Healthy Rivers
PLAN FOR CHANGE
Wai Ora
HE RAUTAKI WHAKAPAIPAI

Draft for discussion purposes

Report No. HR/TLG/2015-2016/1.7

Summary of ground water information for consideration by the Collaborative Stakeholder Group

This report was commissioned by the Technical Leaders Group for the Healthy Rivers Wai Ora Project

The Technical Leaders Group approves the release of this report to Project Partners and the Collaborative Stakeholder Group for the Healthy Rivers Wai Ora Project.

Signed by:

Date: 22 December 2015

Summary of ground water studies conducted for the Waikato/Waipa Healthy Rivers:Wai Ora Project

Prepared by Tony Petch, Technical Leaders Group

Introduction

The Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai project 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 nitrogen load to come as a consequence of today's land use.

A ground water experts panel was convened in October 2014 to define the work required to support Collaborative Stakeholder Group deliberations on policies to restore and protect 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 and, depending on the findings, work that might be required beyond that.

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 and should be considered with previously collected data. 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**
   This report provides a synthesis of ground water resources in the 74 Healthy River Project sub-catchments 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 and near-surface run off during and post rainfall); and ground water chemistry with emphasis on nitrogen, *E. coli*, and other chemical characteristics that indicate nitrogen attenuation potential (e.g Fe, Mn) and that affect the suitability of the ground water 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 how long it will take for land use changes to have a detectable effect on the water quality of the uppermost ground water zone. This is achieved by first predicting the time taken for nitrate-nitrogen to travel from the land surface through the unsaturated (vadose) zone to the ground water table. Subsequently, it is estimated how long it takes the recharged nitrate to mix into the uppermost ground water zone.

4) **Study 4: Predicting the Redox Status of Ground Water on a regional scale.**
   Denitrification, the main nitrate attenuation process, can only occur under oxygen-depleted (i.e. reduced) conditions. Therefore, this study reports on the prediction of the ground water redox status in the Waikato and Waipa catchments. For this purpose, results from the

MBIE[1] funded Groundwater Assimilative Capacity research programme led by Environmental Science & Research were specifically analysed for the Waikato and Waipa catchments and their 74 sub-catchments.

5) **Study 5 Review of historical land use and nitrogen leaching**
   Historical land use in the Waikato and Waipa catchments and estimates of the consequential nitrate-nitrogen leaching are examined in this report for a 40 year period from 1972 to 2012. This report provides important information on the location and extent of land use change and estimates of the consequential loads of nitrate-nitrogen to ground water and surface water within the 74 Healthy Rivers Project sub-catchments.

6) **Study 6: 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, for most, there were adequate data to provide estimates of nitrogen, phosphorus, sediment and *E. coli* loads. The output of the NIWA model is then passed to the economic optimisation model used in the Healthy Rivers Project.

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 sub-catchments. Importantly, land use changes and resulting changes in nitrogen leaching were estimated for the 40-year period from 1972 to 2012.

This work has been completed and final reports have been received. This report provides a summary of the investigations and the main conclusions of the work.

[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

Introduction

The scale of this study and the short time within which to complete it 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 (Wild Impacts Ltd)[4].

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 redox-cline[5] 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[6];
- 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 were completed; 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

---

[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] Hadfield J 2015. Groundwater field investigations over the 2014-15 summer in support of the Healthy Rivers Project. Waikato Regional Council Internal Series Report 2015/38.

[5] A layer of water, having a strong vertical redox gradient, between the upper oxygenated and lower anoxic water

[6] 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.

simultaneous linear gaugings to determine the longitudinal gain in flow downstream and hence the spatial distribution of ground water discharge along these streams.

Summary and findings - Waipa

The results of these field investigations provide greater spatial resolution to the general understanding of ground water resources in the catchments. This information has been incorporated in the hydrogeological models described in Study 2 and is consistent with previous work undertaken 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[7]. The remainder showed no elevation from back ground levels (50 per cent of sampled bores): of this segment some were associated with strong reducing conditions (30 per cent of sampled bores). Nitrate-nitrogen 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 ground water levels of between 4 and 10 m below ground surface. 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 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[8]

---

[7] 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.

[8] 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.

with a mean of 2.5 mg/l and median of 0.75 mg/l. Aerobic conditions, were indicated 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 unambiguously 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 5). 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

Tritium analysis combined with some assumptions on how water moves through the subsurface environment allows the mean age of a water sample to be determined. As a ground water or surface water sample never has one discrete age, the age of the water is usually expressed as mean residence time (MRT[9]). Importantly, the MRT does not provide any information on the age distribution in the sample, which would be required to irrefutably link currently observed water quality to the combination of past actions that have caused it. Nevertheless, determining the MRT is an important step towards establishing cause-effect relationships.

Surface water

The mean age of surface water in the Waipa and middle and lower Waikato catchments (expressed as MRT) during summer base flows is usually less than 15 years and average about 10 years (Figure 1). In contrast, the mean age of surface waters during summer baseflows 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 mean water age of the Waikato River above Karapiro is younger (about 12 years at Karapiro) due to the dominant influence of

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

[9] MRT – mean residence time in years

the water discharged from Lake Taupo, which provides two thirds of the flow. These distinct differences in mean water age demonstrate that the effect of changed land use practices will be seen much earlier in the Waipa, middle and lower Waikato sub-catchments than in the upper Waikato sub-catchments.

Ground water

The mean age of ground water is highly variable throughout the study area (Figure 2). Mean residence times are often much older than surface waters (MRT from latest survey is about 150 years, n=14). 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 as there are confounding factors, such as aquifer confinement, and whether the well is located in a recharge or discharge zone (Figure 3). Nevertheless, 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.

Similarly there is no simple relationship between ground water age and N-N concentration in wells. Typically there is a wedge-shaped distribution showing ground water older than the development of farming is low in N-N, whereas younger ground water ranges in concentration depending on land use intensity and potential for N-N attenuation[10].

The age of ground water in three springs measured in the upper Waikato catchment varies 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 locations in the landscape (recharge vs discharge), 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).

[10] Hadfield J 2015. Refer footnote 4.

Figure 1: Surface water ages (MRTs) for the Waikato and Waipa catchments

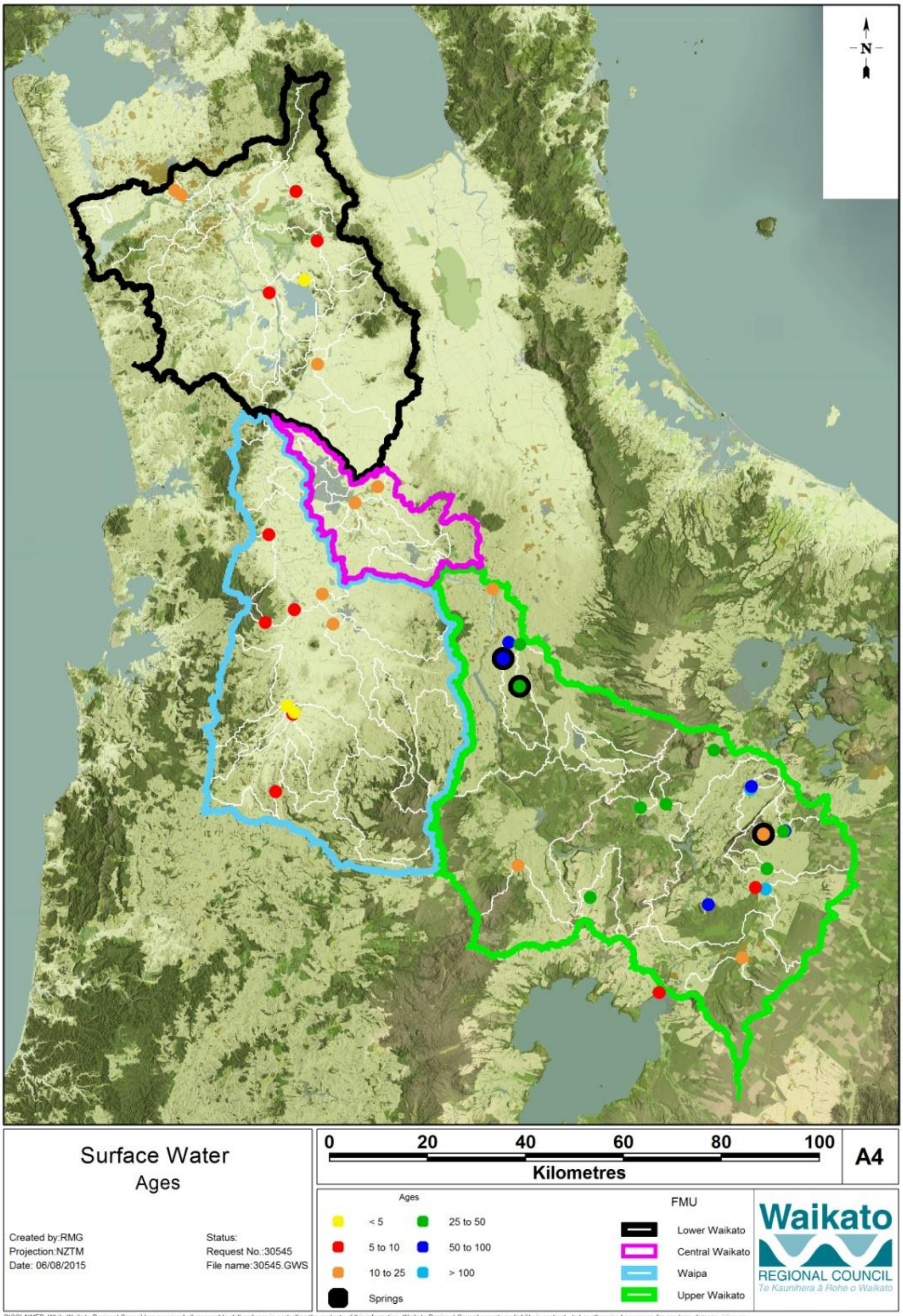


Figure 2: Ground water age (MRT) by depth for the Waikato and Waipa catchments

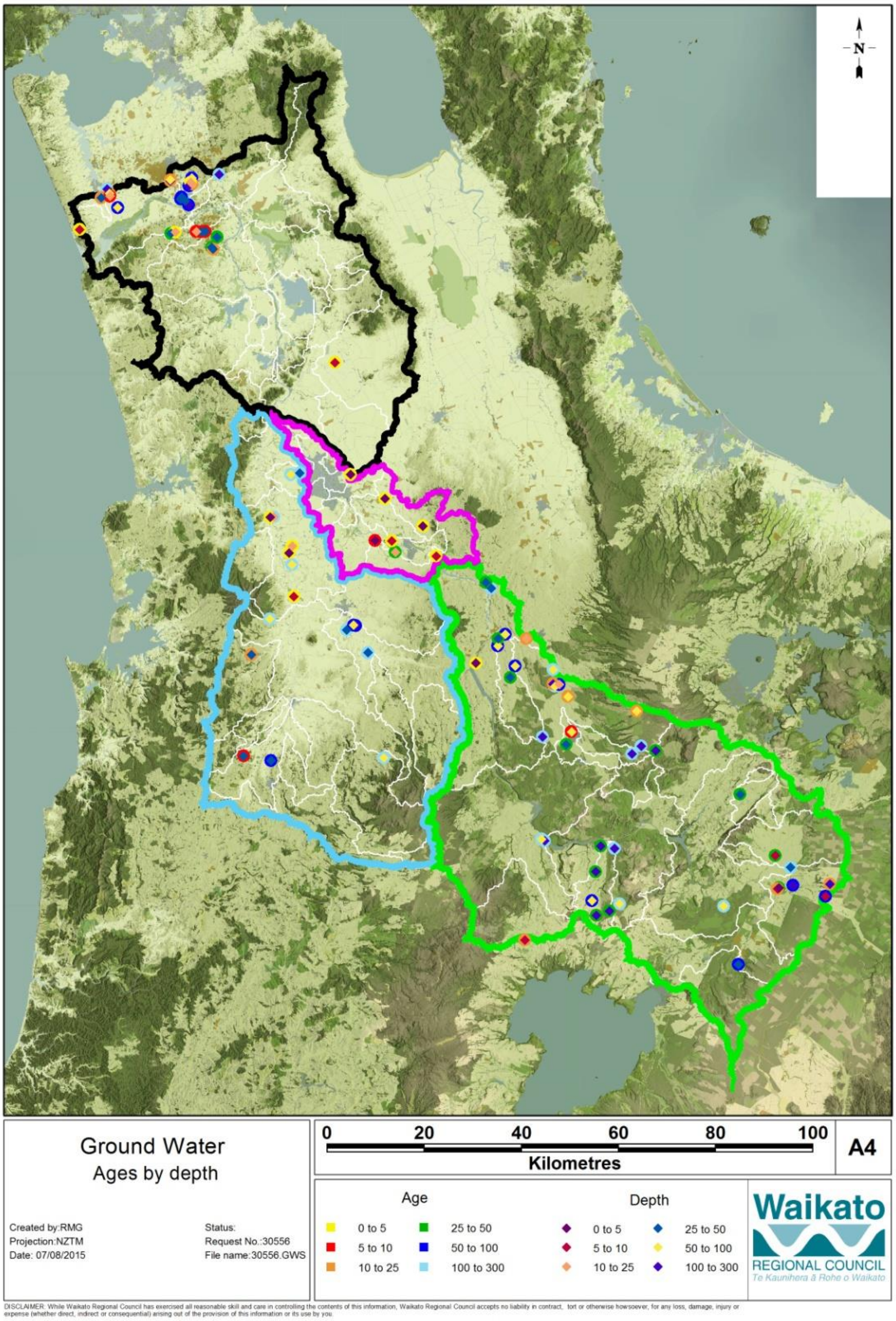
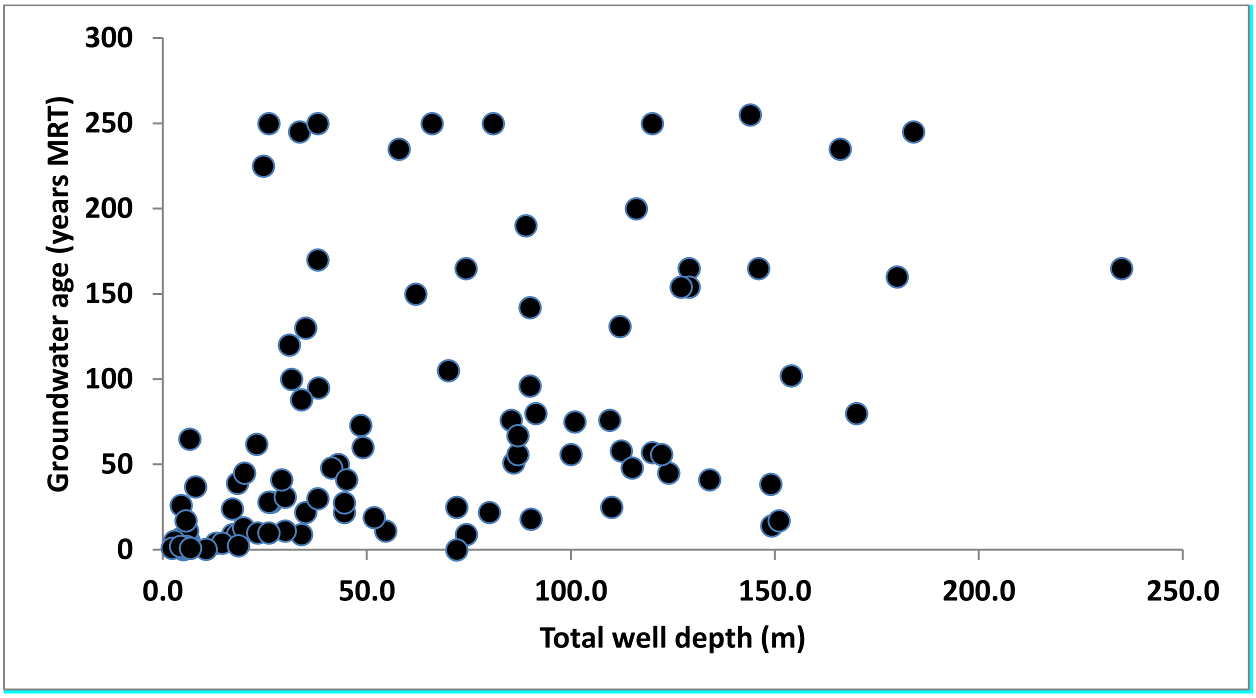


Figure 3: Ground water age by well depth for the Waikato and Waipa catchments



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

Introduction

The report and accompanying appendices identify a range of hydrogeological features for each of the Healthy River catchments: the upper Waikato above Karapiro; the Waipa Catchment; and the middle and lower Waikato river[11].

General

Regional Geology and stratigraphy

Geological units in the Waikato River catchment that are important to ground water flow are identified in Table 1. These units include aquifers and aquicludes (impermeable rock or sediment layers that act as a barrier to the flow of ground water).

Groundwater chemistry

Ground water quality data for 74 sub-catchments in the Waikato and Waipa river catchments were sourced from Waikato Regional Council and the National Ground Water Monitoring programme. The fundamental data set for the catchments comprise ~4,840 samples for 83 analytical parameters collected at 531 wells. Parameters for environmental indicators representing total dissolved solids (electrical conductivity), aquifer redox status (iron, manganese) microbiological indicators (*E.coli*) and nutrients (dissolved reactive phosphorus, nitrogen species) were used in the analysis of state and trends in ground water chemistry. Trend analysis was run on the entire record of each well[12]. Table 2 summarises the state and trends in the environmental indicators.

Water budgets

Water budgets were developed for the 74 sub-catchments by accounting for all surface and ground water inflows and outflows for each sub-catchment and assuming change in water storage is zero[13]. Figure 4 shows a schematic of water budget components.

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 5). The basement[14] rock has large offsets associated with faults and calderas. The Whakamaru Group ignimbrites[15] infill the basement structures, as do a sequence of lake sediments from the ancestral Lake Huka (an important aquiclude), and the Oruanui

---

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

[12] Mann-Wallis seasonally adjusted trend tests and Kruskal-Wallis seasonality tests.

[13] $P + Q^{SW}_{in} + Q^{GW}_{in} = ET + Q^{SW}_{out} + U^{SW} + Q^{GW}_{out} + U^{GW}$: where for a catchment: P is rainfall; Q^{SW}_{in} is surface water inflow; Q^{GW}_{in} is ground water inflow; ET is evapotranspiration; Q^{SW}_{out} is surface water outflow; U^{SW} consumptive water use from surface water; Q^{GW}_{out} is ground water outflow; and U^{GW} is consumptive use of ground water; all assuming change in water storage is zero in the long term

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

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

Table 1: General geological units in the Waikato and Waipa Catchments that are described in the geological models for each catchment

Geological unit	Age	Upper Waikato catchment	Waipa catchment	Lower-middle Waikato catchment
Tauranga Group	Holocene and Pleistocene (0 to 2 Ma)	✓	✓	✓
Oruanui Formation	Pleistocene (27 ka)	✓		
Earthquake Flat Formation	Pleistocene (61 ka)	✓		
Upper Waikato lake sediments	Pleistocene (less than approximately 320 ka)	✓		
Maroa Group ignimbrites	Pleistocene (196 – 283 ka)	✓		
Rhyolite lava domes	Pleistocene (post-date the Whakamaru Group, to approximately 80 ka)	✓		
Kaingaroa Formation	Pleistocene (230 ka)	✓		
Ohakuri Caldera deposits	Pleistocene (240 ka)	✓		
Mamaku Plateau Formation	Pleistocene (240 ka)	✓		
Kapenga Caldera deposits	Pleistocene (275 ka)	✓		
Eastern volcanic cones	Middle Pleistocene	✓		
Whakamaru Group	Pleistocene (320 - 340 ka)	✓		
Pre- Whakamaru Group volcanics	Pleistocene	✓		
Mangakino volcanics	Pleistocene (1.68 to 0.95 Ma)	✓		
Western UW volcanic cones	Pliocene-Pleistocene	✓		
Kerikeri Volcanics	Pleistocene Late Pliocene to Early Quaternary			✓
Kaawa Formation	Early to Late Pleistocene			✓
Alexandra Group volcanics	Late Pliocene to earliest Pleistocene		✓	
Pakaumanu Group	Late Pliocene to earliest Pleistocene		✓	✓
Miocene sediments	Miocene		✓	✓
Te Kuiti Group	Late Eocene to Early Miocene		✓	✓
Basement greywacke	Various units (> ~140 Ma)	✓	✓	✓

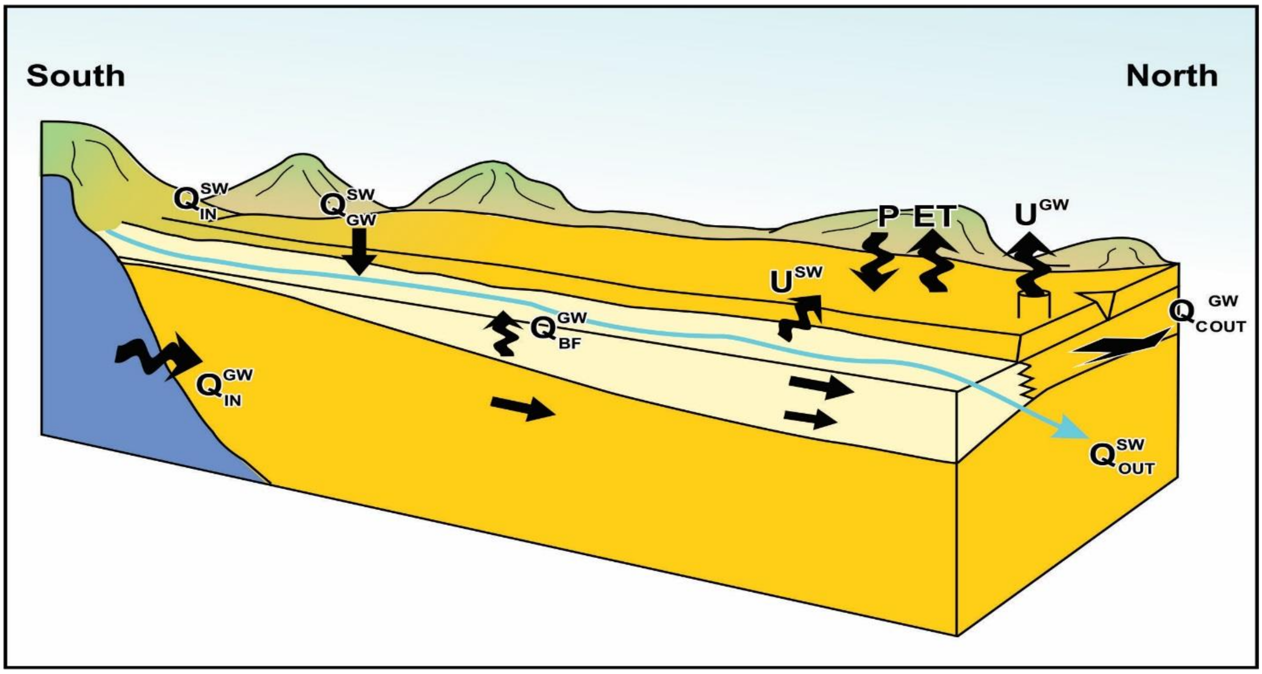
Table 2: Summary of ground water chemistry in sub-catchments in the Waikato and Waipa catchments[16]

Chemical parameter, trends and information on data sources	**Upper Waikato:** (number of sub-catchments in which observation occurs)	**Waipa:** (number of sub-catchments in which observation occurs)	**Lower and middle Waikato:** (number of sub-catchments in which observation occurs)
Median N measured greater than MAV[17] for nitrate-nitrogen	6	2	10
Median N between ½ of MAV and MAV for nitrate-nitrogen	7	3	4
N increasing > 0.1 mg/l per decade	0	2	5
Electrical Conductivity increasing	2	0	6
E. coli cfu > than MAV	1	3	11
Mn > MAV	6	4	3
Fe > guideline	12	3	9
Sub-catchments with few wells/poor data	4	13	17
Sub-catchments with no ground water chemistry data	7	7	8
Number of sub-catchments in area	21	31	29

formation, derived from the Lake Taupo eruption. Modern day alluvial sediments of the Tauranga group appear at the surface of the basins. 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[18] is exposed at the ground surface to the north of the catchment and also provides an important source of ground water.

[16] See Ministry of Health for MAVs and water quality guidelines
[17] MAV – maximum acceptable value
[18] Ignimbrite sheets erupted from the Rotorua Caldera about 240 thousand years ago

Figure 4: Schematic of water budget components



Water budgets

The water budgets and the associated estimates of base flow and quick flow show the ground water system is extremely important to the hydrology of the upper Waikato. Most (94 per cent) of the net rainfall recharge percolates 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 in the headwater areas 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. Effectively, the hydrogeological system of the upper Waikato is closed - the underlying basement is virtually impermeable - and all net rainfall in the upper Waikato ultimately appears as flow in the Waikato River. However, in a few sub-catchments there is evidence that some ground water outflow bypasses the surface water monitoring sites (e.g. Kawaunui, Mangakara, Waiotapu at Homestead and Whirinaki). Nevertheless, due to the location of these sub-catchments, it can be assumed that this ground water is ultimately intercepted by the incised Waikato River and its tributaries.

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 sub-catchments (Figure 6). The topographic divide (catchment boundary) therefore reflects the 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 area but this is of little consequence given the large forestry blocks on the plateau.

Figure 5: Surface geology of the Upper Waikato catchment

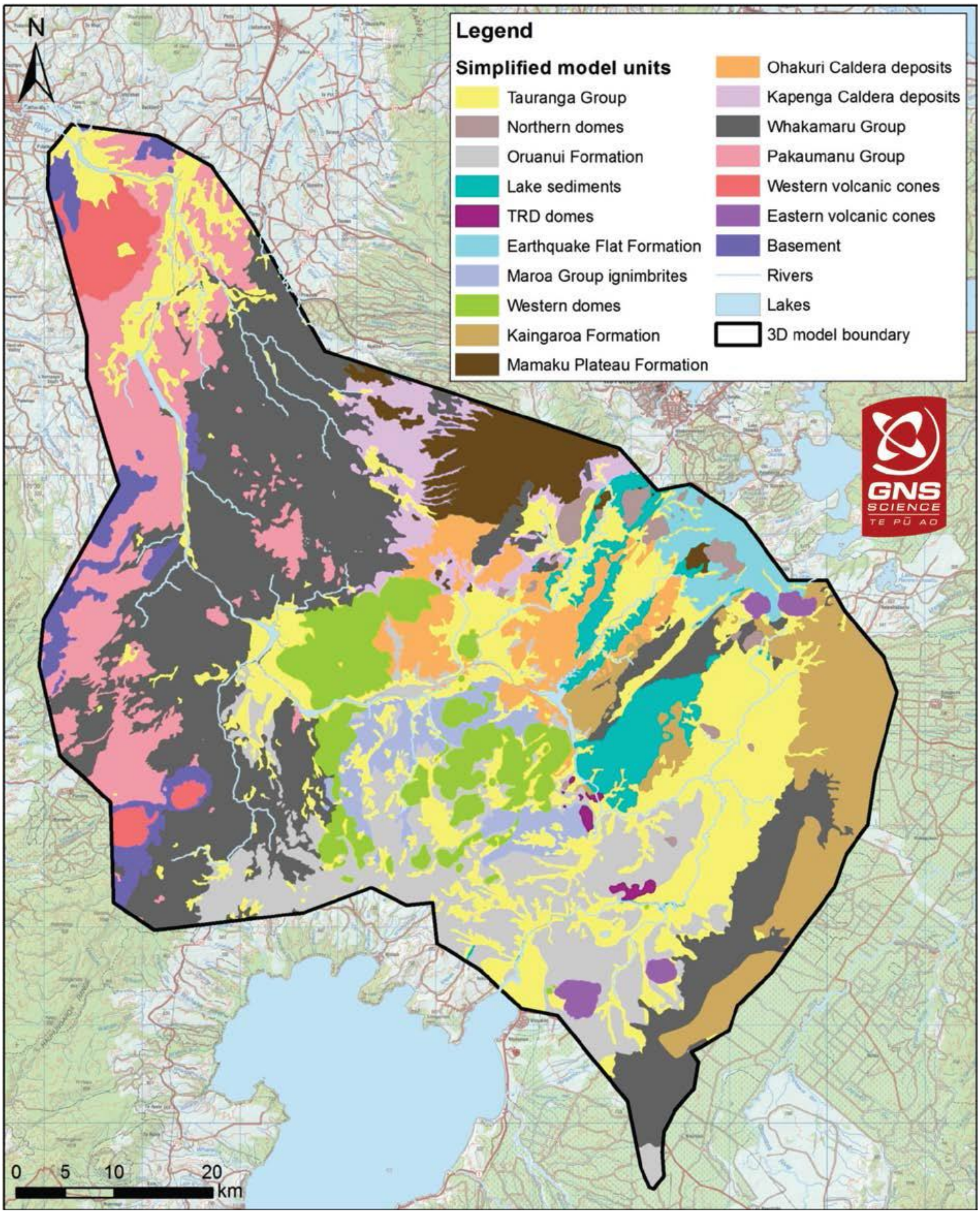


Figure 6: Piezometric surface for the Upper Waikato catchment[19]

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[20]. This indicates past land use activities have impacted on ground water quality. However, nitrate-nitrogen concentrations appear to be not increasing suggesting recent land use intensification has not yet impacted ground water quality. Enhanced manganese (Mn) and iron (Fe) concentrations indicate the presence of anoxic conditions in up to half of the analysed ground water samples.

[19] 10x elevation exaggeration. Note additional piezometric contours from: WVA (1987) – grey; Bromley *et al*. (2000) – red. Fixed head cells of Lake Rotokawa and the Waikato River – light blue; Fixed-head cells of streams – dark blue. View from south to north.

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

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 7). The basement rocks form a basin bounded by up-thrown basement material. The basement is overlain by sediments of the Te Kuiti group[21]. These sediments provide limited water sources from discrete fractured and limestone aquifers. Fine grained, relatively impermeable, Miocene[22] 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[23] 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[24] and more recent Holocene[25] 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[26,27]

The water budget shows the importance of ground water in the Waipa catchment. Across all sub-catchments about 77 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 (above Otorohanga) draining the Te Kuiti group sediments. Further downstream, in the Hamilton Basin, about 60 per cent of net rainfall is transported via ground water to the streams and rivers. As in the upper Waikato, ground water outflow is indicated for some steep headwater sub-catchments. Some of this ground water re-emerges in springs or seeps in the area where the head water sub-catchments meet the relatively flat terrain of the lower permeability Tauranga group sediments in the Hamilton Basin.

Piezometric surface

Ground water elevations follow the topography although the surface is relatively subdued in the lower Waipa catchment (Figure 8). 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 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.

---

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

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

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

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

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

[26] Note in constructing the water budgets the rainfall input of Tait et.al (2006) had to be increased by seven per cent to ensure the water budget flow matched the recorded flow at Whatawhata bridge. Many factors may account for the additional input required: errors in rainfall interpolation, errors in evapotranspiration estimates, and errors in flow measurements or unknown flows from outside the catchment boundaries or a combination of all these factors.

[27] Tait et.al., 2006. Spatial interpretation of daily rainfall for New Zealand. International Journal of Climatology, 26(14): 2079-2115

Figure 7: Surface geology of the Waipa Catchment

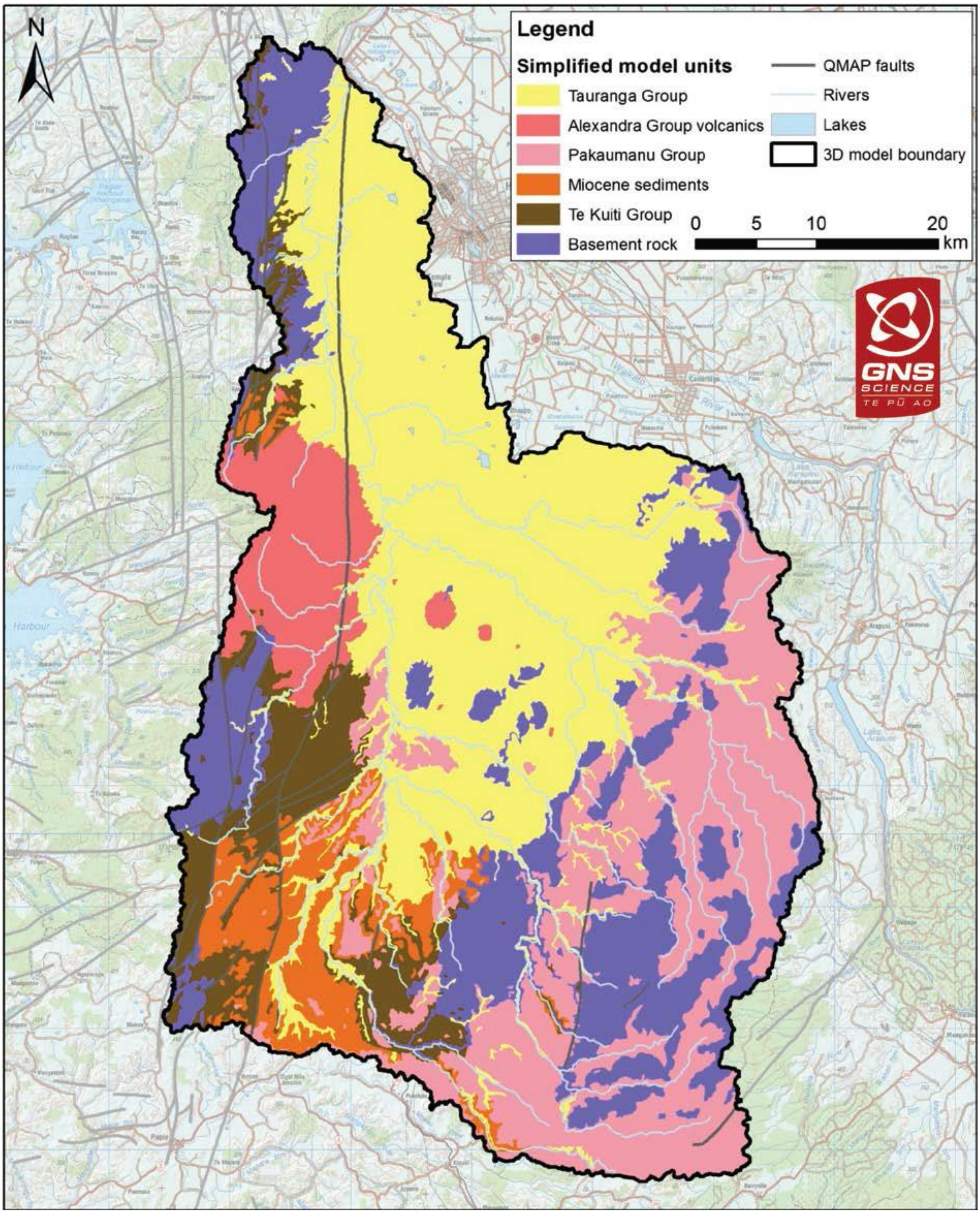


Figure 8: Piezometric surface for the Waipa catchment[28]

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[29]. 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. Ground water manganese and iron concentrations are above MAV and guidelines in a few sub-catchments, indicating that denitrification may be occurring, especially in low lying areas.

[28] 10x elevation exaggeration. Note: Fixed head cells of lakes and the Waikato River – light blue; Fixed head cells of streams – dark blue. View from south to north.

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

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 9). 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 Hakarimata 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 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 overlie the Te Kuiti group. They 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, on average more than 80 per cent of the net rainfall appears as base flow having entered streams and rivers via ground water although, in the middle and lower Waikato, the proportion of ground water sourced stream flow is more variable among sub-catchments. The Hamilton Basin is effectively a closed ground water system underlain by very poorly permeable basement sediments. However, ground water outflow is estimated for some sub-catchments in the middle and lower Waikato indicating that, while the main basins in these areas may be considered closed systems, some sub-catchments within them may not.

Piezometric surface

Ground water elevations follow the local topography (Figure 10). 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 below the ground surface except in shallow depressions where wetlands (now drained) and numerous small shallow peat lakes occur. Artificial drainage is common in the lower Waikato Basin because the low lying surface sediments are often saturated by artesian ground water discharges driven by the elevated terrain surrounding the area.

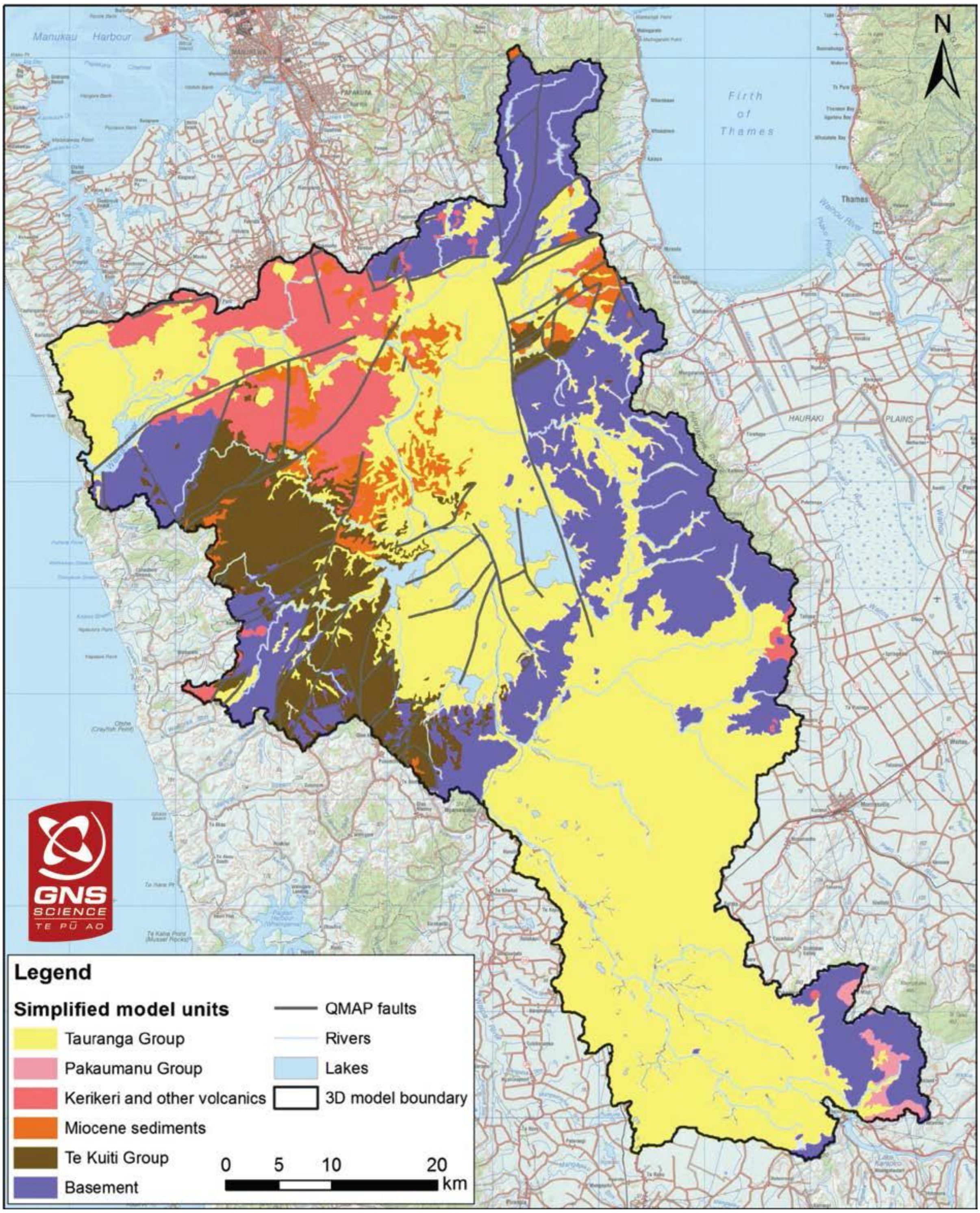
Ground water chemistry

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[30]. Nitrate-nitrogen is

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

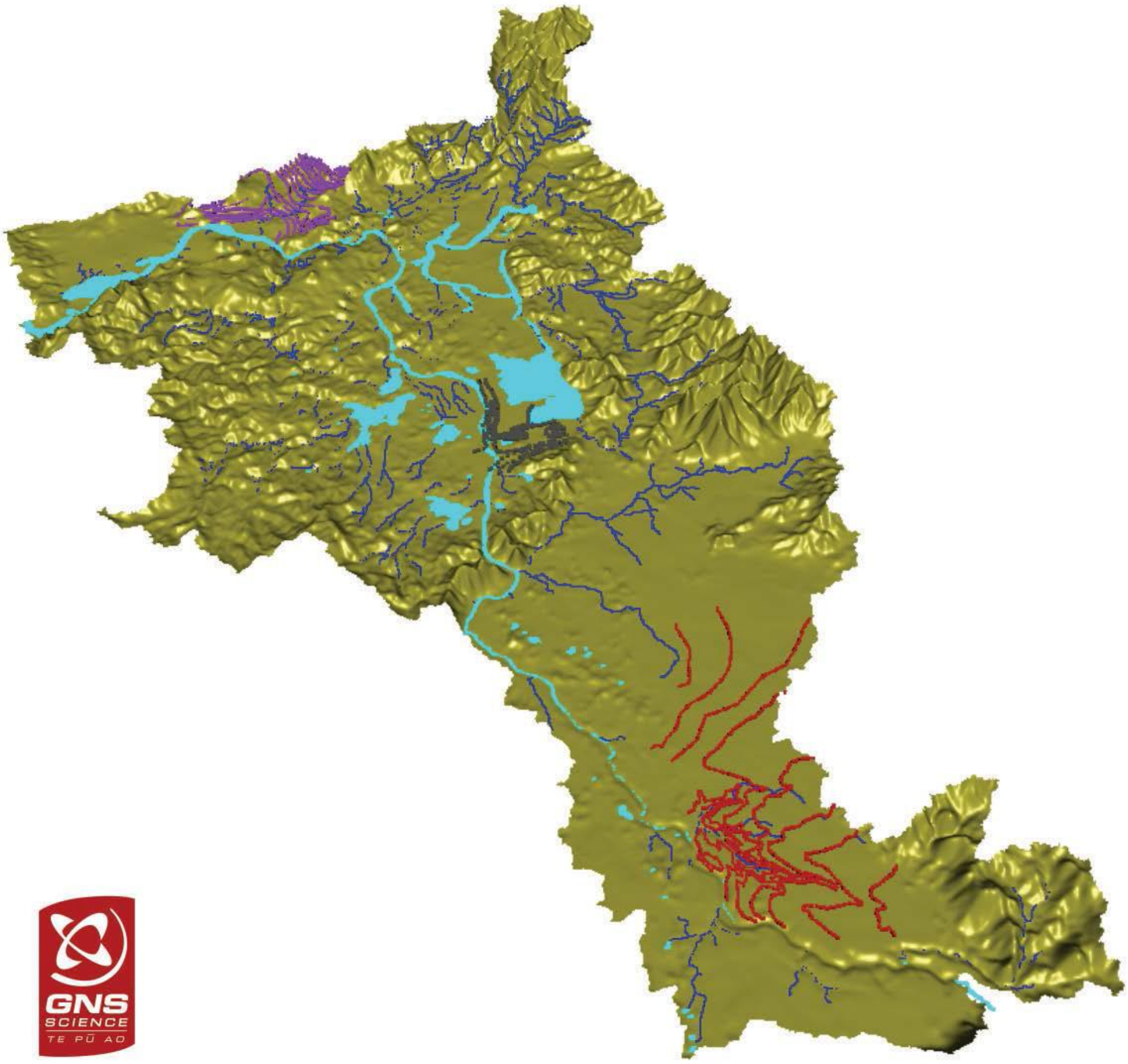
increasing over time in a few wells at rates of 0.27 to 0.42 mg/l per decade[31]. Also, the ground water in these basins is the most likely of all Healthy Rivers catchments showing concentrations of *E. coli* that exceed MAV and that are rising.

Figure 9: Surface geology of the Lower and Middle Waikato Catchment



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

Figure 10: Piezometric surface for the Middle and Lower Waikato catchment[32]



[32] 10x elevation exaggeration. Note additional piezometric contours from: WRC (1991) – purple; WVA (1986) – grey; Marshall & Petch (1983) – red. Fixed head cells of lakes and Waikato River – light blue; Fixed head cells of streams – dark blue. View from south to north.

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

Introduction

Estimating the travel time through the unsaturated/vadose zone is the important first step 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[33]. 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[34] into the upper ground water zone 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[35]. Longer travel times of 10 to 30 years are estimated for the land surfaces above 100m amsl surrounding these basins (Figure 11). The Reporoa Basin estimates show that short travel times (< 10 years) can also occur in the upper Waikato.

Estimated travel times of 30 to 100 years are common in the upper Waikato and also occur to a lesser degree in headwater areas of the Waipa.

The longest travel times (> 100 years) are estimated to occur 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 the 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 zone 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 of ground water determined from tritium concentrations. The model accounts for 75 per cent of the variation in the tritium-derived mean residence times.

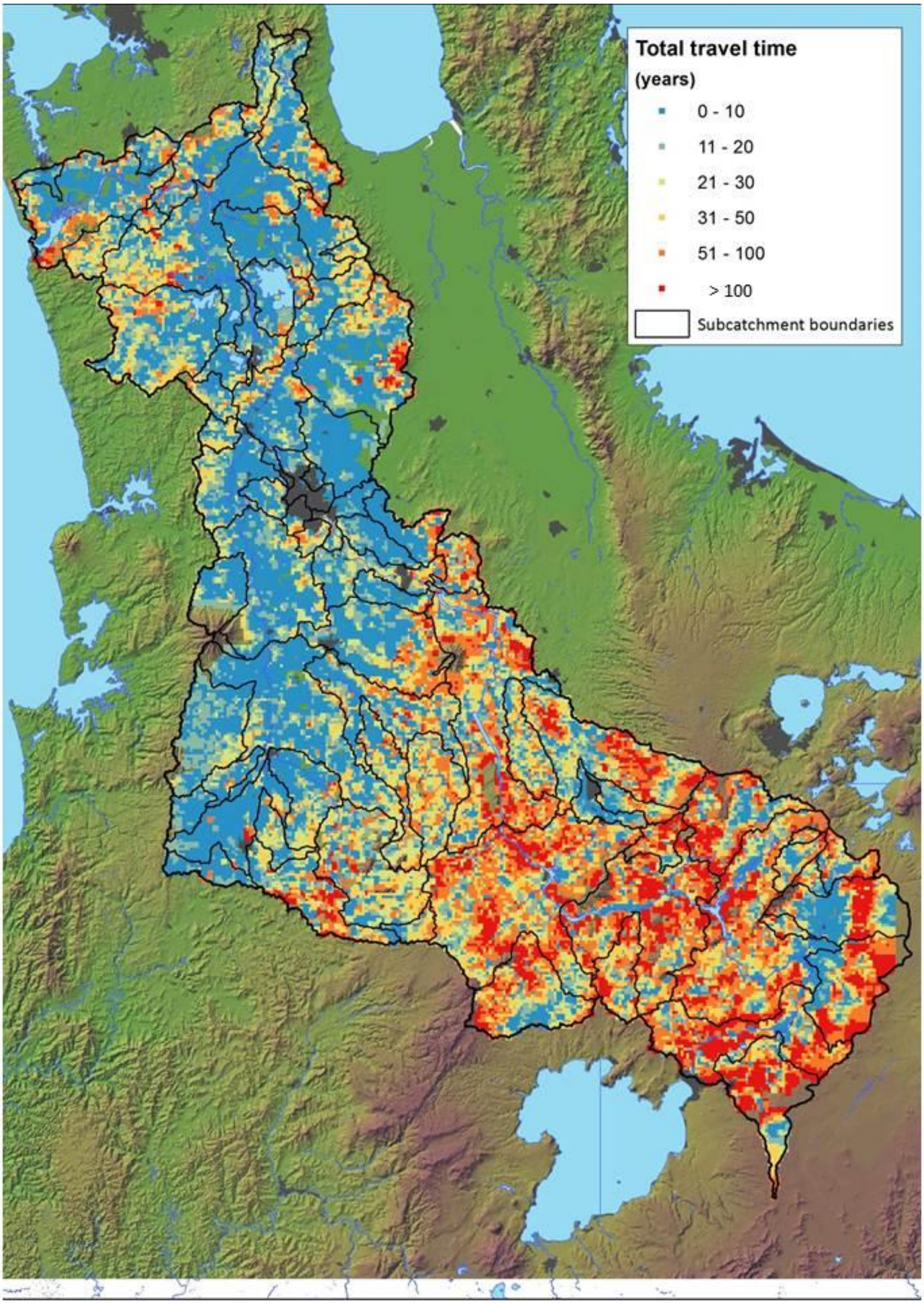
---

[33] 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.

[34] 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

[35] Amsl – above mean sea level

Figure 11: Total travel time of water and nitrate flow through the unsaturated (vadose) zone into the upper ground water zone.



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

Introduction

Reducing conditions are necessary for denitrification to occur and thus the ground water redox status determines how much attenuation of nitrate-nitrogen is likely to occur as nitrate passes through aquifers. This study relates the redox[36] status determined for 554 ground water bores throughout the entire Waikato Region with other factors such as subsurface geology, topography and soil characteristics[37] to allow redox predictions to be made for areas where no measurements are available. An additional report was commissioned to provide this information specifically for the 74 sub-catchments draining to the Waikato and Waipa rivers[38]. The more detailed examination of redox status at individual well sites completed in study one shows the extreme variability of redox potential that occurs on a micro-scale.

Findings

In the entire 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 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.

The findings reported specifically for the Waikato and Waipa sub-catchments are shown in Figure 12 (shallow depth <25m) and Figure 13 (medium depth 25 to 100 m) as these depths are where most of the flow of nitrate-enriched ground water occurs.

Figure 12 shows reducing conditions are suggested for much of the low lying poorly drained areas in the middle and lower Waikato basins and in the Waipa catchment. Oxidising conditions

---

[36] 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.

[37] Close ME et al. 2015. Prediction of the Redox Status of Groundwater on a Regional Scale using Linear Discriminant Analysis. Submitted to HydroGeology Journal.

[38] Close ME 2015. Prediction of Subsurface Redox Status for Waikato Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai. Environmental Science Research client report CSC 15010 for Waikato Regional Council. 21pp.

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 shallow aquifers in the upper Waikato appears less obvious but indicate mainly reducing conditions in shallow volcanic deposits, which often contain organic material from sequences of buried top-soils.

Figure 13 shows similar patterns of redox conditions in deeper ground water in the Waipa and middle and lower Waikato to those shown for shallow ground water. There is strong evidence of increasing reducing conditions with depth in the Hamilton Basin. More prevalent oxic conditions are predicted in deeper ground water in the upper Waikato. This contrasts what is usually observed where reducing conditions are more likely in deeper flow paths with longer residence times (other things being equal). This anomaly probably reflects fewer paleosols evident in deeper volcanic lithologies.

Figure 12: Oxidising and reducing zones in shallow aquifers (< 25 m depth) in the Waikato and Waipa catchments

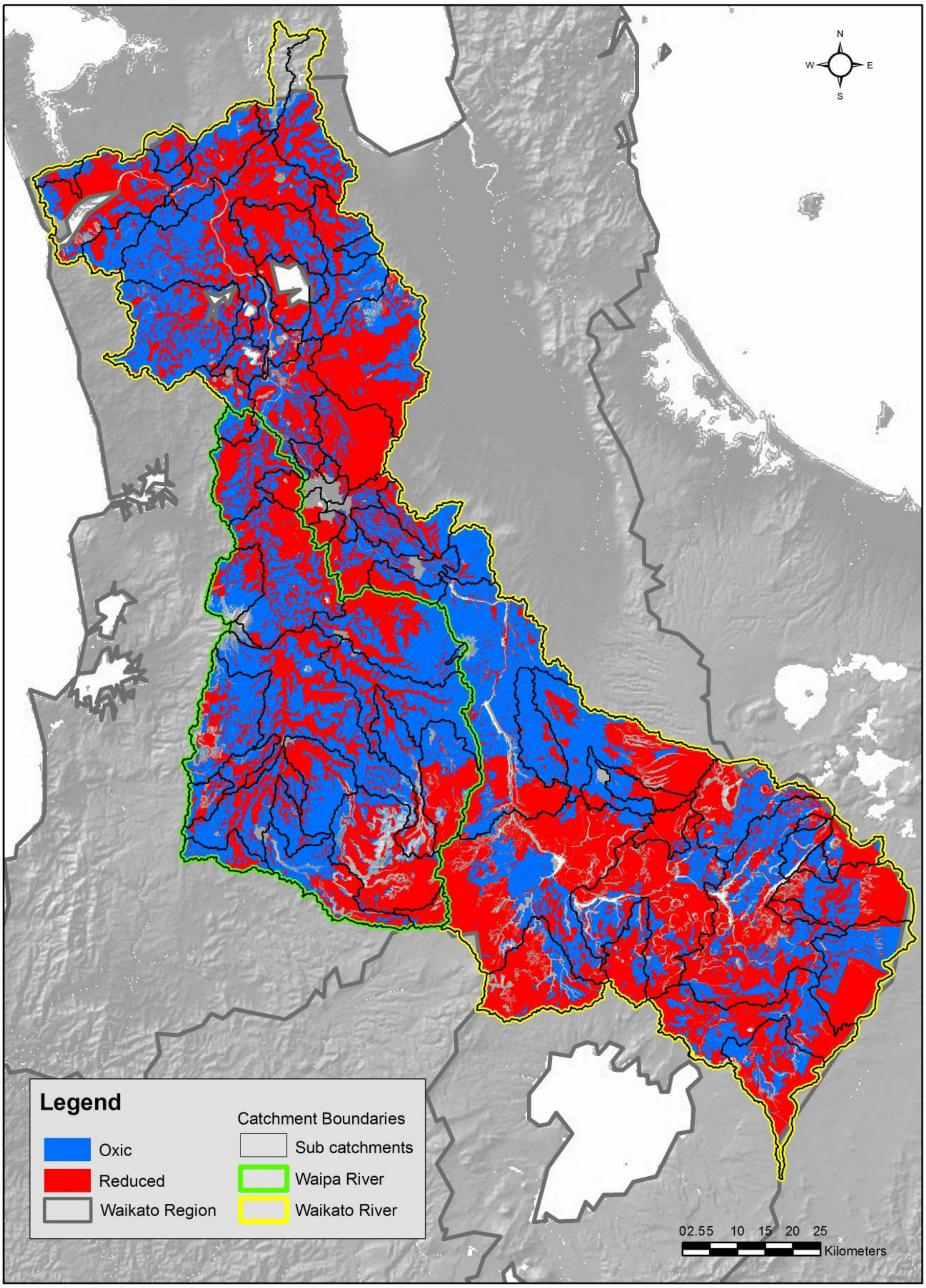
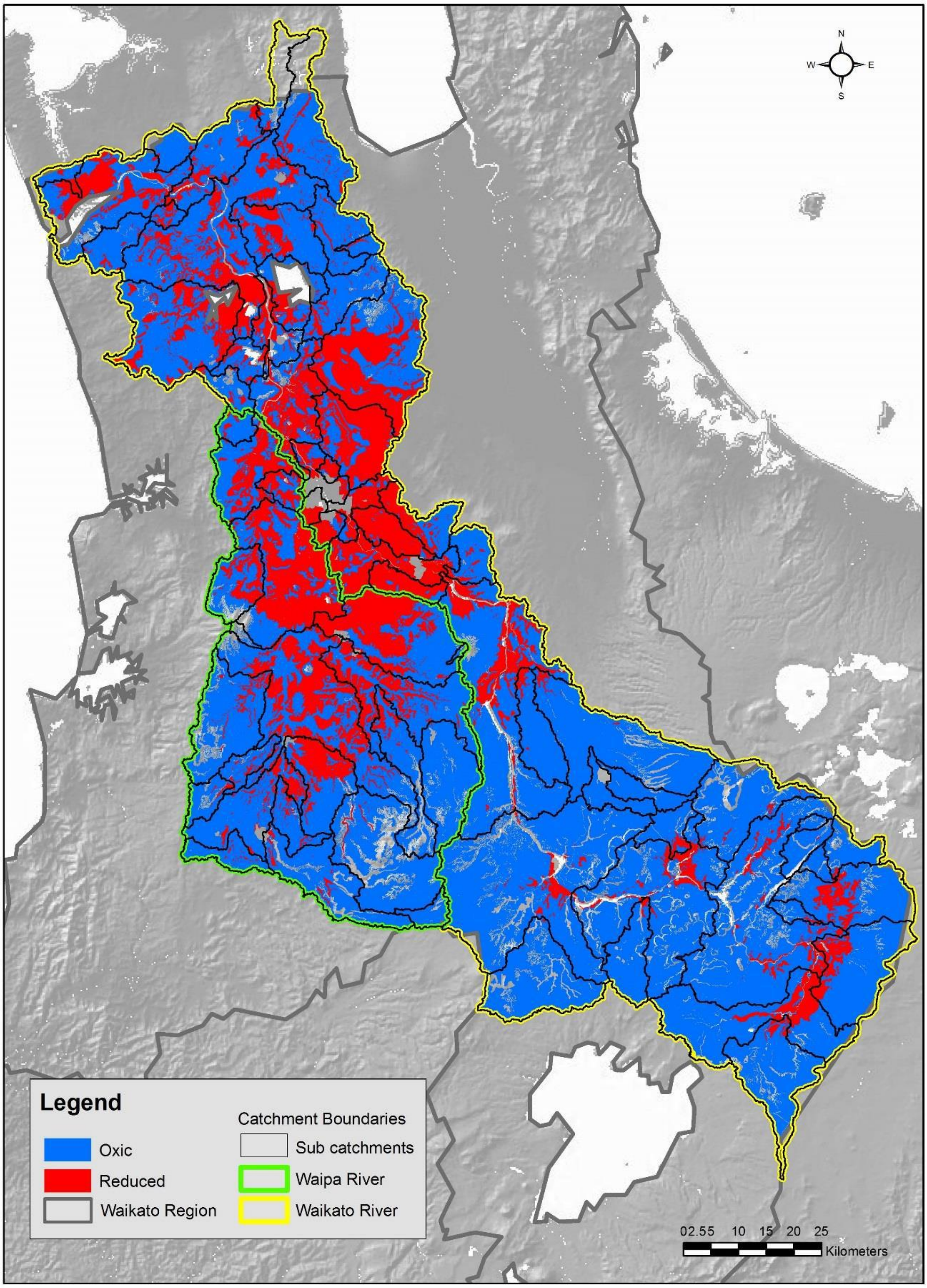


Figure 13: Oxidising and reducing zones in medium depth aquifers (25 m to 100 m depth) in the Waikato and catchments



Study 5 Review of historical land use and nitrogen leaching

Introduction

This study examines changes in land use in the Waikato and Waipa Catchments over a 40 year period from 1972 to 2012[39]. Estimates of the associated N-N leaching are also provided.

Method

Land use

Historical land use data were derived from several sources and collated in a geospatial framework and analysed to provide information regarding land use change over time. Estimates were obtained for the 74 Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai project sub-catchments for the periods 1972, 1986, 1996, 2002, 2008 and 2012. A consistent set of ten land uses[40] was derived to classify all land use over the sub-catchments.

Nitrate-Nitrogen leaching loss

N-N leaching estimates were obtained for the main land uses from New Zealand literature including technical reports prepared for regional councils by Crown Research Institutes, reports prepared by agricultural consultants available in the public domain, conference proceedings and peer reviewed journal articles. Overseer® v5[41] was also used to estimate nitrogen loss from farming enterprises. Emphasis was placed on pastoral land uses, dairy and sheep and beef farming because these land uses are the dominant source of N-N leaching in the Waikato Region. Historic estimates of N-N leaching were obtained from many studies as input to determine trends in N-N leaching, including those studies providing long term estimates of leaching loss for soils typical of the Waikato and Waipa catchments[42].

Estimates of trends in historical leaching were derived by regression for dairy, and sheep and beef farm systems from the historical leaching data. N-N leaching losses for other land uses were obtained from the information utilised in the regional economic model developed for the Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai project[43]. Table 3

---

[39] Hudson, N., Elliot, S., Robinson, B. (2015) Review of historical land use and nitrogen leaching: Waikato and Waipa River catchments. Client report prepared by NIWA for the Wai Ora/Healthy Rivers project (Waikato Regional Council project EVW15219, EVW16203). Report no. HAM2015-082, revision 6: 182 pp.

[40] The ten land uses were: dairy, intensive lowland sheep and beef, hill and high country sheep and beef, other stock, forestry, native forest and scrub, maize, horticulture, urban and miscellaneous.

[41] More recent versions of Overseer® estimate greater N-N losses than V5 but the primary aim of this report the analysis of trends of N-N loss not absolute values.

[42] Judge A, Ledgard S, 2004. Nutrient budgets for Waikato Dairy and Sheep/Beef Farms for 1997/98 and 2002/03. Report prepared by AgResearch Ltd for Environment Waikato. AgResearch Ltd 932109.
Judge A, Ledgard S, 2009. Nutrient budgets for Waikato Dairy and Sheep, Beef and Deer Farms for 1997/98 and 2006/07. Report prepared by AgResearch Ltd for Environment Waikato. AgResearch Ltd 1602965.
Ledgard S, Power I (2006). Nitrogen and Phosphorus losses from 'average' Waikato farms to water ways as affected by best or potential management practices. AgResearch technical report for Environment Waikato 1095998.
Olubade-Awosola F, et al, 2014. Improving water quality in Waikato-Waipa Catchment – options for dry stock and dairy support farms'. Farming to change expectations. NZARES conference August 2014, Nelson.
Perrin Ag, 2012. Farmer Solutions Project. Client report prepared by Perrin Ag Consultants Ltd with AgResearch for Bay of Plenty Regional Council.
Rutherford K, *et al*. 2009. Nitrogen exports from Lake Rotorua catchment – calibration of the Rotan model. BOP08225. Hamilton. NIWA.
Rutherford K, et al, 2011. Prediction of nitrogen loads to Lake Rotorus using the ROTAN model. Client report HAM210-134 prepared for Bay of Plenty Regional Council.

[43] 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.

summarises estimated and relative leaching rates for dairy and sheep and beef farm systems for selected years with the reference year of 2012 - the base year used in the regional economic model.

Table 3: Summary of estimated and relative N-N leaching for selected years, with 2012 as the reference year.

Year	Dairy yield N-N		Sheep and Beef yield N-N	
	Estimated (kg/ha/y)	Proportion of 2012 yield	Estimated (kg/ha/y)	Proportion of 2012 yield
2012	30.6	1	10.8	1
2008	29	0.948	10.6	0.983
2002	26.6	0.871	10.4	0.958
1996	24.3	0.794	10.1	0.933
1992	22.7	0.742	9.9	0.916
1982	18.8	0.613	9.5	0.875
1972	14.8	0.484	9	0.833

The nitrogen yield may be calculated for other calendar years using linear equations:

$$Dairy\ nitrogen\ yield\ (kg/ha/yr) = 0.392 \times year - 758.2$$
$$Sheep\ and\ Beef\ nitrogen\ yield\ (kg/ha/yr) = 0.0452 \times year - 80.119$$

The estimates of N-N leaching shown in Table 3 were applied to land use data to estimate trends in sub-catchment N-N leaching over the past 40 years.

Findings

Change in pastoral land use over time

Change in areas of land use over time are summarised in Table 4 and Figure 14 for the combined area of the Waikato and Waipa catchments. Pastoral land uses have declined slightly over the 40 years from 1972 (7094 km^2 in 1972: 6801 km^2 in 2012). However, within the pastoral sector several trends are apparent. The area of dairying increased 12 per cent from 2748 km^2 to 3080 km^2; the area of intensive sheep and beef increased 44 per cent from 1711 km^2 to 2472 km^2; and the area of hill and high country sheep and beef halved from 2635 km^2 to 1249 km^2. This means that in 2012, 28 per cent of the total area were used for dairying, 22 per cent for intensive sheep and beef farming, 11 per cent for hill and high country sheep and beef farming, 15 per cent for forestry, 16 per cent for native forest and scrub, and 7 per cent for all remaining land uses.

Table 4: Change in land use areas over time for dominant land use categories in the Healthy River catchments.

Pasture includes "dairy", "sheep and beef" (intensive and hill country) and "other animals" categories. "Miscell." includes "horticulture", "maize", "miscellaneous" and "urban" land use classes.

Year	Land use area (km^2)							
	Dairy	Sheep and Beef - Intensive	Sheep and Beef - Hill and High	Pasture	Forestry	Native Forest & Scrub	Miscell.	Total
1972	2748	1711	2635	7094	1452	1154	1285	10985
1982*	2632	1910	2489	7031	1681	1310	954	10976
1992*	2516	2110	2344	6970	1910	1467	623	10970
1996	2470	2190	2286	6946	2002	1529	490	10967
2002	2852	2054	1828	6734	2077	1593	567	10971
2008	2794	2099	2100	6993	1917	1525	533	10968
2012	3080	2472	1249	6801	1695	1727	801	11024

*Interpolated land use.

Changes in areas of other land use over time[44]

The area of non-pastoral land use (forestry, native forest and scrub and miscellaneous (including horticulture, maize, urban and other) land use) increased from 3891 km^2 in 1972 to 4233 km^2 in 2012 (Figure 14). Forestry increased in area by 243 km^2 and native forest and scrub by 573 km^2. The area in native forest and scrub increased almost linearly from 1,153 km^2 in 1972 to 1,726 km^2 in 2012 most probably representing reversion of hill and high country enterprises to scrub land. The increase in native forest and scrub occurred in most catchments especially the upper and lower Waikato and the Waipa. These land use changes may represent afforestation, reversion of marginal hill and high country farms, and the general shift of all farms systems from more gentle to steeper terrain. Miscellaneous land use reduced from 1285 km^2 in 1972 to 801 km^2 in 2012 probably because the ability to discriminate these land uses more accurately in recent decades.

Horticulture occupies a small area of the Waikato and Waipa catchments (average - 0.8 per cent of total land area (88 km^2): low - 0.3 per cent in 1972 (38 km^2); high 1.3 per cent in 2008 (140 km^2)).

The area in urban land increased steadily from 1972 (146 km^2) to 2002 (168 km^2), an increase of 74 ha per year but doubled in the decade 2002 to 2012 (349 km^2), an increase of 1,690 ha per year. This may be an artefact of more detailed information becoming available for this land use during the 2000s. Urban land occupies 3.2 per cent of the Waikato and Waipa catchments. Hamilton, the largest urban centre occupied ~38 km^2 in 2012.

[44] Information drawn from Table 1, Figure 14 and Appendix A of Hudson, N *et al* 2015.

Figure 14: Area of each land use in the Waikato and Waipa catchments from 1972 to 2012

Changes in area of land use in each Fresh water Management Unit (FMU)[45,46]

More subtle changes in land use are apparent in each FMU. Figures 15 to 18 show the change in land use in each FMU by time period.

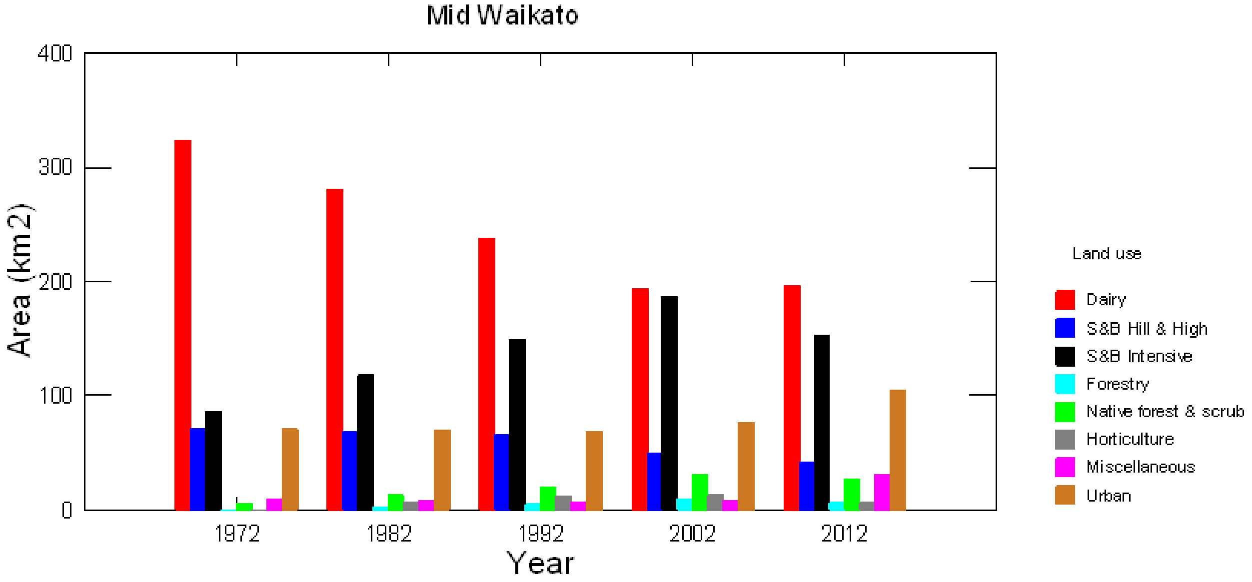
Figure 15: Area of land use in the Upper Waikato FMU from 1972 to 2012

In the upper Waikato FMU the recent conversion of forestry to dairy and intensive sheep and beef systems are obvious (11 of 21 sub-catchments show a consistent increase in dairy area). As well, the area of intensive sheep and beef increased in 16 of 21 sub-catchments. This is offset by net decrease in area of forestry (a decrease in 5 of 21 sub-catchments but a smaller increase in 4 sub-catchments) and a decrease in area of hill sheep and beef units (in 9 of 21 sub-catchments).

[45] FMU for the Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai project are upper Waikato, middle Waikato including Hamilton, lower Waikato and the Waipa.

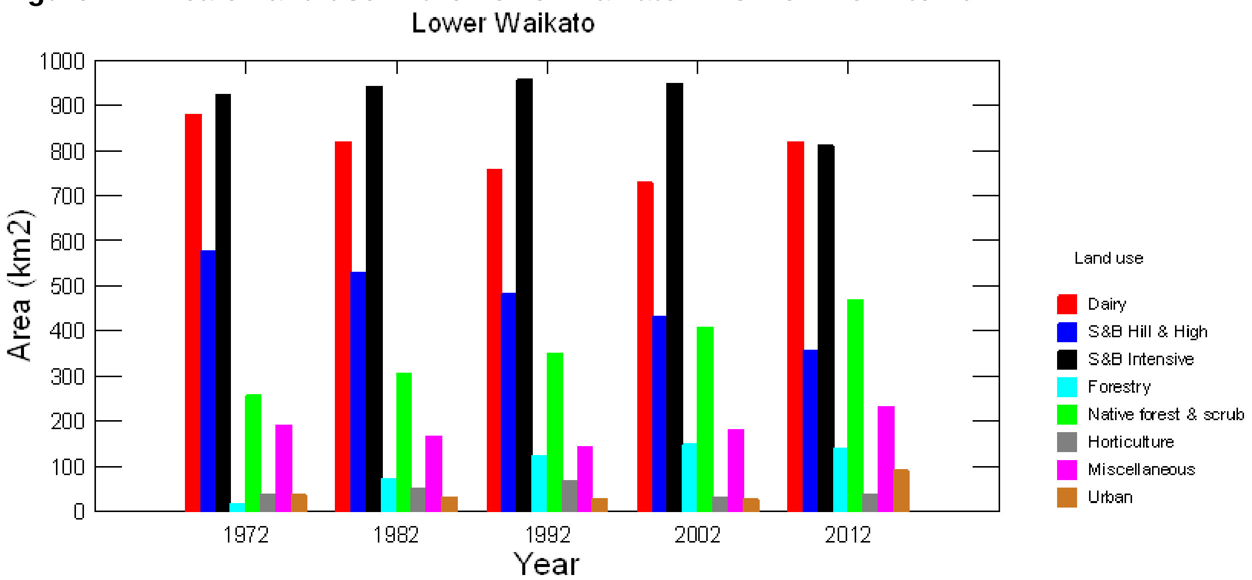
[46] More detailed information and comment is also drawn from Appendix A of Hudson, N *et al* 2015.

Figure 16: Area of land use in the Middle Waikato FMU from 1972 to 2012



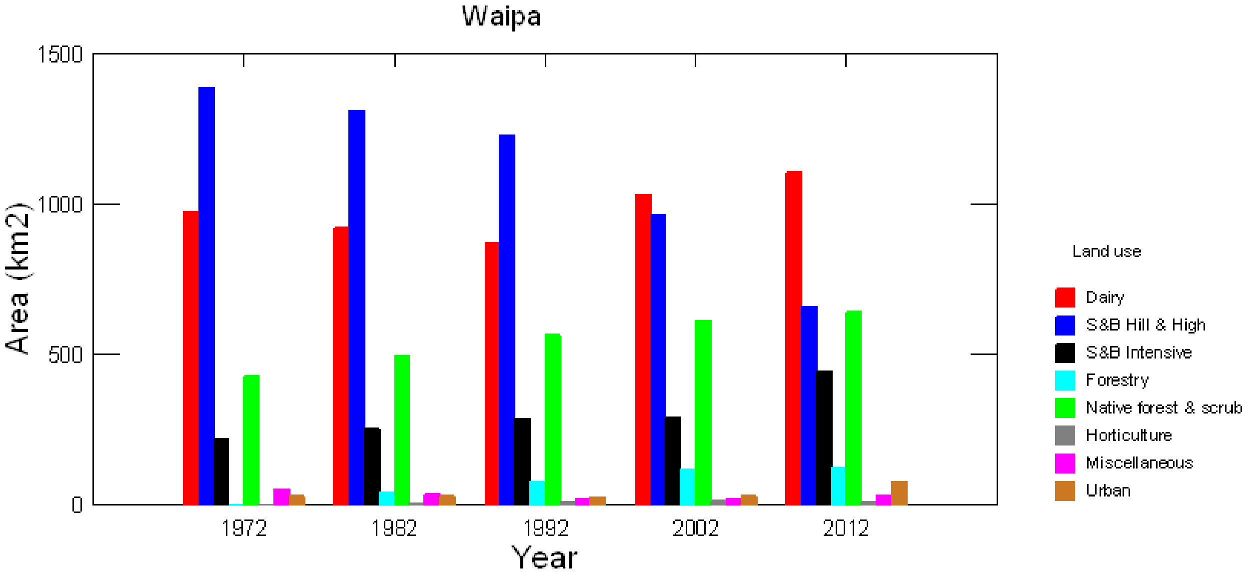
In the middle Waikato FMU, land use change has been more subdued but areas of dairying decreased in most sub-catchments and areas of intensive sheep and beef increased in 8 of 10 catchments. Areas of hill sheep and beef land decreased. Little forestry occurs in the middle Waikato and changes in area have been small.

Figure 17: Area of land use in the Lower Waikato FMU from 1972 to 2012



In the lower Waikato FMU, the net area of dairying decreased (decreases in 10 of 21 sub-catchments and increases in five sub-catchments) as did the area of intensive sheep and beef (decreases in 11 of 21 sub-catchments and increases in 4 sub-catchments). A decrease in area of hill sheep and beef occurred in all sub-catchments where it occurs. Areas of forestry increased in 15 of 21 sub-catchments particularly in steeper sub-catchments. The urban area increased nearly threefold in the decade 2002 to 2012.

Figure 18: Area of land use in the Waipa FMU from 1972 to 2012



In the Waipa FMU, areas in dairy increased in 7 of 21 sub-catchments and declined in only 2 sub-catchments. Areas of intensive sheep and beef increased in 17 of 21 sub-catchments. Areas of hill sheep and beef declined in all sub-catchments in the Waipa offset by increases in forestry, intensive sheep and beef and reversion to scrub land. The land use change in the Waipa probably represents an alignment of land use with land suitability. Afforestation of the hill and high country land in the Waipa catchment is most apparent during the 1970s through to 2002.

Changes in estimated N-N leaching losses over time[47]

Table 5 shows changes in total N-N leaching losses (kt/y) for the Waikato and Waipa catchments.

Table 5: Trend in total nitrogen leaching losses over the entire Healthy Rivers catchment, 1972-2012.

Year	Nitrogen loss by land use type (kt/y)					
	Total	Dairy	Intensive Sheep and Beef	Hill Sheep and Beef	Pasture Total	Non-Pasture
1972	9.24	3.95	1.64	1.90	7.49	1.75
1982	10.65	4.83	1.93	1.88	8.64	2.01
1992	12.00	5.64	2.24	1.86	9.74	2.27
1996	12.53	5.95	2.37	1.84	10.16	2.37
2002	13.51	7.74	2.27	1.52	11.52	1.99
2008	14.87	8.28	2.39	1.78	12.44	2.43
2012	15.35	9.62	2.93	1.09	13.64	1.71

Analysis of these estimates shows for the Waikato and Waipa catchments total N-N leaching losses increased progressively since 1972, with N-N losses 66 per cent larger in 2012 than in

[47] Information drawn from Table 7, Figures 15-18 and Appendix F of Hudson, N *et al.* 2015.

1972. The relative contribution of pasture N-N losses to catchment N-N leaching losses increased steadily from 81 per cent in 1972 to 89 per cent in 2012.

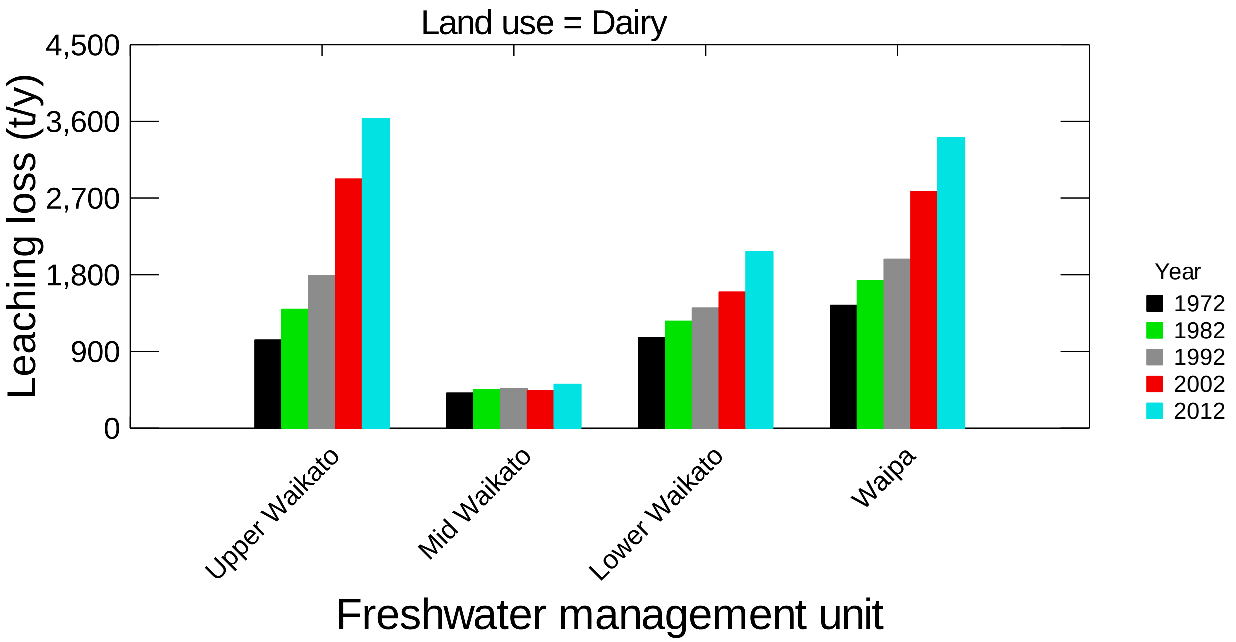
N-N leaching losses from dairy land increased 240 per cent since 1972 (3.95 kt/y in 1972 to 9.62kt/y in 2012) driven by an increase in N-N leaching (a factor of 2.1) and by increased area. The relative contribution of dairy N-N leaching to catchment N-N losses increased from 43 per cent in 1972 to 63 per cent in 2012.

N-N leaching losses from all sheep and beef farms (intensive and hill) increased 4 per cent from 3.54 kt/y in 1972 to 4.02 kt/y in 2012; but the relative contribution of all sheep and beef farms N-N losses to total catchment load decreased from 38 per cent in 1972 to 26 per cent in 2012.

The N-N leaching loss from all other non-pastoral land uses remained approximately similar over the 40 year period.

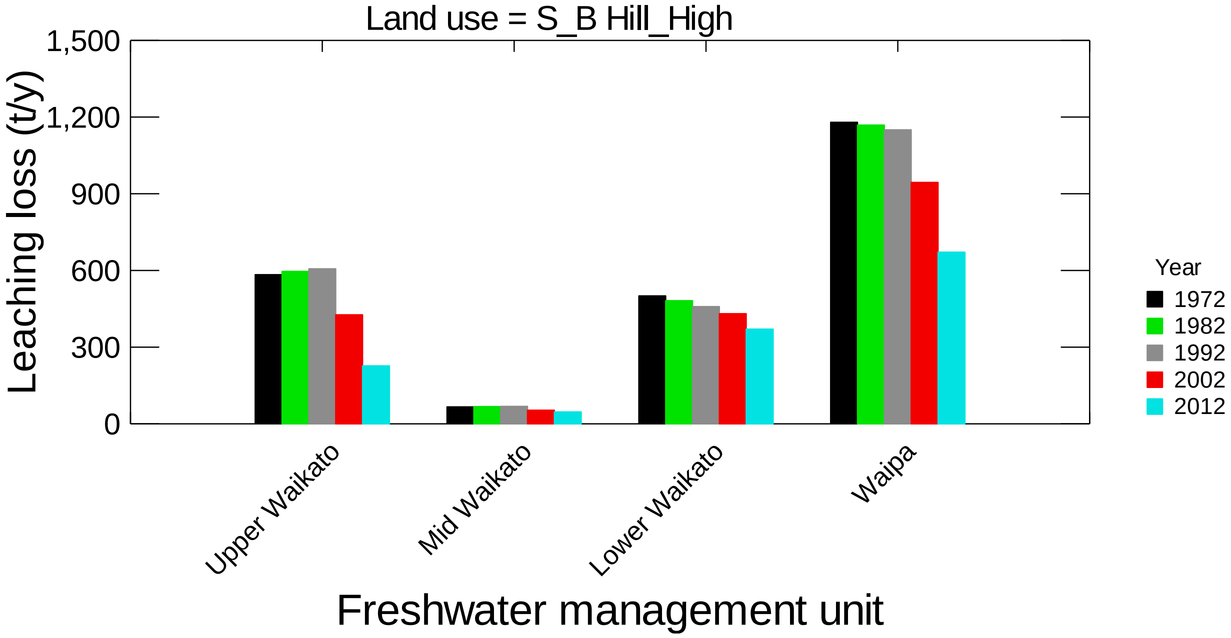
Figures 19 to 22 show changes in total N-N losses (t/y) for land uses in each FMU. These data also show the spatial variability of land use intensification over time.

Figure 19: N-N leaching loss from dairy land in each FMU: 1972 to 2012



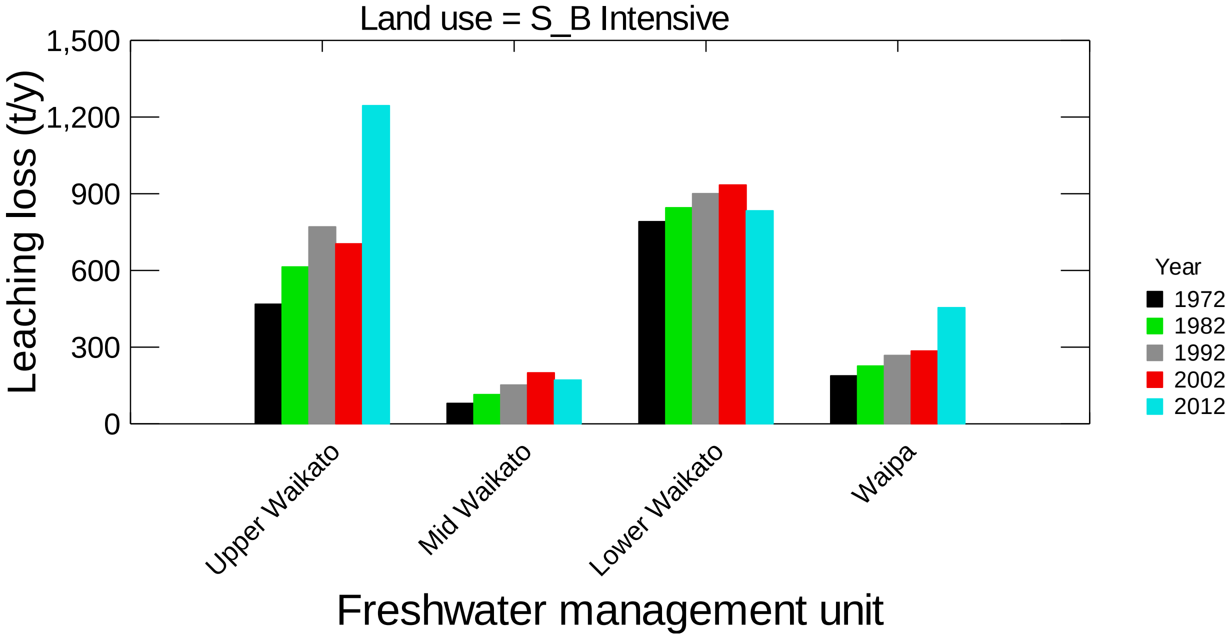
The effects of recent dairy conversions and intensification of dairy systems in the upper Waikato FMU and Waipa FMU are apparent as is the intensification of dairy systems in the lower Waikato. The sub-catchments with greatest increase in N-N leaching losses are Little Waipa, Kawanui, Waipapa and the Waikato at Ohakuri: all in the upper Waikato FMU. Little change in N-N discharges has occurred in the middle Waikato FMU, where increasing N-N leaching losses per hectare were counterbalanced by a decrease in the dairying area.

Figure 20: N-N leaching loss from hill and high country sheep and beef land in each FMU: 1972 to 2012



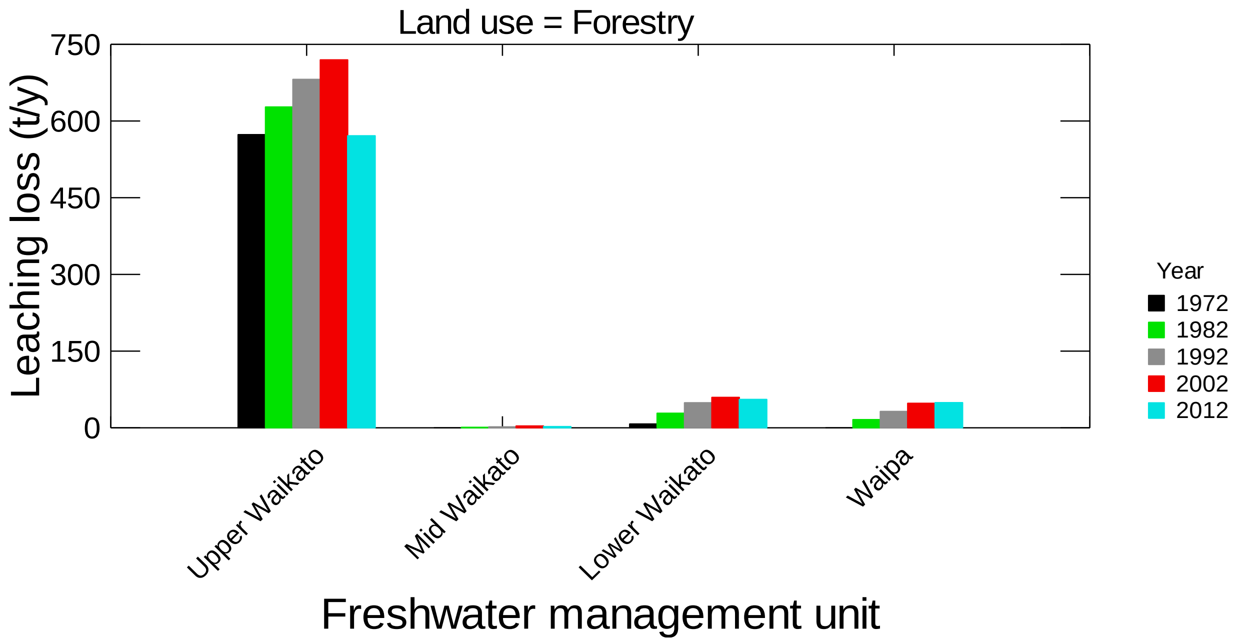
Nitrate-nitrogen leaching from hill and high sheep and beef units declined obviously in the upper Waikato, lower Waikato and Waipa FMU, although the upper Waikato and Waipa these occurred mainly in the two decades following 1992 (Figure 20), probably because of continued intensification of sheep and beef systems in these areas (Figure 21) and some conversion to forestry. Little change in N-N leaching occurred from hill and high country sheep and beef units in the middle Waikato - and there are few properties in this land use category.

Figure 21: N-N leaching loss from intensive sheep and beef land in each FMU: 1972 to 2012



The upper Waikato and Waipa FMU show the greatest increase in nitrate-nitrogen leaching from intensive sheep and beef systems over the forty year period with the most rapid increase in leaching occurring since 2002 in the upper Waikato (Figure 21). The nature of the change observed reflects intensification of sheep and beef properties, including hill and high country enterprises and the conversion of forestry in some FMU to sheep and beef units. Again, little change in N-N leaching occurred from intensive sheep and beef units in the middle Waikato.

Figure 22: Leaching loss from forestry in each FMU: 1972 to 2012



Even though forested land leaches low levels of N-N per ha (typically near background yields (3 kg N/ha/y)) the areas of forests remaining in the upper Waikato FMU contribute most of the forest derived N-N loads in the Waikato and Waipa catchments (Figure 22). The conversion of forestry to dairy land and sheep and beef properties in the last decade is apparent in the upper Waikato FMU. Forest derived N-N discharges from the middle and lower Waikato and Waipa FMU are small reflecting the limited area of this land use in each FMU.

Summary

The information from this study provides, for the first time, a comprehensive view of the location and extent of changes in land use and corresponding N-N leaching loss from land in the Waikato and Waipa catchments since 1972 and underpins the Healthy Rivers - Plan for Change: Waiora He Rautaki Whakapaipai project.

Land use change

Pastoral land uses declined slightly from 1972 to 2012. However, within the pastoral sector several trends are apparent. The area of dairying and intensive sheep and beef increased and the area of hill and high country sheep and beef halved over the forty years.

The area of non-pastoral land uses (forestry, native forest and scrub, horticulture, maize, urban and miscellaneous land uses) increased from 1972 to 2012. Forestry increased in area by 15 per cent and native forest and scrub increased almost linearly by nearly 50 per cent over the period; most probably by reversion of marginal hill and high country in the upper and lower Waikato and the Waipa FMU. Horticulture occupies a small area (~1 per cent) of the Waikato and Waipa catchments. The area of urban land increased steadily from 1972 to 2002 but doubled in the decade 2002 to 2012 to 3.2 per cent of the Waikato and Waipa catchments (349 km2). Hamilton, the largest urban centre occupied ~38 km2 in 2012.

More subtle changes in land use are apparent in each FMU. In the upper Waikato FMU the recent conversion of forestry to dairy and sheep and beef farm systems are obvious. This is offset by net decrease in area of forestry and hill and high sheep and beef units.

In the middle Waikato FMU, land use change has been more subdued. Areas of dairying and intensive sheep and beef increased slightly in most sub-catchments. Areas of hill and high sheep and beef land decreased. Little forestry occurs in the middle Waikato: only small changes in area have occurred.

In the lower Waikato FMU, the net area of dairying decreased as did the area of intensive sheep and beef and hill and high sheep and beef, where it occurs. Areas of forestry increased in many steeper sub-catchments.

In the Waipa FMU, areas in dairy increased consistently as did areas of intensive sheep and beef. Areas of hill and high sheep and beef declined in all sub-catchments in the Waipa offset by small increases in forestry.

Changes in N-N leaching losses over time

Total N-N losses for the Waikato and Waipa catchments increased progressively since 1972, with N-N losses 66 per cent larger in 2012. The relative contribution of pasture N-N leaching losses to catchment N-N leaching losses increased steadily over the period.

N-N leaching losses from dairy land increased 240 per cent since 1972 driven by an increase in N-N leaching (a factor of 2.1) and by increased area. The relative contribution of dairy N-N leaching to catchment N-N leaching losses increased from 43 per cent in 1972 to 63 per cent in 2012. The sub-catchments with greatest percentage increase of N-N leaching are in the upper Waikato FMU: the Little Waipa, Kawanui, Waipapa and the Waikato at Ohakuri.

N-N leaching losses from all sheep and beef farms (intensive and hill) increased 4 per cent from 1972 to 2012. Nevertheless, the relative contribution of all sheep and beef farms N-N leaching losses to total catchment load decreased from 38 per cent in 1972 to 26 per cent in 2012.

N-N leaching loss from all other non-pastoral land uses remained approximately similar over the 40 year period.

Conclusion

The results from the study help understand the causes of trends in nitrogen in ground and surface water and help assess the degree to which water quality is in equilibrium with catchment land use. The results of this study have been incorporated in the catchment models (Study 6) and economic models that estimate consequences of meeting water quality improvement targets on farm and regionally.

The information places in context the extent of change of land use and farm systems that may be needed to protect and restore the Waikato and Waipa rivers.

Study 6: Incorporating this information into a steady-state catchment model

The information from studies 1-5 (above) has been incorporated into a steady-state catchment model developed by NIWA[48] initially for the upper Waikato river catchment but extended to cover all the 74 sub-catchments in the Healthy Rivers Project. Improvements to the inputs for the model and its parameterisation have been possible because of the information from the other five studies and the caucusing among the ground water experts and the modellers. This approach ensured the best interpretation of the ground water information available and to ensure consensus for sub-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 (N attenuation) and the nature of 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 Rivers sub-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[49]. The model predicts mean annual nutrient loads (tonnes per year) and yields (kg/ha/y) for each sub-catchment.

The model has been calibrated against monitored nutrient data. In terms of total nitrogen load, the model explains 99 per cent of the variance between measured and predicted loads for all sub-catchments. Seventy-one per cent of the variance of the yield of total nitrogen is explained for each sub-catchment. Modelled loads (tonnes per year) for 47 of 66 sub-catchments - with data to determine total nitrogen load - are estimated within 20 per cent of the load estimated from the data.

The model is incorporated into an economic optimisation model[50] developed to determine the land use and mitigation options and estimate costs to meet the improvement scenarios for the Waikato and Waipa Rivers considered by the Healthy Rivers Project Collaborative Stakeholder Group.

---

[48] Semadeni-Davies, A, Elliot, S Yalden, S, Hudson, N. 2015. Modelling nutrient loads in the Waikato and Waipa River Catchments. Development of catchment-scale models. NIWA client report HAM2015-089 for Waikato Regional Council.

[49] Refer section 2 of Semadeni-Davies, A et al, 2015 for details of the model construction, the transfer of N and P loads downstream, attenuation processes within reservoirs, streams and ground water, and model calibration.

[50] Doole GJ, 2015. Doole, G.J., Elliott, A.H., and McDonald, G. 2015a. Evaluation of scenarios for water-quality improvement in the Waikato and Waipa River catchments: Assessment of first set of scenarios, University of Waikato Client Report for the Waikato Regional Council, Hamilton.

Doole, G.J., Elliott, A.H., and McDonald, G. 2015b. Evaluation of scenarios for water-quality improvement in the Waikato and Waipa River catchments: Assessment of second set of scenarios, University of Waikato Client Report for the Waikato Regional Council, Hamilton.

Information provided to the catchment model

Information from studies 1 to 5

The information provided from the ground water studies was summarised for each sub-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.

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 N attenuation by denitrification.

Information from Study 5 on historical land use and N-N leaching were directly entered into the model as source loadings for each of the 74 sub-catchments and for each time step.

Summary of ground water studies

A series of 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 vadose zone and aquifers to rivers and streams, and the structural relationships and interactions between ground water and surface water resources. This report provides a summary of these investigations and 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 23).

1. The geological and hydrogeological evidence suggests the hydrogeological systems are closed at a catchment scale: all parts of the Waikato and Waipa catchments are underlain by very slowly permeable sediments. Basins formed in the basement sediments 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 23 #1) to emerge in the Waikato and Waipa rivers and discharge ultimately to the sea (Figure 23 #2). At a sub-catchment scale there is some evidence in a few head water catchments that not all ground water flow is intercepted immediately by streams and is intercepted further downstream in adjacent sub-catchments.

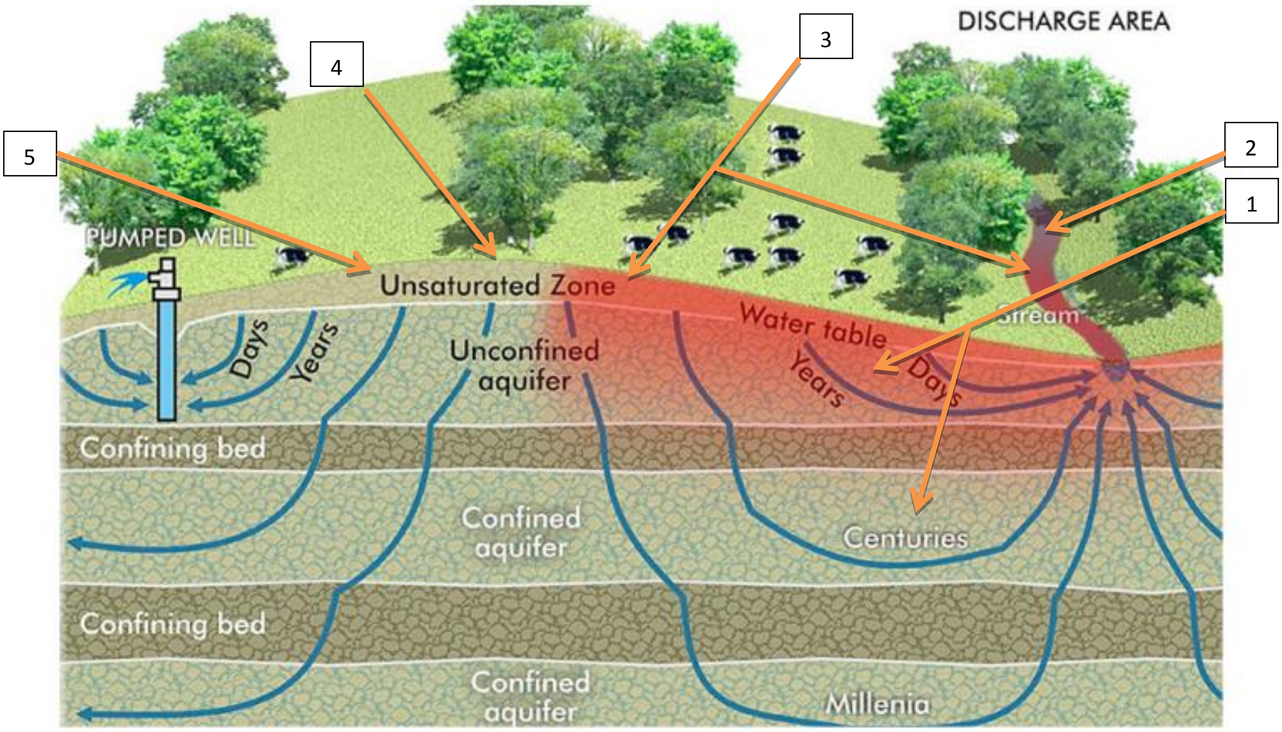
2. Ground water levels vary from a few metres below ground in flat low-lying terrain to between 20 to 50 metres below ground in elevated terrain. Ground water flow paths (driven by piezometric surfaces) indicate spatial patterns of ground water flow are determined strongly by local ground elevation. This pattern is more subdued in deeper aquifers. Ground water flows from higher terrain (where ground water tables are often deeper) to discharge at the low points in the hydrological systems determined by the elevation of the stream and river network (Figure 23 #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 23 #4): there is little evidence of inter-catchment transfers of ground water at a catchment scale. Possible, but unproven, exceptions to this may occur on the elevated, flat terrain of the Kaingaroa plateau and in some low angle sub-catchments in the Waikato lowlands. Some ground water flow may occur between a few small, steep, head water sub-catchments within the main Waikato and Waipa catchments.

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 ground water quality. This finding is consistent with other studies linking land use and ground water quality. Nitrate concentrations are varying only slowly suggesting recent land use intensification has not yet fully impacted ground water quality.

   Ground water nitrogen in the Waipa is sometimes higher than MAV or between half MAV and 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 per cent of sub-catchments.

Figure 23: 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 and into the upper groundwater zone (Figure 23 #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. Under summer baseflow, the mean age of surface water in the Waipa and middle and lower Waikato catchments (expressed as MRT) is generally less than 15 years and averages about 10 years.

   Under summer baseflow, 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 ground water is highly variable throughout the study area. Mean residence times are 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).

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 23).

6. The potential for nitrogen attenuation to occur was examined by predicting reduced ground water zones 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 indicates mainly reducing conditions in shallow volcanic deposits, which often contain organic material from sequences of buried top-soils. Unusually, more prevalent oxic conditions are predicted in deeper ground water in the upper Waikato. 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 the historical land use and nitrogen leaching study shows, for the first time, a comprehensive view of the location and extent of changes in land uses and N-N loss from land in the Waikato and Waipa catchments since 1972.

   Land use. Pastoral land uses declined slightly from 1972 to 2012. However, within the pastoral sector several trends occurred. The area of dairying and intensive sheep and beef increased and the area of hill and high country sheep and beef halved over the forty years. The area of non-pastoral land uses (forestry, native forest and scrub, horticulture, maize, urban and miscellaneous land uses) increased from 1972 to 2012. Forestry increased in area by 15 per cent and native forest and scrub increased almost linearly by nearly 50 per cent over the period; most probably by reversion of marginal hill and high country in the upper and lower Waikato and the Waipa FMU. Horticulture occupies a small area (~1 per cent) of the Waikato and Waipa catchments. The area of urban land increased steadily from 1972 to 2002 but doubled in the decade 2002 to 2012 to 3.2 per cent of the Waikato and Waipa catchments.

   N-N leaching. Estimated total N-N leaching losses for the Waikato and Waipa catchments increased progressively since 1972, with N-N leaching losses 66 per cent larger in 2012. The relative contribution of pasture N-N leaching losses to catchment N-N leaching losses increased steadily over the period. N-N leaching losses from dairy land increased 240 per cent since 1972 driven by an increase in N-N leaching (a factor of 2.1) and by increased area. The relative contribution of dairy N-N leaching to catchment N-N leaching losses increased from 43 per cent in 1972 to 63 per cent in 2012. The sub-catchments with greatest percentage increase of N-N leaching are in the upper Waikato FMU. N-N leaching losses from all sheep and beef farms (intensive and hill) increased 4 per cent from 1972 to 2012. Nevertheless, the relative contribution of all sheep and beef farms N-N leaching losses to total catchment leaching decreased from 38 per cent in 1972 to 26 per cent in 2012. N-N leaching loss from all other non-pastoral land uses remained approximately similar over the 40 year period.

8. 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 improvement scenarios for the Waikato and Waipa Rivers considered by the Healthy Rivers Project Collaborative Stakeholder Group.