Interim summary of ground water information for consideration by the Collaborative Stakeholder Group

Collaborative Stakeholder Group

Healthy Rivers: Wai Ora Project

20 June 2015

Technical Leaders Group report for discussion at a CSG workshop

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Memo

File No:	2015 06 21
Date:	21 June 2015
To:	Chairman, Technical leaders Group
From:	Tony Petch, Tony Petch Consulting Limited
Subject:	**Interim summary of phase 1 ground water investigations commissioned to support the Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai project.**

Introduction

The Healthy Rivers programme requires information on ground water resources of the Waikato and Waipa catchments to help understand how ground water is impacted by contaminant discharges from land use, especially nitrogen. Important factors to understand are: how nitrogen is transformed as it passes through the aquifers, the travel times (lags) for water and nitrogen to pass through the aquifers to rivers and streams, and the structural relationships and interactions between ground water and surface water resources. This information helps understand the extent to which the water quality observed in rivers and streams is in equilibrium with current land use: and, if it is not in equilibrium, the amount of nitrogen load to come as a consequence of today's land use.

A ground water experts panels was convened in October 2014 to define the work required to support Collaborative Stakeholder Group deliberations on policies to restore and protect and restore the Waikato and Waipa Rivers. Given the time available, the experts' panel recommended a staged approach to providing additional information; comprising work required within the first six months, one year and two years.

Initial ground water investigations – information required within six months

The first tranche of ground water investigations comprised:

1) **Study 1: Short term field investigation of ground water resources in the Waikato and Waipa river catchments**
   Knowledge of the ground water resources of the Waikato and Waipa river catchments is highly variable: detailed knowledge is available where specific investigations of ground water resources have been completed; elsewhere little is known but for scattered observations of ground water chemistry, water levels and aquifer hydraulic properties.

   These 'short-term' investigations of ground water resources were aimed to 'fill in' gaps in knowledge of the Waikato regional ground water systems. Comprehensive ground water investigations are notoriously expensive and, since the mid-1980s, have been rarely undertaken.

2) **Study 2: Ground water resource characterisation in the Waikato River catchment for the Healthy Rivers Project**
   A synthesis of ground water resources in 74 Healthy River Project catchment's including summaries of: the general distribution of aquifers; their hydraulic properties, catchment water budgets, including ground water inflows and outflows, stream flow components (base flow - sourced from ground water: and quick flow - involving more rapid surface run off during and post rainfall), and ground water chemistry with emphasis on nitrogen *E. coli*, and other chemical characteristics affecting the suitability of the ground water quality for use.

3) **Study 3: Estimation of lag time of water and nitrate flow through the Vadose Zone: Waikato and Waipa River catchments**
   This study examines the overall lag time between land use changes and associated surface water quality impacts. The report presents results for predicting the time taken for nitrate-nitrogen to travel from the land surface through the unsaturated (vadose) zone into shallow ground water.

4) **Study 4: Predicting the Redox Status of Ground Water on a regional scale.**
   Environmental Science Research was undertaking a MBIE[1] funded study on Redox status of ground water in the Reporoa area of the Upper Waikato catchment and in the Canterbury Plains. An extension of this work was contracted to ESR for the Waikato and Waipa catchments and Hauraki catchments. This study examines the conditions for denitrification to occur and the extent these conditions exist in the Waikato and Waipa catchments.

5) **Study 5: Incorporating this information into a steady-state ground water model**
   NIWA developed a steady-state catchment model[2] for the Economic Joint Venture Initiative (EJVI) for the upper Waikato catchment. The scope of this model was increased to cover the middle and lower Waikato catchments and the Waipa catchment by specifically modelling 74 Healthy Rivers' sub-catchments where there was adequate data to provide estimates of nitrate-nitrogen, phosphorus, sediment and *E. coli* loads to each catchment. The output of the NIWA model is then passed to the economic optimisation model being developed for the Healthy Rivers Project to estimate the costs of meeting a range of scenarios determined by the Collaborative Stakeholder Group to restore and protect the Waikato and Waipa Rivers.

Discussion

All this work was targeted to provide a general understanding of regional ground water resources and particularly ground water age and nitrogen attenuation processes in the catchments. Nitrogen load to come was shown as the main determinant of the cost of maintaining water quality in the Waikato river in the EJVI because the nitrate-nitrogen loads in rivers and streams are not yet in equilibrium with catchment land use. Given the time available to complete the work the experts' panel agreed this work would be used as input to the steady-state catchment model used in the EJVI. The year one and two studies would involve additional studies (if required) and development of time varying (transient) ground water models that could provide a more resolved understanding of the catchment's ground water resources and the timing of nitrogen transport to rivers and streams.

The first tranche of work has been completed and draft reports are being received. This report provides an interim summary of the investigations and the main conclusions of the work to date.

[1] Ministry of Business, Innovation and Employment

[2] Elliott S *et al.*, 2013. Catchment models for nutrients and microbial indicators – Modelling application to the Upper Waikato Catchment. Client report for the Ministry for the Environment. NIWA client report Ham 2013-103.

Study 1: Short term field investigation of ground water resources in the Waikato and Waipa river catchments

The scale of this study and the short time within which to complete this study required it to be broken into two segments: investigations in the Waipa catchment were completed over the 2015 summer by GNS science[3]; and investigations in the upper, middle and lower Waikato catchments were completed over the same period by Waikato Regional Council ground water staff and a contractor (WildImpacts Ltd).

The field investigations in the Waipa comprised:

- collection of 48 samples for analysis of chemistry (23 chemical species or properties including nitrate, iron, manganese, reactive silica, pH, ammoniacal-N and other parameters influencing the suitability of the ground water for a range of uses);
- collection of nine water samples for the dating of ground water;
- the recording of static water levels in 27 bores; and
- nine tests of aquifer hydraulic properties.

The field investigations in the upper, middle and lower Waikato comprised:

- collection of 68 samples for analysis of chemistry (23 chemical species or properties including nitrate, iron, manganese, reactive silica, pH, ammoniacal-N and other parameters influencing the suitability of the ground water for a range of uses);
- the recording of static water levels in about 50 bores;
- a survey of radon concentrations to identify longitudinal ground water inflows in the Poikaiwhenua and Little Waipa streams; and
- sampling to determine the depth to the redoxycline in selected location in the catchments (note the costs for drilling were funded by other agencies).

In addition, three other separate field investigations were completed over the 2015 summer throughout the Waikato and Waipa catchments:

- surface and ground water age sampling including 21 surface water sites and ground water for dating by analysis of tritium, CFC and SF6[4];
- a flow confirmation survey on selected streams (484 sites) in the Waipa and middle and lower Waikato catchment to determine the distribution of low flows (predominately ground water discharge). This survey included locating stream heads and their elevations for piezometric surface (ground water level) analysis and for future ground water modelling.
- Low flow gaugings were completed throughout the Waipa and Waikato catchments to determine discharges for the areas gauged. One hundred and seventy gaugings, including 31 in the Waipa catchment, 68 in the Reporoa area, five on the Pokaiwhenua stream and 66 in the lower Waikato catchment. Some of this work involved simultaneous linear gaugings to determine the longitudinal gain in in flow downstream and hence the spatial distribution of ground water discharge along these streams.

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[3] Rawlinson Z *et al* 2015. Short term field investigation of groundwater resources in the Waipa Catchment: January – April 2015. GNS Science Consultancy Report 2015/54.

[4] Tritium, chlorofluorocarbon (CFC) and sulphur hexafluoride (SF6) are particularly useful for dating ground waters less than 100 years old. Tritium (3H) was introduced into the atmosphere by nuclear testing and has a half-life of 12.4 years. Atmospheric tritium concentrations reached a peak in the 1960s. Ground water dating with CFCs and SF6 is possible because concentrations have been building up in the atmosphere at a known rate since the late 1930s and early 1970s respectively and because the dissolved concentrations in rainfall maintain a unique signature of the atmosphere at that particular time, thereby providing a date from which to age ground water.

Summary and findings - Waipa

The results of these field investigations have been incorporated in the hydrogeological models described in Study 2 and are consistent with previous work undertaken in the catchments. Nevertheless the additional data obtained provide greater spatial resolution to the general understanding of ground water resources in the catchments.

Water chemistry

About 50 per cent of bores showed levels of nitrogen that are elevated compared with background levels (i.e. >1 mg/l), most probably relating to land use activities. These results are consistent with other New Zealand studies[5]. The remainder showed no elevation from back ground levels or were associated with strong reducing conditions. Nitrate contamination was not strongly related with depth with similar proportions of shallow and deep bores with elevated nitrate concentrations.

Water level

Water levels for bores located in shallow aquifers (0-27 m deep) have water ground water levels of between 4 and 10 m below ground. Deeper bores (40 - 90 m below surface) have water levels between 15 and 50 m below ground. The water level gradients observed in adjacent bores (shallow and deep) at lower ground surface elevations indicate ground water recharge is occurring. At higher elevations, the greater depth to water, combined with the greater elevation of ground water surface indicates flow away from upland areas to lower lying terrain and the streams incised within valleys.

Hydraulic properties

The results show the expected trends observed in previous studies: with low permeabilities found in fine grained sediments and greater permeabilities in sands and gravels located near river channels and in fractured, indurated sandstones and limestone material. There is little evidence of strong spatial trends in hydraulic properties because of the complex geology within the catchments.

Summary and findings – upper, middle and lower Waikato

As in the Waipa catchment, the results of these field investigations have been incorporated in the hydrogeological models described in Study 2. The results are consistent with previous work undertaken in the catchments but provide greater spatial resolution to the general understanding of ground water resources in the catchments.

Groundwater chemistry

About 38 per cent of all wells sampled this summer show some contamination of nitrate-N probably related to land-use activities (i.e. > 1 mg/l). The ground water sampling in the Reporoa area showed the nitrate-nitrogen concentration was highly variable ranging from non-detectable to above MAV[6] with a mean of 2.5 and median of 0.75 mg/l. Aerobic conditions, were indicated

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[5] Morgenstern U and Doughney CJ 2012. Groundwater age for identification of baseline groundwater quality and impacts of land-use intensification – The National Groundwater Monitoring Programme of New Zealand. Journal of Hydrology. V 456-457, pp 79-93.

[6] MAV – Maximum acceptable value. The New Zealand MAV for nitrate-nitrogen concentration in drinking water is 11.3 mg/l. This level is based on the World Health Organisation Guideline Value (GV), established to protect infants from a condition known as “blue baby syndrome”. Affected infants have an abnormally high amount of methaemoglobin in their blood, hence the condition - *methaemoglobinaemia*. Unlike haemoglobin, *met*haemoglobin cannot transport oxygen in blood. In the 1950s, infant methaemoglobinaemia was reported regularly in the United States but today it is rare despite increasing exposure to high-nitrate drinking water. Explanations for this anomaly are higher standards of well construction and greater awareness of the importance of avoiding microbial contamination common in shallow ground water. This also explains why the incidence of

at about 36 per cent of the sites and anaerobic conditions (indicating reducing conditions and potential for denitrification) were observed at about 32 per cent of the sites. The potential for denitrification could not be determined at the remainder of the sites.

Water levels

Static water levels were measured at about 50 bores. This information was forwarded to GNS Science for constructing the piezometric surfaces (Study 2). Depth to ground water varies depending on the location of the bore within the catchments. Ground water level is deeper in upland areas and nearer (within a few metres) the surface in low lying areas.

Radon

The sampling for radon along the Pokaiwhenua and Little Waipa streams showed the discrete input of ground water at specific locations (springs) indicating the importance of ground water flow through fractures in these upper Waikato catchments. Ground water flow through fractures can be inferred in much of the upper Waikato where fractured volcanic rocks are present (refer Study 2 Figure 1). Fractures allow the more rapid transmission of ground water and nutrients in aquifers and reduce the opportunities for denitrification if the potential exists.

Oxidising and reducing conditions

Cores from bore holes drilled at 22 sites in Hamilton Basin and adjacent to the Waikato hydro lakes during the summer were tested for the occurrence of anaerobic conditions. The opportunity was taken to test water chemistry, the presence or absence of anaerobic conditions and the occurrence of nitrogen at these locations. Although the depth to anaerobic conditions below the water table was highly variable, spatially and vertically (ranging from a few metres up to 50 m), it occurred at almost half the sites within five metres of the surface indicating the presence of conditions suitable for denitrification.

Summary and findings – field studies completed in both the Waipa and Waikato Catchments

Water age

Surface water

The age of surface water in the Waipa and middle and lower Waikato catchments (expressed as MRT[7]) during summer base flows is usually less than 15 years and average about 10 years.

In contrast, the age of surface waters in the Upper Waikato sub-catchment streams are older with an average MRT of about 52 years (median 35 years; flow weighted mean of about 47 years). The water age of the Waikato River above Karapiro is younger (about 12 years at Karapiro) due to the influence of Lake Taupo, which provides two thirds of the flow.

Ground water

The age of ground water is highly variable throughout the study area. Mean residence times are often much older than surface waters (MRT from latest survey is about 150 years). The MRT is older than suggested by previous investigations (MRT 67 years (n=113)). Initial analysis of the data obtained recently suggests there is no clear relationship between depth of ground water and its mean residence time. Some shallow wells (between 2 and 10m deep) in the middle and lower Waikato catchments and the Waipa catchment, which intersect very shallow ground water, show consistently younger ground water (1 to 2 years MRT). These ages may indicate

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infant methaemoglobinaemia in most developed countries (including New Zealand) is now very low, whereas in developing countries it is relatively common.

[7] MRT – mean residence time in years

shallow, more rapid flow in the active surface zone in the aquifers. The age of ground water in three springs measured in the upper Waikato catchment vary between 11 and 60 years MRT. The age of deeper ground water is consistently older but appears unrelated to depth. This observation may reflect the different sediments from which the ground water was obtained, the degree of fracturing of the aquifers intercepted by the bores and the general variability of the aquifers sampled. Generally, age increases with depth in areas of recharge.

Low flows and stream head elevations

The information from the low flow gauging programme and investigation of stream head elevations was provided to GNS Science for inclusion in the water budgets and piezometric surfaces (Study 2 below).

Study 2: Ground water resource characterisation in the Waikato River catchment for the Healthy Rivers Project

The report and accompanying appendices identify a range of features for each of the Healthy River catchments: the upper Waikato above Karapiro; the Waipa Catchment; and the middle and lower Waikato river[8].

Summary and findings - Upper Waikato

Geology

This catchment has a complex geology dominated by large faults characteristic of the Taupo volcanic zone which has influenced the distribution of sediments and the extent of aquifers in the catchment (Figure 1). The basement[9] rock has large offsets associated with faults and calderas. The Whakamaru Group ignimbrites[10] infill the basement structures, as do a sequence of lake sediments from the ancestral Lake Huka (an important aquiclude), and the Oruanui formation, derived from the Lake Taupo eruption, as do the modern day surface alluvial sediments of the Tauranga group. The Whakamaru group form important aquifers as do the Tauranga group which supplies much of the low volume rural domestic and stock water supplies. A suite of volcanos have formed to the west comprising Pureora, Titiraupenga and Maungatautiri. Ignimbrites of the Pakaumanu Group, from the Mangakino Caldera, are common at the ground surface in the centre and west of the catchment. Eruptions from the Whakamaru Caldera deposited large volumes of ignimbrite in the middle sections of the catchment. The Mamaku Plateau formation[11] is exposed at the ground surface to the north of the catchment and also provides an important source of ground water.

Water budgets

The water budgets and the associated estimates of base flow and quick flow show the ground water system is hugely important to the hydrology of the upper Waikato. Most (94 per cent) of the net rainfall recharge infilters to ground water and reappears later as flow in rivers and streams. Very little runoff occurs as quick flow during and after storms. Hence stream beds are usually dry except during storms. Most stream flow is generated from springs located further downstream where ground water intersects the ground surface; often at the base of scarps or other structural features. Most ground water flow is intercepted by streams and, in the very few catchments where this may not occur, there is evidence that the ground water flow is ultimately intercepted by the incised Waikato River. Effectively, the hydrogeological system is closed - the underlying basement is virtually impermeable - and all net rainfall in the upper Waikato ultimately appears as flow in the Waikato River.

Piezometric surface

The piezometric surface lies between 20 and 100 m below surface in elevated terrain to between 2 and 20 m below the surface on more subdued terrain and nearer streams. The stream elevations represent the local ground water surface. Springs, common in the incised terrain typical in the upper Waikato, represent a focussing of ground water outflows often aggregated through local fractures in the surface sediments.

Ground water flow is driven by topographic gradients and is down slope to local streams in almost all catchments. The topographic divide (catchment boundary) therefore reflects the

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[8] White PA *et al*, 2015. Groundwater resource characterisation on the Waikato River catchment for the Healthy Rivers Project. GNS Science Consultancy report 2015/95

[9] The 'basement' in the North Island generally comprises low grade indurated 'greywacke' of Jurassic age (200 to 145 million years ago)

[10] Widespread plateau forming ignimbrite sheets erupted between 320 and 240 thousand years ago

[11] Ignimbrite sheets erupted from the Rotorua Caldera about 240 thousand years ago

ground water divide. The only potential exception is the boundary on the elevated but flat terrain of the Kaingaroa Plateau to the north east of the upper Waikato: there is no evidence available to clarify the ground water boundary in this areas but this is of little consequence given the large forestry blocks on the area.

Ground water chemistry

Ground water chemistry in the upper Waikato is derived from 21 monitored bores. Nitrate-nitrogen is commonly higher than maximum acceptable values for drinking water (11.3 mg/l) or between half of MAV and MAV[12]. This indicates land use activities are impacting on ground water quality. The trend in nitrate concentrations is varying slowly suggesting recent land use intensification has not yet further impacted ground water quality. Manganese (Mn) and Iron (Fe) concentrations indicate the presence of anoxic conditions in ground water.

Summary and findings - Waipa

Geology

The geology of the Waipa catchment is underlain by basement rocks, of low permeability, and of limited use as an aquifer (Figure 2). The basement rocks form a basin bounded by up-thrown basement material. The basement is overlain by sediments of the Te Kuiti group[13]. These sediments provide limited water sources from discrete fractured and limestone aquifers. Fine grained, relatively impermeable, Miocene[14] marine sediments lie above the Te Kuiti group and form the effective hydrogeological of the Waipa catchment. Above the Miocene sediments lie the Alexandra volcanics[15] forming the mountains of Te Kawa, Kakepuku and Pirongia. Ground water supplies are often plentiful from these sediments as they are strongly fractured. The Pakaumanu group, comprise ignimbrites from the Mangakino caldera and form much of the surface sediments in the east of the Waipa catchment. These sediments form both fractured and porous aquifers. The surface sediments, the Tauranga group[16] and more recent Holocene[17] sediments are the main aquifers used in the Waipa catchment although water quality is often unsuitable for use untreated. These sediments are up to 200 m thick in the north, thinning to a few metres in the south where they cover the underlying sediments.

Water budgets

The water budget for the Waipa shows the importance of ground water in the catchment. Seventy-seven per cent of the net rainfall infiltrates the land surface and passes through aquifers to discharge to streams and rivers. Base flow predominates in the head water catchments draining the Te Kuiti group sediments. Further downstream about 60 per cent of net rainfall is transported via ground water to the streams and rivers. Springs commonly occur in head water catchments where the sloping terrain intersects the shallow, lower permeability Tauranga group sediments.

Piezometric surface

Ground water elevations follow the topography although the surface is relatively subdued in the Lower Waipa catchment. In the lowland plains, the ground water surface is usually between 2 and 5 metres below the ground surface except in shallow depressions where wetlands (now

[12] Thirty per cent of catchments have median ground water nitrate-nitrogen concentrations above MAV and another 32 per cent of catchments have median ground water nitrate-nitrogen concentrations between half of MAV and MAV

[13] A sequence of coals measures, and calcareous marine siltstone, sandstones and limestone laid down between 56 and 20 million years ago

[14] A period of deposition between occurring between 23 and 5 million years ago

[15] Volcanic sediments laid down about 2.5 million years ago

[16] Alluvial sediments laid down between 2 million year ago to about 11 thousand years ago

[17] A period less than 11,700 years ago

mostly drained) and small lakes occur. In the uplands, the piezometric surface lies between 10 and 50 metres below ground. As in the upper Waikato, stream elevations define the local ground water surface. Springs are common in incised gullies draining to the Waipa river.

Ground water chemistry

Ground water chemistry is defined by 22 bores monitored by the Waikato Regional Council. Nitrate-nitrogen is occasionally higher than MAV or between half of MAV to MAV[18]. Moderately high levels of nitrate-nitrogen are common in ground water in the Waipa catchment and are rising slowly, indicating that intensifying land use and conversions to more intensive farm systems are impacting ground water nitrate concentrations. Manganese and iron concentrations are above MAV and guidelines in wells especially in low lying areas.

Summary and findings - Middle and Lower Waikato

Geology

The middle and lower Waikato basins are underlain by a complex surface of basement Mesozoic rocks (Figure 3). These are of low permeability and limited use as aquifers. The basins formed by the basement are complex and faulted. The basement is deepest in the Hamilton Basin (-1300 amsl) yet is at the surface between Hamilton and Cambridge, and forms the Hakiramata and Taupiri range, the Hapuakohe range and the lower hills in east of Lake Waikare and northward to the Hunua range. The basement is -800 m amsl in the Aka Area. A sequence of younger sediments have infilled these basins, starting first with the Te Kuiti group sediments. These sediments are between 700 m thick in the lower Waikato basin and 200 m thick in the Hamilton basin. The Te Kuiti group comprise fine grained marine sediments and are usually unsuitable as aquifers except where fractured. Younger (Miocene) sediments over lie the Te Kuiti group and are used as a source of ground water, although their hydraulic properties restrict extensive water use. The Kaawa formation, comprising marine sands and shell lag deposits, occurs mainly in the Pukekohe and Waiuku area and provides the lower Waikato's most productive aquifers. The Pakaumanu Group comprises ignimbrites from the Mangakino caldera. These sediments provide fractured and porous aquifers. The surface aquifers are found in the Tauranga group, which forms most of the low lying surfaces in the middle and lower Waikato basins. The Tauranga group aquifers are important as water supplies but are usually only moderately productive and limited for domestic and stock use by water chemistry. Volcanic sediments occur to the east of the Hamilton basin and to the north of the lower Waikato basin where they form numerous low- angle volcanic cones and tuff rings at Pukekohe, Pukekawa, Onewhero and Mercer

Water budgets

The water budget for the middle and lower Waikato show the importance of ground water in the catchment. Like the upper Waikato more than 80 per cent of the net rainfall appears as base flow having entered streams and rivers via ground water. The Hamilton basin is effectively a closed ground water system underlain by very poorly permeable basement sediments.

Piezometric surface

Ground water elevations follow the local topography. Ground water in both basins is toward the incised Waikato river. In the lowland plains, the ground water surface is usually between 2 and 5 metres of the ground surface except in shallow depressions where wetlands (now drained) and numerous small shallow peat lakes occur. Drainage is common in the lower Waikato basin

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[18] Six per cent of catchments have median ground water nitrate-nitrogen concentrations above MAV and another 10 per cent of catchments have median ground water nitrate-nitrogen concentrations between half of MAV and MAV. Six per cent of the catchments have median nitrate-nitrogen concentrations increasing at > 0.1 mg/l per decade.

because the low lying surface sediments are often saturated by artesian ground water discharges driven by the elevated terrain surrounding the area.

Ground water chemistry

Ground water chemistry is defined by 29 bores monitored by the Waikato Regional Council. Ground water chemistry shows land use is impacting ground water quality in the basins. Nitrate-nitrogen is commonly higher than MAV and between half of MAV to MAV[19]. Nitrate-nitrogen is increasing over time in a few wells at rates of 0.27 to 0.42 mg/l per decade[20]. Also, the ground water in these basins is the most likely of all healthy rivers catchments showing concentrations of *E. coli* that exceed MAV and that are rising.

[19] Thirty-four per cent of catchments have median ground water nitrate-nitrogen concentrations above MAV and another 14 per cent of catchments have median ground water nitrate-nitrogen concentrations between half of MAV and MAV.

[20] Seventeen per cent of the catchments have median nitrate-nitrogen concentrations increasing at > 0.1 mg/l per decade.

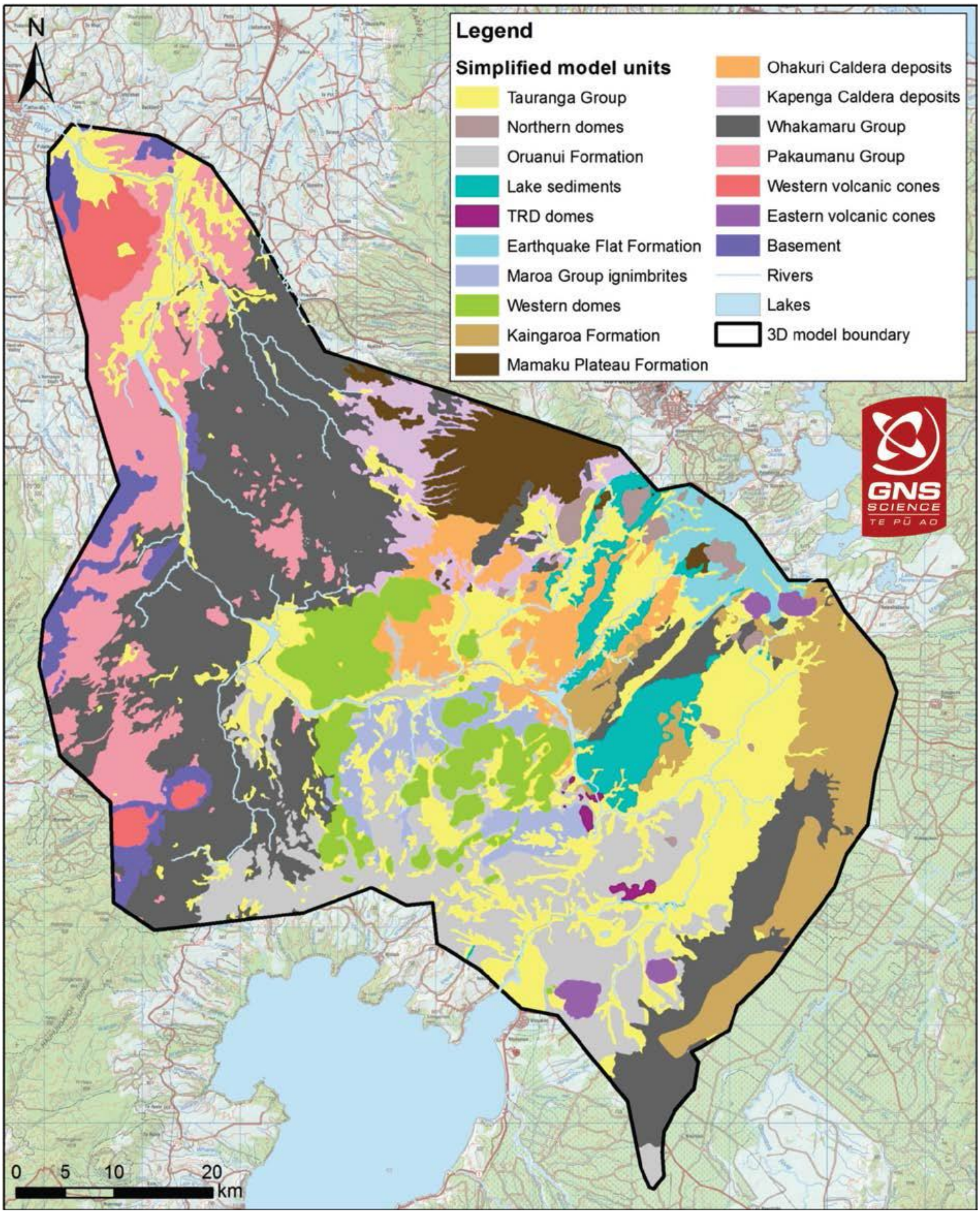

Figure 1: Surface geology of the Upper Waikato catchment

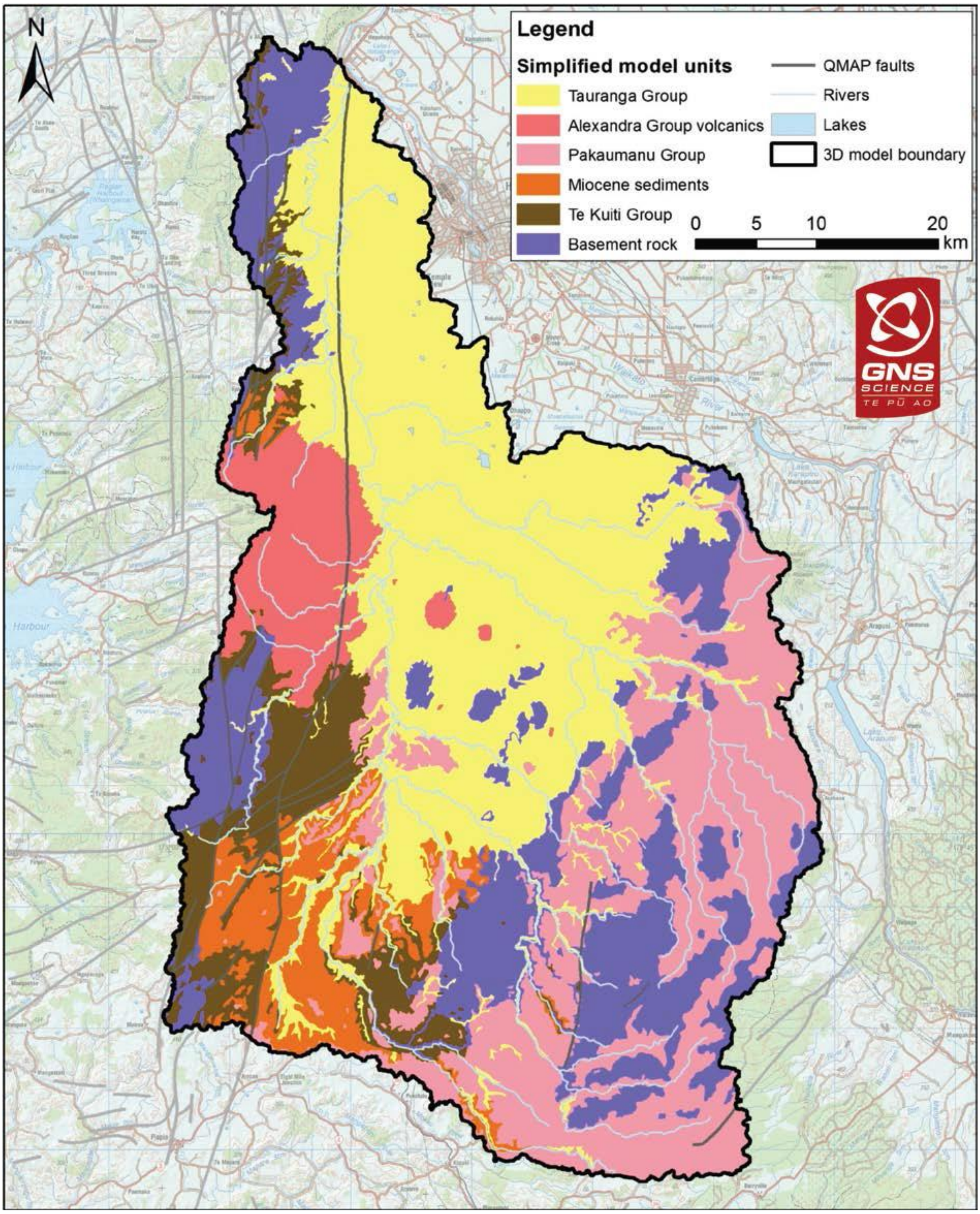

Figure 2: Surface geology of the Waipa Catchment

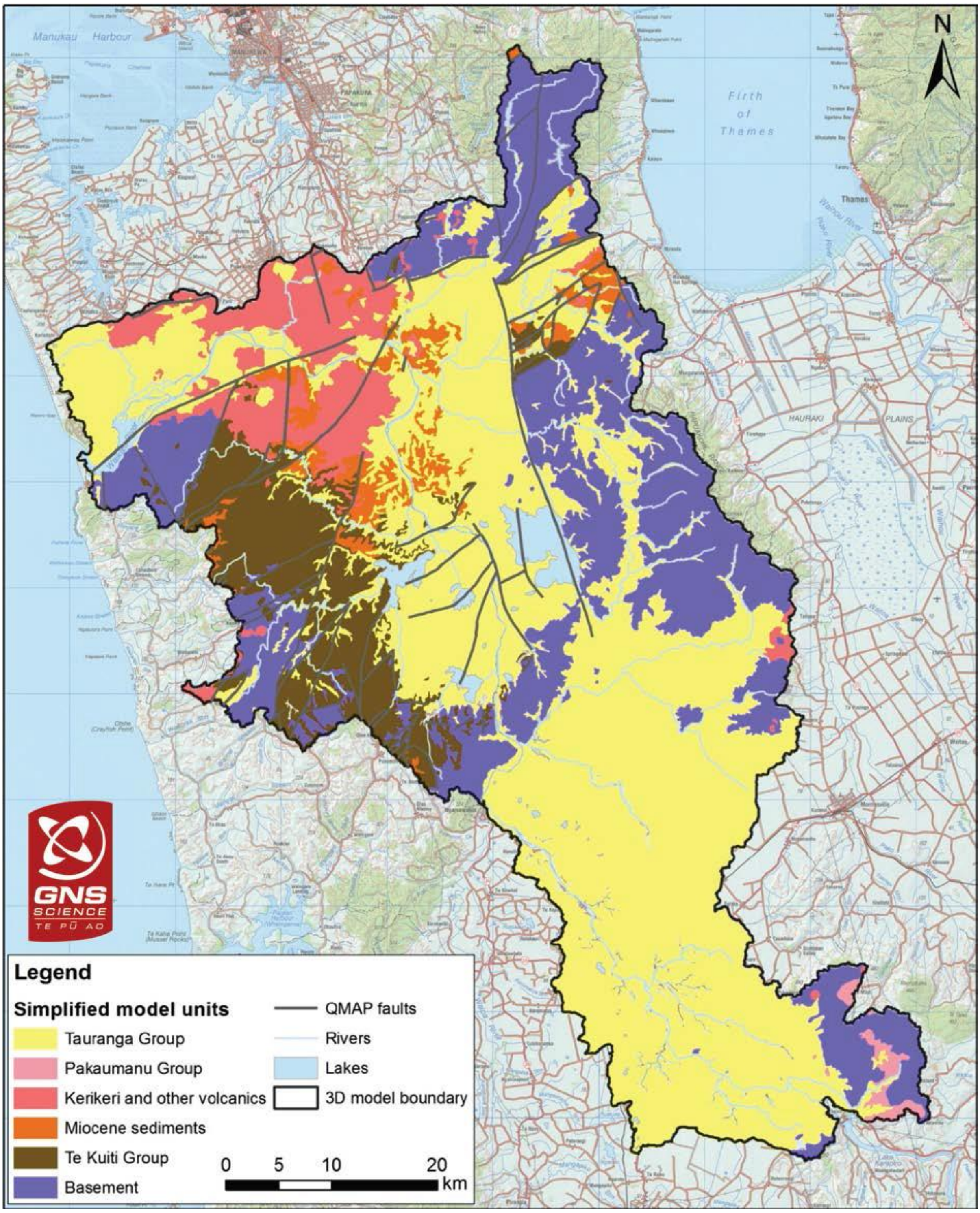

Figure 3: Surface geology of the Lower and middle Waikato catchment

Study 3: Estimation of lag time of water and nitrate flow through the Vadose Zone: Waikato and Waipa River catchments

Travel time through the unsaturated zone is important in determining the overall lag time between land use intensification (often through rapid land use change) and the associated impacts on surface water quality. This report presents results of a modelling study for predicting the time taken for nitrate-nitrogen to travel from the land surface through the unsaturated zone and into shallow ground water[21]. The process of modelling these lag times involves the estimation of land surface recharge; estimation of the time taken to travel through the vadose zone and an estimation of the time taken for water and nitrate to penetrate the uppermost aquifer layer. Input data for these estimations has been sourced from available climate, soil, geological and hydrological databases.

Findings

Total travel times[22] are less than 10 years for most of the lower Waikato, Hamilton and Waipa basins, particularly for the shallow, low angle basin floors and low hills with elevations less than 100 m amsl[23]. Longer travel times of 10 to 30 years are estimated for the land surfaces above 100m amsl (Figure 4).

The longest travel times are estimated beneath and near volcanoes and ranges: mainly as a function of the greater depths to water in these areas. However, there is greater uncertainty in these estimates for these areas because there is only sparse information on depth to water (few bores are drilled at the tops of hills to intersect ground water). The estimates of the total travel times comprise two components: the vadose travel times and the time for water and nitrate-nitrogen to penetrate the more active upper part of the aquifer. The time taken for water to mix in the upper part of the aquifer ranges from 2.5 to 6 years which is between 10 and 40 per cent (average 17 per cent) of the total travel time.

Model predictions compare favourably with reported mean residence times from ground water ages determined from tritium concentrations. The model accounts for 75 per cent of the variation in the tritium mean residence times.

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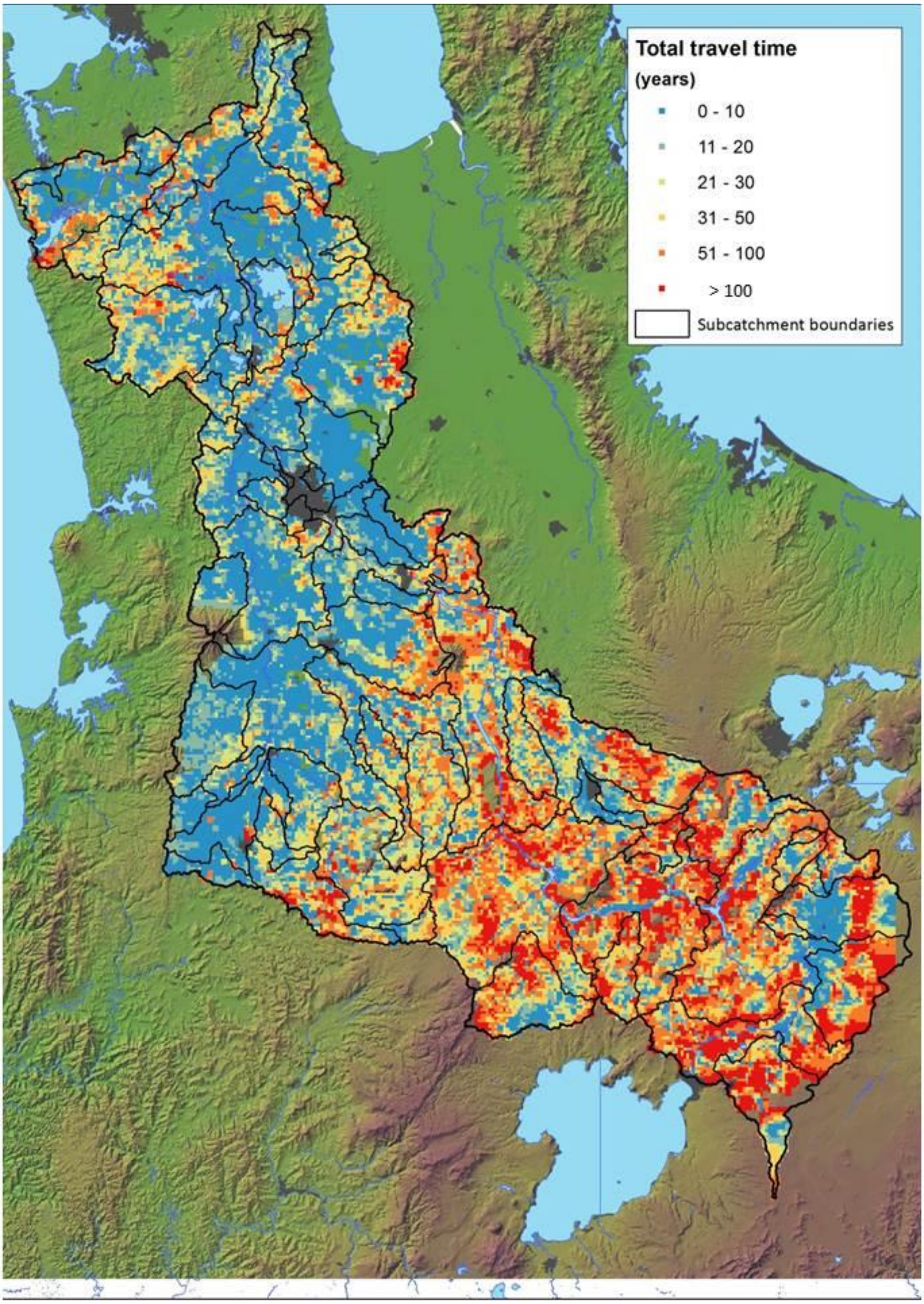
[21] Wilson S, Shokri A 2015. Estimation of lag time of water and nitrate flow through the Vadose Zone: Waikato and Waipa River Catchments. Lincoln Agritech Ltd Report 1058-9-R1.

[22] Total travel time includes travel time through the unsaturated zone and the time taken for water and nitrate-nitrogen to penetrate the upper active parts of the aquifer

[23] Amsl – above mean sea level

Figure 4: Total travel time of water and nitrate flow through the unsaturated (vadose) zone



Study 4: Predicting the Redox Status of Ground Water on a regional scale.

Reducing conditions are necessary for denitrification to occur and thus the attenuation of nitrate-nitrogen as it passes through aquifers. Thus the ground water redox status can be used to identify ground water zones where potentially significant reduction of nitrate-nitrogen can occur. This study relates redox[24] status from 554 ground water bores throughout the Waikato and Waipa catchments with other mapable factors such as subsurface geology, topography and soils characteristics[25]. The more detailed examination of redox status completed in study one shows the extreme variability of redox potential that occurs on a micro scale.

Findings

In the Waikato (including the Hauraki catchment with similar soils and sediments) 56 per cent of the wells indicate oxic conditions, 22 per cent indicate reducing conditions and 22 per cent indicate a mixed condition (sometimes oxic: sometimes anaerobic). The analysis was completed for three different bore depths (<25 m, 25 to 100m and >100 m). The percentage of oxidised ground water decreases with increasing bore depth. The average agreement between predicted and measured redox status was 62 per cent for the Waikato region. The models were incorporated into a GIS model and the prediction of redox status extended over the whole region including steep land. The study therefore estimates the spatial distribution of reducing ground water zones and, when combined with ground water flow paths, improves estimates of where denitrification occurs.

Figure 5 show the oxidising and reducing zone in the shallow ground water (<25m) where most of the rapid ground water flow occurs. Reducing conditions are suggested for much of the low lying poorly drained areas in the lower and middle Waikato basins and in the Waipa catchment. Oxidising conditions are suggested for the elevated terrain forming the ranges in the middle and lower Waikato and Waipa catchments. The pattern of oxidising and reducing conditions in the upper Waikato appears less obvious but may relate to certain lithologies that promote reducing conditions; the Kaingaroa Formation, the Whakamaru group, the Ohakuri Caldera deposits and the Mamakau Plateau formation.

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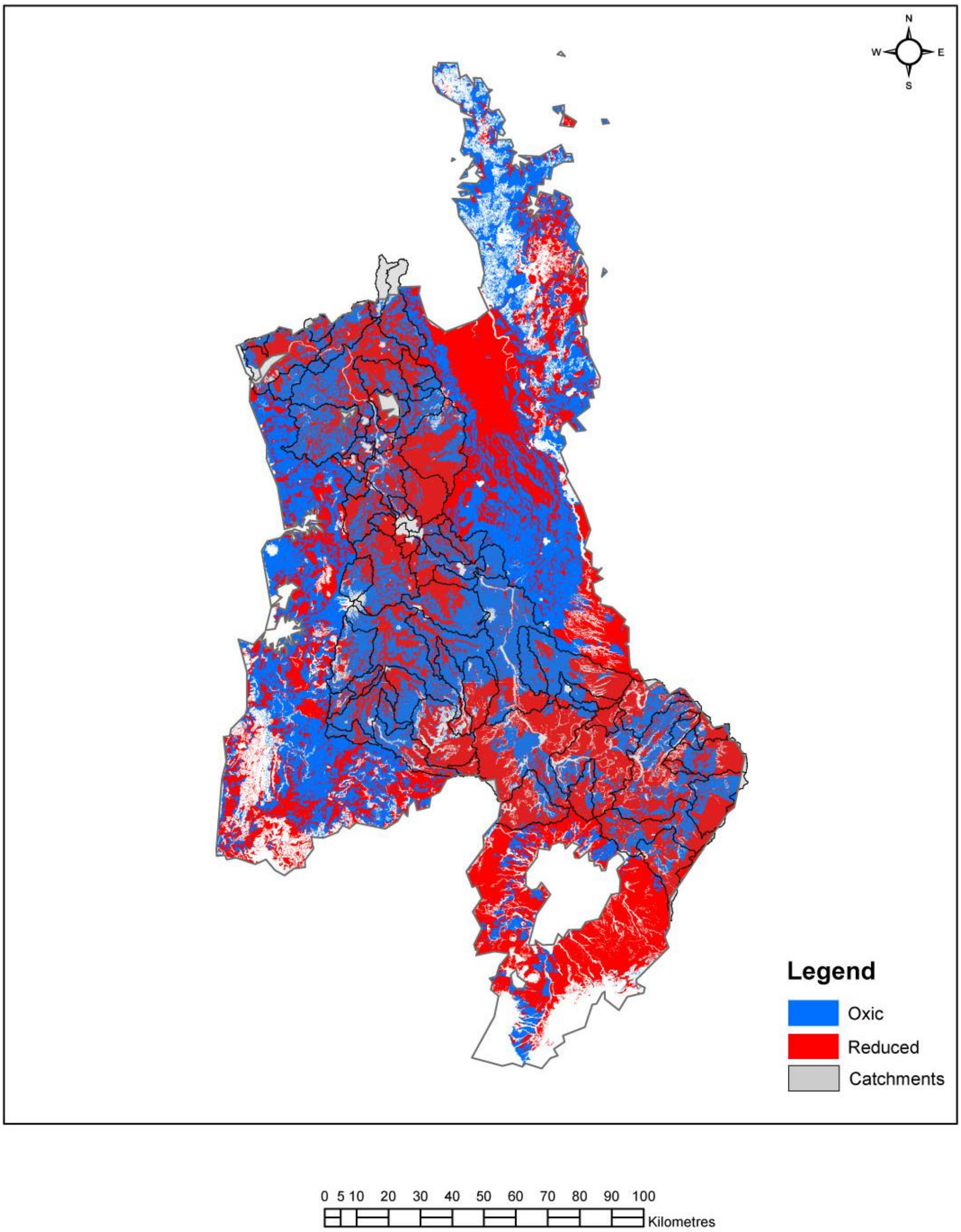
[24] Redox reactions include all chemical reactions in which atoms have their oxidation state changed usually involving transfers of electrons between chemical species. The term 'redox' comes from two concepts of electron transfer; reduction and oxidation. Oxidation is the loss of electrons or an increase in oxidation state by a molecule, atom or ion. Reduction is the gain of electrons or a decrease in oxidation state by a molecule, atom or ion.

Therefore for a redox reaction to occur there must be an electron donor and an electron acceptor. The most common electron donor in ground water is dissolved and particulate organic carbon although minerals such as Pyrite (FeS_2) and glauconite (iron rich clays) may act as electron donors. The most common electron acceptors are dissolved oxygen (O_2), nitrate (NO_3^+), manganese (Mn^{4+}) and ferric iron (Fe^{3+}). Ground water redox reactions are largely driven by bacteria that use organic material as a source of energy to transfer electrons to electron acceptors. Once O_2 has been depleted from ground water the bacteria move on to the next most energy favourable electron acceptor - nitrate (NO_3^+) followed by manganese and iron. Where NO_3 is introduced to a reduced ground water system, microbes will quickly utilise the nitrate and convert it to nitrogen gas (N_2) or gaseous nitrous oxides (N_2O). This process is called denitrification and effectively reduces the concentration of nitrate from ground water and may prevent it from subsequently reaching surface water. However, if the ground water is oxic (contains abundant dissolved oxygen) nitrate will accumulate in ground water and be available for transport to surface water.

[25] Close ME, *et al in prep*. Prediction of the Redox Status of Groundwater on a Regional Scale using linear Discriminant Analysis.

Figure 5: Oxidising and reducing zones in shallow aquifers (< 25 m depth) in the Waikato Region (inc Hauraki and Taupo)



Study 5: Incorporating this information into a steady-state catchment model

The information from studies 1-4 (above) has been incorporated into a simple steady-state catchment model developed by NIWA[26] for the upper Waikato river catchment but extended to cover all the 74 catchments in the Healthy Rivers Project. Improvements to the original model have been incorporated for this project. The information for input to the modelled catchments from all ground water studies was agreed by caucusing among the ground water experts and the modellers. This approach was used to ensure the best interpretation of the ground water information was available to the modellers and to ensure consensus for catchments where there was little information available. Note the main focus was on providing plausible estimates of the nitrogen load to come, the potential for denitrification and nature of the ground water flow processes in each catchment.

The catchment model

The catchment model estimates total nitrogen and total phosphorus loads for the outlets of the 74 healthy River's catchments. The model takes source loadings of nutrients from pasture and other land uses, adds known point source loadings including geothermal sources of nitrogen, accounts for the accumulations and decay between the source, streams and reservoirs, and in ground water. The loads are routed and accumulated downstream. The model predicts mean annual nutrient loads for each catchment. The model is incorporated into an economic optimisation model[27] being developed to determine the land use and mitigation options and estimate costs to meet the rehabilitation scenarios for the Waikato and Waipa Rivers considered by the Healthy Rivers Project Collaborative Stakeholder Group.

Information provided to the catchment model

The information provided from the ground water studies was summarised for each catchment. As an example the following descriptions for two catchments are provided.

> *Pokaiwhenua Stream: NZ Reach 3023849*
>
> *Surface flow is dominated by base flow and ground water outflow from the catchment is likely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Spring-fed streams drain the Mamaku Plateau across the catchment. Ground water ages are highly variable 17-255+ years. Baseflow dominated, large storage capacities. Little seasonality evident. Drains Mamaku plateau north of Tokoroa, through an area being converted from forest. TN concentrations increasing post 2000 from a moderately high base concentration, reflecting an increase in pasture area by about 50%. Anticipate increased concentration rise due to some of the long response times to recent conversion. Good ground water information around Lichfield. Oxidising conditions are suggested at medium ground water depth, with some evidence of reducing conditions in shallow ground water. Low denitrification potential in medium ground water but possible denitrification in shallow ground water. Overall low-medium attenuation, a fast ground water response component but with some load to come. Median ground water age in the Pokaiwhenua stream 31 years.*

[26] Elliott S *et al.*, 2013. Catchment models for nutrients and microbial indicators – Modelling application to the Upper Waikato Catchment. Client report for the Ministry for the Environment. NIWA client report Ham 2013-103.
[27] Doole GJ, 2013. Evaluation of policies for water quality improvement in the Upper Waikato catchment. University of Waikato Client Report for the Ministry for the Environment.

Waitawhiriwhiri Stream: NZ Reach 3017487
Base flow and quick flow are both important to surface flow and ground water outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include: the Hinuera Formation where infiltration is relatively rapid; and drained peats, where infiltration is slow. No water age information exists for this sub-catchment. The hydrogeology setting suggests the lag is likely to be moderately short. This streams drains through Hamilton and is subject to increasing urbanisation, along with associated storm water and tradewaste control (Lake Rotoroa/Hamilton catchment). Information suggests shallow and deep ground water are potential reducing zones. About 50% of the catchment is urban (excluded from the reducing zone assessment model). Attenuation is likely to be moderate to high. N Load to come is likely to be low.

This type of information is used by the modellers to categorise the catchment in terms of nitrogen load to come the importance of ground water contributions to stream flow and the potential for denitrification. The Pokaiwhenua catchment has long term water quality monitoring and this site can be used to calibrate the model.

Summary of ground water studies

A series for studies have been completed to improve understanding the regional hydrogeology, how nitrogen is transformed as it passes through the aquifers, the travel times (lags) for water and nitrogen to pass through the aquifers to rivers and streams, and the structural relationships and interactions between ground water and surface water resources. This report provides an interim summary only of these investigations: some reports are still in draft form: most the ground water dating information has just been received – results for some samples are yet to come; and this is the first attempt of integrating the findings from the investigations commissioned. The focus of all investigators has been to provide the main findings as soon as possible to support the modelling required for the Healthy Rivers Project.

The paragraphs below summarise the general findings to date. Some of the points made are illustrated in a schematic (Figure 6).

1. The geological and hydrogeological evidence suggests the hydrogeological systems are closed: all parts of the Waikato and Waipa catchments are underlain by very slowly permeable sediments. Basins formed in the basement by structural faulting have been infilled with a sequence of sedimentary, volcanic and alluvial sediments. These sediments form aquifers of differing hydraulic performance and some provide ground water of useable quantities and quality. The closed nature of the Waikato hydrogeological systems means that all net rainfall arriving on the land surface either: runs off during rainfall or shortly after (interflow); or infiltrates the soil to enter ground water and travels by various pathways (some shallow: some deeper; Figure 6 #1) to emerge in the Waikato and Waipa rivers and discharge ultimately to the sea (Figure 6 #2).

2. Ground water levels vary from a few metres below ground in flat low-lying terrain to between 20 to 50 metres below ground in elevated terrain. Ground water flow paths (driven by peizometric surfaces) indicate spatial patterns of ground water flow are determined strongly by local ground elevation. This pattern is more subdued in deeper aquifers. Ground water flows from higher terrain (where ground water tables are often deeper) to the low points in the hydrological systems determined by the stream and river network (Figure 6 #3). The ground water is at the surface in many low lying areas adjacent to streams, in wetlands and in poorly drained soils. In most parts of the Waikato and Waipa catchments the ground water divide closely follows the catchment divide (Figure 6 #4): there is little evidence of inter-catchment transfers of ground water. Possible, but unproven, exceptions to this may occur on the elevated, flat terrain of the Kaingaroa plateau and in some low angle catchments in the Waikato lowlands.

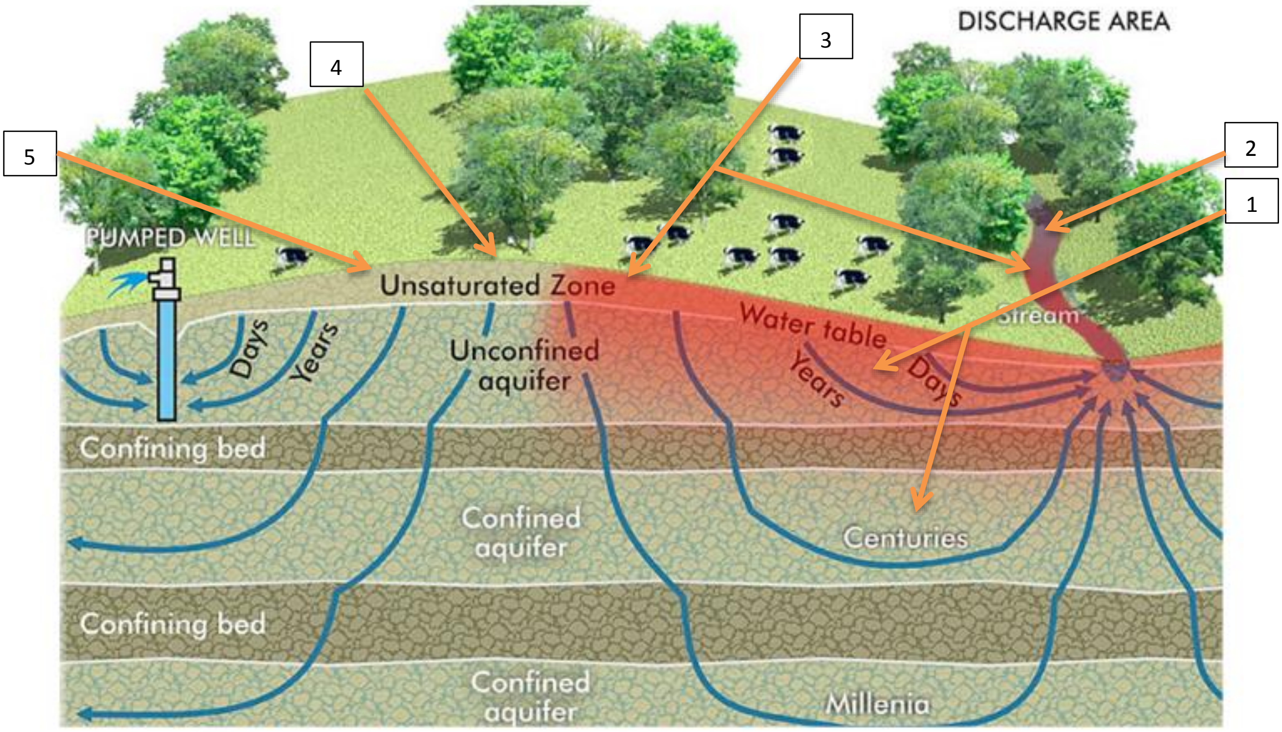
3. Ground water nitrogen in the upper Waikato is commonly higher than MAV or between half MAV and MAV, suggesting land use is impacting on use ground water quality. This finding is consistent with other studies linking land use and ground water quality. Nitrate concentrations are varying slowly suggesting recent land use intensification has not yet full impacted ground water quality.

   Ground water nitrogen in the Waipa is sometimes higher than MAV or between half MAV. Ground water nitrate levels are rising slowly indicating that intensifying land use is impacting ground water.

   Ground water nitrogen in the lower and middle Waikato is commonly higher than MAV or between half MAV and MAV and is increasing in 17 percent of catchments.

   Throughout the Waipa and Waikato catchments there is no simple relationship between age and nitrate-nitrogen concentration in ground water. Typically there is a wedge-shaped distribution showing that ground water older than the recent development of farm land is low in nitrogen, whereas younger ground water ranges in concentration depending on land-use, potential attenuation and flow pathways, particularly the presence of fracturing (Figure 6: graduated red shaded area).

Figure 6 shows a schematic of a ground water system illustrating some of the points in this summary.



4. Travel time through the unsaturated zone is important in determining the overall lag time between land use intensification (often through rapid land use change) and the associated impacts on surface water quality. Total travel times through the unsaturated zone (Figure 6 #5) are less than 10 years for most of the lower Waikato, Hamilton and Waipa basins, particularly for the shallow, low angle basin floors and low hills with elevations less than 100 m amsl. Longer travel times of 10 to 30 years are estimated for the land surfaces above 100m amsl. Substantially longer travel times (50 to more than 100 years) are estimated for the elevated terrain in the Upper Waikato and in the ranges in other parts of the Waikato and Waipa catchments. These observations are consistent with the observed ages for ground water.

5. The age of surface water in the Waipa and middle and lower Waikato catchments (expressed as MRT) are generally less than 15 years and average about 10 years.

   The age of surface waters in the Upper Waikato sub-catchment streams are older with an average MRT of about 52 years (median 35 years; flow weighted mean of about 47 years).

   The water age of the Waikato River above Karapiro is younger (about 12 years at Karapiro) due to the influence of Lake Taupo which provides two thirds of the flow.

The age of <u>ground</u> water is highly variable throughout the study area. Mean residence times often much older than surface waters (mean residence time from the latest surveys is about 150 years). The mean residence time is older than suggested by previous investigations (mean residence time 67 years (n=113)).

Initial analysis of the data obtained recently suggests there is no clear relationship between depth of ground water and its mean residence time. Some shallow wells (between 2 and 10m deep) in the middle and lower Waikato catchments and the Waipa catchment, which intersect very shallow ground water, show consistently younger ground water (1 to 2 years MRT). These ages may indicate shallow, more rapid flow in the active surface zone in the aquifers. The age of ground water in three springs measured in the upper Waikato catchment vary between 11 and 60 years MRT. The age of deeper ground water is consistently older but appears unrelated to depth. This observation may reflect the different sediments from which the ground water was obtained, the degree of fracturing of the aquifers intercepted by the bores, and the general variability of the aquifers sampled. Generally, age increases with depth in areas of recharge (Figure 6).

6. The potential for nitrogen attenuation was examined by estimates of where denitrification is likely to occur in the Waikato and Waipa catchments. Reducing conditions are suggested for much of the low lying poorly drained areas in the lower and middle Waikato basins and in the Waipa catchment. Oxidising conditions are suggested for the elevated terrain forming the ranges in the middle and lower Waikato and Waipa catchments. In the Upper Waikato the pattern of oxidising and reducing conditions appears less obvious but may relate to certain sediments that promote reducing conditions: e.g. the Kaingaroa Formation, the Whakamaru group, the Ohakuri Caldera deposits and the Mamakau Plateau formation. Other studies of oxidising and reducing conditions completed for this project show the occurrence of these conditions is highly variable, spatially and with depth - most likely because of the special conditions required for their occurrence.

7. Information from these investigations has been forwarded to the developers of a catchment model that estimates the mean annual loads of nitrogen from each catchment. The estimates of nitrogen loads (and other water quality parameters) will be passed to an economic optimisation model being developed to incorporate land use and mitigation options and to estimate costs to meet the rehabilitation scenarios for the Waikato and Waipa Rivers considered by the Healthy Rivers Project Collaborative Stakeholder group.