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COMBINING SURFACE WATER MONITORING, AGE-DATING, AND PARSIMONIOUS MODELLING TO UNRAVEL WATER AND CONTAMINANT PATHWAYS THROUGH CATCHMENTS

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Abstract

The water flow and chemistry time series that exist from State of the Environment monitoring programmes in all parts of Aotearoa New Zealand provide a valuable basis for unravelling water and contaminant pathways through catchments. We demonstrate the benefit of supplementing the routine suite of analytes with targeted age-dating, and utilising a parsimonious model for hydrograph separation and contaminant load partitioning. This allows the link between observed surface water quality and past and present land use to be established more reliably than otherwise possible.

In our pilot study, we focussed on five river monitoring sites in the Upper Hauraki lowlands and the Central Plateau uplands. Piako and Waitoa represented rivers with very dynamic flow, while Waihou, Pokaiwhenua, and Waiotapu are characterised by modest relative flow variation. We complemented the existing data with 5-7 tritium analyses, strategically carried out to capture the range of flows observed at these sites. For each sampled flow, the mean transit time (MTT) was calculated based on its tritium concentration. The BACH model was used to estimate the flow contributions made by fast, medium, and slow flow components, representing near-surface flows (e.g. surface runoff, interflow), shallow (local, seasonal) groundwater, and deeper (regional, continual) groundwater, respectively.

All five rivers showed a substantial MTT variation (23-67 years) across their flow range. MTTs varied between 24 and 70 years at the lowest, and 1 and 11 years at the highest flows. While young water leaving catchments at high flows has frequently been described before for rivers characterised by dynamic flow, it is worth noting that the rivers with relatively little flow variation (Waiotapu, Pokaiwhenua, Waihou) also featured MTTs ≤ 11 years. The BACH modelling demonstrated that near-surface and shallow groundwater pathways contributed substantial flow proportions under high-flow conditions, even in these rivers with modest flow variation. These results confirm that in many catchments most streamflow originates from a thin veneer of total groundwater storage. High-flow conditions are particularly important for nitrogen exports, as at least tentatively positive concentration-discharge relationships were observed at all sites. The MTT, flow paths, and concentrations information together suggest that the nitrogen load-to-come might be lower than often assumed for upland catchments with large underlying groundwater stores and modest relative flow variation.

Introduction

Surface water chemistry time series data in typically monthly resolution exist in all parts of Aotearoa New Zealand from State of the Environment monitoring programmes. Where concurrent water flow data exist, they provide a valuable basis for unravelling water and contaminant pathways through their corresponding catchments.

The flow and chemistry time series represent the combined effect of the temporally and spatially varying contributions that near-surface, shallow groundwater, and deep groundwater pathways make to stream flow and contaminant delivery. Due to the variation in pathway contributions, the '*lag time*' between a contaminant being lost from the soil zone and its delivery to the surface water monitoring site, also varies in space and time.

In this pilot study, we demonstrate the benefit of supplementing the routine suite of monitored analytes with targeted age-dating, and utilising a parsimonious model for hydrograph separation and contaminant load partitioning. This allows the connection between pathway contributions and associated lag times to be revealed. The link between observed surface water quality and past and present land use can thus be established more reliably than otherwise possible.

Materials and Methods

Five Waikato catchments for which at least 15 years' worth of continuous flow and monthly water chemistry data exist were selected for this study (Fig. 1). Their geographic spread reaches from the Upper Hauraki lowlands in the northwest to the Central Plateau uplands in the southeast.

The monitoring sites comprise Piako at Kiwitahi, Waitoa at Landsdowne Rd, Waihou at Okauia, Pokaiwhenua at Putaruru Rd, and Waiotapu at Homestead Rd.
(see https://www.lawa.org.nz/)

The corresponding topographical catchment areas range from 104 km^2 for Piako to 801 km^2 for Waihou.

The Piako and Waitoa Rivers feature rather flashy hydrographs, i.e. they respond very quickly to rainfall, and flows vary by two or more orders of magnitude during the year. In contrast, flow in the other three rivers is comparatively steady in relative terms.

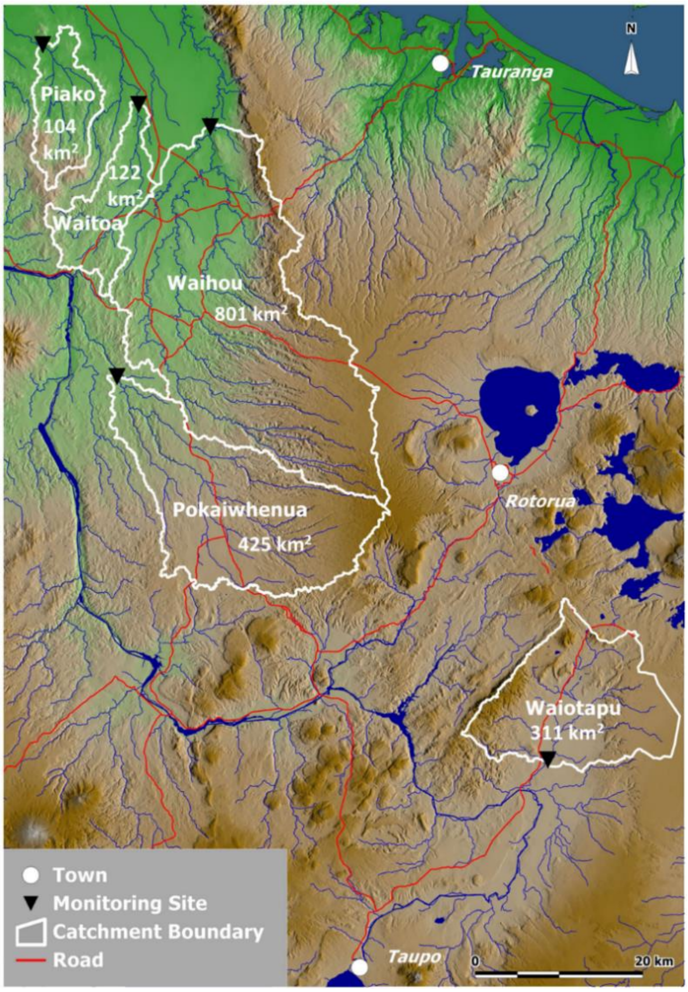

Figure 1 *Map showing the five Waikato catchments selected for this study.*

Surface water dating has in the past largely been carried out under usually not well defined '*baseflow conditions*'. In contrast, we have aimed to capture the entire flow range, as illustrated in Fig. 2 for one example of a flashy river (Piako) and a steady river (Pokaiwhenua). Based on existing information on the cumulative flow frequency in our rivers, we scheduled 5-7 tritium-samplings between 2016 and 2021, as indicated by the symbols on the graphs. The mean transit times (MTTs) were derived from the measured tritium concentrations by applying an exponential piston flow model (EPM) with an exponential fraction of the total flow volume of 70%. A scaling factor (0.84 – 0.90) was used to adjust the tritium input time series from Kaitoke for each catchment (Morgenstern et al., 2010).

While flow maxima are fairly similar for both rivers (approx. 8 $m^3 s^{-1}$), the steady Pokaiwhenua River never drops below approx. 2 $m^3 s^{-1}$, while the flashy Piako River sometimes drops to less than 0.2 $m^3 s^{-1}$.

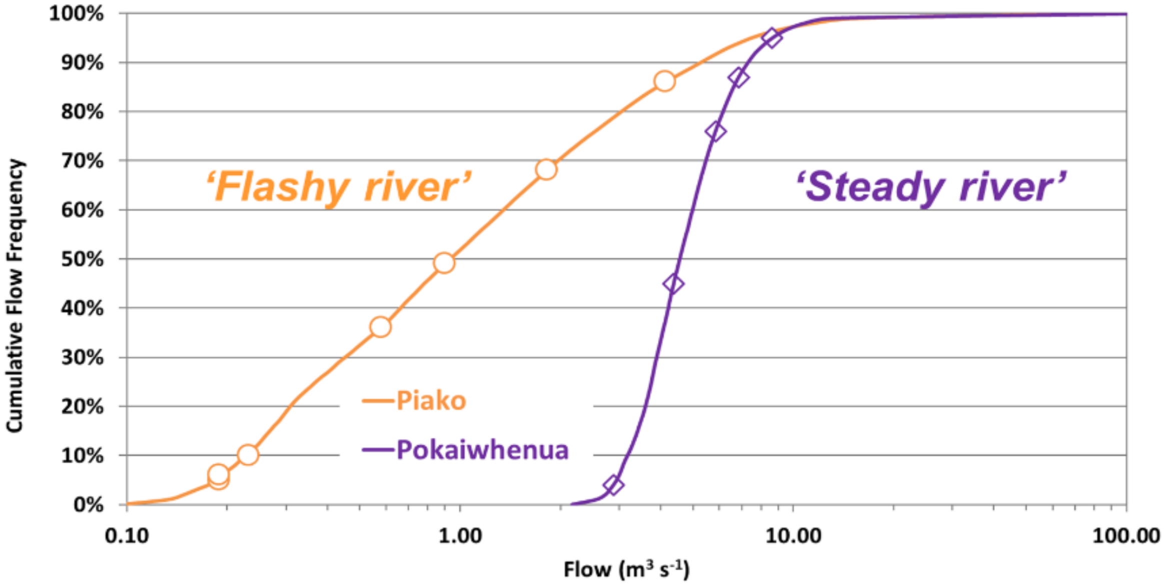

Figure 2 *Flow duration curves for the flashy Piako River and the steady Pokaiwhenua River. Tritium-samplings indicated by symbols on graphs.*

The availability of at least 15 years' worth of flow hydrographs and water quality time series data enabled the parsimonious BACH model to be applied (Woodward and Stenger, 2018+2020). Its Bayesian parameter inference scheme enables a chemistry-assisted 3-component flow separation to be carried out and concentrations and loads of two tracers to be estimated separately for each flow component/pathway (Fig. 3).

The fast flow component relates to near-surface (NS) pathways like surface runoff and interflow, the medium flow relates to shallow (local, seasonal) groundwater (SGW), and the slow flow to deeper (regional, continual) groundwater (DGW).

A range of routinely measured analytes can be used as tracers for hydrograph separation (e.g. major cations, EC). Nitrate+Nitrite Nitrogen (NNN) and Total Phosphorus (TP) have the particular advantage that they are not only routinely measured and in many catchments suitable as tracers, but are also of interest in their own right as agricultural pollutants.

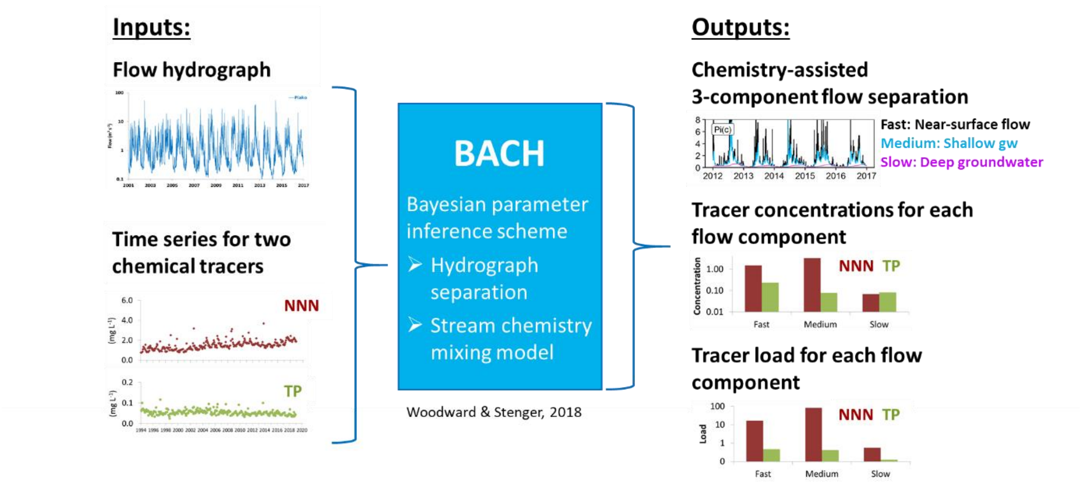

Figure 3 *Schematic of the parsimonious BACH model.*

Results and Discussion

Spatiotemporal variability of river water Mean Transit Times (MTTs)

The tritium-derived Mean Transit Time (MTT) represents the average length of time the water molecules contained in a volume of sampled river water had spent in the subsurface environment before being discharged into the river (see Morgenstern et al, 2010). In all rivers, MTT decreased steadily with increasing flow (Fig. 4). At the lowest sampled flow, MTTs ranged from 24 years at Waitoa to 70 years at the neighbouring Piako catchment. The maxima of the other three rivers were between 29 and 46 years. However, at the highest flow, MTTs had dropped to only 1 year at Waitoa, approx. 3 to 4 years at Piako and Pokaiwhenua, and approx. 9 to 11 years at Waihou and Waiotapu. The low high-flow MTTs of 4 to 11 years in the three fairly steady rivers draining volcanic upland areas with significant underlying groundwater reservoirs are particularly noteworthy.

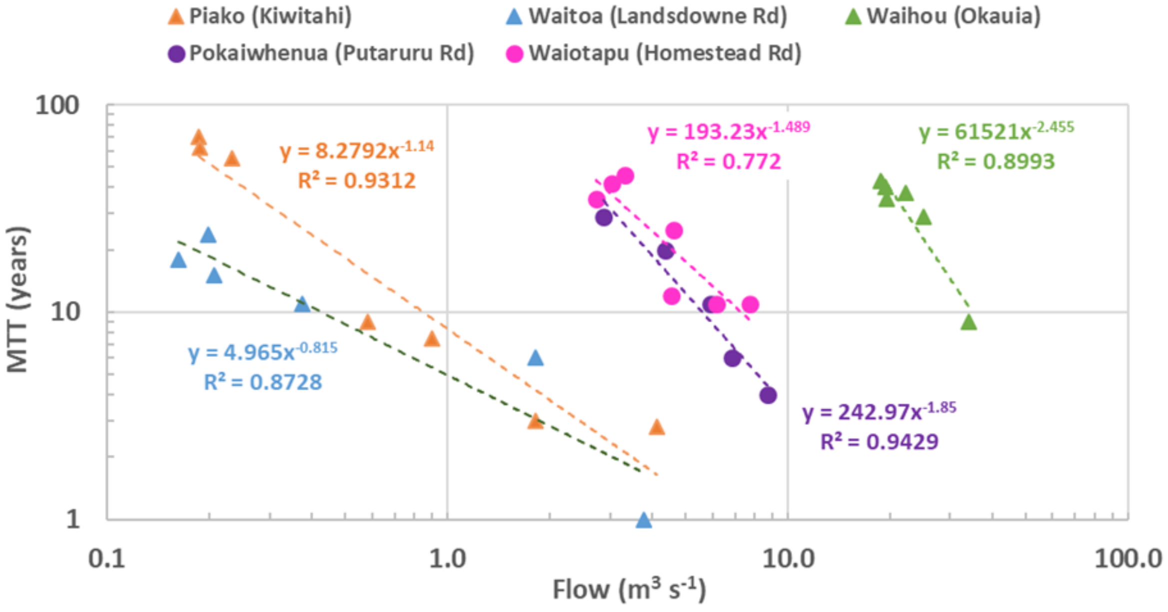

Figure 4 *Mean Transit Time (MTT) graphed against flow at the sampling date. Note the log-log scale.*

Concentration-discharge relationships (CDRs) for NNN

The concentration-discharge relationships for these sites demonstrate that, on average, NNN concentrations increase in each catchment with increasing flow (Fig. 5). This observation reinforces the great importance of high-flow conditions for nitrogen discharges from these catchments.

Particularly low NNN concentrations occurred at Piako at flows below the median. Based on earlier work in the area (see Woodward et al., 2013), we interpret this as being largely due to denitrification occurring in anoxic parts of the groundwater system, while low original NNN concentrations at the time of recharge (i.e. several decades ago), and in-stream plant uptake, are contributing factors.

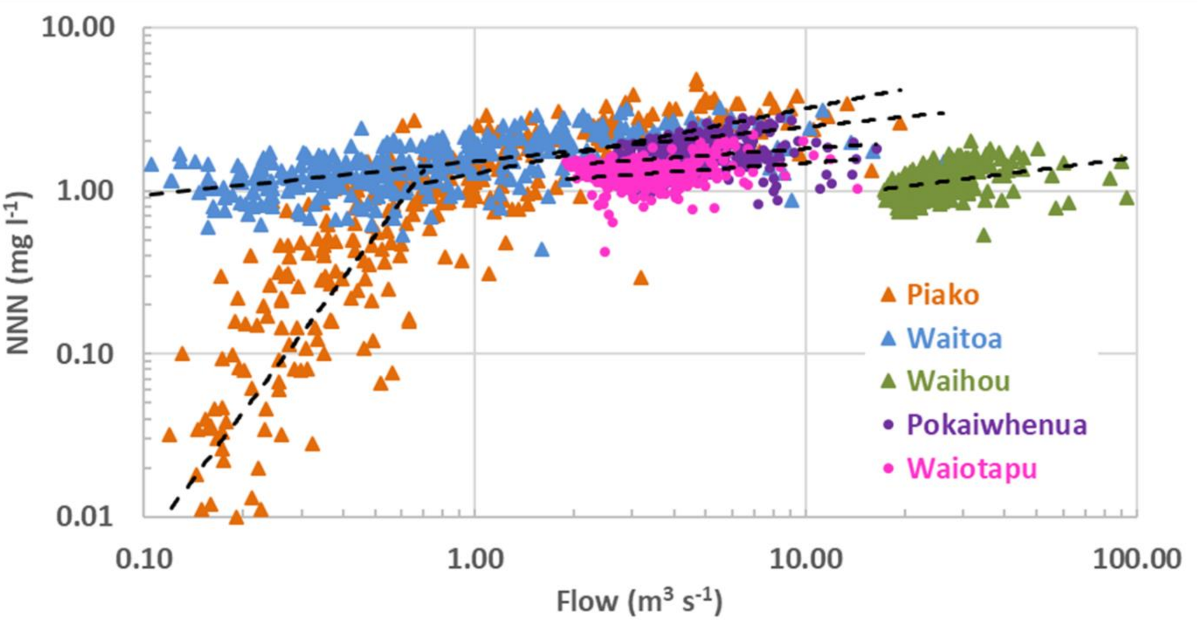

Figure 5 *Concentration-discharge relationships (CDRs) for NNN in the five rivers. Note the log-log scale.*

Long-term average pathway contributions

Before discussing in detail the temporal variation of pathway contributions, it is useful to take note of the differences between the five catchments in long-term averages. The 15-year averages from the BACH modelling suggest that the shallow groundwater pathway contributes nearly 60% to the stream flow in the two flashy lowland catchments (Fig. 6). Near-surface flows make the second-highest contribution (24-30%) and deeper groundwater flow accounts for less than 20%. In stark contrast, deeper groundwater contributes 58-70% of the flow in the three steadier rivers, followed by shallow groundwater (20-36%), and less than 15% near-surface flows. These results demonstrate that in each of these catchments, there are two pathways that contribute at least 20% of the stream flow, challenging the notion of a single dominant pathway in each catchment.

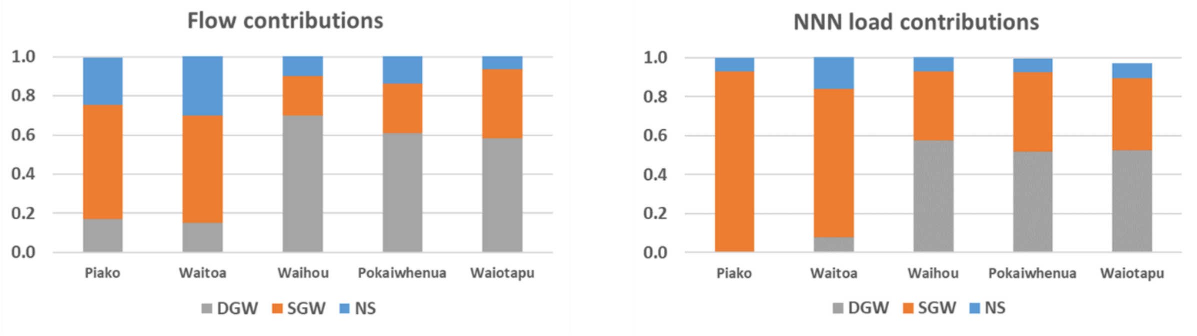

Figure 6 *15-year averages of the relative contributions of the three pathways to water flow (left) and NNN load (right). Near-surface (NS) pathways, Shallow groundwater (SGW), Deep groundwater (DGW).*

Given that the average NNN concentrations differ between the pathways, the NNN load contributions show a somewhat different pattern than the flow contributions (Fig. 6). As shallow groundwater tends to have the highest NNN concentrations (see below), its relative contribution to N loads exceeds its flow contribution. While a single pathway can be very dominant with regards to NNN delivery to the lowland rivers (SGW accounting for 93% in Piako and 76% in Waitoa), two pathways contributed at least 35% each in the three upland catchments (DGW>SGW). This finding reinforces the importance of pathway understanding when interpreting river water quality data across a range of catchments.

The variation in NNN concentrations between the pathways is largely due to two factors, the typical range of lag times associated with the pathway and the attenuation potential encountered along the pathway. In catchments characterised by steady land use intensification, the younger water discharged from shallow pathways tends to have higher NNN concentrations than older water travelling on deeper pathways. However, where substantial natural attenuation capacity for NNN exists (largely due to denitrification in anoxic zones), this pattern can be modified. Where denitrification predominantly affects the deeper pathway, NNN concentrations can be further reduced to values near the detection limit, as frequently observed in the Piako dataset at low flows (see Fig. 5). In other catchments, denitrification may more strongly affect shallower pathways, e.g. where a substantial proportion of flow enters the river via riparian wetlands.

Intra-annual variation of pathway contributions and resulting MTTs and NNN concentrations

Using the calendar year 2016, when most of the tritium analyses were carried out, as example, Figures 7 and 8 illustrate how pathway contributions change during a year, and what this means for MTTs and NNN concentrations of the river water. Piako River results (Fig. 7) are shown as example for the flashy rivers, while Pokaiwhenua results (Fig. 8) are shown to represent the steady rivers. Note that symbols represent measurements, while dotted lines represent estimates derived from the MTT vs. flow regression equations (cf. Fig. 4) and NNN CDRs (cf. Fig. 5).

Flow in the flashy Piako River was very low in the first half of 2016 (< 0.3 m^3 s^{-1}) and, apart from a few short-lived peaks in response to rainfall, sustained by deeper groundwater. The corresponding NNN concentrations were also very low (< 0.2 mg l^{-1}) and MTTs were predominantly high (40-75 years). When near-surface flows became more frequent in early winter and shallow groundwater became the dominant pathway, flow and NNN concentrations increased substantially (peak flows up to ≈ 10 m^3 s^{-1} and NNN peaks up to ≈ 3.5 mg l^{-1}), while

MTTs decreased substantially (largely <5 years till mid-October). When stream flow receded in late spring/early summer, deep groundwater once again became the dominant flow pathway; NNN concentrations decreased and MTT increased, accordingly. Note that the Bayesian parameter inference scheme of the BACH model estimates that deep groundwater is virtually devoid of NNN (0.01 mg l^{-1}), shallow groundwater has the highest concentration (2.60 mg l^{-1}), and near-surface flows contain 0.52 mg l^{-1}. It is worth noting that NNN is generated in agricultural soils within the soil profile, rather than being applied as fertiliser onto the surface. Accordingly, its concentration in surface runoff is typically low, which explains why the estimated NS pathway concentrations are usually lower than the SGW concentrations (see Figs. 7 and 8).

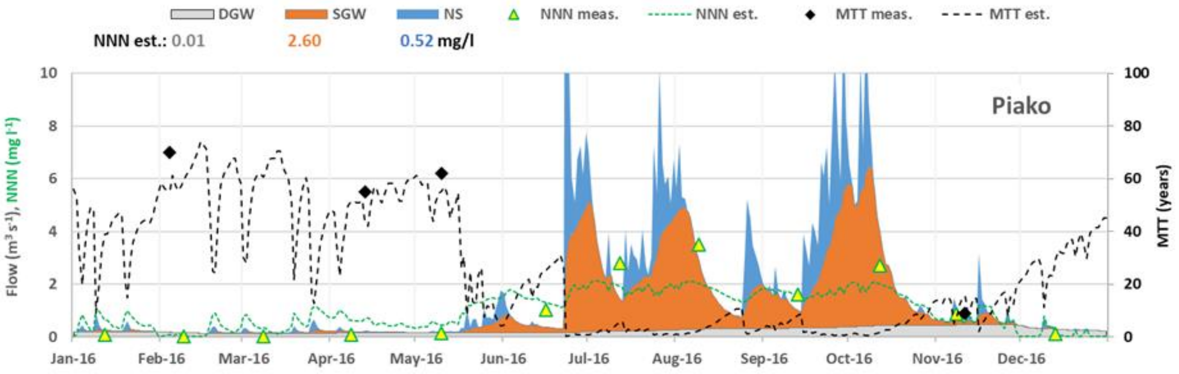

Figure 7 *Estimated pathway contributions, MTTs, and NNN concentrations in Piako River during 2016. Black diamond symbols represent MTTs calculated from tritium samples, yellow triangles measured NNN concentrations.*

At the comparatively steady Pokaiwhenua River, even summer low flows never dropped below ≈ 3 m^3 s^{-1}, NNN concentrations increased only moderately with flow (1.6-2.6 mg l^{-1}), but MTTs still dropped from predominantly 25-35 years during summer and autumn to predominantly 1-15 years during winter and spring. The smaller intra-annual variation of NNN concentrations compared to Piako reflects the smaller flow variation and the smaller differences in NNN concentrations estimated for the contributing pathways. While the shallow groundwater once again was estimated to have the highest NNN concentration (3.13 mg l^{-1}), deeper Pokaiwhenua groundwater discharging into the river was also estimated to be NNN enriched (1.51 mg l^{-1}).

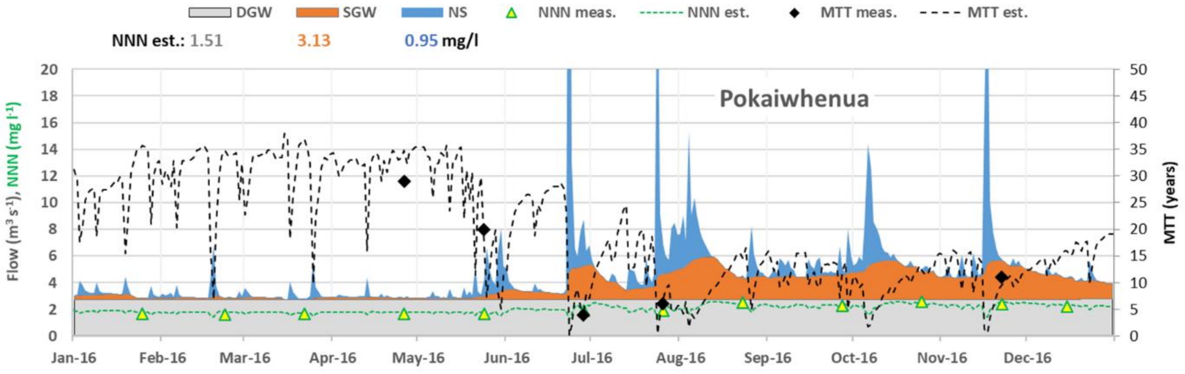

Figure 8 *Estimated pathway contributions, MTTs, and NNN concentrations in Pokaiwhenua River during 2016. Black diamond symbols represent MTTs calculated from tritium samples, yellow triangles measured NNN concentrations.*

Intra-annual MTT variation across all five catchments

To facilitate direct comparison between all five catchments, Fig. 9 shows their estimated MTT dynamics for 2016 in one chart. A wide spread of MTTs from less than 20 to over 70 years is evident under the drier conditions in summer and autumn. However, the water becomes generally younger and much more similar between the catchments during a few short-lived high-flow events spread throughout the year and particularly for extended periods during winter and spring. As outlined above, this MTT drop reflects the activation of shallower and shorter pathways (NS, SGW) during the high-flow periods that are particularly important for NNN exports from the catchments.

While it has previously been documented that young water dominates discharge from flashy catchments during high-flow periods (e.g. Morgenstern et al, 2010), it is noteworthy that the MTT also dropped repeatedly to below approx. 10 years in the three rivers characterized by relatively steady flow.

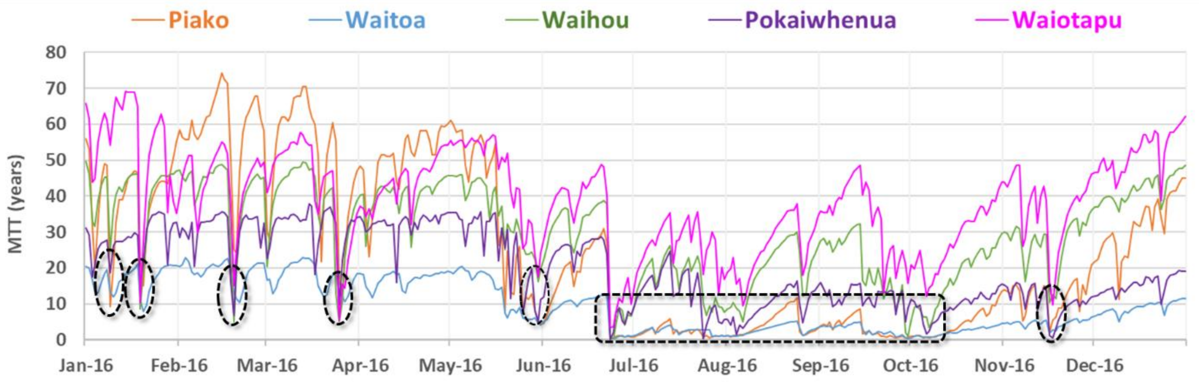

Figure 9 *Estimated MTT dynamics for all five catchments during 2016.*

Conclusions

The activation of NS and SGW pathways during the wet season, combined with the generally observed positive concentration-discharge relationships for NNN mean that a substantial fraction of young and typically NNN-enriched water can get quickly discharged into rivers on shallow and short pathways, even in catchments with large underlying groundwater reservoirs and relatively steady river flows. These results are in agreement with the earlier finding that most streamflow originates from a thin veneer of total groundwater storage (see Berghuijs & Kirchner, 2017). Accordingly, the '*load to come*' from past land use may be smaller than often feared for such catchments, e.g. on the North Island's Central Plateau.

Outlook

As this pilot study has been limited to a small number of catchments in the Upper Hauraki lowlands and the Central Plateau uplands, it will be extended from 2022 onwards to a total of 18 catchments that cover the wide range of environmental and land use conditions found across the Waikato region.

Acknowledgements

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