waters were clearly younger (<50 years), and the age interpretations of the tritium results were ambiguous. Two mean residence times were possible for the western catchment streams—several decades or less than three years. The tritium time series were too short to resolve the age ambiguity. Therefore, assumptions had to be made on limited hydrogeologic information to exclude one of the two possible ages. The geohydraulic conditions in the northern and western catchment were assumed to be relatively uniform. Therefore, such a large age difference between >50 and <3 years was assumed to be unrealistic and the possibility of a very young age of <3 years was excluded.

The northern part of the catchment is dominated by the relatively thick Taupo ignimbrite, which overlies an older rhyolitic ignimbrite, the Oruanui ignimbrite (c. 26,500 years old). The western part of the catchment is underlain by the much older Whakamaru Group ignimbrites (also rhyolitic: c. 340,000-320,000 years old). These are overlain by the Oruanui ignimbrite. The south-western part of the catchment is underlain by andesitic and basaltic lava, overlain by the Oruanui and Taupo ignimbrites. Historic tritium data from the Kuratau River demonstrated that a significant fraction of the water in the western catchment is very young (<1 year). Therefore, the geohydraulic parameters are not as uniform through the northern and western catchment as previously assumed, with the Taupo and Oruanui ignimbrites having very different water storage capacities compared to the Whakamaru ignimbrite.

With new tritium analyses in 2007, it was hoped the remaining age ambiguity in the western catchment could be resolved by using the new 5-years tritium time-series because the old bomb-tritium shows a decline over that period, while the young cosmogenic tritium should remain constant over that time at constant tritium input. Unfortunately over the last 10 years the concentration of tritium in New Zealand rain has dropped considerably. This drop coincides with the decline in bomb-tritium in old water and has a similar magnitude. Therefore, the young and old age water have identical tritium outputs at the present time and the ambiguity cannot be resolved for some streams on the basis of tritium data only. Despite this ambiguity, the improved hydrogeological information available now strongly indicates that the stream waters in the western catchment have mostly very young waters (<3 years).

Consistent with the initial age interpretation, the streams in the northern catchment contain old water, with the following mean residence times: Whangamata 84 y, Mapara 75 y, Kawakawa 60 y, Otaketake 49 y, and Omoho 42 y. The streams in the western catchment, however, contain significantly younger waters, with the following mean residence times: Waihora 10.5 y, Waihaha and Whanganui 2.5 y, and Whareroa 9 y. Kuratau and Omori on the boundary between the two geologic formations, which have different water storage capacity, contain mostly young water of <1 y from the Andesite/Whakamaru ignimbrite, but also some older fractions from the Oruanui and Taupo ignimbrite, with mean residence times of 30 and 40 years, respectively.

In regard to future total nitrogen (TN) loading from surface streams to Lake Taupo, the estimate for the western catchment is now significantly lower then in the previous estimate as a consequence of the higher fraction of young water. Most of the western streams are already in a steady-state with respect to post-1955 landuse water and only a moderate TN load increase of 5 t/y is expected from the western lake catchment areas, mostly from the Kuratau and Omori areas that have significant partial Taupo and Oruanui Ignimbrite cover. A larger increase in TN loading of 16 t/y from surface flows is expected in the northern catchment, in agreement to the previous estimate. This area has thick Taupo and Oruanui ignimbrite cover. The TN load from the surface stream flows in the western and northern catchment are estimated to increase by 21 t/y, from 289 to 310 t/y.

It should be noted that the above estimate of total nitrogen load increase in the northern and western catchment of Lake Taupo covers only the surface stream flows. These, however, form only a fraction of the total discharge from some sub-catchments, particularly in the North. Approximately 80% of the water in the northern catchment discharges to Lake Taupo directly by groundwater seepage via the lake bed, with an equivalent TN load of about 110 t/y. Most of this loading from the northern catchment groundwater seepage is still to come, because the underlying groundwater seepage-flows are likely to be even older than the surface stream flows. The expected large TN load increase from direct groundwater seepage via the lake bed is not included in the TN budget of this report.

1 INTRODUCTION

The near pristine water of Lake Taupo has begun to deteriorate, mainly as a result of delayed arrival of nitrate from farming. Large areas in the catchment were developed into pastoral agriculture 40 to 50 years ago (Vant & Smith, 2004). Nitrogen concentrations in streams draining pasture have slowly risen since the 1970s, and are still increasing, despite little change in the intensity of farming since then. This delay between pasture development and the associated nitrogen increase in streams and groundwater draining the catchment suggests that water residence times in the aquifer are several decades.

Nitrogen travels from farms to the lake mostly via groundwater. The groundwater enters the lake via groundwater-fed streams, and directly by groundwater seepage via the lake bed.

This study was initiated by Environment Waikato (EW) in 2001 (Vant & Smith, 2004) to quantify the delayed arrival of landuse nitrogen into the lake via the streams, by measuring the age of the water in all the larger streams in the northern and western parts of the Lake Taupo catchment which has the largest impact from land-use. The age distribution of the water enables identification of future arrival of post-landuse water, and therefore to predict future nitrogen mass loading to Lake Taupo from current landuse.

Groundwater systems are usually very complex and difficult to understand. Therefore, multidisciplinary approaches are necessary, including isotope and chemistry signature of the groundwater, and hydrogeology. The groundwater flow for groundwater-fed streams is even more difficult to understand because the stream water can originate from a series of different and complex groundwater systems. In addition, complementary dating tools like CFCs and SF_6 cannot be used because of gas exchange between the stream water and the air.

Tritium dating was the only applicable method, but also the method of choice because it was known from two earlier measurements in Mapara Stream that water ages up to more than 50 years can be expected thus allowing for identification of unambiguous pre-bomb tritium. For the younger waters, tritium time-series is expected to resolve ambiguous results which are caused by the fact that a high tritium concentration could indicate very young water, or water with several decades residence time with remaining bomb-tritium.

In 2001/02, water samples for tritium analyses were collected at the stream mouths four times over a period of 5 months, at various flow conditions. The results from these samples gave reasonable estimates of ages. However, because the tritium time-series span only half a year and are too short to resolve the age ambiguity for several streams, assumptions had to be made which were based on the best knowledge at the time. Shortly after the 2001/02 study we found historic tritium data from the Kuratau River that allowed for excellent age distribution (Morgenstern & Stewart, 2004). This data demonstrated that streams in the western catchment can have very young water, and it demonstrated the need for better hydrogeological information in the western catchment of Lake Taupo.

In 2004 we analysed samples (GNS-funded) collected by EW from many of the stream mouths, in an effort to obtain longer tritium time series and to resolve remaining age ambiguities. In addition, EW staff collected two further samples from most of the stream mouths in late 2006 and early 2007. The tritium data from between 2001 and 2007 form the basis of the age interpretation of this report (except Kuratau where historic data is also included). Also included in the interpretation are the stream mouth data that were collected by EW in 2002 on longitudinal transects from several streams in a separate project (Piper 2004).

The historic tritium data from the Kuratau River demonstrated that significant fractions of the water in the western catchment are very young (<1 y) and therefore, that the geohydraulic parameters are not as uniform through the northern and western catchment as previously assumed, and that the Taupo and Oruanui ignimbrites have very different water storage capacities to the Whakamaru ignimbrite. Detailed geological maps were available only from parts of the catchment. We now have a more detailed geological map available for the whole Lake Taupo catchment which has helped to resolve the age ambiguities.

2 METHODOLOGY OF GROUNDWATER AGE DATING

2.1 Tritium, CFC and SF6 method

Tritium is produced naturally 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 concentrations (Fig. 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 in the groundwater allows for establishment of groundwater mixing models and age distribution of the groundwater (Morgenstern 2004). Groundwater dating using tritium is described in more detail in Cook & Herczeg (1999), Stewart & Morgenstern (2001), and Morgenstern & Taylor 2005. The low-level tritium analysis procedure used at GNS Science is described in detail in Morgenstern & Taylor (2005).

As a result of the superimposed atmospheric tritium "bomb" peak in the 1960s, ambiguous ages can occur with single tritium determinations (i.e., the tritium concentration can indicate any of several possible groundwater ages between 0 and 40 years). This ambiguity can be overcome by using a second tritium determination after about three or more 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 during that time and therefore can resolve tritium ambiguity if they are not altered in the aquifer.

Chlorofluorocarbons (CFCs) are entirely man-made contaminants. They were used for refrigeration and pressurising aerosol cans, and their concentrations in the atmosphere have gradually increased (Fig. 1). CFCs are relatively long-lived in the atmosphere and slightly soluble in water and therefore enter the groundwater systems with groundwater recharge. Their concentrations in groundwater record the atmospheric concentrations when the water was recharged, allowing determination of the recharge date of the water. CFCs have been phased out of industrial use in the 1990s 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.

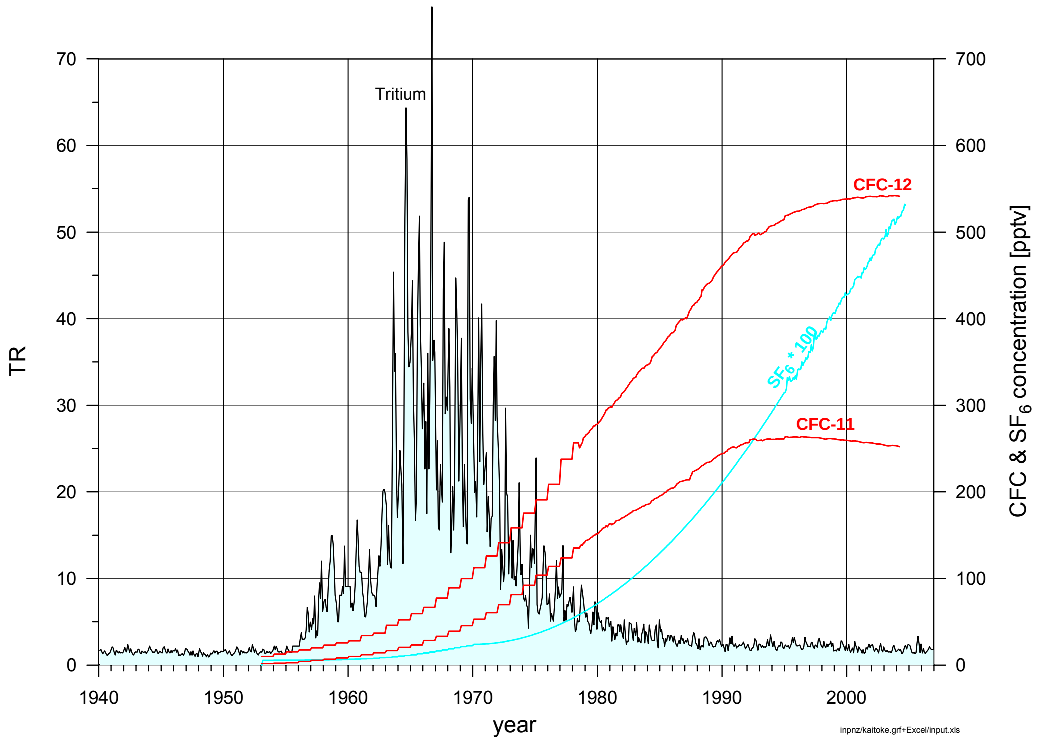

Figure 1. Tritium, CFC and SF_6 input for New Zealand rain. Tritium concentrations are from rain at Kaitoke, 40 km north of Wellington (monthly data), and CFC and SF_6 concentrations are for southern hemispheric air. TR=1 represents a $^3H/^1H$ ratio of 10^{-18}, and 1 pptv is one part per trillion by volume of CFC or SF_6 in air, or 10^{-12}. Tritium data from before 1960 are reconstructed from Antarctic ice cores. Pre-1978 CFC data are reconstructed according to Plummer & Busenberg (1999), and scaled 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 & Brenninkmeijer (1998), and post-1995 data was measured in Tasmania.

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, leading to increasing atmospheric concentrations (Fig. 1). The residence time of SF_6 in the atmosphere is relatively long (800-3200 years). It holds considerable promise as a dating tool for post-1970s groundwater because, unlike CFCs, atmospheric concentrations of SF_6 are expected to continue increasing for some time (Busenberg & Plummer, 1997).

Tritium is a conservative tracer in groundwater. It is not affected by chemical or microbial processes, or by reactions between the groundwater and aquifer material. Tritium is an isotope of hydrogen and therefore is a component of the water molecule. Therefore, age information is not distorted by any bio- or geo-chemical reaction occurring underground. For CFCs, a number of factors can modify the concentrations in the aquifer, including microbial degradation of CFCs in anaerobic environments (CFC-11 is more susceptible than CFC-12), and CFC contamination from local anthropogenic sources (CFC-12 is more susceptible to this) Plummer & Busenburg (1999). CFC-11 has been found in New Zealand to be less susceptible to local contamination and age estimates agree better with tritium data. Note that CFC and SF_6 ages do not take into account travel time through unsaturated zones.

Tritium with its pulse-shaped input into groundwater systems (Fig. 1) is very sensitive to the flow model (distribution of residence times in the sample). With a series of tritium measurements, and/or additional CFC and SF_6 measurements, age ambiguity can usually be resolved. In that case, both the mean groundwater age and the age distribution can be obtained.

2.2 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. Various mixing models with different age distributions describe different hydrogeological situations (Maloszewski & 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 groundwater systems which lie between these two extremes can often be described by a combination of the exponential and piston-flow models representing the recharge, flow and discharge parts of a groundwater system. 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, cannot be estimated from hydrogeologic information, then several independent tracers (tritium and CFC/SF_6) or several tritium measurements over time are necessary.

Schematic groundwater flow situations are shown in Figure 2. The unconfined aquifer situation is described by the exponential model (EM). Flow lines of different length containing water of different age converge in the well or the stream, and the abstracted water has a wide range of ages with an exponential age distribution. The confined aquifer situation is described by the piston flow model (PM) with a narrow range of ages. The partly confined aquifer situation is described by the exponential-piston flow model (EPM). The free parameter is the fraction of mixed (exponential) flow within the total flow volume (represented by E_%PM, with the fraction given in %), or the ratio η of the total flow volume to the volume of the exponential part. The water has a wide range of ages, but because part of the flow is piston flow, the age distribution has a minimum age (no water can be younger than the time necessary to pass through the piston flow part). The piston flow part can be represented by a partly confined flow with no vertical input of young water from the surface, or it can be represented by a significant unsaturated zone with vertical piston flow toward the water table and mixing of different ages below the water table.

As an example, the age distribution for the exponential-piston flow model for different fractions of mixed flow is shown in Figure 3 for water with a mean residence time of 50 years. Water with a high fraction of exponential flow of 90% has a wide range of ages, starting at 5 years and still significant contributions of old water with ages over 150 years. Despite the mean residence time of 50 years, significant fractions of the water are younger than 50 years. The discharging water can therefore partly be contaminated before the mean residence time of 50 years has elapsed. About 2% of the water can already be contaminated after five years. With each further year, increasingly contaminated water arrives at the spring or well. The total fraction of water within a certain age range can be obtained by integrating the age distribution over the specified age range. This is equal to the area below that part of the curve, with the total area below the whole curve being 100% water fraction. The fraction of water that is younger than a specified age is called the young water fraction (yf). The young water fraction younger than 40 years is 54% in the example in Figure 3 (hatched area).

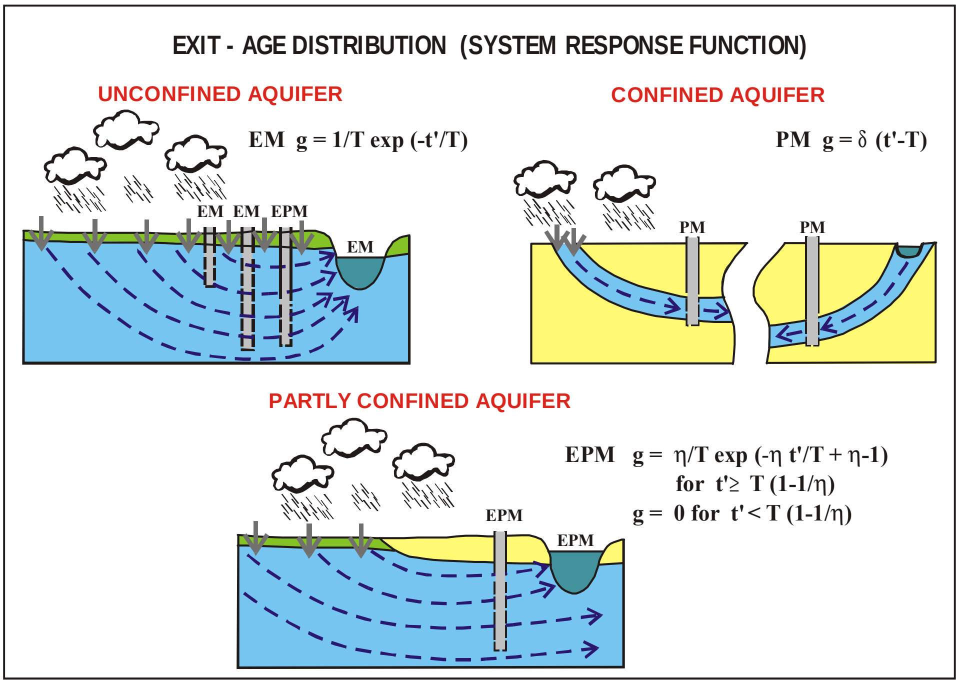

Figure 2. Schematic groundwater flow situations and corresponding age distribution functions (see Maloszewski & Zuber (1982) for theoretical background).

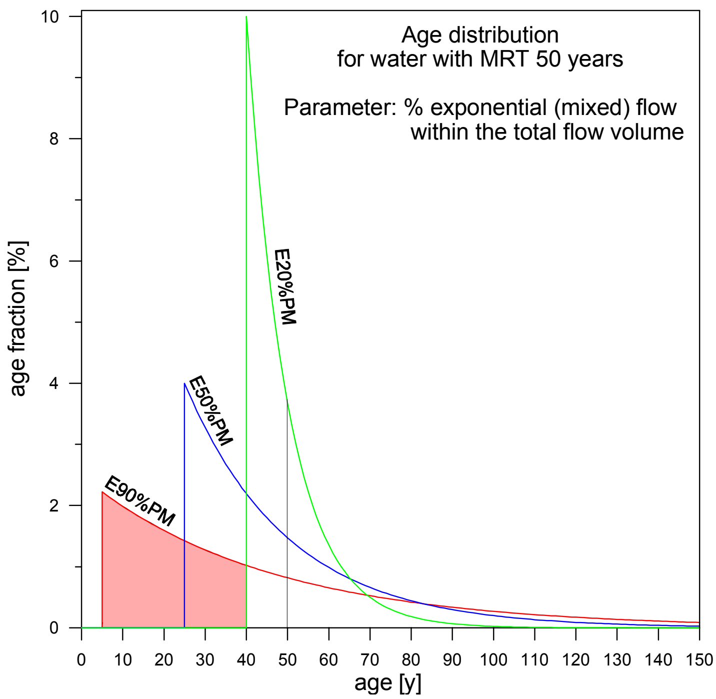

Figure 3. Age distribution for the exponential-piston flow model.

In a flow situation with less mixed (exponential) flow, the age distribution of the water is less wide-spread. At 50% exponential flow, the minimum age is 25 years, and the water does not contain significant fractions older than 150 years. At only 20% exponential flow, the age distribution is relatively peaked around the mean residence time. The minimum age is 40 years, and there is an insignificant amount of water older than 100 years. This water would just start to show a contaminant introduced 40 years ago, but this contaminant would arrive in a relatively sharp front, with 10% contribution in the first year of arrival after 40 years time.

3 RESULTS

In 2001/02 the streams were sampled four times over a period of 5 months. The tritium results were listed in Vant & Smith (2004). The new tritium results are listed in Table 1. All stream flows at the time of sampling were at average dry (baseflow) conditions except January 2002 which followed a period of increased rain with elevated streamflow (Whanganui and Whareroa were turbid).

The tritium time-series are plotted and interpreted into age distributions in section 6. For resolving remaining ambiguities in age interpretation, information about relative water storage capacities in the different geologic formations is necessary. Therefore, the following section describes relevant hydrogeological information for the northern and western catchment of Lake Taupo.

Table 1. Tritium results for the samples from Lake Taupo stream mouths.

Identity	Code	Date	TR	±TR
Mapara Stream	TT605	11.05.04	0.792	0.039
Mapara Stream	TT653	28.09.06	0.857	0.031
Mapara Stream	TT691	21.02.07	0.857	0.032
Whangamata Stream	TT606	11.05.04	0.596	0.029
Whangamata Stream	TT654	28.09.06	0.745	0.027
Whangamata Stream	TT692	21.02.07	0.770	0.029
Otaketake Stream	TT607	11.05.04	1.64	0.04
Otaketake Stream	TT655	29.09.06	1.64	0.04
Otaketake Stream	TT693	21.02.07	1.51	0.04
Kawakawa Stream	TT662	28.09.06	1.15	0.04
Kawakawa Stream	TT694	21.02.07	1.06	0.04
Waihora Stream	TT656	28.09.06	1.29	0.04
Waihora Stream	TT695	21.02.07	1.16	0.04
Waihaha Stream	TT657	28.09.06	1.57	0.04
Waihaha Stream	TT696	21.02.07	1.54	0.04
Whanganui Stream	TT609	11.05.04	1.65	0.04
Whanganui Stream	TT658	28.09.06	1.62	0.04
Whanganui Stream	TT697	21.02.07	1.45	0.04
Whareroa Stream	TT610	11.05.04	1.41	0.04
Whareroa Stream	TT659	28.09.06	1.38	0.04
Whareroa Stream	TT698	21.02.07	1.32	0.04
Kuratau River	TT611	11.05.04	1.71	0.05
Kuratau River	TT660	28.09.06	1.59	0.04
Kuratau River	TT699	21.02.07	1.43	0.04
Omori	TT608	11.05.04	1.64	0.05
Omori	TT661	28.09.06	1.63	0.04
Omori	TT700	21.02.07	1.61	0.04

4 HYDROGEOLOGY

The Lake Taupo catchment is underlain largely by rhyolitic volcanics (Fig. 4, QMAP geological mapping, GNS Science). The northern part of the catchment is dominated by the relatively thick Taupo ignimbrite, which overlies an older rhyolitic ignimbrite, the Oruanui ignimbrite (c. 26,500 years old). The western part of the catchment is underlain by the much older Whakamaru Group Ignimbrites (also rhyolitic: c. 340,000-320,000 years old). These are overlain by the Oruanui ignimbrite. The south-western part of the catchment is underlain by andesitic and basaltic lava, overlain by the Oruanui and Taupo ignimbrites. The tritium data (see below) demonstrate that each of these geological units have very different hydraulic properties with very different water residence times.

An additional indication of the different hydraulic properties between the northern and the western catchment is obtained from the specific water yield which was investigated by Schouten et al. (1981). The results are summarised in Vant & Smith (2004, p.3). The essential data from that report are listed in Table 2 and discussed below in relation to the geologic structures because this is useful for a qualitative understanding of differences in age distribution, and therefore helps resolving age ambiguities.

Table 2. Mean stream flow, specific water yield via stream, and stream runoff from the catchment. Details are described in Vant & Smith (2004). See text below for explanation of the colour code.

Stream	Mean flow L/s	Specific water yield L/s/km^2	Runoff mm/y
Mapara	85	4	125
Whangamata	110	3	110
Otaketake	135	7	220
Omoho	60	3	100
Waihora	1900	29	900
Waihaha	5530	42	1312
Whanganui	1230	39	1250
Whareroa	944	16	775
Kuratau	7000	36	1135
Omori	560	21	650

The streams from the northern catchments are characterised by low flow, specific water yield and runoff (yellow highlight, Table 2). This appears to be the result of the thick Taupo Ignimbrite which extends well below the current lake level, allowing most groundwater to enter the lake through seepage on the lake bed, and indicates a large groundwater storage reservoir. In this geological unit, only about 20% of the water reaches the lake via streams (assuming 100% to be about 1200 mm/y runoff in the western catchment and somewhat less in the northern catchment). These rough estimates qualitatively demonstrate the general flow pattern.

Most streams from the western catchments are characterised by high flow, specific water yield, and runoff (pink highlight, Table 2). The common rock types in these catchments are Whakamaru Group ignimbrites and andesitic and basaltic lava. The high specific yield and runoff via streams indicate that in these sub-catchments only little water reaches the lake directly via seepage, because the geological units have a much lesser hydraulic conductivity. Much smaller residence times for the active surface water flow are expected for the areas dominated by Whakamaru Group ignimbrites and andesitic and basaltic lava.

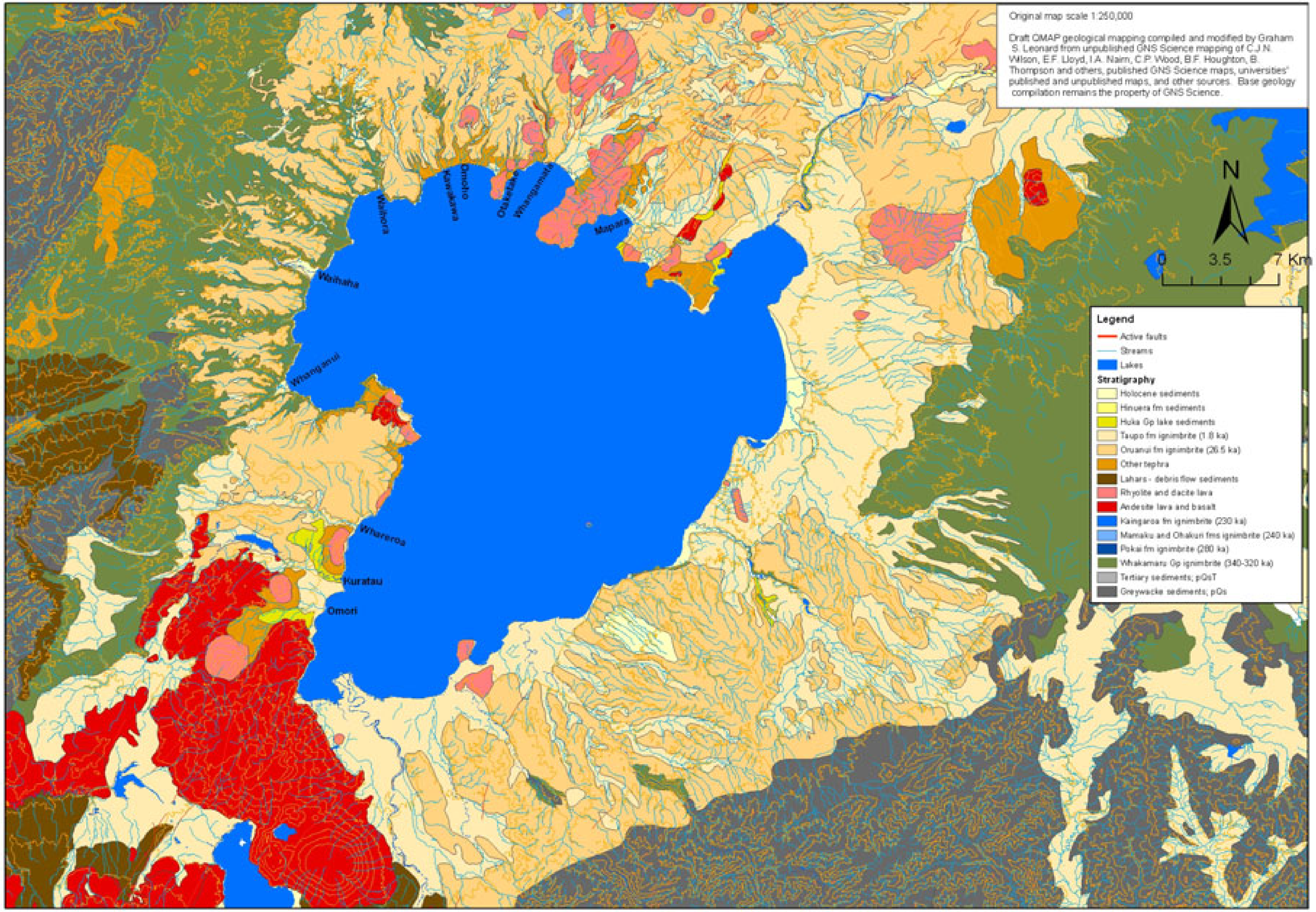

Figure 4. Geological map of Lake Taupo catchment.

Streams not highlighted in Table 2 have intermediate flow, specific water yield, and runoff and are from the boundary zone between the two geologic formations which have different hydraulic conductivity. Waihora is from a boundary zone between the Oruanui and Whakamaru Group ignimbrites. In the Whareroa catchment a significant layer of Oruanui and Taupo ignimbrites overlie the Whakamaru Group ignimbrites. In the Omori catchment andesite lava and basalt are overlain by tephra and, closer to the lake, by Taupo Ignimbrite. The relatively low runoff is probably a result of the influence of the Taupo Ignimbrite close to the lake.

5 AGE AMBIGUITY – YOUNG COSMOGENIC TRITIUM VERSUS OLD BOMB TRITIUM

The tritium time-series of several streams (Otaketake, Waihora, Waihaha, Whanganui, Whareroa) are still ambiguous on the basis of tritium alone. Old ages (MRT c.50 y) and very young ages (MRT 2-9 y) are possible. It was hoped that tritium time series over 5 years would resolve this ambiguity, because the old bomb-tritium does show a decline over that period, while the young cosmogenic tritium should remain constant over that time. However, there is the coincidence that over the last 10 years the concentration of tritium in New Zealand rain has dropped considerably (Fig. 5, blue line). This drop is similar to the expected drop in bomb-tritium in old water. Therefore, the young and old age water have identical tritium outputs at the present time and the ambiguity cannot be resolved on the basis of tritium data only. However, the hydrogeologic information can be used to exclude the very young or old age and therefore resolve ambiguity. Two more possibilities for resolving the age ambiguity are listed below.

We assume that the further drop in tritium over the last 10 years is a result of reduced production of cosmogenic tritium due to modulation by the solar field, because the wash-out of bomb-tritium from the atmosphere was basically concluded in 1990 (Fig. 5). The solar field shields the earth from the cosmic rays that produce the tritium, therefore low tritium at high solar activity. We expect that this process should reverse over the next few years according to the solar cycle. If so, then the slight increase in tritium will be a robust tool to distinguish old bomb tritium (declining over time) from young cosmogenic tritium (increasing over time).

Another way of distinguishing between the very young and very old age solutions is using the hydrochemistry data. Several chemical parameters have shown strong correlation with age in other catchments, particularly Si, F and P (Morgenstern et al., 2005). By measuring the chemistry in all stream waters (and possibly some dated groundwaters), the age correlation of these parameters can be established, and in return the chemical parameters can potentially resolve the age ambiguity in the ambiguous samples.

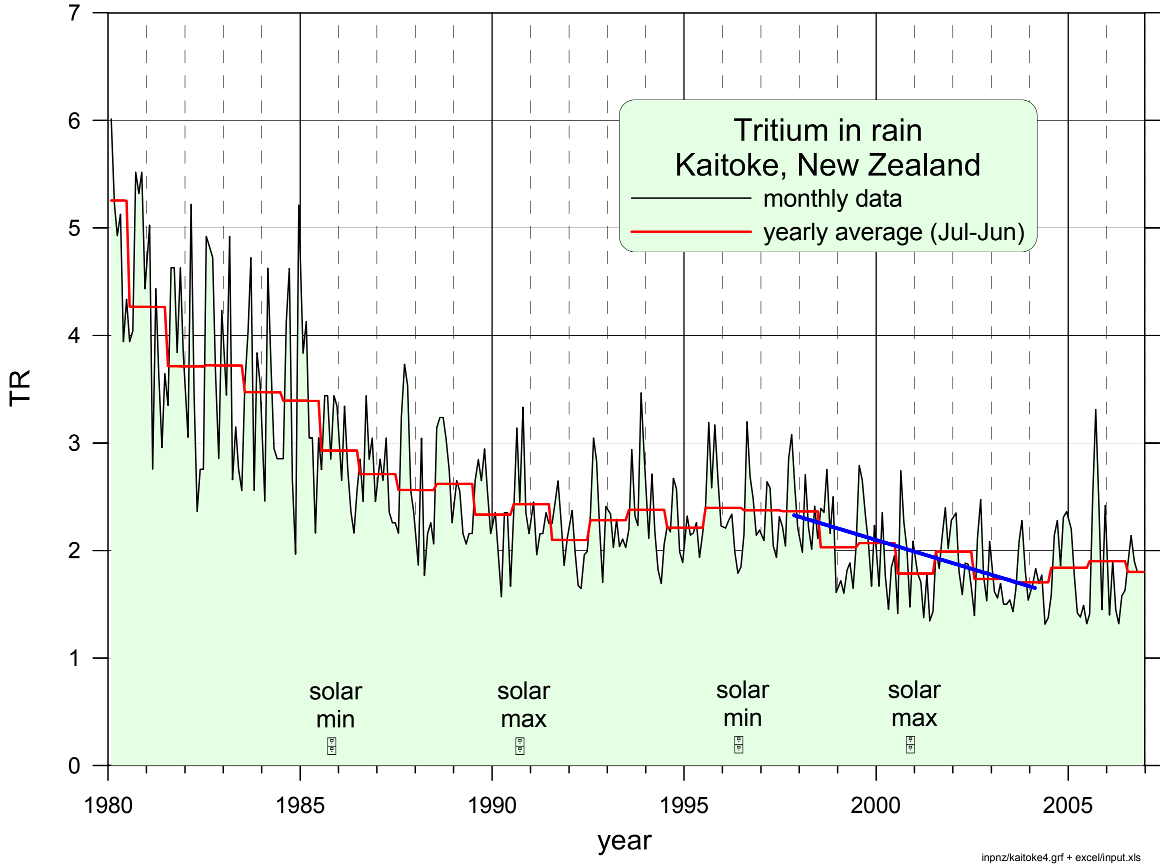

Figure 5. Tritium in recent rain in Kaitoke. Note the drop in tritium over the last decade (blue line).

6 AGE INTERPRETATION

6.1 Northern Catchment Streams

The tritium time series from the northern catchment streams Mapara, Whangamata, Otaketake, Omoho, and Kawakawa are shown in Figure 6.

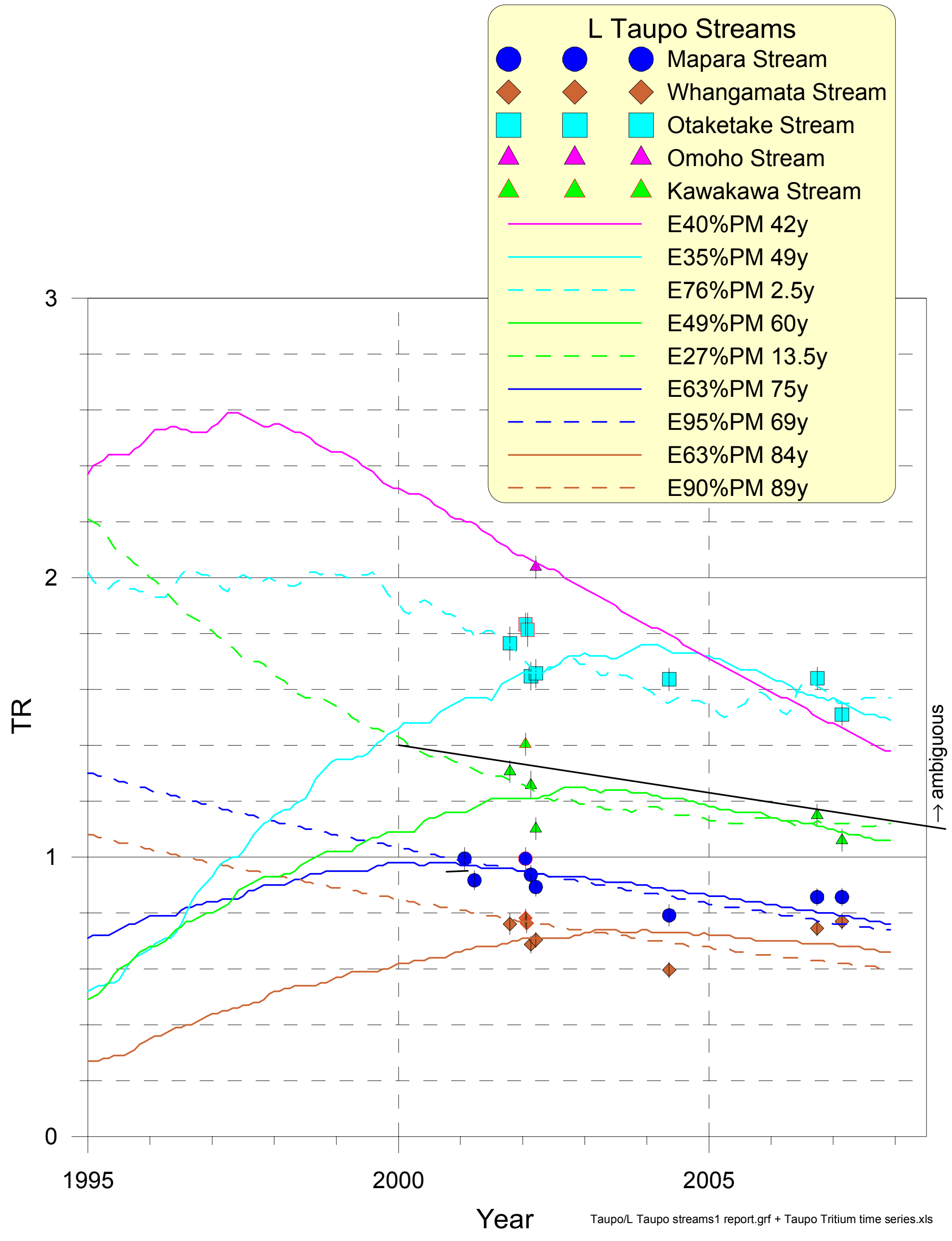

Figure 6. Tritium time-series of Mapara, Whangamata, Otaketake, Omoho, and Kawakawa Streams. Model outputs are calculated using the Kaitoke tritium input. Symbols with a red outline are for samples collected at elevated flow. Two age distributions are plotted if these are possible, with the more realistic age distribution as solid line (see text). The two parameters are the mean residence time in years, and the fraction of mixed flow within the total flow volume.

The tritium data show that these stream waters have a wide range of mean residence times, between 40 and 85 years.

The black line indicates roughly the boundary for ambiguous results. The data below the line have low pre-bomb tritium concentration without ambiguity in age interpretation, and the data above the curve are ambiguous. The latter could be old waters from around the nuclear weapons testing period, or young waters. Note that the ambiguous tritium range will diminish over the next 3-5 years because the bomb-tritium is now declining below the current level of tritium in rain.

Whangamata clearly contains the oldest water (MRT 84 y), followed by **Mapara** (MRT 75 y) and **Kawakawa** (MRT 60 y) Streams. The best match was achieved for a mixed (exponential) flow of 50-65% which seems low compared to data obtained in the Mamaku Ignimbrite in the Lake Rotorua area with typically 90-95%. However, no good matches can be achieved (broken lines) using 90% mixed flow for Whangamata and Mapara. This indicates that the Taupo catchment hydrogeology seems to be characterised by relatively low mixed flow fractions as indicated previously by the 2001/02 results.

Low mixed flow fractions (or in other words, high piston flow fractions) can explain the occurrence of still relatively high tritium concentrations found in the streams because the high bomb-tritium concentrations are preserved due to little mixing of bomb-tritium water with waters of different ages and lower tritium concentration. The age interpretations were also performed with a 10% higher tritium input compared to Kaitoke to test if the occurrence of these high tritium concentrations could be a result of higher tritium input to the Lake Taupo catchment. However, the matches between the modelled output and the measured tritium data do not improve and the current assumption of equal tritium input in Kaitoke and Taupo does not need reconsideration.

For **Kawakawa** Stream, another tritium output with a young age is plotted for comparison (MRT 13.5 y and 27% mixed flow). This illustrates the problem that close to the black line young age solutions become possible. However, an unrealistic low mixed flow of 27% would be necessary to allow for such a young solution. This young age solution is unrealistic.

The tritium time-series of the **Otaketake Stream** are still ambiguous. Old age (MRT 49 y) and very young age (MRT 2.5 y) are theoretically possible. However, the young age is not realistic and can be excluded because the hydrogeologic situation is similar for all northern catchment streams and therefore such a large age difference between Otaketake and the other streams in the northern catchment is unlikely.

Only one measurement was available for the **Omoho Stream**. The tritium concentration was highest and above the ambiguous range. Therefore, a unique age distribution could be obtained: MRT 42 y and 40% mixed flow.

The Omoho Stream was not re-sampled. Negligible surface flow and nitrogen load were observed in 2002 for Omoho. However, in the light of the present results, re-sampling Omoho stream would provide an excellent opportunity to verify the low mixed flow fractions (40%). A steep tritium decline should be observed over the next five years.

It is important to note that during high stream flow (rainy period prior to sampling) the tritium data are only slightly elevated (data points with red outline). This shows that in all the streams with old water discharge from a large groundwater reservoir, the increased flow originates mainly from displaced old groundwater and not from direct surface runoff. Therefore, water quality and age are relatively independent on flow. This was also found in the streams in the Mamaku Ignimbrite in the Lake Rotorua area (GNS unpublished results).

6.2 Waihora and Waihaha Streams

The tritium time series for the Waihora and Waihaha Streams are shown in Figure 7.

A young and an old age distribution matches the tritium data for **Waihaha Stream (**MRT 2.5 y with 83% mixed flow, and MRT 49 y with 36%). Hydrogeological evidence points toward the young age solution, because of absence of large groundwater storage formations (Taupo/Oruanui ignimbrite), and high specific yield and runoff (see section 4). A mean residence time of 49 years would be similar to that of thick Taupo/Oruanui ignimbrite, and is highly unlikely in the Whakamaru Ignimbrite formation. In addition, the young age of MRT 2.5 y is in line with the age of the young water in Kuratau River. That young age was derived from historic tritium data (see below) and is very robust. In summary, the most realistic age distribution for Waihaha Stream is MRT 2.5 y with 83% mixed flow.

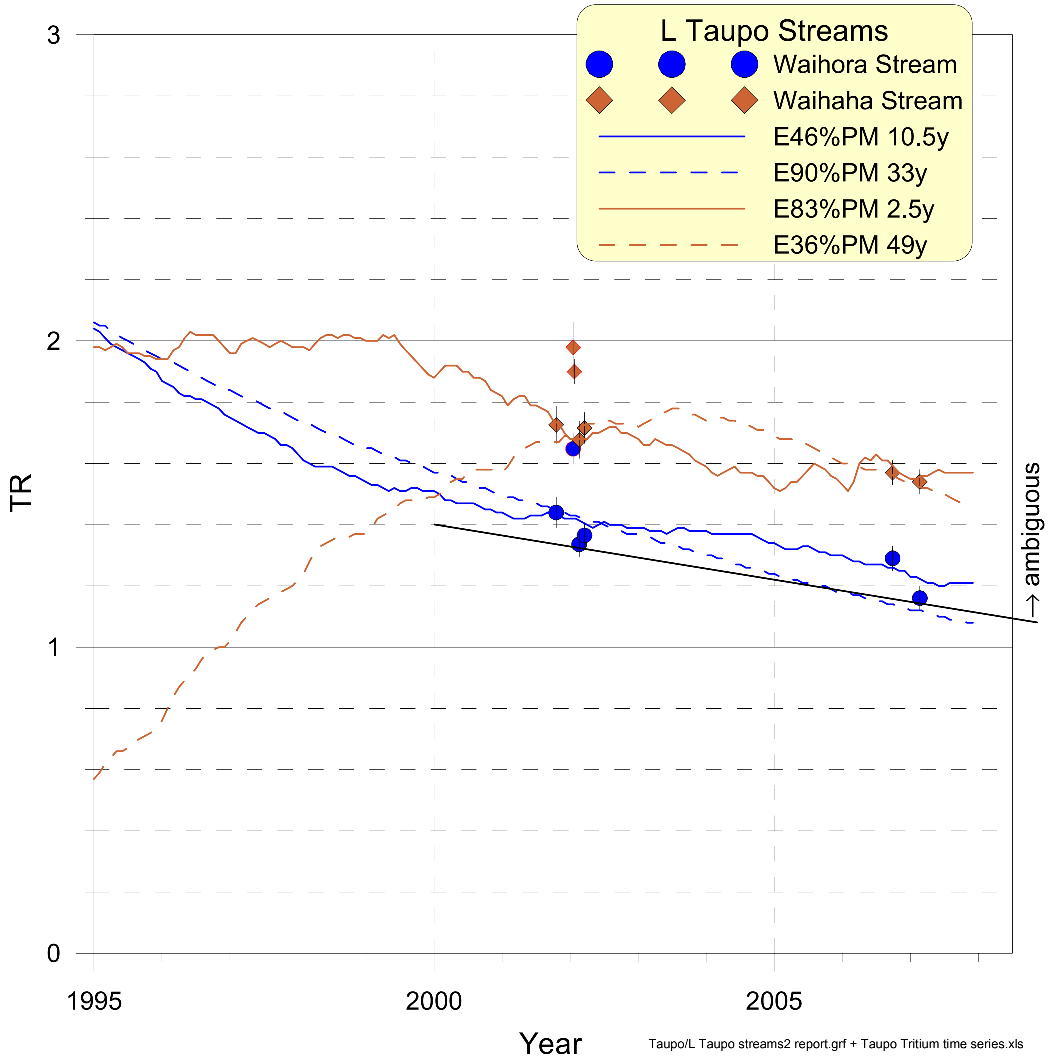

Figure 7. Tritium time-series of Waihora and Waihaha Streams. See Figure 6 caption for explanation.

It is important to note that for the streams with a smaller groundwater storage capacity, the tritium concentrations at high flow are more significantly elevated compared to the streams with old water in the northern catchment. Direct surface runoff seems to be of more importance in such hydrologic systems with little water storage capacity.

6.3 Whanganui and Whareroa Streams

The tritium time series for the Whanganui and Whareroa Streams are shown in Figure 8.

The tritium data for the **Whanganui Stream** are very similar to those of the Waihaha stream. A young and an old age distribution can match the tritium data equally: MRT 2.5 y with 77% mixed flow, and MRT 50 y with 38%. Hydrogeological evidence points toward the young age solution, because of the absence of large groundwater storage formations (Taupo/Oruanui ignimbrite), and high specific yield and runoff (see section 4). A mean residence time of 50 years would be similar to that of thick Taupo/Oruanui ignimbrite, and is highly unlikely in the Whakamaru Ignimbrite formation. In addition, the young age of MRT 2.5 y is in line with the age of the young water in the Kuratau River which was derived from historic tritium data (see below) and is very robust. So, the most realistic age distribution for Whanganui Stream is MRT 2.5 y with 77% mixed flow.

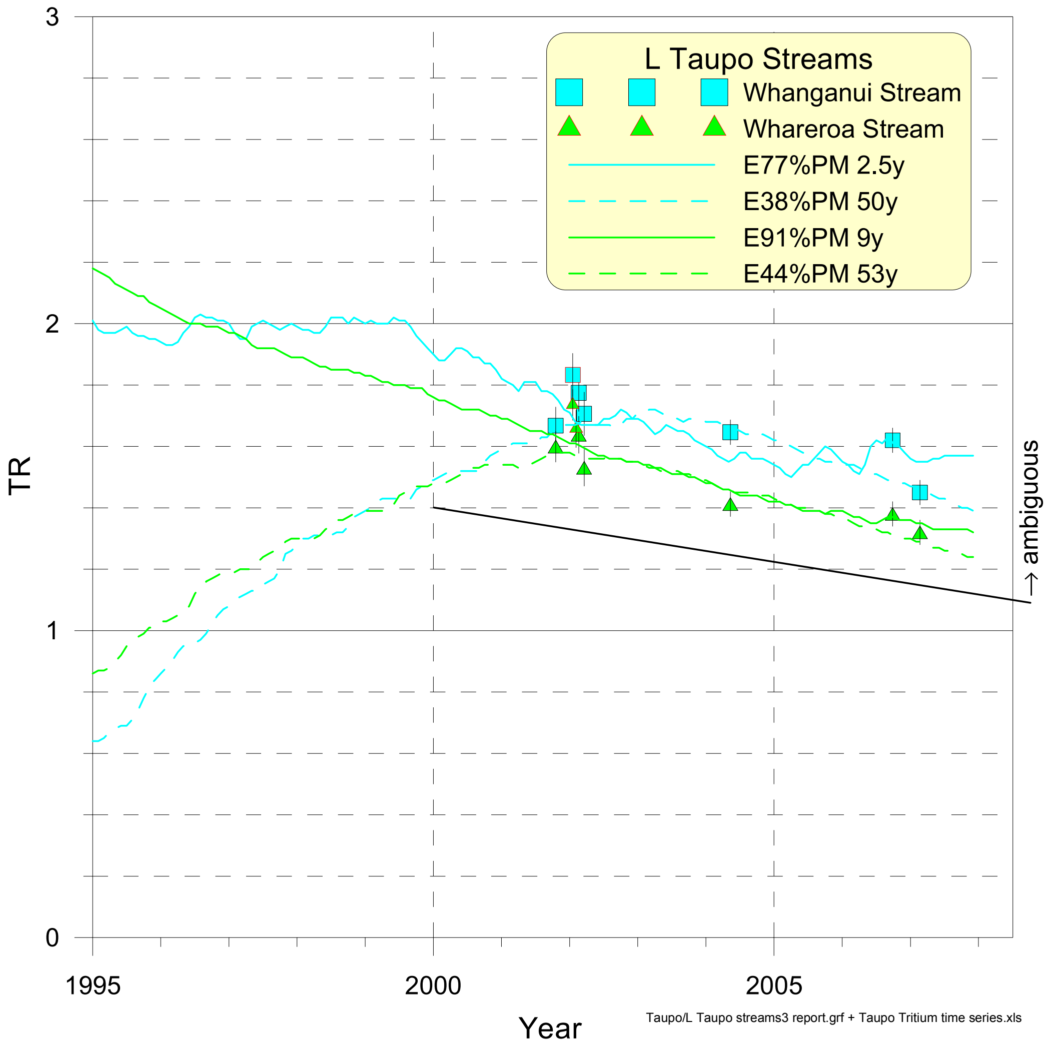

Figure 8. Tritium time-series of Whanganui and Whareroa Streams. See Figure 6 caption for explanation.

A medium and an old age distribution match the tritium data for the **Whareroa Stream** (MRT 9 y with 91% mixed flow, and MRT 53 y with 44%). Hydrogeological evidence points toward the medium age solution. The Whareroa stream has about 65% specific yield and runoff (see section 4), and the Whareroa catchment has only a thin layer of Oruanui and Taupo ignimbrite overlaying the Wakamaru group ignimbrite. A large groundwater reservoir and old water age similar to the northern catchment is unlikely. Therefore, an intermediate age between the old northern streams and the young western streams is likely. In summary, the hydrogeological evidence point toward a MRT of 9 y and 91% mixed flow for Whareroa.

Increase in tritium concentration at elevated flow due to more rain is relatively small indicating little direct surface runoff.

6.4 Kuratau River and Omori Stream

The Kuratau and Omori are the south-western most streams and are largely influenced by the relatively impermeable andesite with very short residence times in the catchment. The Hutt River represents a similar situation with its greywacke catchment and a residence time of the water in the catchment of less than six months (GNS, unpublished results). However, the Kuratau has also some significant Taupo/Oruanui ignimbrite cover, and the Omori has tephra and Taupo ignimbrite cover. Therefore, a combination of two age distributions is necessary to describe these hydrologic systems: a large fraction of very young water from the areas dominated by the Whakamaru Group ignimbrites and andesitic and basaltic lava, and a smaller fraction of older water from the Taupo/Oruanui ignimbrites and tephras.

A model combination of an Exponential Piston Flow model with older MRT in parallel to an Exponential model with very young MRT match the tritium data very well. For the Kuratau River, the model combination is robust and could be constrained very accurately, because historic tritium data were available from the time of increasing bomb-tritium. These data are extremely sensitive for constraining the flow model. The tritium time series for the Kuratau River and Omori Stream are shown in Figure 9, and the historic tritium data with model output for the Kuratau River are shown in Figure 10.

The water in the **Kuratau River** is a mixture of 63% exponential flow model with MRT 1 y, and 37% water of Exponential Piston Flow model with MRT 30 y and 50% mixed flow. Determination of these parameters is very robust due to the historic tritium data. Clearly, most of Kuratau water is post-1955.

No historic tritium data are available for the **Omori Stream**. The hydrogeologic situation here is similar to the Kuratau river, just on a smaller scale, so a similar model combination was used. A mixture of 51% exponential flow model with MRT 0.5 y, and 49% water of Exponential Piston Flow model with MRT 40 y and 39% mixed flow resulted in a good match of the model output to the measured data.

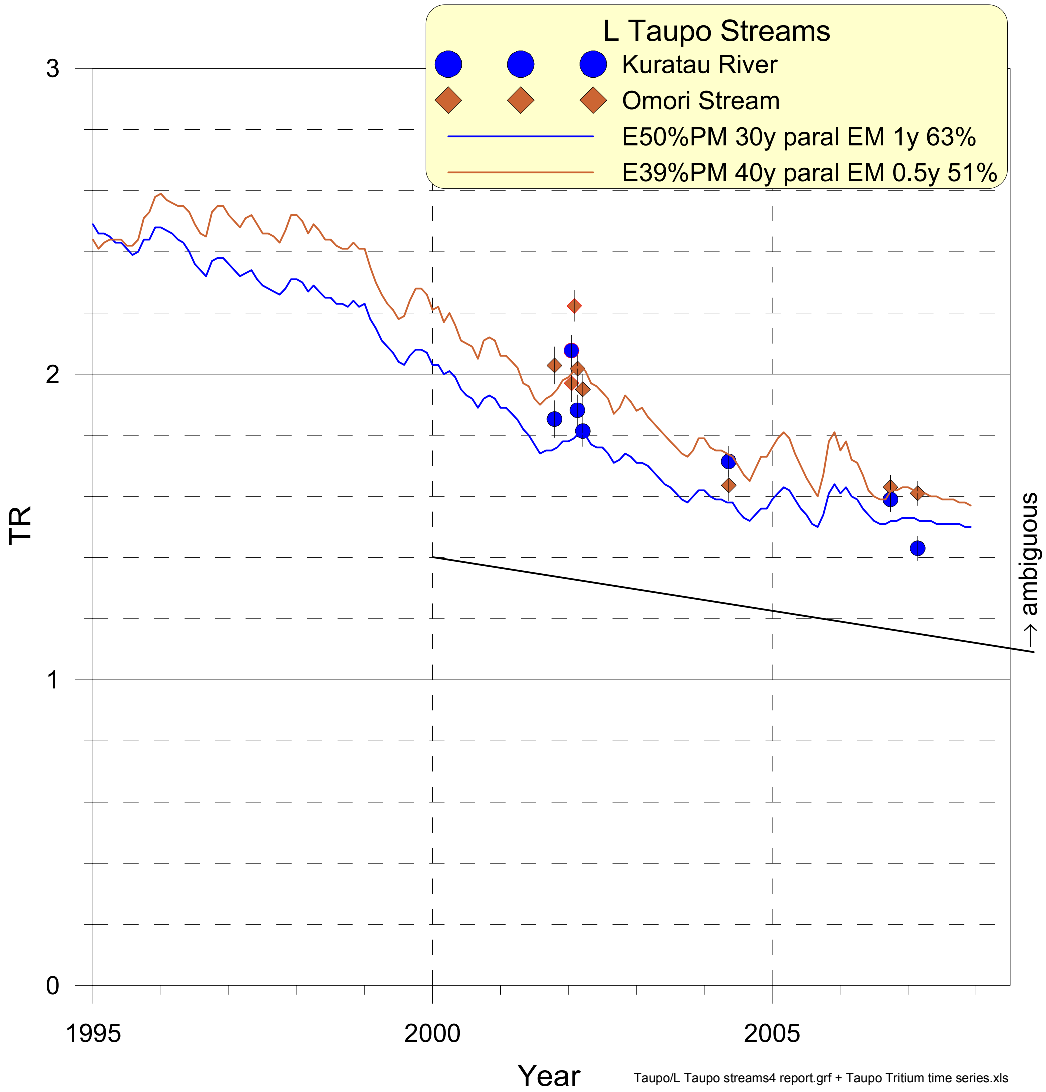

Figure 9. Tritium time-series of Kuratau River and Omori Stream. See Figure 6 caption for explanation.

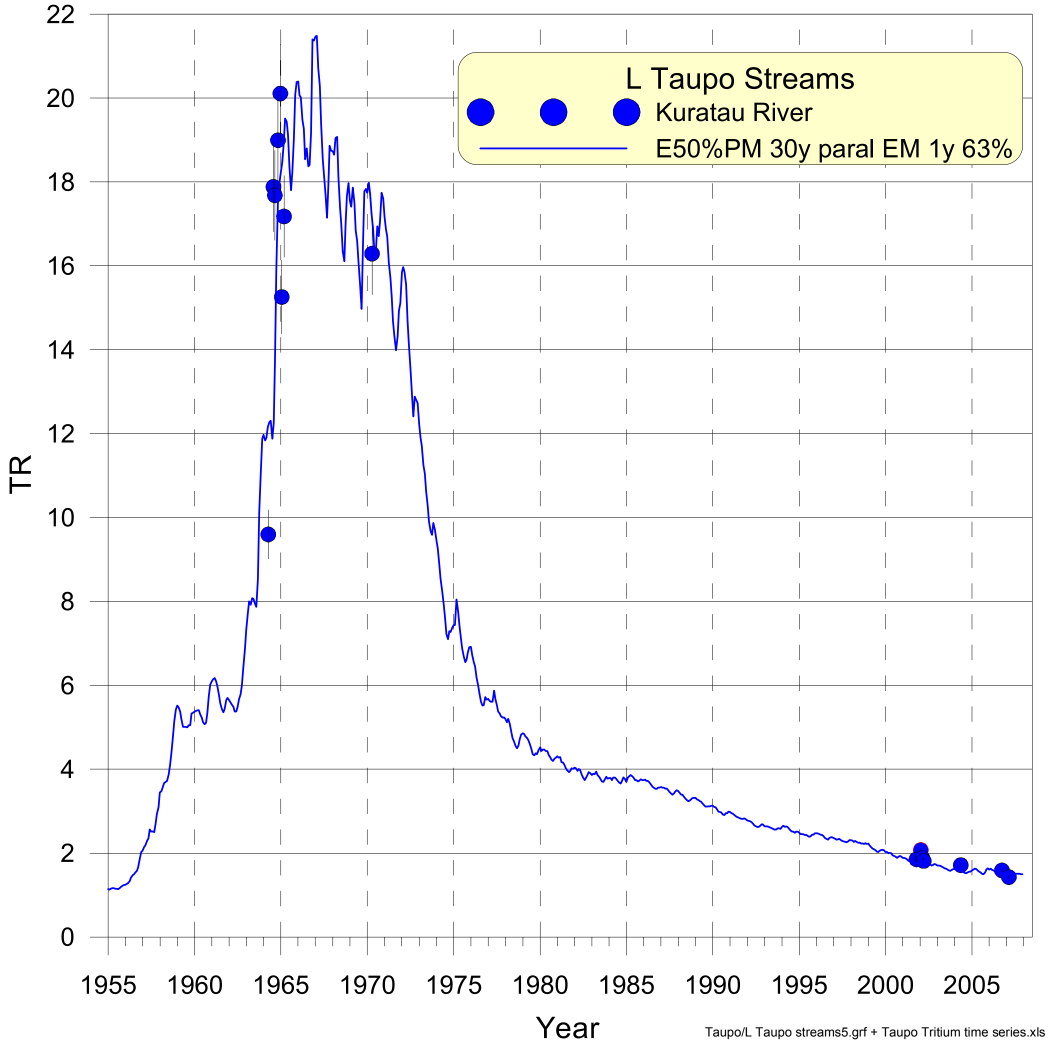

Figure 10. Tritium time-series for Kuratau River with historic data. See Figure 6 caption for explanation.

7 YOUNG WATER FRACTION AND PROJECTED TOTAL NITROGEN LOADS

Table 3 summarises all age distributions. While in several streams the tritium data alone leave some ambiguity in age interpretation, this could be resolved with relative confidence using available hydrogeologic information. For comparison, the theoretically possible second age distributions are also listed in Table 3. The reasons that make the second age distributions unlikely are described in section 6.

Table 3. Age distribution data for the northern and western streams of Lake Taupo. With the 5-year time series of tritium data there remains still some ambiguity (see section 5), so two theoretically possible age solutions are listed. The **First solution** is more realistic based on hydrogeological and isotope evidence (see section 6), but the **Second solution** is also shown for comparison.

	Age interpretation						Previous	New estimate of	
	first solution			second solution			estimate*1	post-1955 water in*2	
Stream	E%PM	MRT [y]	yf [%]	E%PM	MRT [y]	post-1955	yf (45y)	2002	2007
Mapara	**63**	**75**	**40.1**	95	69	52.3	**30**	**33.5**	**40.1**
Whangamata	**63**	**84**	**32.7**	90	89	41.6	**24**	**26**	**32.7**
Otaketake	**35**	**49**	**69.1**	76	2.5	100	**78**	**58.7**	**69.1**
Omoho	**40**	**42**	**79.7**				**76**	**72.7**	**79.7**
Kawakawa	**49**	**60**	**51.7**	27	13.5	100	**39**	**42.8**	**51.7**
Waihora	**46**	**10.5**	**100**	90	33	80.6	**47**	**100**	**100**
Waihaha	**83**	**2.5**	**100**	36	49	69	**82**	**100**	**100**
Whanganui	**77**	**2.5**	**100**	38	50	66.9	**82**	**100**	**100**
Whareroa	**91**	**9**	**99.8**	44	53	61.6	**79**	**99.6**	**99.8**
Kuratau		see text					**95**	**95.6**	**96.9**
Omori		see text					**95**	**88.5**	**91.6**

*1 Previous estimates of the young fraction are the estimates based on the limited isotope and hydrogeological evidence that was available in 2002 and 2004.
*2 New estimates are based on long-term tritium data combined with better hydrogeological information and are therefore more robust.

The young water fractions, with young water being defined as post-1955 water (this is the fraction of water recharged since and affected by landuse), are listed in Table 3 for the years 2002 and 2007. Note that the young water fractions have increased in 2007, because 5 more years have elapsed and therefore the fraction of post-1955 water has increased.

Also listed in Table 2 are the young water fractions that were established in the previous analysis (Vant & Smith, 2004), labelled yf(45y). This allows for comparison of changes in young water fraction due to the revised age distributions with the availability of long-term tritium data and new hydrogeological information. The previous estimates can be compared to the new estimates of post-1955 water in 2002.

Northern Streams

The young water fractions for the northern catchment (Mapara to Kawaka) have not changed significantly, but are now based on more robust age distributions. Small increases for the new estimates are because of slightly different timing (yf 45 years in 2002 meant post-1957 water). The young water fraction has decreased significantly only for the Otaketake stream, because with the long-term tritium data it is now possible to establish the older age of Otaketake (compared to the highly ambiguous result in 2002).

Western Streams

The young water fractions for the western catchment (Waihora to Omori streams) have changed significantly in the new estimates. The reason is that for the ambiguous age data the younger ages are now considered to be more realistic. The possibility of a younger age solution was mentioned in the previous report, but was rejected in that age interpretation because the hydrogeology was thought to be relatively uniform in the western and northern catchment and therefore would not be consistent with such a large age difference. While the tritium data alone still leave some ambiguity between the very young and old age possibilities (Section 5), the new evidence from long-term tritium data and from hydrogeological information point strongly toward relatively young water in the western catchment (Section 6). As a result the young water fraction of the western streams is close to 100%, and only small changes in nitrogen load due to landuse changes around 1955 are expected for these streams.

In Table 4 the total nitrogen loads are listed for the northern and western streams. Future TN loads were calculated for the year 2002 because new TN concentrations are not available, and because this allows for comparison to the previous TN load estimates. The new estimates are based on the new and more robust age distributions.

While the estimates of TN loading for the northern surface stream flows are similar to the previous estimates, the estimates for the western catchment have decreased significantly as a consequence of the higher young water fraction. The expected TN load increase is estimated now to be 21 instead of 45 t/y. The drop in total additional nitrogen load is significant because the western steams are the streams with the highest flow rates.

Table 4. Total nitrogen loads estimated for the northern and western streams of Lake Taupo, based on mean flow and TN data from Vant & Smith (2004). The projections of future nutrient loads are based on the assumptions that (i) the N input to groundwater from land use remains at the current level, and (ii) post-1955 water is affected by land-use. The background **(bkg) TN** load is the natural load (product of mean flow and background TN concentration). For the background TN concentration a plausible estimate of 0.2 g/m^3 is used (Vant 2006). **Total TN load** is the current load (product of mean flow and mean TN concentration), and **land-use** is the TN load caused by land-use (difference between total and bkg). The future TN load is the expected load at steady state, when all of the discharge water is post-1955 (recharged after land-use intensification). **Total future TN load** (the total predicted nutrient load) is the sum of future land-use change load and the background load. **Add future TN load** is the additional load at steady state.

	mean flow	TN	2002 TN load [t/y] *1			previous prediction of future TN load [t/y] *2		New prediction of future TN load [t/y] *3	
Stream	[m^3/s]	[g/m^3]	bkg	landuse	total	total	additional	total	add.
Mapara	0.09	0.95	0.5	2.0	2.5	7.2	4.7	6.5	4.0
Whangamata	0.11	1.05	0.7	3.0	3.6	12.9	9.3	12.0	8.4
Otaketake	0.19	0.74	1.2	3.3	4.5	5.4	0.9	6.8	2.3
Omoho	0.06	0.26	0.4	0.1	0.5	0.5	0.0	0.5	0.0
Kawakawa	0.06	0.73	0.35	0.9	1.3	2.7	1.4	2.5	1.2
Waihora	1.90	0.37	12.0	10.2	22.2	33.1	11.2	22.2	0.0
Waihaha	6.47	0.29	40.8	18.4	59.2	62.3	3.9	59.2	0.0
Whanganui	2.58	0.50	16.3	24.5	40.8	46.5	5.4	40.8	0.0
Whareroa	0.94	0.62	6.0	12.5	18.5	22.0	3.4	18.5	0.1
Kuratau	7.00	0.54	44.2	75.1	119.3	123.2	4.0	122.7	3.5
Omori	0.56	0.92	3.5	12.7	16.3	16.9	0.7	17.9	1.7
			126	163	289	333	45	310	21

*1 2002 TN load is the estimated TN load in 2002 based on TN and flow data from Vant & Smith 2004.

*2 Previous prediction of future TN load is the estimate based on the age interpretation with the limited isotope and hydrogeological evidence that was available in 2002 and 2004.

*3 New prediction of future TN load is based on age interpretation with long-term tritium data combined with better hydrogeological information and is therefore more robust. For better comparison with the previous prediction and because there are only the 2002 TN data available, this prediction is still related to the year 2002.

In summary, only moderate TN load increases of 5 t/y are expected from the western lake catchment areas. These moderate increases are expected from the Kuratau River and Omori Stream areas that have significant Taupo and Oruanui Ignimbrite cover. The largest TN load increase of 16 t/y from surface flows is expected in the northern catchment with thick Taupo and Oruanui Ignimbrite cover.

It must be noted that the above TN load budget covers only the surface stream flows. These, however, form only a fraction of the total discharge from these catchments. The underlying groundwater flows are likely to be even older than the surface stream flows, so much larger increases in TN loading can be expected from the groundwater seeping directly into the lakebed.[1] The TN load via direct groundwater seepage through the lake bed is not included in the above budget.

8 CONCLUSIONS

Tritium time series over the last five years were established and interpreted into age distributions to quantify the delayed arrival of landuse nitrogen into Lake Taupo via the streams. Robust age distributions could be obtained in the northern part of the catchment. In the western part of the catchment, some of the tritium data (tritium data on their own) are still ambiguous because of a coincidence of tritium decline in NZ rain over the last 10 years. However, in combination with the hydrogeological evidence, the ambiguity could be resolved.

The stream waters in the western catchment of Lake Taupo are mostly very young with residence times of several years. The stream waters in the northern catchment with thick Taupo and Oruanui Ignimbrite cover are old with mean residence times 40-85 years.

In regard to future nitrogen loading to Lake Taupo, most of the western streams are already in steady-state to post-1955 landuse water and no significant increases are expected in this part of the catchment. The largest increase in nitrogen loading is expected in the northern catchment.

9 ACKNOWLEDGEMENT

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[1] The following estimates give a rough estimate of the expected increases in TN loading for the northern catchment: As the surface flow represents only approximately 20% of the total flow, the expected TN discharge from the groundwater seepage in the northern catchment is about 110 t/y. Most of this is still to come. The deeper groundwater seepage flow is expected to be older than the surface flow and has an estimated young fraction of only 30% currently. Therefore, of the estimated 110 t/y TN from seepage, around 80 t/y are still to come. The numbers are only rough estimates because TN and age data are not yet available from groundwater seepage. However, the numbers indicate the order of magnitude of TN load increase from the old seepage water.

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