AQUALINC RESEARCH LIMITED

Estimated Age in Surface Water and Changes in Nitrogen Concentration in Groundwater in the Upper Waikato Catchment

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EXECUTIVE SUMMARY

An economic analysis of the trade-offs around managing water quality and land-use intensification was initiated by a consortium of parties comprising Ministry for the Environment, Ministry for Primary Industries, Department of Conservation, Dairy NZ, Waikato Regional Council and the Waikato River Authority. The economic analysis used the Upper Waikato River Catchment as a case study.

To complete the economic study, robust and accurate hydrological and surface water quality information was required. Groundwater lag times (the time delay between water infiltrating into the soil and it discharging into surface water) complicate the analysis of land-use effects on surface water quality. Groundwater lags mean that it is unclear whether the currently observed surface water quality represents a catchment's complete response to an increase (for example) in nitrogen leaching or whether there will be an increase in the concentrations and loads of nitrogen in the future. This increase is referred to as the "load to come".

NIWA used a catchment model to predict the long term equilibrium nitrogen concentrations at the water quality sites in the Upper Waikato River Catchment. These predictions are based on the current contaminant sources including point sources (municipal and industrial wastewater and geothermal) and diffuse losses from farms, and included the effects of attenuation (permanent removal) on these loads. However, while the long term equilibrium nitrogen concentrations are being predicted, the time delay or lag in the system is not considered. The current loads observed at the water quality monitoring sites are less than the predicted long term equilibrium concentrations due to attenuation of contaminants within the catchment (and groundwater time lag). Attenuation is caused by natural processes in the catchment that remove contaminants by sedimentation and burial, denitrification and die off in the case of microbes. Attenuation provides a degree of resilience to the effects of land use/contaminant discharge and its quantification is therefore important.

The accurate quantification of attenuation of nitrogen in the Upper Waikato catchment is complicated by a lack of knowledge of the historical leaching loads to groundwater, and the lag time in delivery of this load to the monitored water quality sites. Nitrogen concentrations measured at the surface water monitoring sites are increasing in the catchment. How long these trends will continue is unknown, due the complication of groundwater lags. In a simplified approach, the catchment water quality response to increased contaminant loads (resulting from land use changes) may be considered the result of two processes;

- A rapid adjustment to land use changes (increased contaminant loads), transmitted via shallow flow paths,

- A slower adjustment to land use changes, resulting from a component of the contaminant load moving through the deeper groundwater system (the “lag” component).

The groundwater lag time means that if intensification stopped, the trend in surface water would continue, albeit at a reduced rate, until equilibrium conditions are established. The length of time that the trend will continue is associated with the mean resident time (MRT) for the surface water, fed by groundwater. A lagged response means that the future contaminant loads and concentrations in surface water will be larger than currently measured, due to the load to come.

To assist with understanding the expected changes in surface water quality, this current study has estimated groundwater time lags for surface water tributary catchments in the Upper Waikato River Catchment. To do this two separate methods, one based on surface water chemistry and the second using simulation modelling techniques, have been used. To additionally characterise the changes occurring in nitrogen concentrations in groundwater (contributing to surface water) long term surface water quality measurements and associated flow data have been analysed.

Tritium dating of surface water at two of the Upper Waikato tributary water quality sites indicates that MRT measured in surface waters are in the order of 50 years. By relating SiO_2 concentrations measured in the surface water to MRT estimates it was possible to estimate MRT for the surface water at eight additional water quality sites. At seven of these sites the estimated MRT of the surface water was between 36 and 75 years, with an average of 52 years. The other water quality site had a relatively young MRT of 16 years.

A groundwater flow model was used to estimate the distribution of water ages contributing to the surface water flow at water quality sites, in addition to the MRT estimates. The modelling indicated that the MRT for all water contributing to the average flow at tributary water quality monitoring sites can vary between 5 to 101 years, with an average of 51 years. The estimated mean time of travel of water infiltrating from land areas that are most likely to have been subjected to intensification to the tributary water quality monitoring sites ranges between 1 and 112 years, with an average time of 41 years. At average flow conditions, the groundwater model predicted that 77% of the surface water at the tributary water quality monitoring sites is sourced from groundwater. This indicates that groundwater is making the predominant contribution to flow and it is also therefore likely that groundwater is making the predominant contribution to the total load of nitrogen.

The trend in the groundwater nitrogen concentrations in the catchment was estimated from the trend in the nitrogen concentrations in the surface water samples taken during low-flows. This is based on the assumption that groundwater is the only water source contributing to surface water flow during low-flows. At all five sites where it was possible to undertake this analysis, the nitrogen concentrations in the groundwater were shown to be increasing.

From the analysis, it is reasonable to assume that nitrogen concentrations in the surface water that is sourced from groundwater are likely to continue to increase. The rate and time period over which this increase will occur is however poorly known.

Estimating the eventual load of nitrogen (when the catchment comes to equilibrium) is very difficult, because we do not have a good history of land use change, the degree of attenuation of nitrate, and groundwater flow is complex.

1 INTRODUCTION

An economic analysis of the trade-offs around managing water quality and land-use intensification was initiated by a consortium of parties comprising Ministry for the Environment, Ministry for Primary Industries, Department of Conservation, Dairy NZ, Waikato Regional Council (WRC) and the Waikato River Authority. The economic analysis used the Upper Waikato River Catchment as a case study. To undertake this study, robust and accurate hydrological and water quality information was required.

NIWA (Elliot and Semadeni-Davies, 2013) used a catchment model to predict the long term equilibrium nitrogen concentrations at the water quality sites in the Upper Waikato River Catchment for the current contaminant loadings. This prediction accounts for current contaminant sources including point sources (municipal and industrial wastewater and geothermal) and diffuse losses from farms and included attenuation (permanent removal) effects on these loads. However, the time delay or lag in the system, as to when this equilibrium concentration is achieved is not considered. Loads observed at surface water quality monitoring sites were less than the estimated source loads due to attenuation of contaminants within the catchment. Attenuation is caused by natural processes in the catchment that remove contaminants by sedimentation and burial, denitrification and die off in the case of microbes. Attenuation provides a degree of resilience to the effects of land use/contaminant discharge and its quantification is therefore important. However, some of these attenuation processes are spatially and temporally variable, so a good understanding of the dynamics of these processes is necessary to be able to reliably estimate the long-term equilibrium concentrations.

The accurate quantification of attenuation of nitrogen in the Upper Waikato catchment is complicated by a lack of knowledge of the historical leaching loads to groundwater, and the lag time in delivery of this load to the monitored water quality sites. The nitrogen concentrations in the surface water are increasing in the catchment (WRC, 2013). How long these trends will continue is unknown, due to the complication of groundwater lags. In a simplified approach, the catchment water quality response to increased contaminant loads (resulting from land use changes) may be considered the result of two processes;

- A rapid adjustment to land use changes (increased contaminant loads), transmitted via shallow flow paths,
- A slower adjustment to land use changes, resulting from a component of the contaminant load moving through the deeper groundwater system (the “lag” component).

The lag means that if intensification stopped, the trends would continue, albeit at a reduced rate until equilibrium conditions are established. The length of time that the trend will continue is associated with the “travel times” for the groundwater. Groundwater lags mean that the currently observed water quality represents an incomplete catchment’s response to existing nitrogen discharges and there will be an increase in the concentrations and loads of nitrogen in the future – this is referred to as the “load to come”.

A better understanding of the groundwater lag times is needed to understand the likely (i.e. equilibrium) water quality status of the catchment and thereby correctly estimate the costs of complying with water quality criteria under existing and future land use.

1.1 Lag Times versus Nitrogen Attenuation

Provided that flow paths are known, there are two unrelated but confounding factors that can cause differences between the load of nitrogen applied to the catchment, and that measured in the receiving surface water monitoring site. The first is the time that it takes nitrogen applied to the land surface to travel vertically downwards through the unsaturated zone and then laterally through the saturated zone to eventually discharge into the surface water. The second factor is the amount of attenuation (loss of nitrogen, primarily by denitrification) that occurs along this flow path. The combination of these two factors results in the nitrogen load delivered to the surface water being a non-unique combination of the mass of nitrogen discharged in the catchment and the degree of attenuation occurring along the flow path. For example, the same nitrogen concentration at a water quality site could be due to either:

- a recent, high-intensity nitrogen-leaching land use, combined with a high degree of attenuation and short lag time; or
- an older, low-intensity nitrogen-leaching land use, with a low degree of attenuation and long lag time.

The critical difference in these two scenarios is how the nitrogen load will change with time. A catchment with high attenuation is resilient and will maintain a lower nitrogen concentration in the surface water under land-use intensification. In contrast, a system that has currently low nitrogen concentrations only because the response is lagged, may be subject to an increase in load in the future due to the historic land-use intensification.

To develop a better understanding of the water quality status in a catchment requires the quantification of, amongst other things, current and historical land uses, the hydrological flow paths between the land and the water monitoring sites, the travel times for nitrogen between the bottom of the root zones and the surface water quality monitoring sites, and the amount of attenuation (permanent removal) of nutrients that occurs along this flow path.

This report estimates lag times associated with the surface water flows at water quality monitoring sites in the Upper Waikato Catchment using chemical analysis and a simulation model. In addition, trends in the nitrogen concentration of groundwater contributing to the surface flows at these sites are also determined.

1.2 Estimation of Lag Times in the Surface Water

NIWA is the lead contractor for the hydrological modelling and water quality analysis for the project to assess the economic impacts of land use change (Elliot and Semadeni-Davies, 2013). They have acknowledged that the available information on lag times in the surface water due to the groundwater delivery within the catchment is poor and that estimates of the true attenuation of nitrogen occurring in the catchment are uncertain. We used two approaches to estimating lags in the surface water; a regional groundwater model and chemical dating.

The groundwater flow paths and travel times in the catchment were estimated with the Upper Waikato Regional Groundwater Model. This groundwater model is currently under development by Aqualinc (Weir, 2012) for the WRC. The model has been calibrated to surface flow data, and very good flow results have been achieved. A full calibration of the contaminant transport model has yet to be completed; however, the current regional flow model can be used to estimate, within the limitations of a regional scale model, the flow paths and travel times of groundwater in the catchment.

The regional groundwater model was used to estimate the distribution of travel times of the water to the various water quality monitoring sites used in this study, from the contributing catchments either by groundwater flow paths or surface water tributaries.

A supplementary source of information, used to assist with validating the predicted travel times from the groundwater model were two estimates of the mean resident time (MRT) in water samples using tritium analysis (GNS, 2007). This limited data series was extended to other water quality sites by deriving a relationship between measured SiO_2 concentrations in surface water and MRT for catchments of similar geological formations within the Lake Taupo and Upper Waikato region.

1.3 Analysis of Surface Water Quality

There are a total of 25 surface water quality sites in the study catchment that have nitrogen concentration data collected on a monthly basis from 1993 until the present day (WRC, 2013). Seven of these water quality sites are located on the Waikato River, and 18 are located on surface water tributaries that contribute flow to the Waikato River. Two of these tributary sites are below Lake Karapiro, which is outside of the domain of the regional groundwater model and are therefore not considered in this report.

To identify the trend in nitrogen concentrations in the groundwater contributing flow to a water quality site, we fitted a linear regression through the nitrogen concentration of the samples that lie within the lowest 10% of flow rates. These flows are assumed to be base-flow conditions, when groundwater is the only source of flow to the water quality site.

The estimated long-term increase in the annual load of nitrogen entering the Waikato River due to changes in the nitrogen load to Lake Taupo has also been assessed.

1.4 Outputs from the Study

For each of the 16 water quality sites on tributary surface water quality sites, and each of the 7 sites on the Waikato River, we have estimated;

1. Mean age and distribution of ages in the surface water.

2. The volume of water and estimated mean age for the fractions of groundwater, surface water tributaries and Lake Taupo water (where appropriate).
3. Travel times from high quality pastoral land in each surface water catchment.
4. Generalised groundwater flow lines through the catchment.
5. Where possible, MRT of the surface water has been estimated using a derived relationship between SiO_2 and MRT.

In addition, we have also;

6. Estimated the change in nitrogen concentrations in the groundwater contributing to surface water at five water quality sites based on measured data from the past 20 years.
7. Estimated the increase in the nitrogen load to enter the Waikato River and Upper Waikato catchment from Lake Taupo.

2 MODELLED LAG TIME

2.1 Method

The age distribution of water at the surface water quality monitoring sites was estimated using an integrated groundwater–surface water model. The model estimates the water travel time from different locations in a catchment (or sub-catchment) to its end point using particle tracking. A particle is released into the groundwater table at the centre of each of the cells shown in Figure 1, and the time each particle takes to travel to the water quality site is calculated. This enables the mean age and age distribution of water at the water quality site to be estimated independently of the estimates described in Section 3.

Particle tracking from the lands that are classified as *high-producing exotic grassland* in LCDBv3 (Landcare, 2012) was conducted separately from other land-use types. It is highly likely that these high-producing grasslands are being used or will be used for farming activities and intensification, and tend to produce higher nitrogen loads under this land use. Therefore, it was considered important to determine whether the travel time from these land areas is materially different to travel times from the catchment as a whole.

A brief description of the model, approach and results are presented in the following sections.

2.2 Overview of the Model

A regional scale MODFLOW model has been developed for the Upper Waikato region. The model simulates steady-state saturated flow and particle transport for the area between Lake Taupo and Lake Karapiro (and associated tributaries). The model was developed under a long-term programme by WRC and is documented in Weir (2012).

In order to use the model for this MfE project, it was further developed as follows:

- The model domain was expanded to the west to include the surface water areas that were previously not included. These areas were previously considered unimportant for regional groundwater contribution, but are now important for complete surface water accounting.
- The river network has been expanded to include more of the smaller tributaries, and all flow sites that are being used in this project.
- Surface water inflows have been assigned to some tributaries so that modelled surface water flows match measured average flows (this includes specific reaches and overall catchment surface flows at Karapiro); this accounts for quick flow component (e.g. interflow and laterally moving shallow groundwater) into these tributaries.
- Groundwater and surface water properties have been further adjusted to calibrate groundwater levels, river flows, and groundwater and surface water ages, given the above modifications.

The spatial extent of the model domain and the modelled river network are shown in Figure 1.

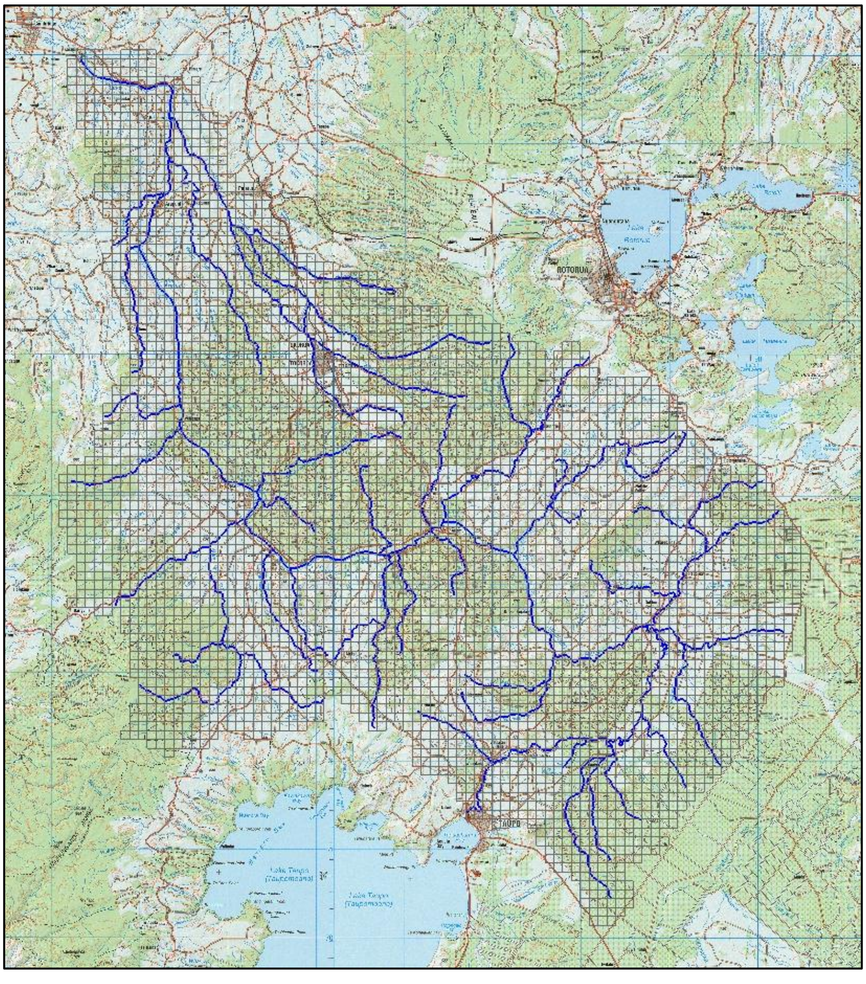


Figure 1: Model domain and river representation.

Figure 2 presents a plot of simulated versus measured groundwater levels for the observation wells used for calibrating the groundwater model. For a model perfectly calibrated at every observation well considered, all points would lie exactly along the solid line running diagonally through the plot. The amount of scatter either side of this line provides an indication of the goodness of fit. Some scatter around this line is normal for any model that simplifies a complex real-world system.

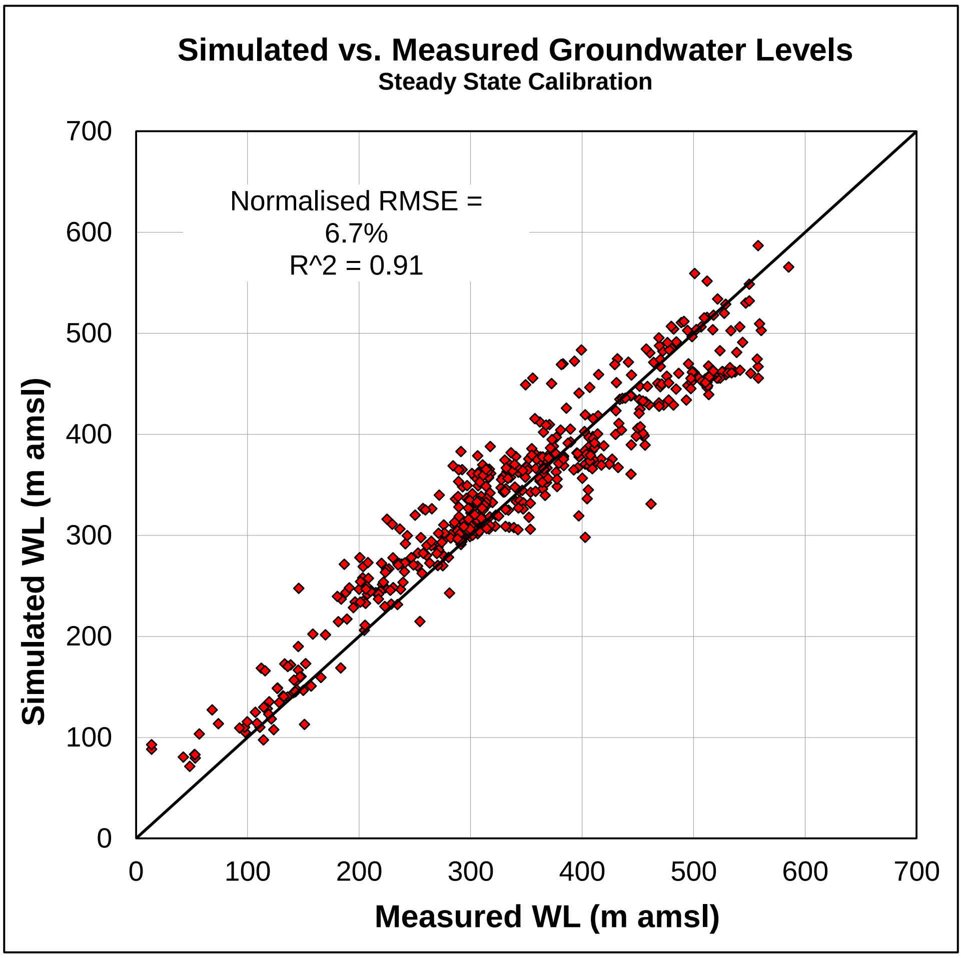


Figure 2: Simulated versus measured groundwater levels.

The fit to measured groundwater levels results in the calibration statistics presented in Table 1.

Table 1: Groundwater level objective function values and other statistics for the calibrated steady-state model.

Objective function or statistic	**Value**
Mean error (ME)	1.89 m
Root mean square error (RMS)	27.4 m
Normalised RMS	6.7%
R^2	0.91

To determine the adequacy of the model calibration, the United States Army Corps of Engineers use a rule of thumb of normalised RMSE as 10% of the total head difference when considering groundwater flow calibration or verification (Donnell *et al.*, 2004). The 2001 Australian Groundwater Flow Modelling Guidelines indicate that the normalised RMSE should be less than 5% (MDBC, 2001), though the revised 2012 guidelines (Barnett *et al.*) suggest that alternative (larger) values may be acceptable depending on the model scope. As the normalised RMSE is 6.7% for the calibrated regional model (Table 1), the model is considered suitably calibrated based on accepted industry standards.

2.2.1 Vadose Zone

The MODFLOW model described in Section 2.2 does not simulate the flow through the vadose (unsaturated) zone. However, it was expected that travel times through the vadose zone in parts of the would be significant given the depths to groundwater in some areas of the catchment; and that the average simulated vadose zone thickness for the model area is 60 m. An estimate of the travel time through the shallow vadose zone has been derived from tracer experiments completed at the Taupo SPYDIA site (Barkle *et al*, 2011). Tracer experiments in the Taupo Ignimbrite horizon have yielded an average travel rate of between 2.5 and 6.0 mm for every 1 mm of drainage below the root zone (Wöhling *et al*, 2012 and Barkle, *pers. comms.*). However, these rates are applicable only for the shallow vadose zone within the depth the experiments were conducted. Hence, it was assumed that the average travel rate of water is 4 mm for every 1 mm of drainage within the first 10 m below ground level. The travel rate below 10 m will be higher as the soils are likely to be and the unsaturated hydraulic conductivity increases as volumetric water content increases (Fetter, 1965). In the absence of measurement-based estimates, a travel rate within the deeper vadose zone (ie, below 10 m) of 20 mm for every 1 mm of drainage was assumed. The average vadose zone travel time estimated by this method is 10 years for the modelled area, with a range of approximately zero and 109 years, depending on the total unsaturated thickness.

2.2.2 Generalised Flow Paths

The simulated water travel paths by the integrated groundwater–surface water model are shown in Figure 3. The flow paths originate at the centre of each of the model cells. To assist the reader with identifying general flow patterns from different parts of the model area, a few selected flow paths are shown in Figure 4. The black dots indicate the origin of the flow path.

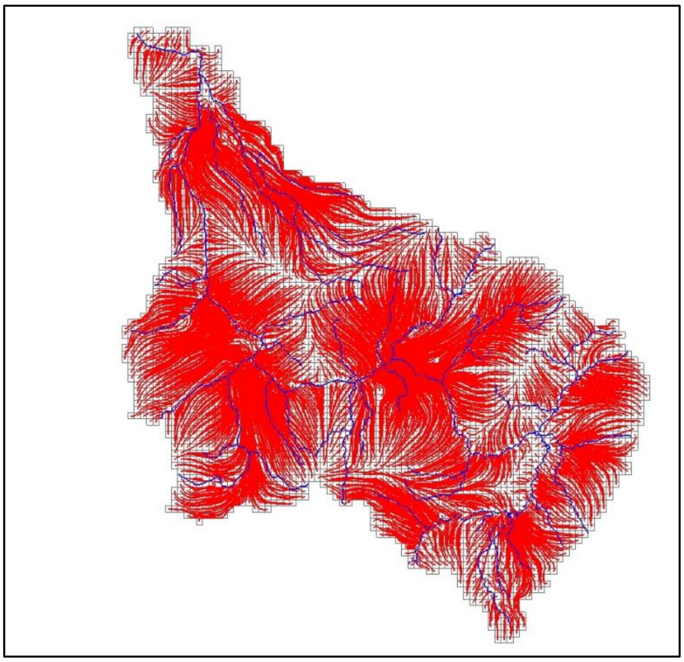


Figure 3: Simulated water travel paths for the whole model.

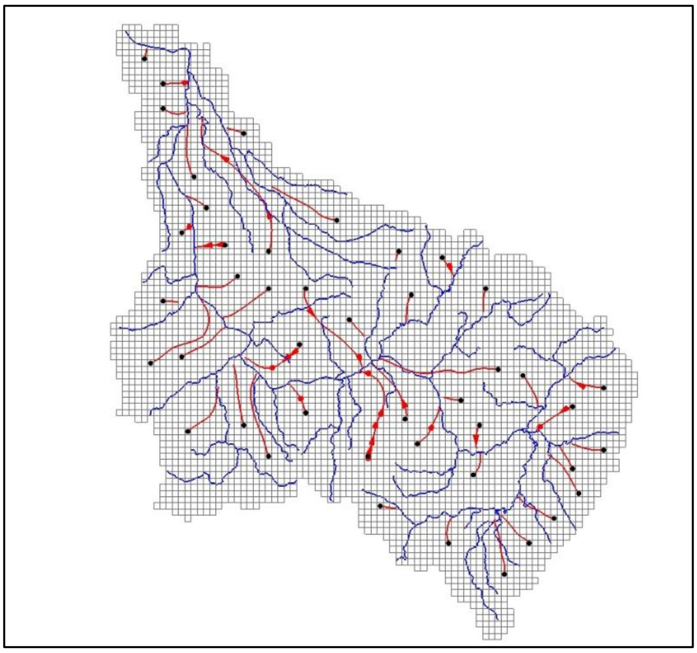


Figure 4: Selected simulated water travel paths.

2.2.3 Land Use

The nitrogen loads that leach into groundwater are dependent on land use. Therefore, this analysis included identification of areas that currently are, or are likely to be in the future, utilised for farming activities. The groundwater flow paths that start under these farming areas were assessed separately from flow paths originating under other land uses such as forestry, based on Land Cover Database version 3 (LCDBv3) (Landcare, 2012), to try to identify the likely water quality response time to changes in land-use intensity in these areas. Figure 5 shows the land-use types along with sub-catchments for the study area.

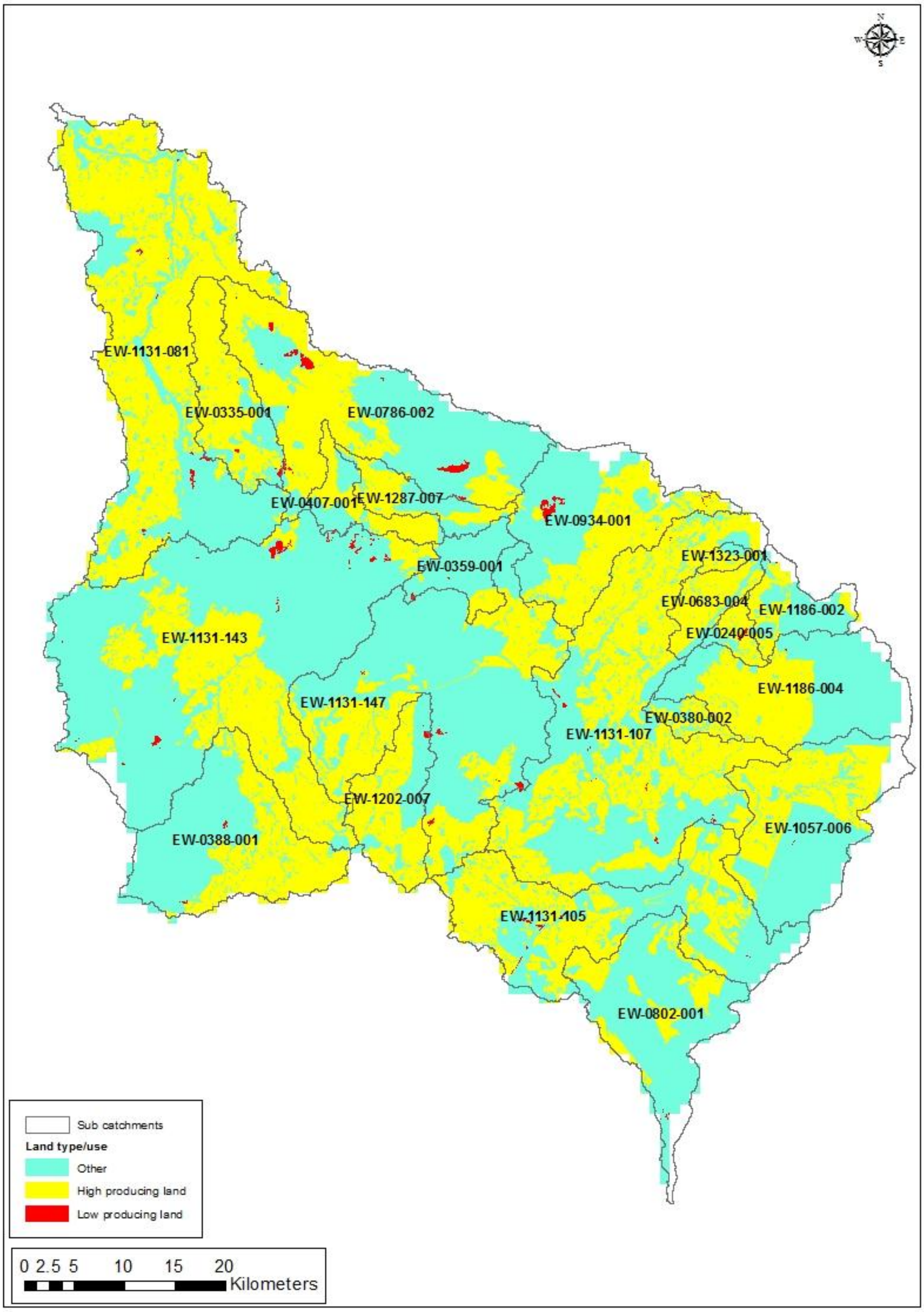


Figure 5: Land-use types (LCDBv3) (Landcare, 2012) and sub catchments.

2.3 Modelled Flows at Water Quality Sites Compared to Other Flow Estimates

This section reports on the modelled age distribution of the surface water at the quality monitoring sites. The locations of water quality sites are shown in Figure 6.

The modelled average river and stream flows along with WRC measured and NIWA estimations based on a rainfall–runoff model are given in Table 2. This table shows that the modelled flows are in reasonably good agreement with the measured and estimated flows.

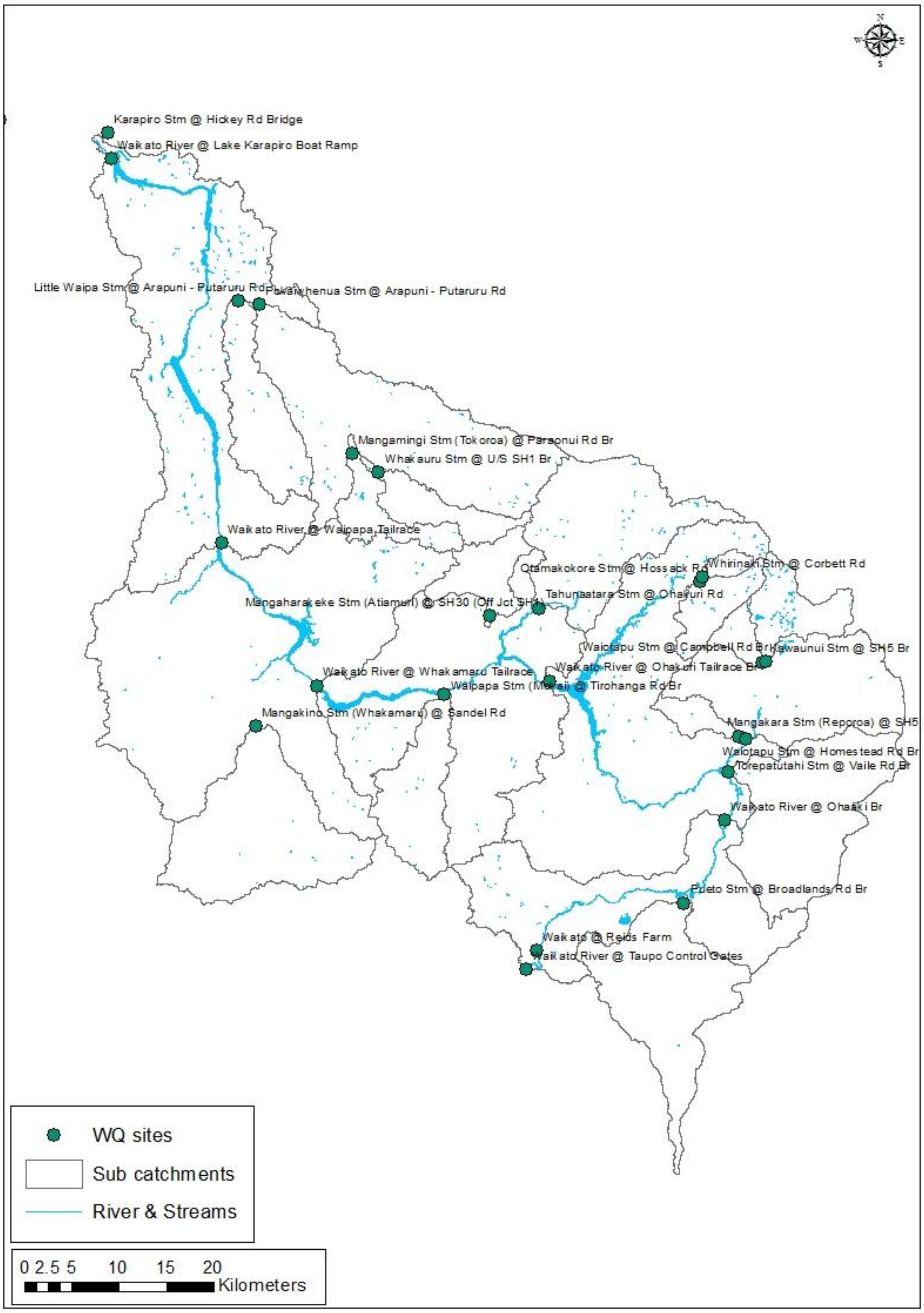


Figure 6: Surface water quality sites.

Table 2: Modelled, measured and estimated flows at surface water quality sites.

WQ Site	Flow (m^3/s)		
	Modelled	Measured	NIWA Estimate[#]
Downstream Huka Falls	162.0		
Pueto	2.3		3.1
Ohaaki Bridge	170.2		
Waikato River @ Ohaaki Bridge	170.4	182	
Torepatutahi Stm @ Vaile Rd Bridge	2.5		3.6
Waiotapu Stm @ Campbell Rd Bridge	1.3	1.5	
Kawaunui Stm @ SH5 Bridge	0.1		0.5
Waitapu Stm @ Homeestead Rd Bridge	3.9		4.2
Mangakara Stm (Reporoa) at SH5	0.3	0.38	
Otamakokore Stm @ Hossack Rd	0.2	1.1	
Whirinaki Stm@ Corbett Rd (WAI/A)	0.2		0.3
Ohakuri Tailrace Bridge	183.8	176	
Tahunaatara Stm @ Ohakuri Rd	4.4	4.7	
Mangaharakeke	1.2		1.3
Waipapa Stm (Mokai)	1.1	1.6	
Whakamaru Tailrace	204.1	203	
Mangakino River (Whakamaru) @ Sandel Rd	5.3	7.3	
Waipapa Tailrace	230.1	218	
Little Waipa Stm @ Arapuni - Putaruru Rd	1.1		1.6
Whakauru Stm @ U/S SH1 Br	0.7		1.0
Mangamingi Stm (Tokoroa) @ Paraonui Rd Br	1.2		1.9
Pokaiwhenua Stm @ Arapuni - Putaruru Rd	5.9	6	
Lake Karapiro Boat Ramp	245.0		
Waikato @ Karapiro	246.4	247	

[#] Estimated flow using NIWA rainfall-runoff model

2.4 Mean Age Results at Water Quality Sites

2.4.1 Lake Taupo Age

The water that enters the Waikato River from Lake Taupo has not been included in the water age distribution analysis. The reason for this exclusion is that the age distribution of Lake Taupo water is unknown. However, an assessment of the nitrogen load that originates from Lake Taupo, and how this load could change in the future is presented in Section 5.

2.4.2 Ages between Lake Taupo and Karapiro

The mean age of mean water flows at the tributary water quality sites are given in Table 3. This table shows that the mean age for waters coming from high-producing lands are less compared to all waters in the upper parts of the catchment (i.e. towards Lake Taupo – first five rows in Table 3). The locations of high-producing lands shown in Figure 5 agree with the lower ages as they are largely located at lower parts of each sub-catchment closer to the water quality sites, requiring relatively short travel times. The mean ages for water quality sites at lower parts of the catchment (i.e. near Karapiro – last five rows in Table 3) show that there is no significant difference between the age for all waters and that coming from high-producing lands.

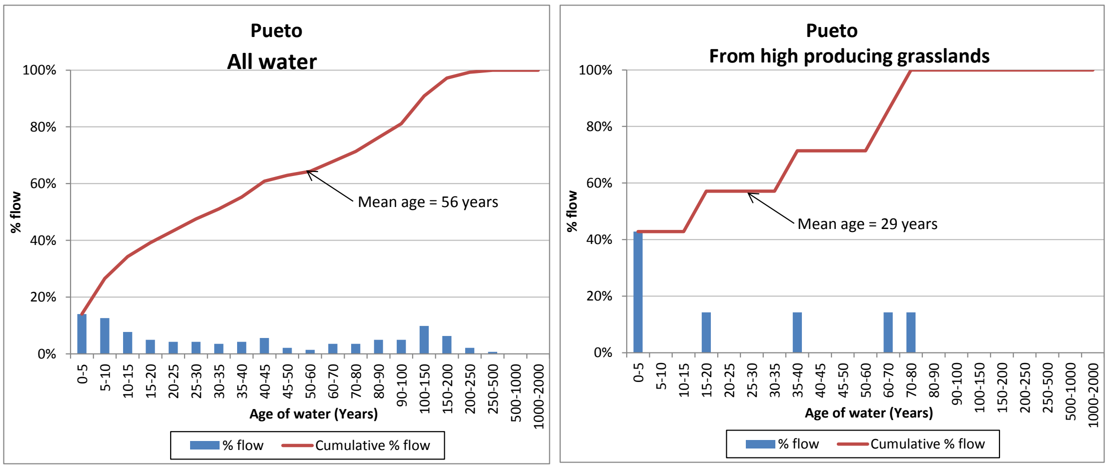
Table 3: Mean age of water at tributary water quality sites at average flow.

Water quality Site	**Age of water (years)**	
	From all lands	**From high-producing lands only**
Pueto	56	29
Torepatutahi Stm @ Vaile Rd Bridge	91	67
Waiotapu Stm @ Campbell Rd Bridge	47	5
Kawaunui Stm @ SH5 Bridge	78	48
Waitapu Stm @ Homeestead Rd Bridge	67	40
Mangakara Stm (Reporoa) at SH5	50	60
Otamakokore Stm @ Hossack Rd	101	112
Whirinaki Stm@ Corbett Rd (WAI/A)	49	49
Tahunaatara Stm @ Ohakuri Rd	49	47
Mangaharakeke	60	76
Waipapa Stm (Mokai)	44	3
Mangakino River (Whakamaru) @ Sandel Rd	17	18
Little Waipa Stm @ Arapuni - Putaruru Rd	51	53
Whakauru Stm @ U/S SH1 Br	5	6
Mangamingi Stm (Tokoroa) @ Paraonui Rd Br	5	1
Pokaiwhenua Stm @ Arapuni - Putaruru Rd	43	45

Appendix A presents the age distribution at tributary water quality sites for both all waters and water leaching through high-producing lands. As stated in Section 2.2, surface water inflows have been assigned to some tributaries to account for quick flow and as a calibration mechanism to get better water balances with measured data. This is more relevant as the MODFLOW model is a saturated groundwater model and it does not simulate the vadose zone and near-surface water movements accurately; thus, assigned surface water inflows offset the model's limitations. However, it is not possible to accurately assign surface water inflows at correct locations along the surface water tributaries and at correct ages; this analysis assumed that the age of assigned water is between 0 and 5 years, which is likely to be plausible. Nevertheless, there will be some uncertainties associated with model estimates of lag times, primarily for steep head-water sub-catchments. However, as the contributions of flows from these small catchments are relatively minor (Table 2), the overall errors at larger catchment level are likely to be insignificant.

As the age distribution of the Lake Taupo water is unknown, overall distribution of water for the water quality sites in the Waikato River cannot be estimated. However, the distributions for in-catchment waters are given in Appendix B.

An example of the age distribution for a tributary water quality site at Pueto is given in Figure 7: (a) for all the water that originates across the whole catchment; (b) for the water that originates from high-producing lands only. These figures show that it is important to identify the age distribution in addition to the mean age, which can be somewhat misleading. The mean age of *All water* at Pueto (Figure 7) is 56 years. However, the age of more than 64% of flows (from *All water*) is less than the mean age. The mean age can be skewed by smaller flows with large ages. Therefore, it is important to consider the age distribution when assessing the water quality trends against land-use trends.



(a) (b)

Figure 7: Age distribution of water at Pueto water quality site: (a) all water; (b) water coming from high-producing lands.

2.5 Groundwater Age Estimates

WRC have collated measurements of groundwater age using tritium analysis. The locations of the measurements are shown in Figure 8. The MRT are listed in Table 4. These measurements show that the age of groundwater can be very high, and agree with the groundwater model predictions presented in Section 2.4.

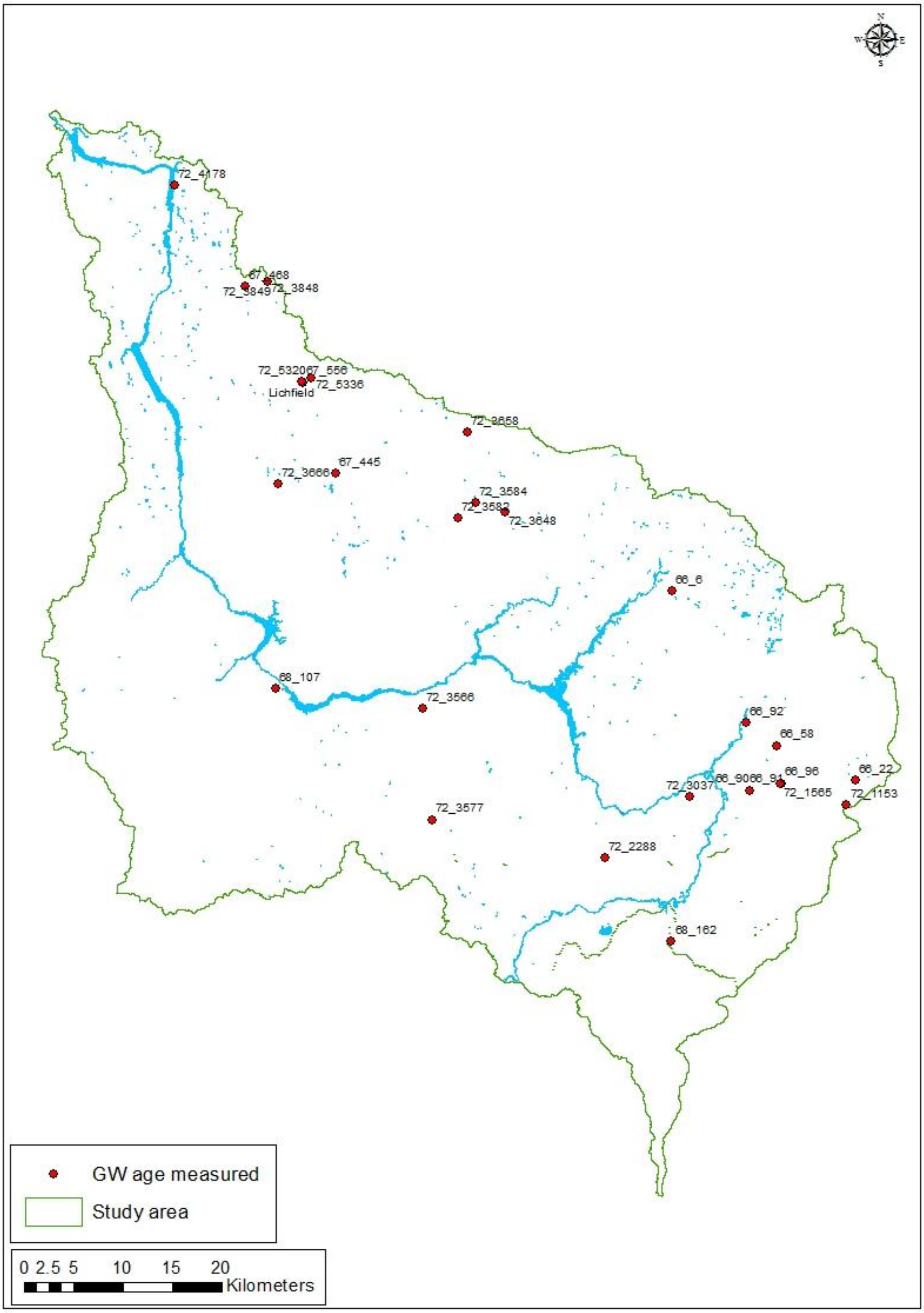


Figure 8: Bore locations where groundwater age is measured.

Table 4: Mean groundwater ages estimated from Tritium analysis.

Bore No.	MRT (y)
66_22	25
66_58	180
66_6	30
66_90	11
66_91	26
66_92	4
66_96	200
68_162	48
72_1153	47
72_1565	58
72_2288	11
72_3037	75
72_3648	45
72_3658	15
72_3666	80
67_556	17
72_3849	54
Lichfield	59
72_3848	125
72_3566	131
72_3577	105
67_468	24
72_5320	275
72_5336	62
72_3584	235
68_107	220
72_4178	265
67_445	9
72_3582	265

3 MEAN RESIDENT TIMES

3.1 MRT Using Tritium Analysis

Surface water was sampled from the Waipapa Stream at Mokai (1202-007) and the Oraka Stream (669-6) in September 2006 for MRT estimation using tritium analysis. In February 2007, the Little Waipa Stream (335-001) was also sampled for the same analysis. The Oraka Stream water quality site is in the headwaters of the Waihou River, approximately 10 km outside the Upper Waikato surface water catchment boundary. However it was considered to have similar water chemistry properties and geology to catchments within the Upper Waikato region and consequently it was included in this preliminary analysis. The results for the MRT analyses are presented in GNS letter report 2007/184LR (GNS, 2007) and summarised in Table 5.

Table 5: Tritium results and age interpretations (GNS, 2007).

Water Quality Site	**Date sampled**	**Tritium Ratio**	**MRT (years)**
Oraka Stream @ Pinedale	28/9/06	1.11	21
Waipapa Stream @ Tirohanga Rd	28/9/06	0.862	48
Little Waipa Stream @ Arapuni-Putararu Rd.	21/02/07	0.795	51

An exponential piston flow model with 80% exponential (mixed) flow was used to determine these MRTs. This choice of model was based on GNS experience in similar catchments in Lake Taupo and Lake Rotorua catchments. The age interpretation for Oraka was considered slightly ambiguous, where a MRT range of 12–24 years best matches the tritium concentration within statistical uncertainty, but 21 years, as presented, was the best match. The Waipapa and Little Waipa Streams have older water and their age interpretations are not considered ambiguous.

3.2 Relationship between SiO_2 and MRT

To assist with verification of the groundwater model, estimates of the MRT at additional water quality sites were made by determining a relationship between SiO_2 concentrations in surface water and MRT measured using tritium. The basis of this relationship is that SiO_2 concentrations in rainfall in humid regions are generally very low, but concentrations increase as water infiltrates deeper into the soil and passes through the underlying sub-surface materials, due to dissolution of silicate minerals (White, 1995). The longer the water resides in a zone with silicate minerals, the higher the SiO_2 concentration becomes. Because the geological composition of the subsurface material affects the relationship between SiO_2 concentrations and water age, we have determined and applied the relationship only in catchments with ignimbrite geology. Due to the dissolution of volcanic glass in areas affected by volcanic activity, such as Lake Taupo and the Upper Waikato catchments, non-geothermal groundwater concentrations in New Zealand can be up to 90 mg/l SiO_2 (Rosen, 2001). Note: Catchments that are subject to the influence of geothermal effects are not included in this analysis due to elevated water temperatures enhancing the dissolution of SiO_2.

3.2.1 MRT Estimates from Average SiO_2

Over a 12-month period from September 2010 to 2011, monthly samples from water quality sites had SiO_2 concentrations determined. The non-geothermal sites in the Lake Taupo and Upper Waikato regions, where MRT estimates (GNS, 2007; GNS, 2012) and SiO_2 measurements (WRC, 2012) are available, are listed in Table 6. As surface water SiO_2 concentrations are related to the source of the water, i.e. near-surface or deeper groundwater, the 12-monthly SiO_2 data (date supplied by WRC *pers. comm.*) were corrected for the effect of flow by removing any samples taken at high flows where surface sources would have been contributing to and diluting the SiO_2 concentration.

Table 6: Water quality sites where MRT measured using tritium (GNS, 2007; GNS, 2012) and yearly average SiO_2 (WRC supplied data) were available.

Site (Catchment)	**MRT determined from tritium (years)**	**Average SiO_2 (mg/l)**
Mapara Stream (L. Taupo)	61	70.1
Waihaha Stream (L. Taupo)	4-17 (11)	35.9
Whanganui Stream (L. Taupo)	4-17 (11)	38.2
Whareroa Stream (L. Taupo)	24	50.3
Waitahanui River (L. Taupo)	38	57.7
Kuratau River (L Taupo)	12	44.9
Little Waipa Stream (Upper Waikato)	51	63.0
Oraka Stream (Hauraki)	21	64.7

3.3 Results

An exponential model fits well to the data where both MRT and SiO_2 concentration in stream water are available (Figure 9). In the two instances where a range of MRT values were reported (GNS, 2012), the average MRT value was used in this analysis. The model represented by the lower exponential line, as shown in Figure 9, includes the Oraka stream data (coloured in blue), while the upper and better fitting model excludes this data point. When the MRT data at Oraka was reported, it was suggested that there was some ambiguity in the determination of the MRT, and while this catchment is close to the Upper Waikato catchment, it is outside of the Upper Waikato catchment, so these are reasons it could be excluded.

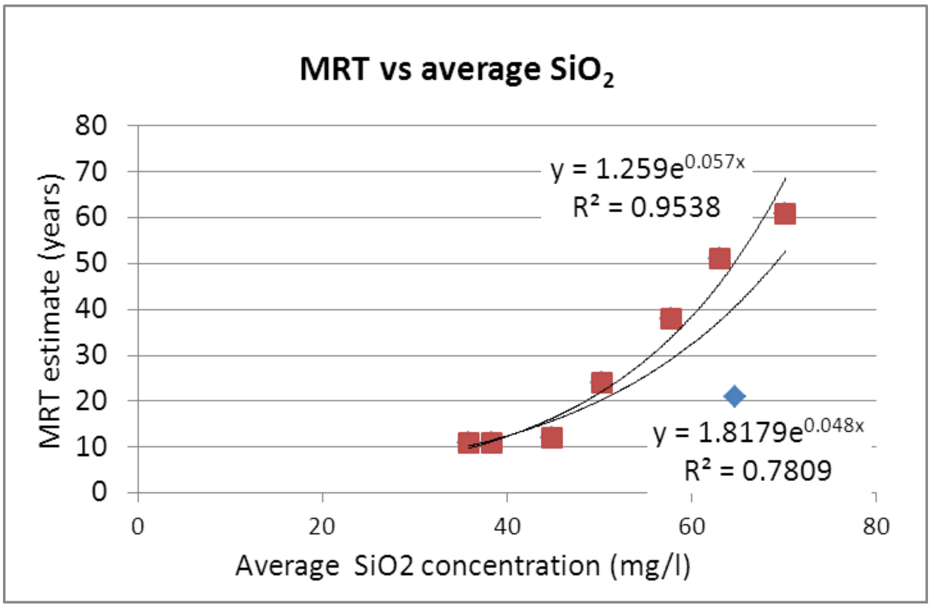


Figure 9: MRT versus SiO_2 concentration in stream water from ignimbrite catchments in the Taupo and Upper Waikato regions.

Table 7 presents the predicted MRT for eight Upper Waikato water quality sites using the two exponential models derived above (Figure 9).

Table 7: MRT estimated from annual SiO_2 data using the two exponential models shown in Figure 9.

Water Quality Sites	**Average SiO_2 † (mg/l)**	**MRT (all data (y)**	**MRT (Oraka excluded) (y)**
Torepatutahi Stream	70.0	52	68
Tahunaatara Stream	62.2	36	44
Mangaharakeke Stream	69.1	50	65
Mangakara Stream	66.3	44	55
Kawaunui Stream	71.8	57	75
Pueto Stream	63.9	39	48
Whirinaki Stream	68.2	48	62
Mangakino Stream	45	16	16
† Flow corrected			

4 GROUNDWATER NITROGEN CONCENTRATIONS

4.1 Contributions of Water to Surface Flow

In this analysis, the flow paths by which nitrogen reaches surface water are conceptually divided into either a quick flow (e.g. interflow and laterally moving shallow groundwater) or base-flow, which is assumed to be sourced from groundwater. At times of low-flow (base-flow), groundwater is assumed to be the only source of water contributing to the surface water flow. When precipitation occurs and flow increases, the majority of the increase in flow is considered to be generated from quick flow.

There are a total of 16 surface water quality sites in tributary catchments in the Upper Waikato region that have monthly nitrogen concentration data since 1993 (WRC, 2013). At five of these sites where flow data was available, the change in the nitrogen concentrations in the groundwater contributing to the surface water flow was estimated from the nitrogen concentrations in surface water samples collected only at low-flows.

Not all water leaving a tributary surface water catchment is occurring as surface water flow. A proportion leaves the catchment via groundwater flow. Near-surface flow (e.g. interflow and laterally moving shallow groundwater) generation in the Upper Waikato region generally occurs in areas where water tables are high. Under high water table conditions, the lateral quicker pathways become an important mechanism for the export of nitrogen to the surface water. In locations where the water table is deep and vertical sub-surface flow is prevalent, deeper groundwater flow paths are likely to dominate the export of nitrogen from the land and the catchment. Under this scenario, the nitrogen exits a tributary catchment predominantly via groundwater rather than surface water.

At four of the five water quality sites, where the relationship between flow rate and nitrogen concentrations was available, over the majority of the flow the nitrogen concentrations increase linearly with flow. This linear relationship holds until the concentrations are approaching their maximum; the rate of increase in the concentration with flow then reduces. See Figure 10 for examples from the Tahunaatara and Otamakokore catchments (NIWA supplied data). The exception to this strong relationship between flow and nitrogen concentration is at the Mangakino water quality site. Here, the nitrogen concentration in the stream demonstrates a weak relationship with flow. This could be because the quick flow has a nitrogen concentration similar to the deeper groundwater; therefore, the change in nitrogen concentration with increasing flow cannot be discerned.

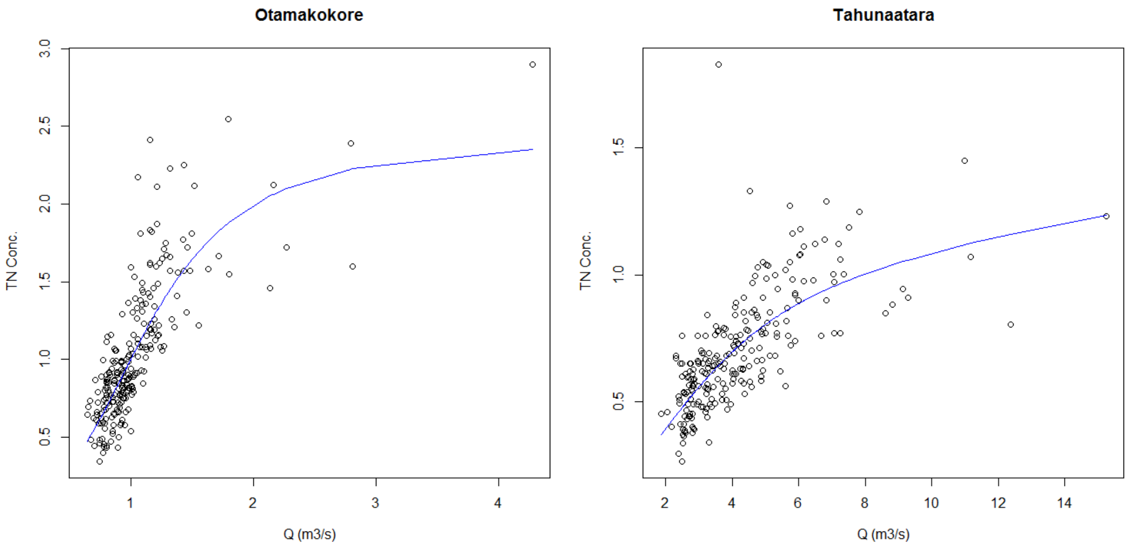


Figure 10: Total nitrogen concentration (g/m^3) versus flow (m^3/s) in the Otamakokore and Tahunaatara tributary catchments. (NIWA supplied data.)

The increase in nitrogen concentration with flow evident in Figure 10 informs us that the quick flow has an elevated nitrogen concentration compared to the groundwater. The quick flow has a faster response to changes in land use and is therefore expected to have a higher nitrogen concentration than the historical effects in the deeper groundwater. As a consequence of this quicker response of the quick flow to land-use changes, it is also assumed that this pathway provides a mechanism by which the effects of changes in land use will manifest themselves sooner on surface water than in groundwater. It is also reasonable to assume, due to closer connection, that the quick flow will reach equilibrium concentrations with land use sooner than the deeper groundwater.

The time for groundwater to reach an equilibrium concentration with land use is difficult to estimate and is related to a number of factors, including the spatial distribution of changes in land-use intensity in the catchment, the network of surface water streams in a catchment, the MRT, and the age distributions of the water occurring in the groundwater.

4.2 Estimation of the Trend in Groundwater Nitrogen

At the five water quality sites where flow and nitrogen concentration data were available, two linear regression lines were fitted to the data (Figure 11). One line (red) was fitted through all of the data and a second line (blue) was fitted through only those samples for which the flow rate at the time of sampling was within the lowest 10% of flow rates (data points coloured blue). The blue line fitted through the lower flows is assumed to represent the trend in the nitrogen concentration in the groundwater contributing to the surface water at the water quality site. While numerical values are obtained for the slopes, these are only considered indicative of the rate of change in the groundwater as this method is a simplification of the actual processes occurring.

4.3 Results

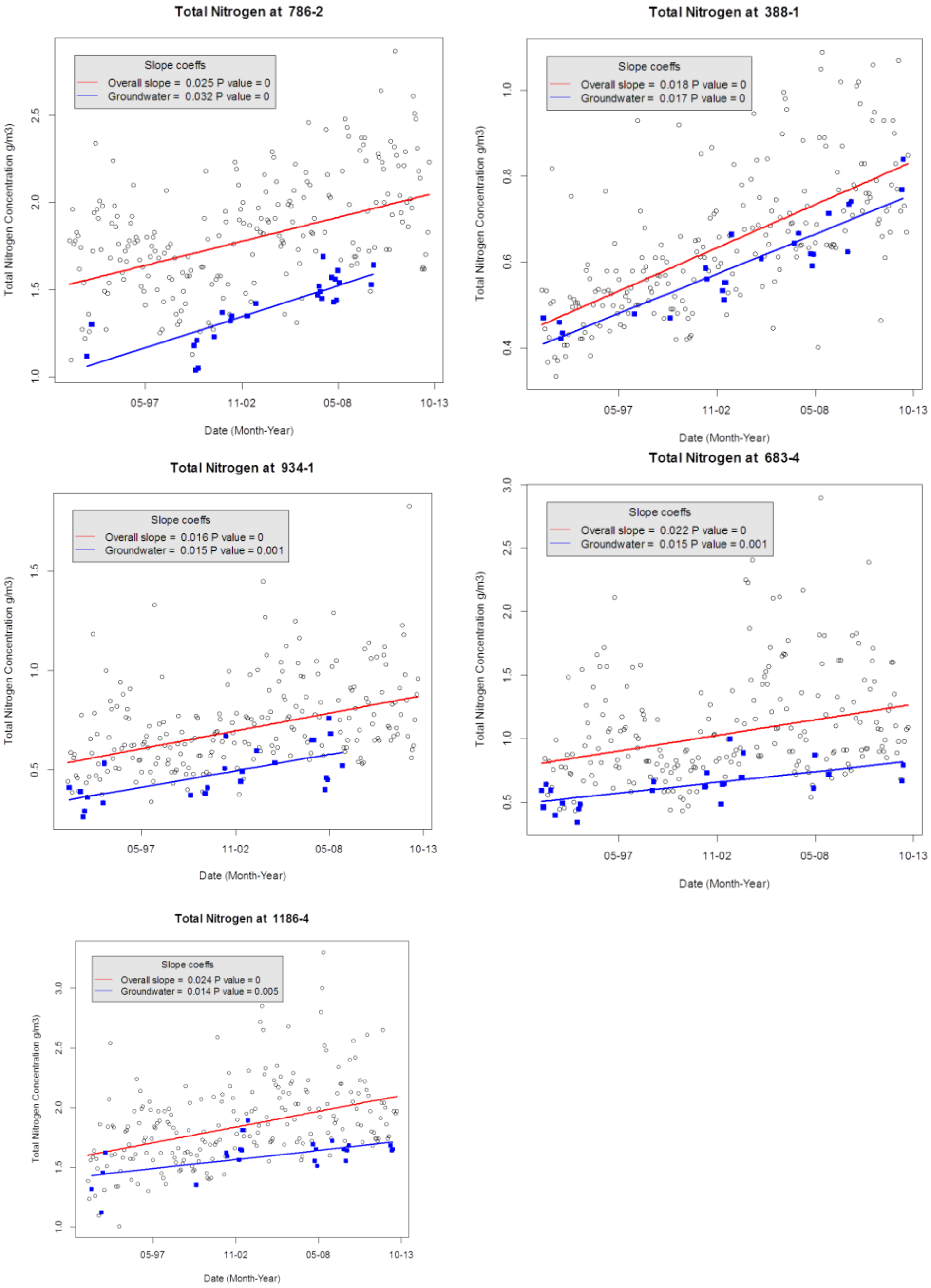


Figure 11: Linear regression lines fitted through all the data (red) and through the lowest 10% of flows (blue) for data from five water quality sites in the Upper Waikato region. (NIWA supplied data.)

Figure 11 contains the graphs of the nitrogen concentrations with time, including the two linear regression lines, at the five water quality sites. All lines fitted were significant at the 0.5% level. Table 8 contains the information on the slopes of the fitted lines. In all cases, the slope of the lines fitted to the lowest 10% of flows was positive. This shows that the nitrogen concentrations in groundwater are increasing with time.

Table 8: Slopes of liner lines fitted through all data, and through lowest 10% of flow, for water quality sites where data was available within the Upper Waikato region.

Water Quality Site	**Slope of line fitted through all flows (g/m^3/year)**	**Slope of line fitted through lowest 10% of flows (g/m^3/year)**
786-2 Pokaiwhenua	.025	.032
388-1 Mangakino	.018	.017
934-1 Tahunaatara	.016	.015
683-4 Otamakokore	.022	.015
1186-4 Waiotapu	.024	.014

From the groundwater modelling of the average flows in the tributary catchments, it is estimated that 77% of the surface water flow is contributed by groundwater. This indicates that, at average flow conditions, groundwater is still making a significant contribution to flow at the water quality sites.

5 NITROGEN LOAD TO COME FROM LAKE TAUPO

In the caucusing prior to the Environment Court hearings in 2007 regarding Waikato Regional Council’s (WRC) Regional Plan Variation Five, a statement of agreed matters between technical experts for the appellants and respondent was prepared (Environment Court, 2007). In this document, the estimated load of nitrogen to come into Lake Taupo was discussed. Based on the evidence provided by Mr Vant and Mr Hadfield, who were acting as technical experts for WRC, an estimate of the load that is likely to come from Lake Taupo into the Waikato River follows.

Recent dialogue with Mr Vant confirms that while some changes have occurred in the nitrogen loads and the understanding of nitrogen attenuation in the Lake Taupo catchment since this document was prepared, they have generally been of a compensating nature. He confirmed that the information contained in this 2007 document and the WRC evidence still remains the best estimate of nitrogen loads to come into Lake Taupo. The estimated attenuation factor that describes the permanent removal of nitrogen due to atmospheric losses and other loss pathways in Lake Taupo is assumed to be 0.7; that is, 30% of what enters Lake Taupo is assumed to exit via the Waikato River (Bill Vant WRC, *pers. comm.* 2013).

In summary, from the Environment Court statement (Environment Court 2007):

- The combined nitrogen load from all sources currently into Lake Taupo is estimated to be 1320 t/year. Accounting for the Lake attenuation, this equates to approximately 396 t/year of nitrogen currently entering the Waikato River.

- The total increase in the nitrogen load to the Lake from nitrogen in groundwater in the Lake Taupo catchment is estimated between 160 to 210 t/year. Using an attenuation factor of 0.7, the increase in nitrogen load exported to the Waikato River is estimated to increase by between 48 to 63 t/year.
- Offsetting this increase, but on a different time scale, is the impact of the purchase of nitrogen exported from existing land-use conversion by the Lake Taupo Trust. The Trust aims to reduce the manageable load of nitrogen (520 t/year) in the Lake Taupo catchment by 20%. This represents a decrease in the nitrogen load to the Lake of 104 t/year (0.2 x 520 t/year). Using the same attenuation factor, the estimated decrease in the long-term export to the Waikato River from the Trusts activities is 31 t/year.
- In the long term, when equilibrium conditions are established, and when the impact of the Trusts activities are realised in the export to the Lake combined with the increase in the load to the Lake from groundwater nitrogen, the estimated increase is between 56 to 106 t/year. This equates to an increase in the long term to the Waikato River and the Upper Waikato catchment of between 17 to 32 t/year.

6 CONCLUSIONS

There are three pieces of information that indicate that the surface water flow at many water quality sites is old, i.e. averaging in the order of many decades in age:

- Measured MRT of surface water using tritium analysis (GNS, 2007) at two water quality sites in the Upper Waikato region.
- Annual average SiO_2 concentrations in the stream water at seven of the eight additional water quality sites related to comparable concentrations in similar catchments, where both SiO_2 and MRT are available.
- Results from the regional groundwater modelling.

In many of the catchments, located in the central and lower parts of the upper Waikato region, the time of travel from the higher quality land, which is more likely to have been intensively developed, is generally of a similar age to the travel time from the catchment as a whole.

The nitrogen concentration in groundwater contributing to surface water flow at five surface water quality sites is increasing, based on the nitrogen concentration in samples collected during low-flow conditions at these sites.

At average flow conditions, the groundwater model predicts that 77% of the surface water at the tributary water quality monitoring sites is sourced from groundwater. This indicates that groundwater is making the predominant contribution to flow, and it is also therefore likely that groundwater is making the predominant contribution to the total load of nitrogen.

Collectively, these results indicate that it is reasonable to expect that groundwater's contribution of nitrogen to surface water quality at the monitoring sites will continue to increase. However, rate of increase and the time over which it occurs is poorly understood.

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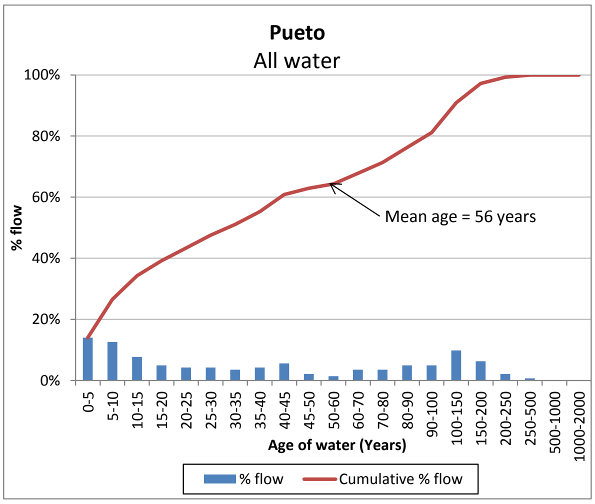
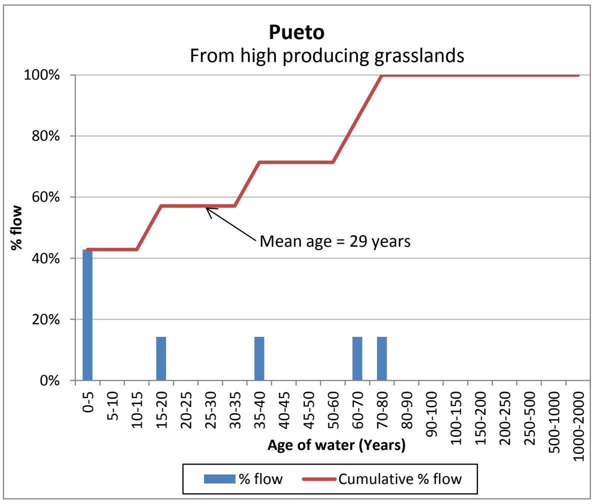
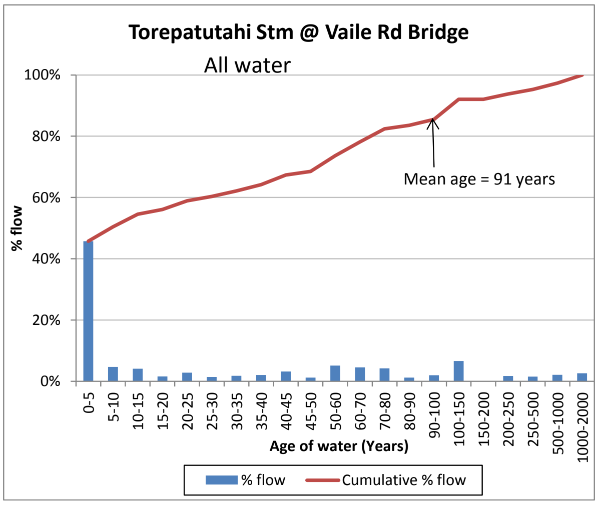
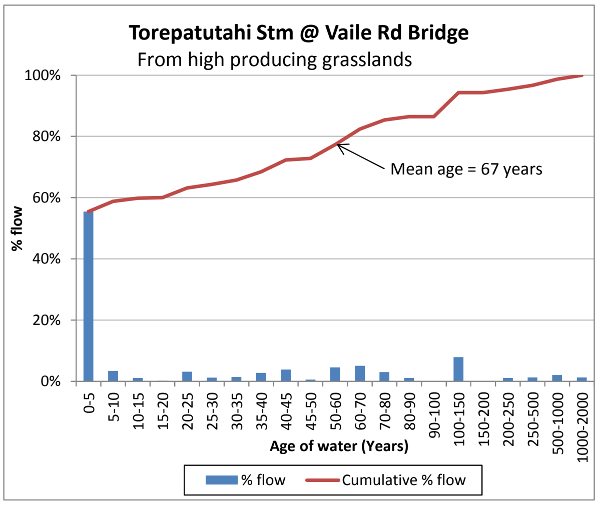
Appendix A: Age distribution of water at tributary water quality sites for average flow conditions

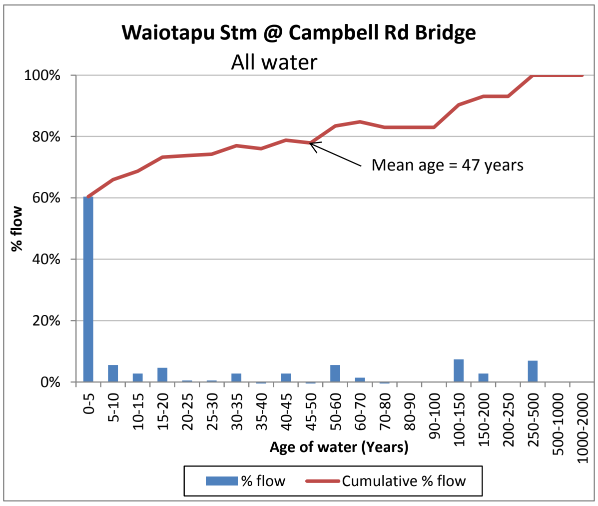
The following figures show the age distribution of water at quality sites when average flow conditions exist. The figures on the left show the distribution for all waters (i.e. flow originating from whole catchment). The figures on the right show the estimated age distribution of waters that originate from high-producing grasslands.

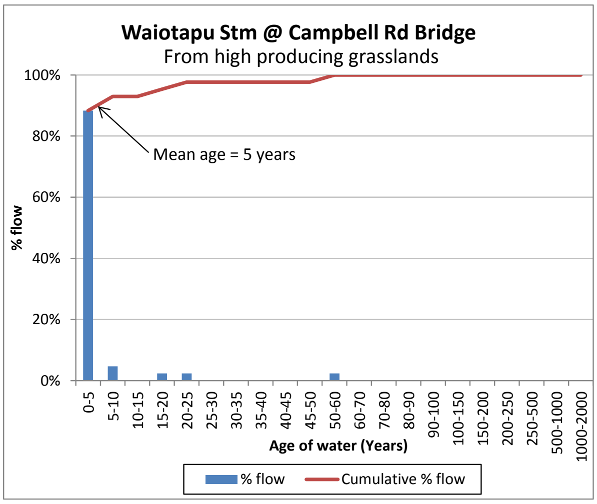


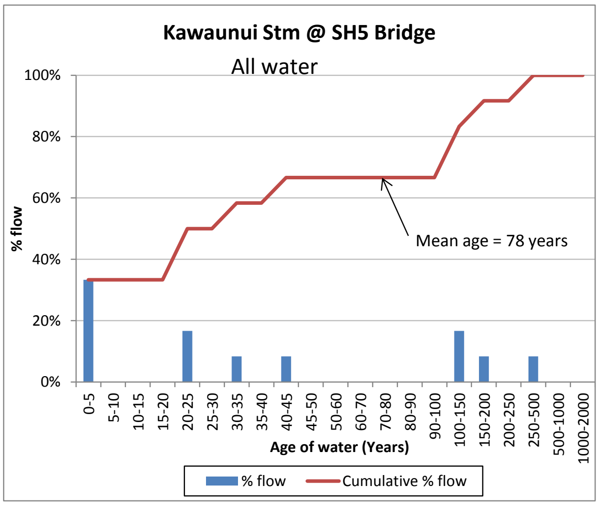


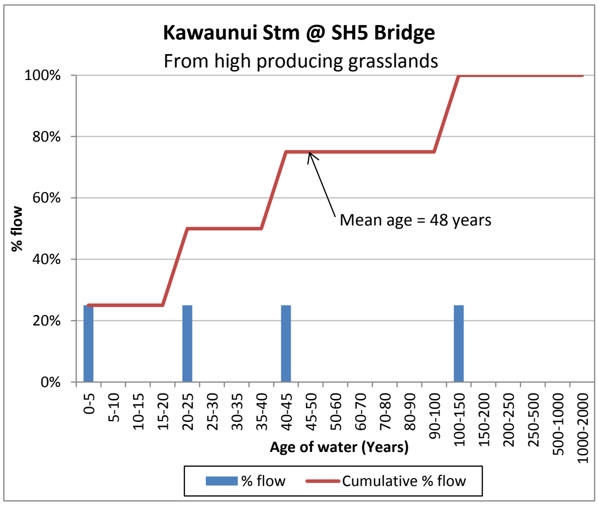


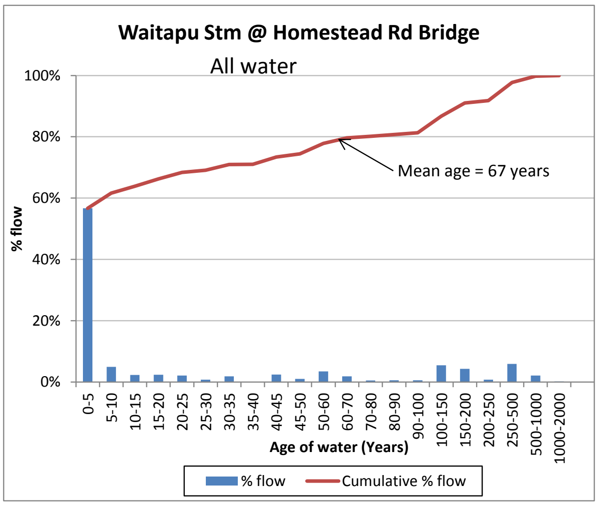


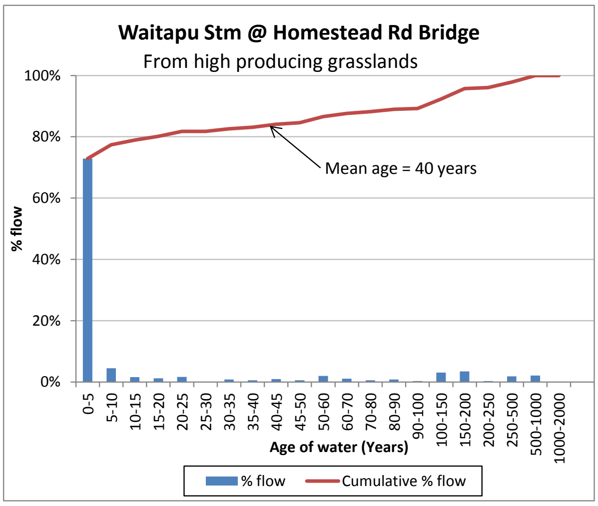


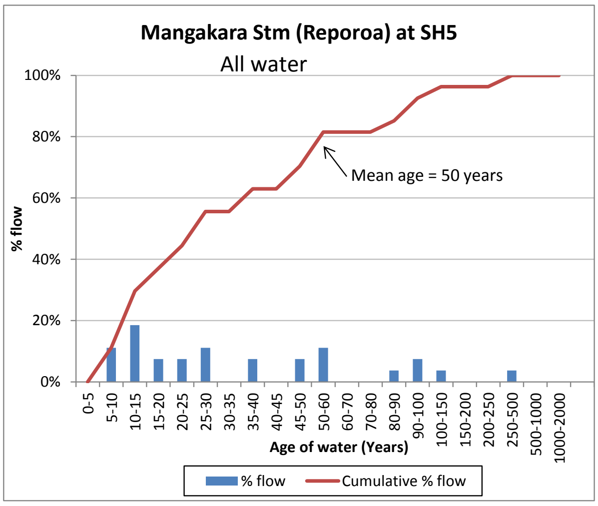


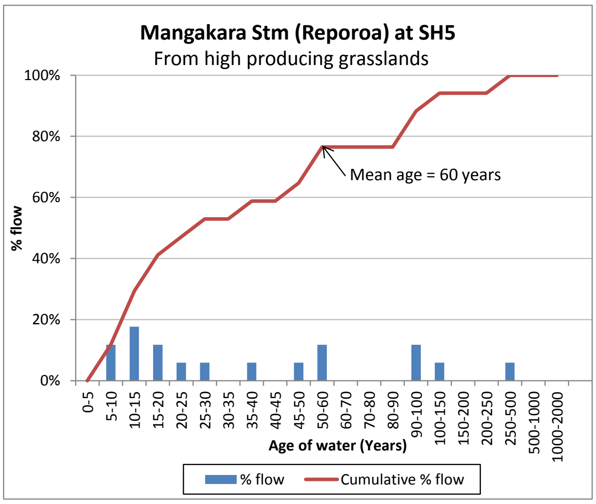

Kawaunui Stm @ SH5 Bridge
All water
100%
80%
60%
40%
20%
0%
% flow
Mean age = 78 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

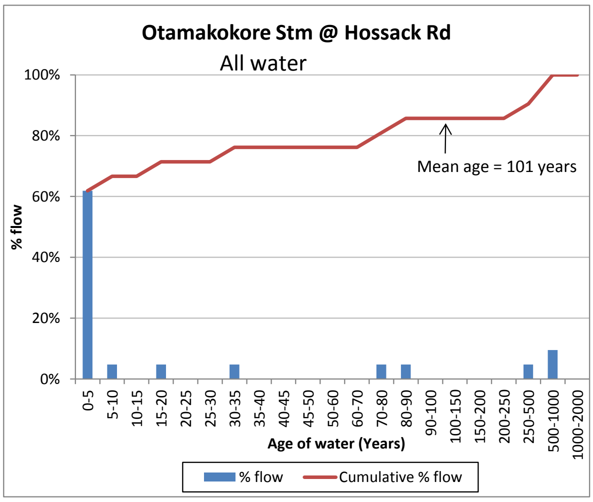

Kawaunui Stm @ SH5 Bridge
From high producing grasslands
100%
80%
60%
40%
20%
0%
% flow
Mean age = 48 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

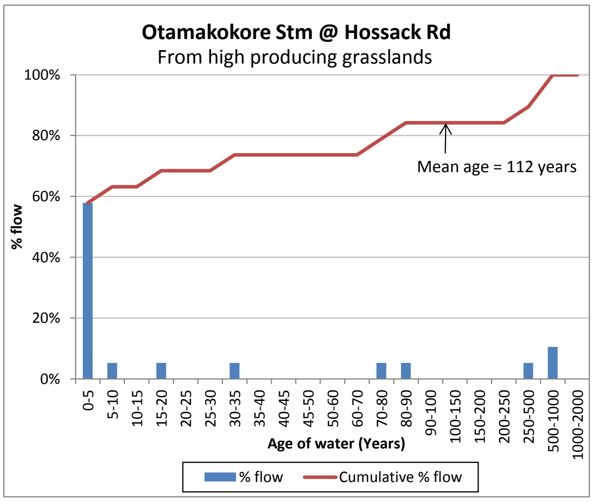

Waitapu Stm @ Homestead Rd Bridge
All water
100%
80%
60%
40%
20%
0%
% flow
Mean age = 67 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

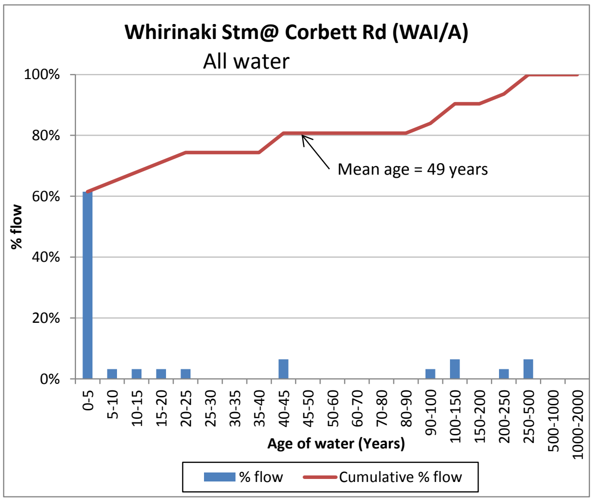

Waitapu Stm @ Homestead Rd Bridge
From high producing grasslands
100%
80%
60%
40%
20%
0%
% flow
Mean age = 40 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

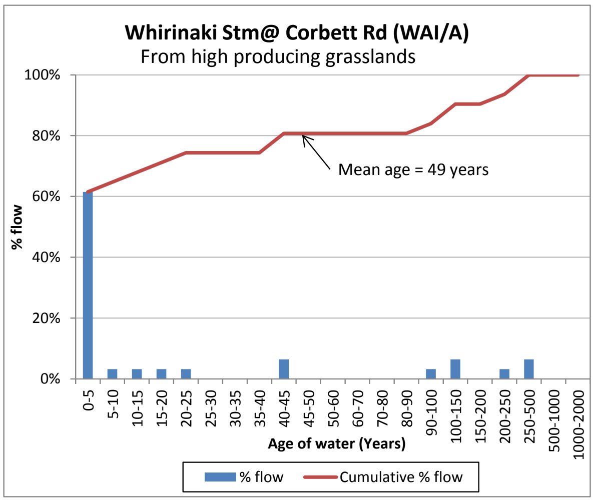

Mangakara Stm (Reporoa) at SH5
All water
100%
80%
60%
40%
20%
0%
% flow
Mean age = 50 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

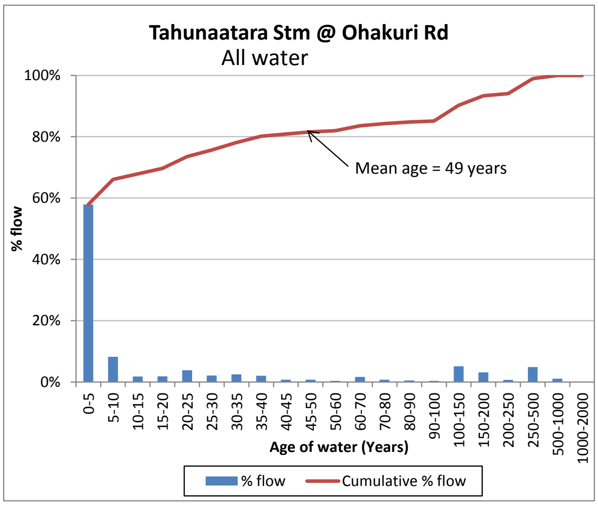

Mangakara Stm (Reporoa) at SH5
From high producing grasslands
100%
80%
60%
40%
20%
0%
% flow
Mean age = 60 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

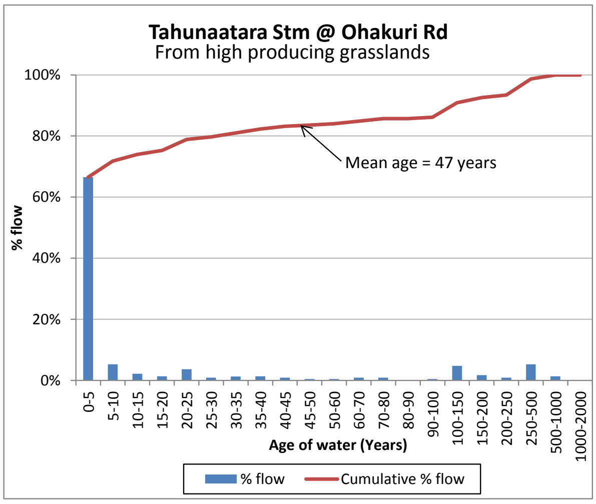

Otamakokore Stm @ Hossack Rd
All water
100%
80%
60%
40%
20%
0%
% flow
Mean age = 101 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

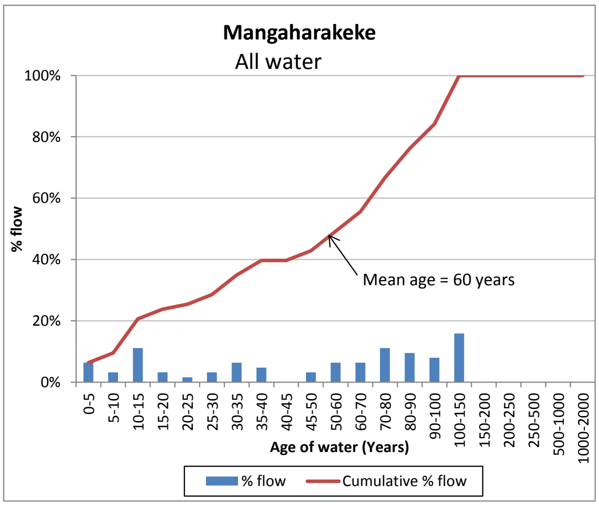

Otamakokore Stm @ Hossack Rd
From high producing grasslands
100%
80%
60%
40%
20%
0%
% flow
Mean age = 112 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

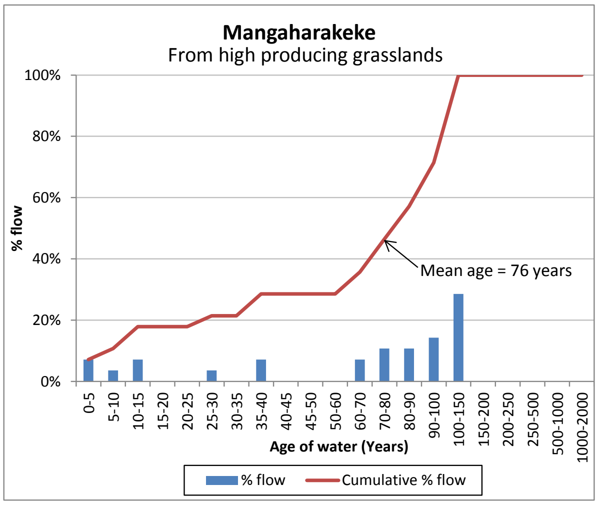

Whirinaki Stm@ Corbett Rd (WAI/A)
All water
100%
80%
60%
40%
20%
0%
% flow
Mean age = 49 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

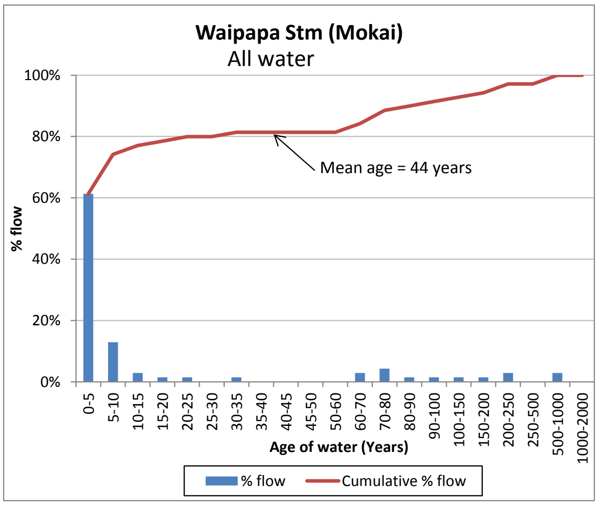

Whirinaki Stm@ Corbett Rd (WAI/A)
From high producing grasslands
100%
80%
60%
40%
20%
0%
% flow
Mean age = 49 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

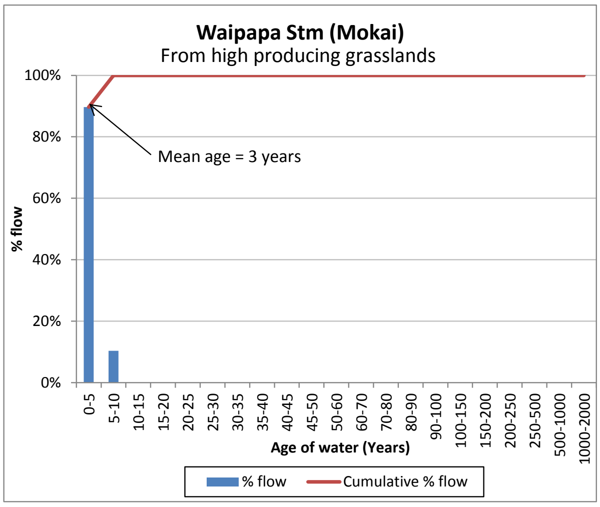

Tahunaatara Stm @ Ohakuri Rd
All water
100%
80%
60%
40%
20%
0%
% flow
Mean age = 49 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

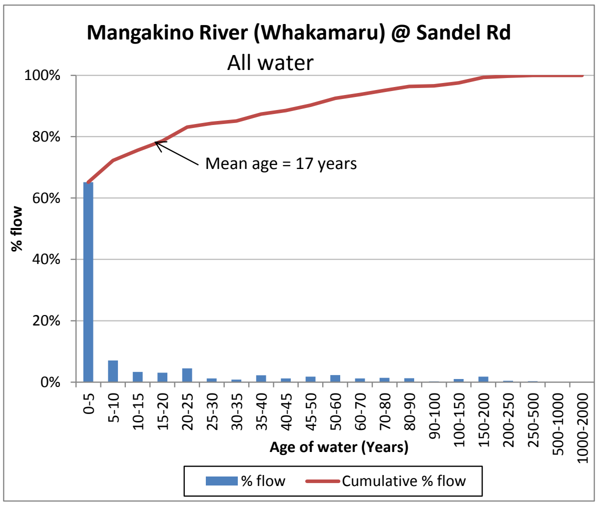

Tahunaatara Stm @ Ohakuri Rd
From high producing grasslands
100%
80%
60%
40%
20%
0%
% flow
Mean age = 47 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

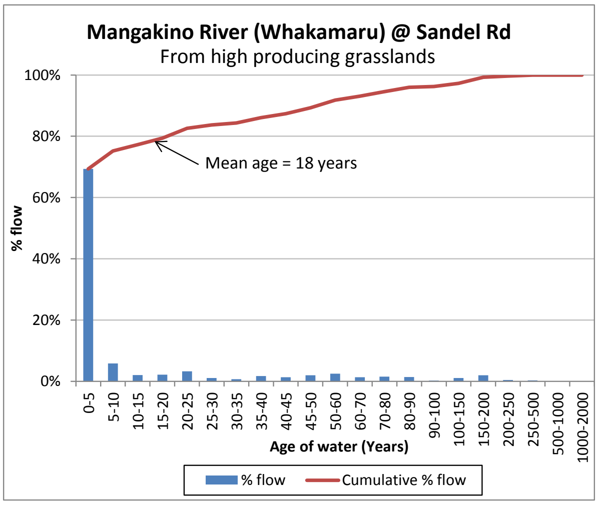

Mangaharakeke
All water
% flow
100%
80%
60%
40%
20%
0%
Mean age = 60 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

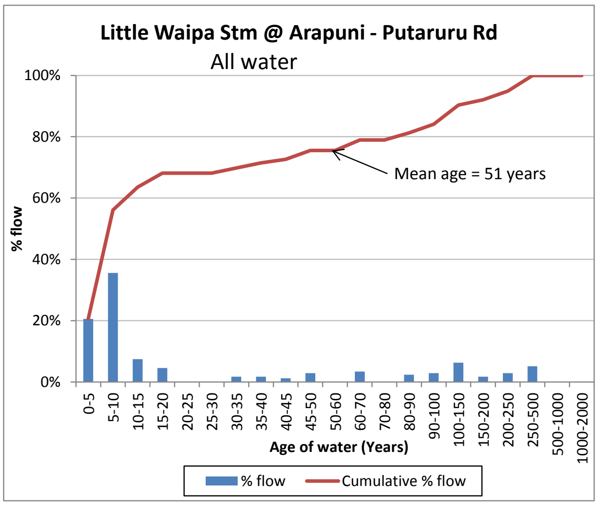

Mangaharakeke
From high producing grasslands
% flow
100%
80%
60%
40%
20%
0%
Mean age = 76 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

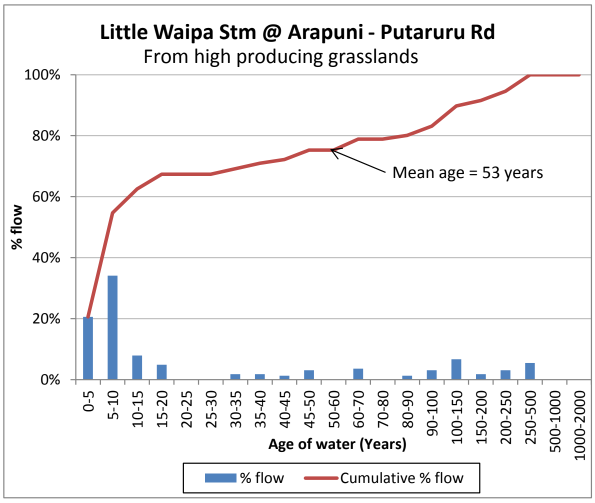

Waipapa Stm (Mokai)
All water
% flow
100%
80%
60%
40%
20%
0%
Mean age = 44 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

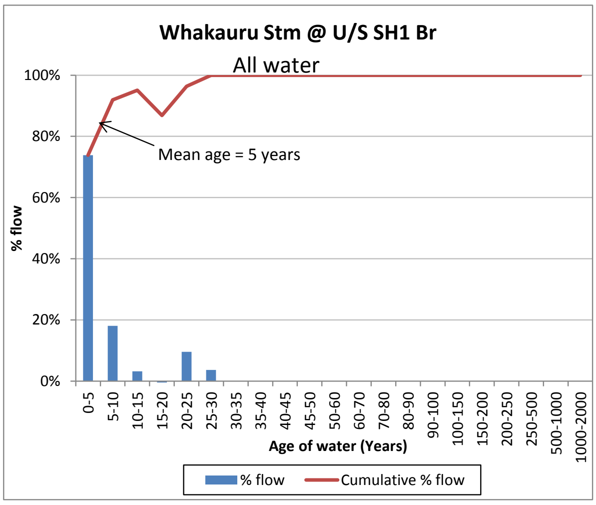

Waipapa Stm (Mokai)
From high producing grasslands
% flow
100%
80%
60%
40%
20%
0%
Mean age = 3 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

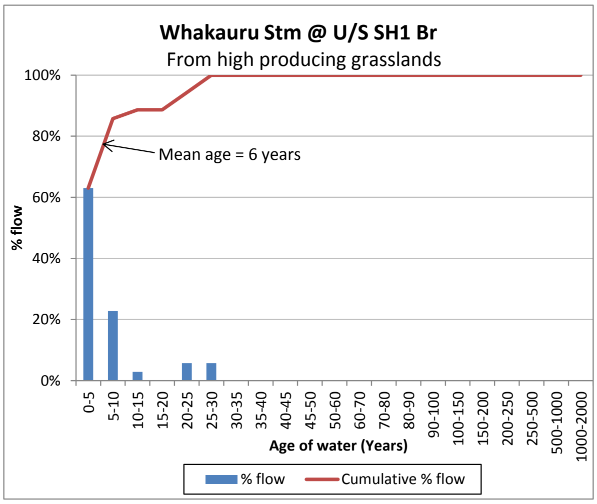

Mangakino River (Whakamaru) @ Sandel Rd
All water
% flow
100%
80%
60%
40%
20%
0%
Mean age = 17 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

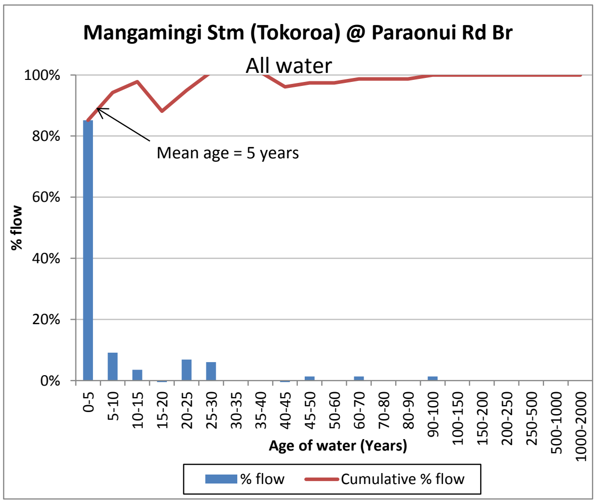

Mangakino River (Whakamaru) @ Sandel Rd
From high producing grasslands
% flow
100%
80%
60%
40%
20%
0%
Mean age = 18 years
0-5 5-10 10-15 15-20 20-25 25-30 30-35 35-40 40-45 45-50 50-60 60-70 70-80 80-90 90-100 100-150 150-200 200-250 250-500 500-1000 1000-2000
Age of water (Years)
% flow
Cumulative % flow

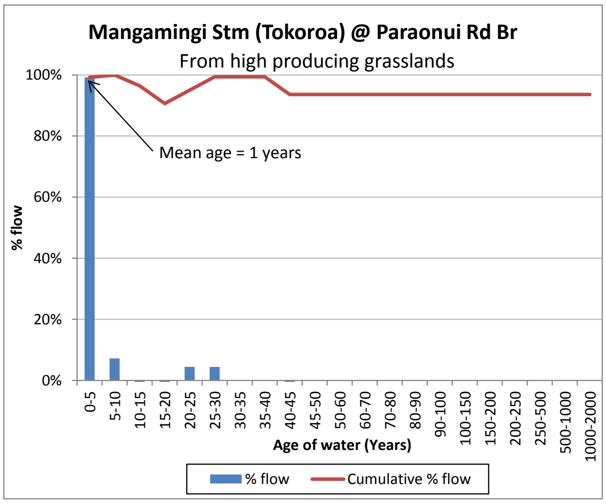

Little Waipa Stm @ Arapuni - Putaruru Rd
All water
Mean age = 51 years
% flow
0%
20%
40%
60%
80%
100%
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

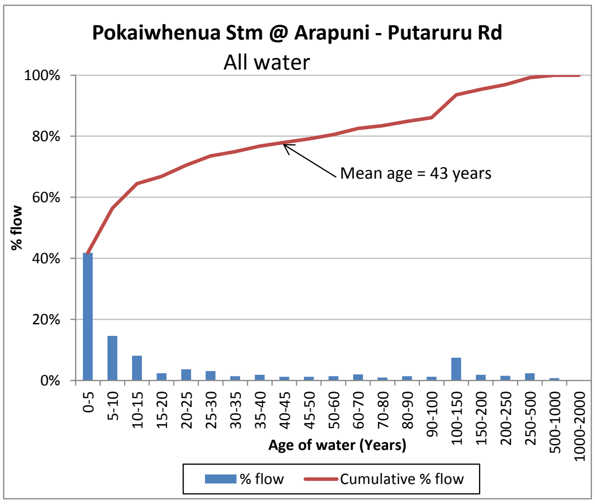

Little Waipa Stm @ Arapuni - Putaruru Rd
From high producing grasslands
Mean age = 53 years
% flow
0%
20%
40%
60%
80%
100%
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

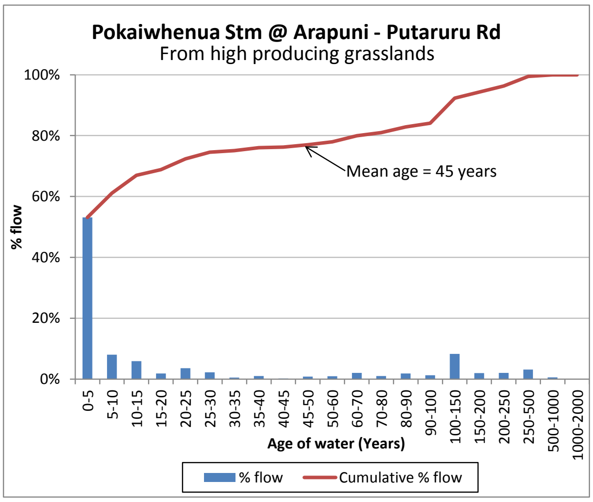

Whakauru Stm @ U/S SH1 Br
All water
Mean age = 5 years
% flow
0%
20%
40%
60%
80%
100%
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow


Whakauru Stm @ U/S SH1 Br
From high producing grasslands
Mean age = 6 years
% flow
0%
20%
40%
60%
80%
100%
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow


Mangamingi Stm (Tokoroa) @ Paraonui Rd Br
All water
Mean age = 5 years
% flow
0%
20%
40%
60%
80%
100%
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow


Mangamingi Stm (Tokoroa) @ Paraonui Rd Br
From high producing grasslands
Mean age = 1 years
% flow
0%
20%
40%
60%
80%
100%
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

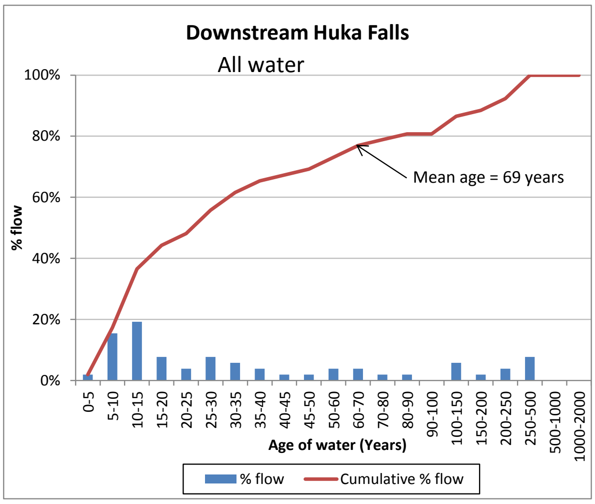

Pokaiwhenua Stm @ Arapuni - Putaruru Rd
All water
% flow
100%
80%
60%
40%
20%
0%
Mean age = 43 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

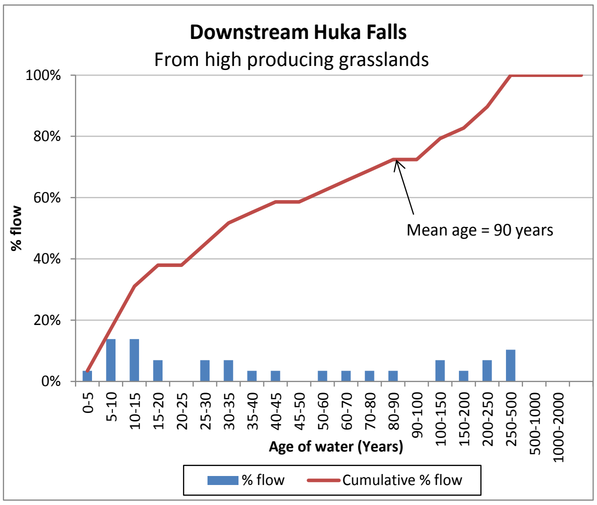

Pokaiwhenua Stm @ Arapuni - Putaruru Rd
From high producing grasslands
% flow
100%
80%
60%
40%
20%
0%
Mean age = 45 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

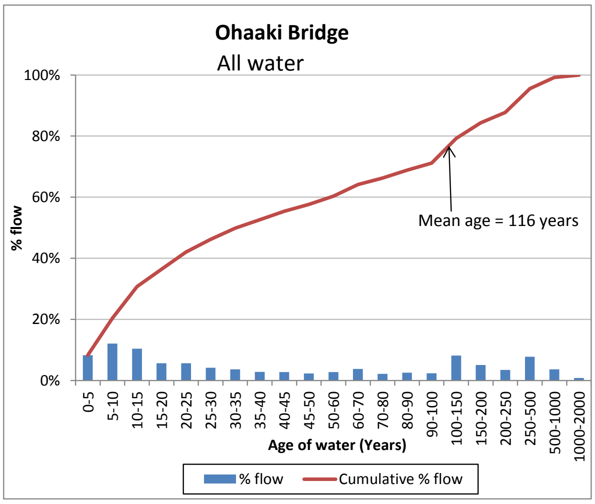
Appendix B: Age distribution of water at the Waikato River water quality sites for average flow conditions

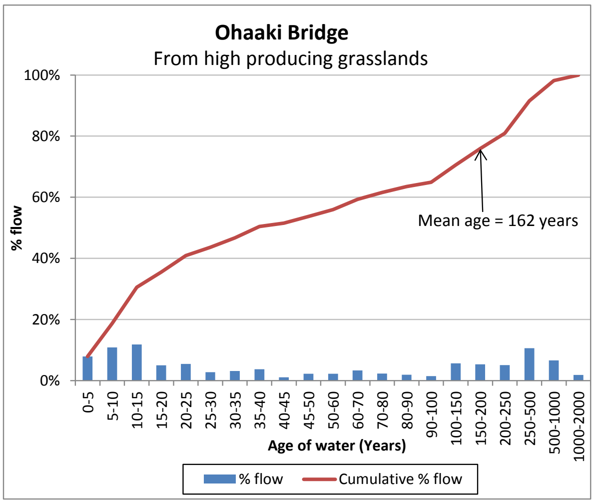
This Appendix presents the age distribution of water at water quality sites that are located on the Waikato River when flow is at average flow condition. As described in Section 2.4.1, the age distribution of Lake Taupo water is unknown. Therefore, it is not possible to estimate the age distribution of mixed water (i.e. Lake Taupo water with flows within the catchment). Therefore, the following figures and tables give the age distribution for the catchment water only (i.e. excluding Lake Taupo water). Thus, this data should be interpreted with caution.

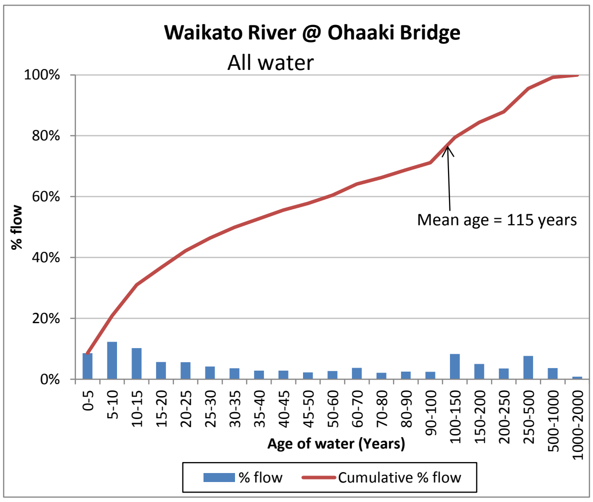
The figures on the left show the distribution for all waters (i.e. flow originating from the whole contributing land area). The figures on the right show the estimated age distribution of waters that originate from high-producing grasslands.

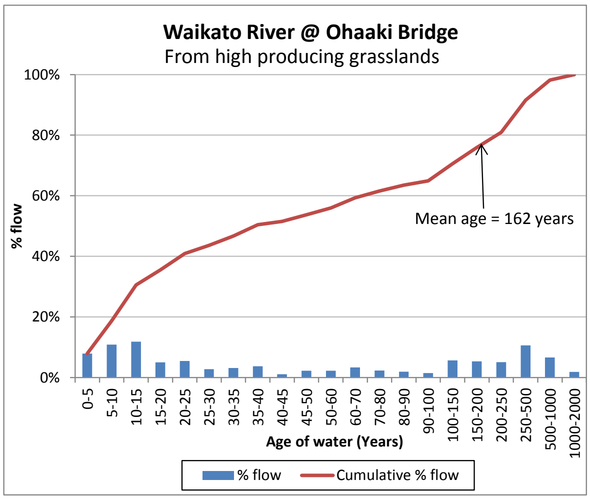


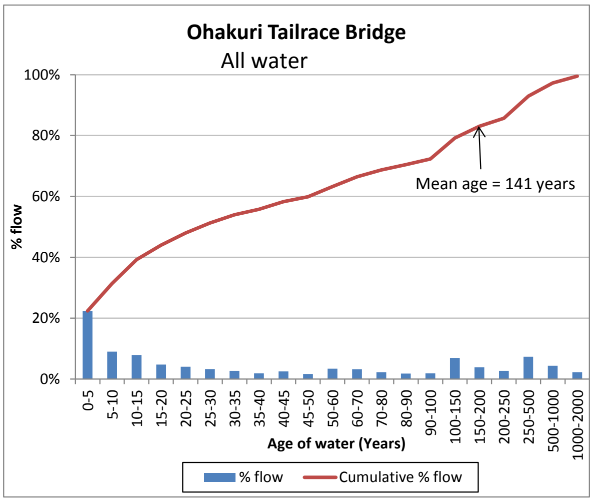


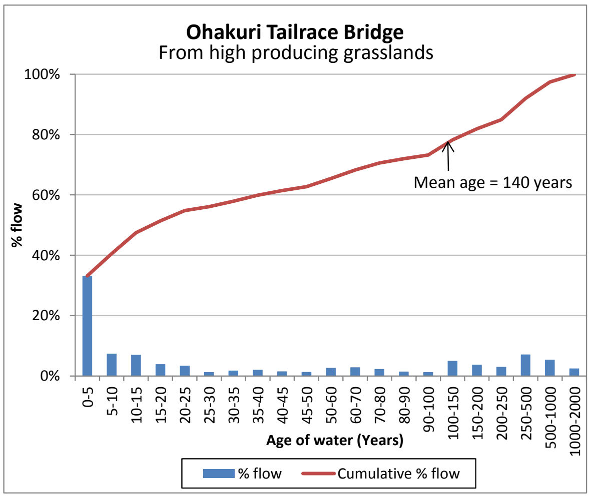


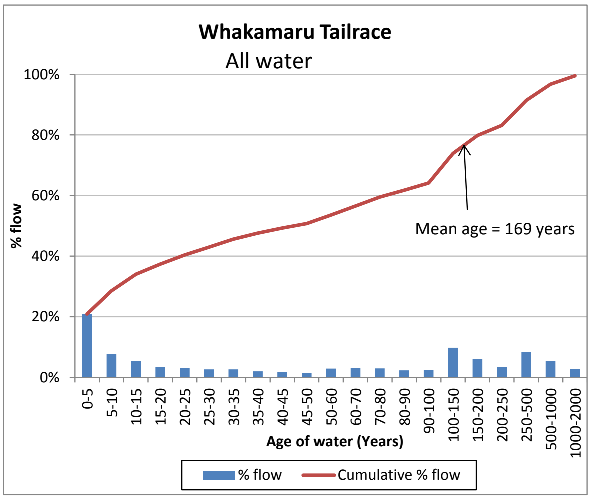


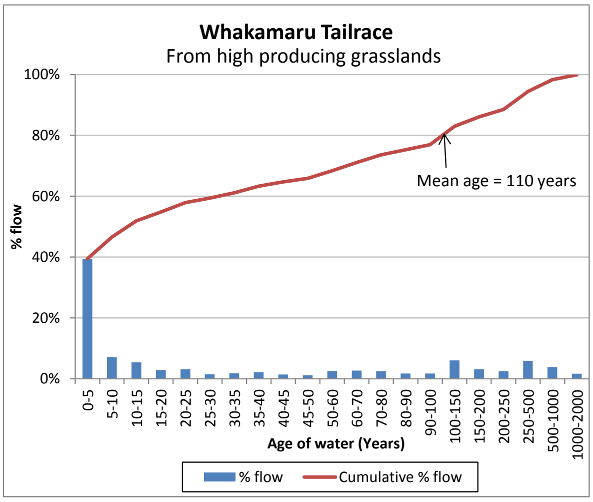

Waikato River @ Ohaaki Bridge
All water
% flow
100%
80%
60%
40%
20%
0%
Mean age = 115 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

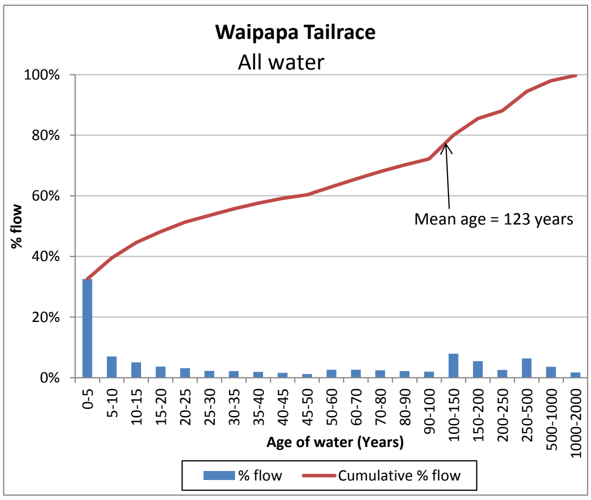

Waikato River @ Ohaaki Bridge
From high producing grasslands
% flow
100%
80%
60%
40%
20%
0%
Mean age = 162 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

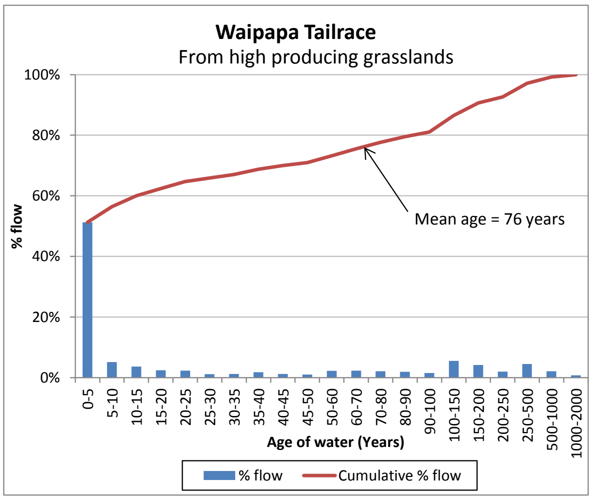

Ohakuri Tailrace Bridge
All water
% flow
100%
80%
60%
40%
20%
0%
Mean age = 141 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

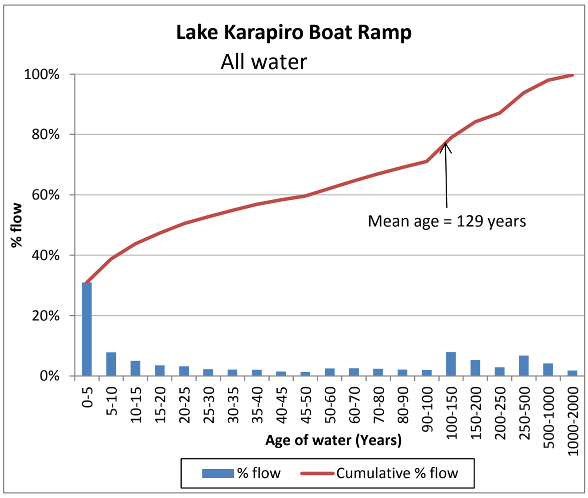

Ohakuri Tailrace Bridge
From high producing grasslands
% flow
100%
80%
60%
40%
20%
0%
Mean age = 140 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

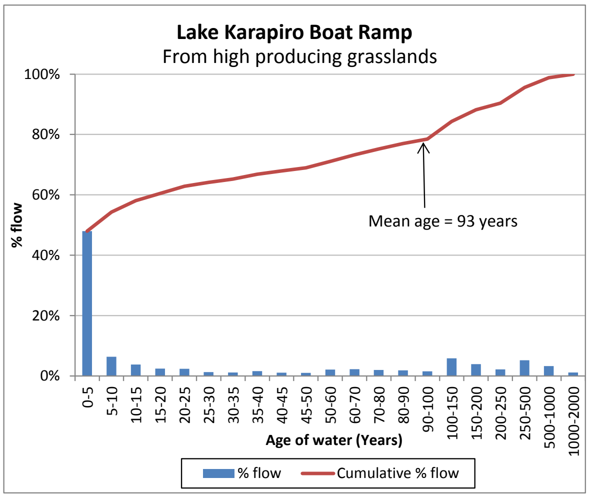

Whakamaru Tailrace
All water
% flow
100%
80%
60%
40%
20%
0%
Mean age = 169 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

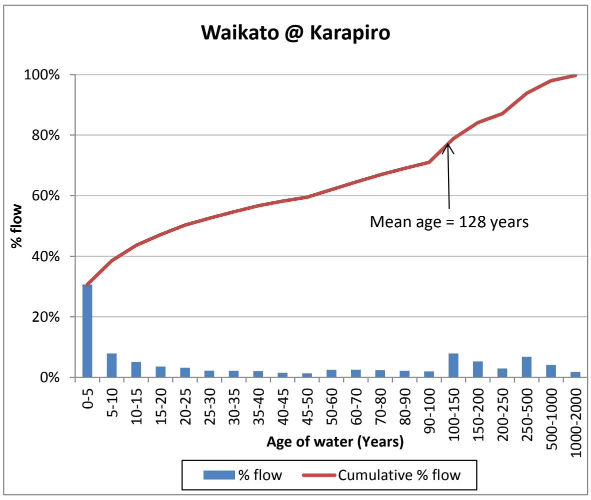

Whakamaru Tailrace
From high producing grasslands
% flow
100%
80%
60%
40%
20%
0%
Mean age = 110 years
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
200-250
250-500
500-1000
1000-2000
Age of water (Years)
% flow
Cumulative % flow

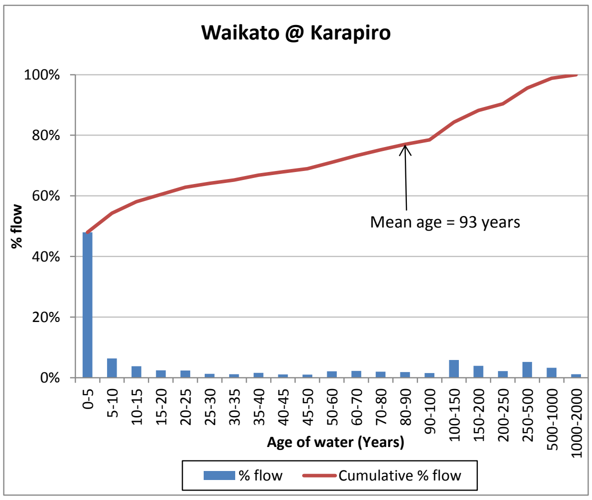

Waipapa Tailrace
All water


Waipapa Tailrace
From high producing grasslands


Lake Karapiro Boat Ramp
All water


Lake Karapiro Boat Ramp
From high producing grasslands


Waikato @ Karapiro


Waikato @ Karapiro