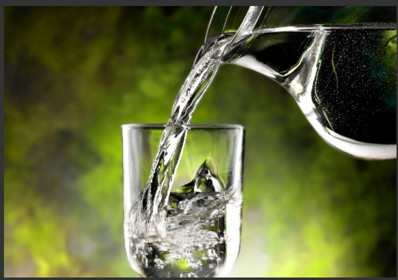
Kōmanawa Solutions Ltd



Report No: Z22014OLW.4

The Power of the Current Monitoring Network to Detect Nitrate Reductions in the Selwyn Wai-hora Zone

19/02/2024

Prepared by Kōmanawa Solutions Ltd. for Environment Canterbury

Komanawa.com

Kōmanawa:

1. (verb) to spring, well up (of water)
2. (verb) to spring, well up (of thoughts, ideas)

Kōmanawa Solutions Limited (KSL) is a water resource consultancy and research company specialising in water resource investigation and modelling, environmental limit setting and water resource impact assessment. Our goal is to provide excellent science to facilitate the robust management of natural resources in our changing climate. Clients include New Zealand enterprises in the private sector, central and local government agencies and community groups. Our vision KSL delivers high quality science and research. We aspire to be at the forefront of creativity and innovation to address our increasingly complex water resource challenges; mō tatou, ā, mō kā uri ā muri ake nei (for us and our children after us).

Our mission

Our mission is to develop solutions to the increasingly challenging water resource management issues we now face by providing a clear vision of the pathway from problem to solution. We work closely with our partners, communities, and stakeholders, deploying state-of-the-art scientific methods and building trust through knowledge and honest science communication.

Limitations

Version Control

Date	Status	Comment
13/12/2023	Draft	First Draft by Matt Dumont
20/12/2023	Draft	Review by Zeb Etheridge
22/12/2023	Final Draft	Review by Matt Dumont and provided to Environment Canterbury
02/02/2024	In Review	Review by Lisa Scott & Phillipa Aitchison-Earl of Environment Canterbury
14/02/2024	In Review	Matt Dumont response to Environment Canterbury review
19/02/2024	In Review	Final review by Lisa Scott & Phillipa Aitchison-Earl of Environment Canterbury
19/02/2024	Final	Matt Dumont conducts minor edits and finalize

Authors

Matt Dumont: *Lead Computational Hydrogeologist, Kōmanawa Solutions Ltd*

Zeb Etheridge: *Director & Principal Water Resource Scientist, Kōmanawa Solutions Ltd*

Contributors

This work was partially funded and supported by the Our Land and Water National Science Challenge project Monitoring Freshwater Improvements (https://www.monitoringfreshwater.co.nz/). In particular, we would like to thank:

- **Olivier Ausseil** - *For providing his expert guidance and steering throughout the Our Land and Water project.*
- **Richard McDowell** - *For his support in the development of the methodologies used in this project.*

Suggested Citation

Dumont and Etheridge, (2024). *The Power of the Current Monitoring Network to Detect Nitrate Reductions in the Selwyn Waihora Zone*. Report: Z22014OLW.4 prepared by Kōmanawa Solutions Ltd for Environment Canterbury.

Key Findings

Key Findings

Our key findings are:

- The current monitoring programme is not well suited to detecting reductions in nitrate at the scale required by PC_1 (Plan Change 1). Note that this is only one aspect of the monitoring programme and our findings do not comment on the overall quality of the programme.
- It will likely be 30 or more years before PC_1 reductions can be detected by the current monitoring regime.
- If we incorrectly ignore NO_3-N (nitrate nitrogen) noise and only consider WAD-MRT (water age distribution and mean residence time) (e.g, lag) then the PC_1 reductions should be detectable much sooner (< 15 years for many sites).
- The ultimate NO_3-N concentration (once all the NO_3-N has made it to the sampling point) and the ability of the surface water features to detect changes in NO_3-N is highly sensitive to the assumed WAD-MRT.
- Obtaining water age data for all key monitoring sites, particularly in surface water courses, is a key recommendation.
- There is a trade-off between the scale of NO_3-N mitigations and the cost of the monitoring programme required to detect the effectiveness of these mitigations. Very large mitigations are easy to detect, but may not be realistic for other reasons. Smaller mitigations are typically more tenable, but require a more expensive monitoring programme to detect.
- This report demonstrates that bespoke monitoring programmes may often be required to assess the effectiveness of a plan change. We suggest that analysis of the monitoring programme needed and its cost should be an integrated component of the plan change itself.
- Finally, detecting PC_1 or similar changes requires a significant investment in monitoring infrastructure and data collection.

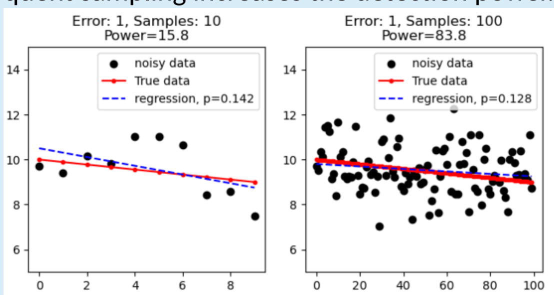
Executive Summary

PC$_1$ (Plan Change 1) of the Canterbury Land and Water Regional Plan included requirements for farmers in the Selwyn Waihora catchment to reduce nitrate discharges to groundwater to support water quality improvements. PC$_1$ became operational in 2016 with a requirement for NO_3-N (nitrate nitrogen) reductions to be fully implemented by 2022. Very few monitoring sites in the Selwyn Waihora catchment and assessed by this report show decreasing NO_3-N concentrations to date. This study evaluates the change detection power analysis of 56 sites (46 groundwater wells and 10 surface water features) to identify when and if PC$_1$ reductions might become detectable in the current monitoring programme.

Our analysis suggests that the current monitoring programme is not well suited to detecting reductions in nitrate at the scale required by PC$_1$. PC$_1$ requires nitrate load reductions between 2-30% depending on land use (see Box 1.1). Here we assume at a 20% reduction in nitrate loads is equivalent to a 20% reduction in leachate nitrate concentrations; however changes in coincident land surface recharge (e.g., the move to efficient irrigation), could yield lower than expected reductions in nitrate leachate concentrations. Our analysis suggests that only approximately 60% of groundwater monitoring sites will ever show decreasing NO_3-N concentrations (negative slope) if nitrate concentrations in source soil drainage reduce by 10-20%. The remaining 40% of sites are likely to plateau and larger reductions would be required to observe decreasing concentrations. Note that these steady state concentrations will be lower than if PC$_1$ had not been implemented. The impact of PC$_1$ on these "plateau" sites will not be detectable via slope monitoring (looking for a decreasing concentration trend), but future work may be able to detect these changes using a counterfactual approach (i.e., asking whether the NO_3-N concentration is significantly different to the concentration without reductions). There is significant uncertainty in these estimates due to the lack of WAD-MRT (water age distribution and mean residence time) data in c. 60% of the groundwater monitoring locations we investigated. However, if our WAD-MRT estimates are correct then the nitrate reductions required under PC$_1$ should be detectable in c. 30% of the monitoring wells (50% of those which can have a decreasing trend) by c. 2060. Increasing sampling frequencies to monthly or weekly would allow detection of the reductions in c. 30% of the monitoring wells by 2040 or 2035, respectively.

What is Detection Power

Essentially, detection power describes the chance that you can see whether concentrations are changing over time. More specifically, detection power is the percent probability of detecting a statistically robust trend in the receptor concentration time series. Noisy data reduces the detection power while more frequent sampling increases the detection power.



Surface water features generally receive water from a much larger catchment than individual wells and are therefore more likely to provide a landscape scale representation of policy and land management action effectiveness. However, no water age data are available for surface water courses in the Selwyn Waihora catchment, making robust predictions of change detection power impossible. We therefore derived detection power estimates by assuming a range of WAD-MRT values. Our results show that the detection power of the surface water features is highly sensitive to the assumed WAD-MRT value.

As an example, our analysis of Hart's creek highlights the uncertainty associated with our assumed water ages. Results indicate that the maximum steady state NO_3-N concentration could be as low as 7.6 mg/l (assuming a WAD-MRT of 5 years) or could be as high as 12.0 mg/l (assuming a WAD-MRT of 30 years). A stated goal of PC$_1$ was to set an annual limit across all the shallow groundwater of not more than 8.5 mg/L. The Hart's creek results may indicate that the PC$_1$ reductions are sufficient to achieve this goal, or that the reductions are insufficient to prevent shallow groundwater from exceeding the maximum acceptable value in drinking water (11.3 mg/L). Obtaining age data for the surface water network would constrain these predictions and allow integrated analysis of detection power across the groundwater and surface water monitoring programme. The programme could then be optimised in terms of the number and location of sites and monitoring frequency for change detection power, spatial representativeness and monitoring cost. Age data collection for surface watercourses would also help to constrain the likely maximum NO_3-N concentration in a stream that will arise from current and past land use; this will provide a much clearer picture of policy and land management actions required to achieve water quality objectives.

We conclude that the current groundwater monitoring programme is unlikely to detect whether the nitrate reductions mandated under PC_1 have improved water quality within the timeframes required for effective water resource management (within 30 years or less). Previous analysis has focused on lag times as the key constraint on detecting change, but this analysis shows that statistical power is an equally important constraint under the current sampling frequency. We recommend that the change detection monitoring design framework described in the *Water quality monitoring for management of diffuse nitrate pollution report* (Etheridge et al., 2023) should be applied to improve the surface water and groundwater monitoring programme for change detection. Key tasks will include:

- Obtaining water age data for all key monitoring sites, particularly in surface water courses.
- Developing a basic conceptual model of the spatial distribution and rate of expected nitrate loss reductions, water flow paths, potential attenuation and travel times.
- Carrying out an integrated analysis of groundwater and surface water detection power for existing sites in the monitoring area using the information provided in this report, updated with new water age data where required, and identifying the highest detection power sites.
- Evaluating the representativeness of high power monitoring sites in relation to the expected spatial distribution and distribution of nitrate loss reductions and the number of sites required to confidently detect change.
- Identify new monitoring sites if existing network detection power and/or representativeness is inadequate.
- Undertaking a sampling frequency cost-benefit analysis.
- Undertaking more sophisticated statistical analysis to extract additional information from the existing data.
- Finalising network and monitoring design.
- Reviewing data after 1, 3 and 5 years of sampling to determine whether detection power and timeframe requirements have changed in light of new information.

We note that these recommendations will require a significant investment in monitoring infrastructure and data collection. A companion study found that a 100-300% increase in investment is likely required nationally to meet these goals (Dumont et al., 2024). This highlights the discrepancy between the goals of national monitoring programmes and the resources available to regional councils to meet these goals. This can be further exacerbated by the desire for smaller or more gradual interventions; the larger the change in NO_3-N the easier it is to detect that change. This is a national challenge for regional councils and communities across New Zealand.

A key caveat of this report is that we only focused on one aspect of the monitoring programme: detecting changes in NO_3-N concentrations. The network serves and was primarily designed for multiple other purposes some of which are counter to high detection powers (e.g., characterising the state of the deep aquifer system). We also have not assessed the spatial representativeness of the monitoring network in this analysis (for either change detection or more broadly) as it was beyond the scope of this project.

Contents

Key Findings iii

Executive Summary iv

Contents vi

List of Figures vii

List of Tables vii

Table of Breakaway Boxes vii

Definitions and Abreviations viii

Definitions and Abreviations viii

1 Introduction 1

2 Methods 2

2.1 Data Processing 2

2.2 Pathways 6

2.3 Detection Power Methods 6

3 Results and Discussion 9

3.1 Site Results 9

3.1.1 Plateau Sites 10

3.2 Mean Residence Time Impacts 13

3.3 Network Detection Power 14

3.4 Counterfactual Approach 20

3.5 Possible Network Improvements 20

4 Limitations 21

5 Conclusions 22

6 Recommendations 23

References 24

Appendices 25

Appendix A Full Data Table 25

List of Figures

2.1 Sites L36/0871 & L36/0477: note the "true" outliers (black) and the trend outliers(red) 4

2.2 Final Site Locations 5

2.3 Site M36/0698 as an example of the source concentration prediction 8

3.1 An example of the individual site detection power plots 10

3.2 An example of a Plateau Site 11

3.3 The NO_3-N reductions needed at a given site to yield a negative slope rather than a lower steady state concentration (wells only) 12

3.4 The impact of assumed WAD-MRT on the steady state NO_3-N concentrations and the potential to detect PC_1 reductions (red.) 14

3.5 Sampling duration until the probability of detecting a reduction is $\geq 80\%$ 16

3.6 The proportion of the groundwater network whick is likely to detect the full PC_1 reductions (20%) 17

3.7 The propotaion of the groundwater network which is likely to detect reduction at the current quarterly sampling frequency 18

3.8 The proportion of the groundwater network whick is likely to detect the full PC_1 reductions (10%) 19

List of Tables

3.1 Percent of the groundwater network that will level off but never show a decreasing trend in the receptor at a theoretical reduction level at the source 10

A.1 Overview of data used in this study. 25

List of Breakaway Boxes

0.1 Suggested Citation ii

0.2 Key Findings iii

0.3 What is Detection Power iv

1.1 Box 1.1: Plan Change 1 1

2.1 Box 2.1: How mean residence time is identified 3

2.2 Box 2.2: What is Detection Power 7

2.3 Box 2.3: Source to Receptor Concentration 9
3.1 Box 3.1: Counterinuitive Results 13
3.2 Box 3.2: Historical mean well sampling frequency 14

Definitions and Abreviations

ECAN Environment Canterbury

NO_3-N nitrate nitrogen

PC_1 Plan Change 1

Project Github Repo Project Github Repository

WAD-MRT water age distribution and mean residence time

1 Introduction

NO_3-N (nitrate nitrogen) is a contaminant of significant concern both worldwide and in Aotearoa / New Zealand. At concentrations > 0.8 mg/l, NO_3-N can stimulate the growth of periphyton and phytoplankton (McDowell et al., 2020); concentrations greater than 2.4 mg/l can cause toxicological effects to in stream fauna (Camargo et al., 2005; Horak et al., 2019; Wagenhoff et al., 2017); finally concentrations above the maximum acceptable value (>11.3 mg/l) can cause human health impacts (Rahman et al., 2021).

The Selwyn Waihora zone is a large catchment in the Canterbury plains south of Christchurch. The catchment stretches from the foothills of the Southern Alps to the coast. There is significant agricultural activity, as well as many high value ecosystems including Te Waihora / Lake Ellesmere and the Kaitorete Spit. The Selwyn Waihora zone is also home to many significant cultural sites for Ngāi Tahu, the local iwi. NO_3-N concentrations in the Selwyn Waihora zone are elevated with many surface water sites exceeding the National Bottom Line for Nitrate Nitrogen of 2.4 mg/l (Ministry for the Environment, 2020). PC_1 (Plan Change 1) of the Canterbury Land and Water Regional Plan, operative from 1st February 2016, includes provisions to reduce nitrate leaching concentrations in the Selwyn Waihora; however there was acknowledgment NO_3-N concentrations could initially continue to increase after implementing PC_1 reduction. In addition, PC_1 predated the National Policy Statement for Freshwater Management 2020 and therefore the National Bottom Line for Nitrate Nitrogen of 2.4 mg/l was not a requirement of PC_1. PC_1 NO_3-N reductions ranged from 2-30% Box 1.1. Implementation of these NO_3-N reductions were expected to begin in 2017 and should have been fully implemented by 2022.

Box 1.1: Plan Change 1

Objective: Reduce NO_3-N concentrations in the Selwyn Waihora zone to reduce the load to Te Waihora / Lake Ellesmere and ensure that average groundwater NO_3-N concentrations are not more than 8.5 mg/L.

NO_3-N reductions required by PC_1 (Plan Change 1) vary by land use:

- 30% for dairy
- 2% for dryland sheep, beef or deer
- 22% for dairy support
- 7% for arable
- 20% for pigs
- 5% for fruit, viticulture or vegetables
- 5% for irrigated sheep, beef or deer

Note that these reductions are applied to the NO_3-N load. We assume that a NO_3-N load reduction is equivalent to a NO_3-N concentration reduction, but changes land surface recharge (e.g., the move to efficient irrigation), could yield lower NO_3-N concentration reductions.

Environment Canterbury maintains a network of monitoring wells and surface water sites to track NO_3-N concentrations in the Selwyn Waihora zone as is required by the The Resource Management Act 1991. The monitoring programmes are reviewed periodically with the most recent review of the groundwater quality and water level network being in 2022. The state purpose of the groundwater monitoring programme is to:

- Monitor long-term groundwater state and trends.
- Improve scientific understanding of Canterbury groundwater systems and help Environment Canterbury manage groundwater in the region.
- Assess progress against freshwater outcomes.
- Inform the effectiveness of regional policies and plans (Knottenbelt et al., 2023).

Although many landowners have stated they have already fully implemented the required reductions (Scott, 2023), NO_3-N concentrations at most sites in the Selwyn Waihora zone have not yet shown any significant reductions (Knottenbelt, 2023). This discrepancy could be caused by a number of factors including:

- Lag
  - NO_3-N concentrations have not yet reached steady state with the monitoring network.
  - Historical increases in NO_3-N concentrations that have yet to reach steady state with the monitoring network.
  - NO_3-N stored in the unsaturated (vadose) zone.
- Insufficient precision in the NO_3-N monitoring programme (a lack of detection power).
- Nitrate loss mitigations are less effective than expected.
- The difference in NO_3-N load and NO_3-N leachate concentration. PC_1 reductions are defined as percent reductions in NO_3-N load. Changes in coincident land surface recharge changes (e.g., more efficient irrigation) can yield increasing or decreasing NO_3-N leachate concentration.
- Poor or incomplete implementation of on-farm mitigations.
- Other factors such as climatic variations and boundary condition changes (e.g., changes in losses from leaky water races) impacting groundwater recharge.

The purpose of this study is to better understand:

1. when the implemented reductions should be observable in the current monitoring programme
2. obstacles to detecting NO_3-N reductions in the Selwyn Waihora zone.

We focus on the potential statistical errors that can arise from the monitoring programme design. The monitoring programme detecting a trend when none is present (Type I error), failing to detect a real trend (Type II error), or estimating a trend that is opposite to the one present (Type III error); could affect any management decisions based on the monitoring results could undermine rather than support the management objectives.

2 Study Methodology

2.1 Receptors, Data processing, and analysis

ECAN (Environment Canterbury) provided us with NO_3-N concentration data for approximately 100 sites which included groundwater monitoring wells, spring fed streams and the Selwyn Waikirikiri River at Coes Ford. The Selwyn Waikirikiri River has both hill fed and spring fed components, but in the lower catchment it is a gaining stream and the low flows are dominated by spring fed flow. We worked collaboratively with ECAN to select a subset of sites for analysis (Figure 2.2). Our final set of sites includes 46 groundwater wells and 10 surface water features. The raw data and all outputs are available in the Project Github Repo (Project Github Repository) and a summary table of the data is available in Appendix A. Groundwater age data (WAD-MRT (water age distribution and mean residence time) and age distribution parameters) were also provided by ECAN. Note that the age data is not available for all sites.

Box 2.1: How mean residence time is identified

Groundwater ages are typically estimated from measured environmental tracers such as chlorofluorocarbon, tritium and sulfur hexafluoride. We have historical atmospheric concentrations of these tracers. Because these tracer are conservative (concentrations do not change over time) or breakdown at a known rate we can use them to estimate the age of the groundwater. This is typically done using simple 1D mixing models, such as the exponential piston flow model. These mixing models provide a distribution of ages for the water in the sample and the mean of this distribution is the mean residence time. Because these mixing models simplify the systems there is some inherent, often unquantified, uncertainty in the age estimates. Nevertheless, these ages provide useful constraints on the distribution of ages in the aquifer and are useful for understanding the potential pathways of contaminants.

The data was processed as follows:

1. **Outlier Identification**: we identified two types of outliers (see Figure 2.1):
   (a) True outliers: values which based on a statistical and visual analysis were clearly outside the measured values for the site. These values were removed from the dataset. It is worth noting that these "true outliers" are not necessarily erroneous data, but they are not representative of the site's typical NO_3-N concentration. For instance, recharge events can cause a spike in NO_3-N concentration, which is not representative of the long-term trend.
   (b) Trend outliers: data which precede the most recent / current trend and could erroneously affect the fit of the current historical trend. These values were not included in the historical trend analysis or NO_3-N noise estimation.
2. **Estimate the age distribution, wells**: where sites did not have age sampling and modelled groundwater age distributions we estimate the parameters from nearby sites. The method was somewhat manual and was often site specific. Details on how we estimated the age distribution for each site are available in the Project Github Repo.
3. **Estimate the age distribution, streams**: There was no age estimates for the spring fed streams and the Selwyn-Waikirikiri; therefore we assessed the detection power assuming a range WAD-MRT values centered on: 5, 10, 20, and 30 years. The other age model parameters were assumed to be the median of all sites within (7.5 or 10 km) and <=10m depth. Further details are available in the Project Github Repo

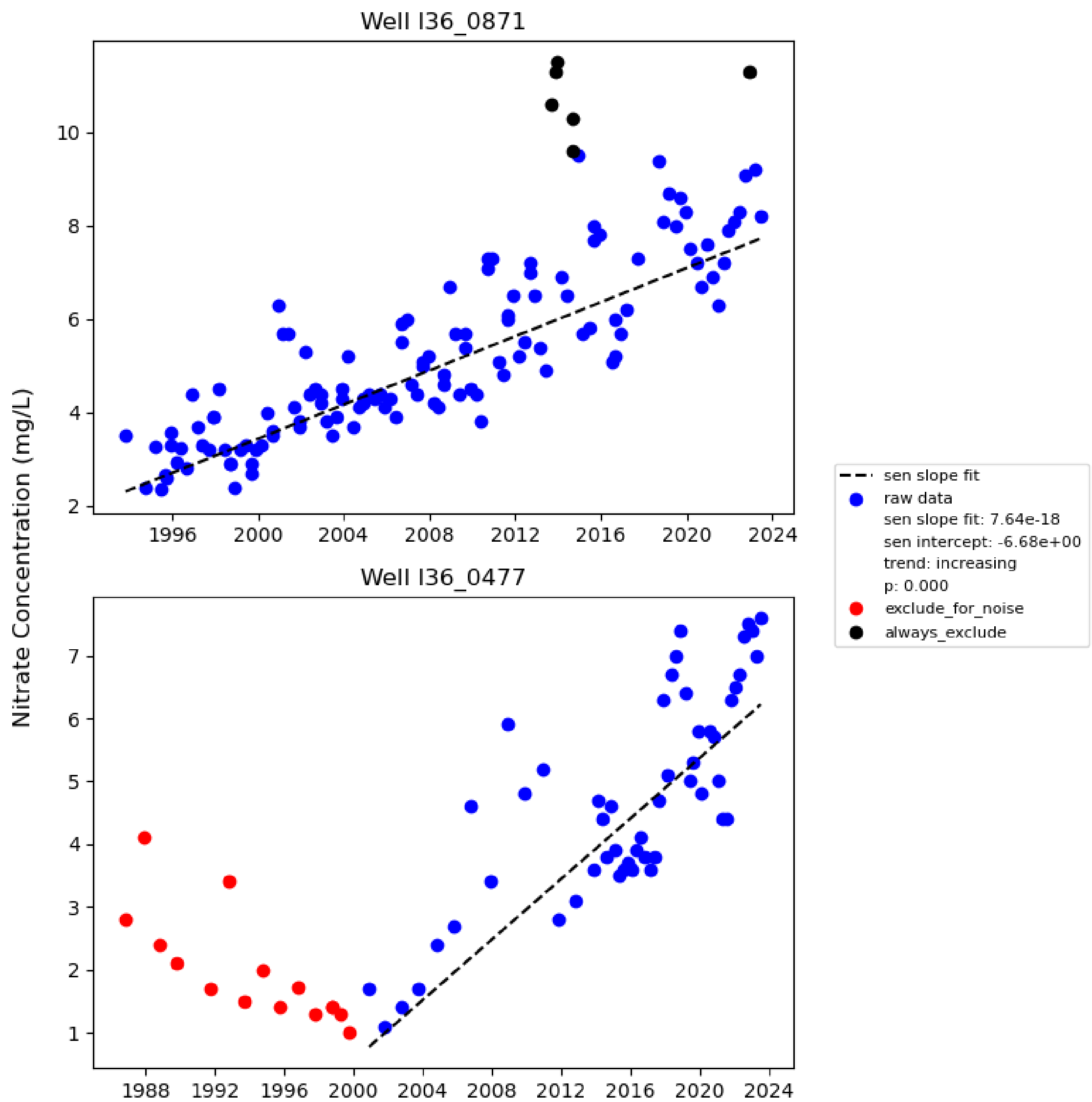


Figure 2.1: Sites L36/0871 & L36/0477: note the "true" outliers (black) and the trend outliers(red)

KSL

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

Figure 2.2: Final Site Locations

KSL

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

2.2 Assumed Pathways

In consultation with ECAN we generated the following assumed pathways for the implementation of NO_3-N reductions:

- **No change**: no change in NO_3-N source concentrations.
- **5% reduction**: a 5% reduction in NO_3-N source concentrations implemented linearly between 2017 and 2022.
- **10% reduction**: a 10% reduction in NO_3-N source concentrations implemented linearly between 2017 and 2022.
- **20% reduction**: a 20% reduction in NO_3-N source concentrations implemented linearly between 2017 and 2022.
- **30% reduction**: a 30% reduction in NO_3-N source concentrations implemented linearly between 2017 and 2022.

While PC_1 specifies the required nitrate load reductions, it does not apply to all land uses. The source zones for wells and spring fed streams will comprise a mixture of land use types and hence nitrate load loss reduction rates, but these source zones are either unknown or poorly constrained. The mandated nitrate reduction rate within the catchment area of each monitoring site could range between zero (if the catchment/source zone encompasses only land uses for which nitrate load loss reductions are not required) and 30% (if the catchment contains only high intensity land use for which a 30% reduction is required). We therefore modelled a range of nitrate loss reductions (aka assumed pathways).

2.3 Detection Power Methods

The method to calculate the detection power of a given site was implemented after Dumont et al. (2024) using our open source package (Dumont, 2023b). Briefly the methodology is as follows for each site:

1. Ascertain whether the historical concentration data has a statistically robust trend (e.g. via a Mann-Kendall test, see Figure 2.1)
2. Estimate the noise in the receptor concentration time series
   (a) If the historical concentration data has an increasing statistically robust trend, then the noise can be estimated as the standard deviation of the residuals from a model (e.g. a linear regression or Sen-slope/ Sen-intercept).
   (b) If the historical concentration data does not have a statistically robust trend, then the noise can be estimated as the standard deviation of the receptor concentration time series.
   (c) If the historical concentration data has a statistically robust decreasing trend, we assumed that the receptor was at steady state and considered the site in the same fashion as a site with no statistically robust trend. This assumption was used because it is very difficult to estimate the historical pathway of a decreasing trend as the maximum concentration is unconstrained. While this will likely underestimate the detection power, it is a conservative approach and only affects a small number of sites (only 3 of 46 sites in this study).
3. Estimate the average source zone concentration (i.e., at the base of the root zone) from the historical trend (if any) and the groundwater age distribution.

4. Predict the true receptor concentration time series (e.g., the concentration at the receptor if there was no noise) based on the aforementioned source concentration, assumed pathway and the groundwater age distribution.

5. Resample the true receptor concentration time series to the desired sampling frequency and duration (e.g., quarterly sampling for 10 years).

6. Calculate the statistical probability of detecting the change

   (a) generate a synthetic sample of the receptor noise (e.g., by sampling a normal distribution)

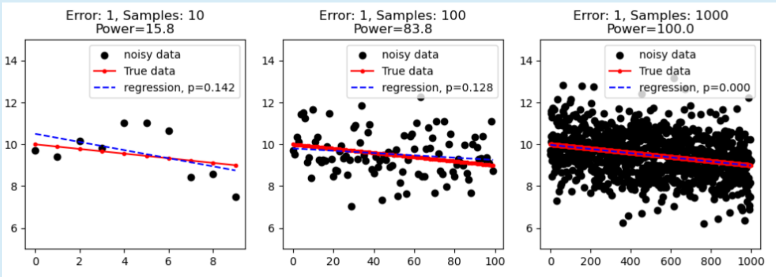
   (b) add the synthetic noise to the true receptor concentration time series

   (c) conduct a statistical test (here we used a Mann-Kendall test or a Multipart Mann Kendall test) to determine if the synthetic receptor concentration time series has a statistically robust trend

   (d) repeat steps a-c many times (we used 1000 iterations). The probability of detecting the change is the number of times the synthetic receptor concentration time series had a statistically robust trend divided by the number of iterations.

Box 2.2: What is Detection Power

Essentially, detection power describes the chance that you can see what's really going on in the data. More specifically, detection power is the percent probability of detecting a statistically robust trend in the receptor concentration time series. Noisy data reduces the detection power while more frequent sampling increases the detection power.



The source concentration was estimated by fitting a simple source to receptor model. The source concentration was set via a parameterised trend and minimum value. The assumption is that the source concentration has been monotonically increasing with time from a minimum value of 0.01 mg/l NO_3-N. The source concentration was then transformed to the receptor concentration via the exponential piston flow model see Box 2.3. We then conducted curve fitting to find the best fit of the source concentration to the receptor concentration. Figure 2.3 provides an example of the source concentration estimation. Site M36/0698 has a statistically robust increasing trend, approximately 0.12 mg/l/yr NO_3-N. Given the WAD-MRT of 22.75 years the best fit of the data (solid gold line) suggests that the peak source concentration is likely to be c. 7 mg/l NO_3-N (dashed gold line). More details on this process are available in Dumont et al. (2024); Dumont (2023a)

For the statistical test we used:

- A **Mann-Kendall test** for sites without an increasing trend

- A **Multipart Mann-Kendall test** for sites with an increasing trend. We used a Multipart Mann-Kendall test here as an increasing trend can continue after the implementation of PC_1, due to historical increases in NO_3-N source concentrations which have not reached steady state at the receptor. A traditional Mann-Kendall test would require the absolute knowledge of the time of the maximum NO_3-N receptor concentration. A Multipart Mann-Kendall test does not require this knowledge. For more information see Dumont (2023c)

We set the critical level at 5% (<0.05) for both tests. For the Mann-Kendall test this means that the trend was detected if p<0.05. For the multipart Mann-Kendall test this means that the trend was detected if there was

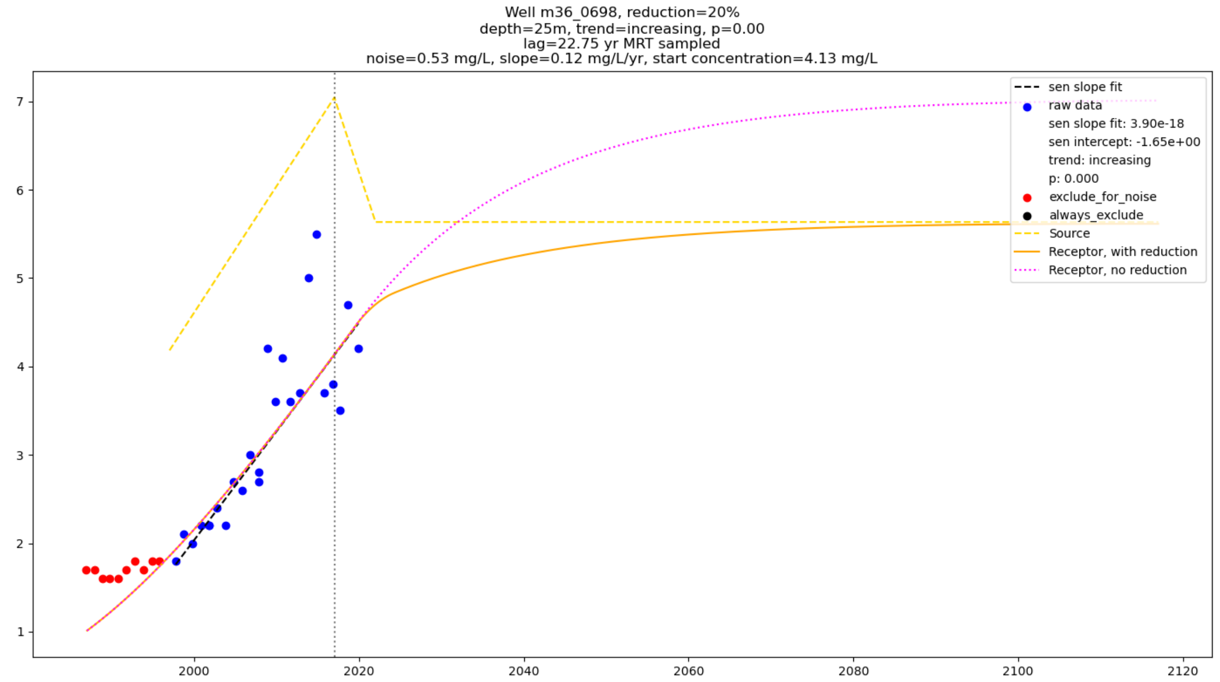


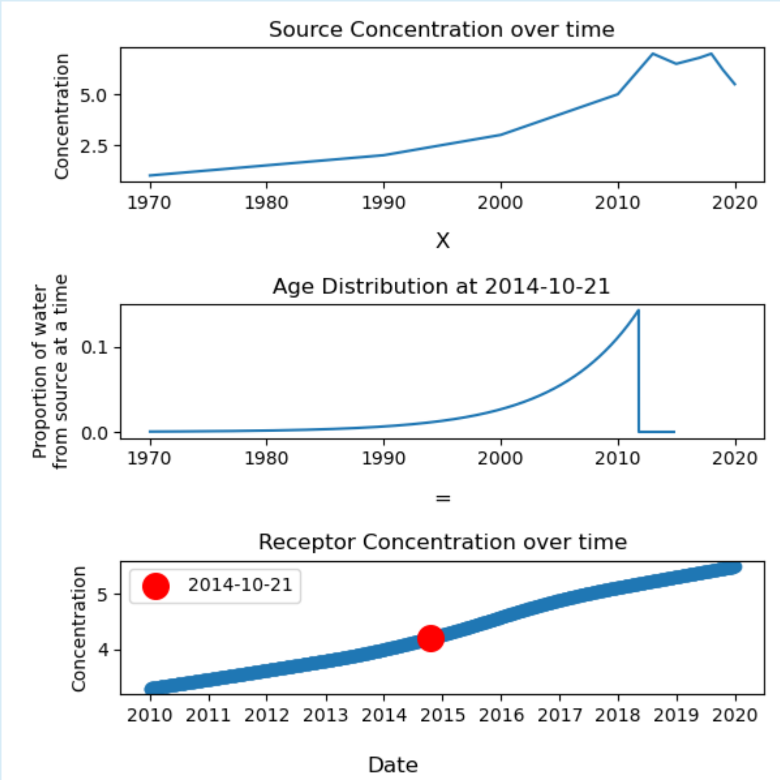
Figure 2.3: Site M36/0698 as an example of the source concentration prediction

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

any breakpoint where the older data was increasing ($p<0.05$) and the newer data was decreasing ($p<0.05$). Note that a minium of 5 datapoints were required for each part in the multipart Mann-Kendall test. Finally, some sites will not have a decreasing NO_3-N concentration because the implemented nitrate loss reduction is insufficient to reduce steady state concentrations below the current level. In this case the aforementioned multipart Mann-Kendall test would never detect a trend. Therefore, we conducted a subsequent multipart Mann-Kendall test which identified a breakpoint where there was an earlier increasing trend ($p<0.05$) and subsequently no trend ($p>0.5$). These plateau sites are further discussed in Section 3.1.1.

Box 2.3: Source to Receptor Concentration

The receptor concentration at a given time is calculated from the source concentration using a exponential piston flow model. For instance below the concentration in the receptor at 2014-10-21 (red circle) is calculated as the sum of the source concentration time series times (plot 1) the proportion of the water in the receptor on 2014-10-21 that originated from the source at that time (plot 2).



3 Results and Discussion

3.1 Results for Individual Sites

Although we have produced results and figures for each site, it is beyond the scope of this report to discuss the detection power of each site; however all figures are available in the Project Github Repo. An example of the individual site detection power plots is shown in Figure 3.1. The figure details the detection power of site M36/3588 assuming a 30% reduction in nitrate concentrations. There are two subplots; for both the x-axis is the sampling duration/date. For the top plot the y-axis is NO_3-N concentration (mg/l). The raw sample data and whether those data were included in the analysis (blue included, red/black not included), the predicted source concentration (yellow), the predicted receptor concentration with (gold) and without the implemented reduction (fuchsia) are all plotted. In the lower subplot the y-axis depicts the likelihood that a change in nitrate concentrations will be detected. The color of the line represents the sampling frequency (e.g. monthly, quarterly, etc.). Note that the black/grey line is the detection power assuming that the receptor has no NO_3-N noise. Effectively, the black/grey line is when the change would be detected if only lag was considered. The correct interpretation of this plot is that the lag at this well only allows a theoretical change detection at or after 2027 (grey line). However, if we consider the obscuration of noise, then with quarterly sampling the detection power is only likely to exceed 80% in 2037 (gold line). We use the cutoff of 80% as it is typically used nationally and internationally as the acceptable threshold for confidently drawing conclusions and/or making decisions from the monitoring results interpretation (Dumont et al., 2024).

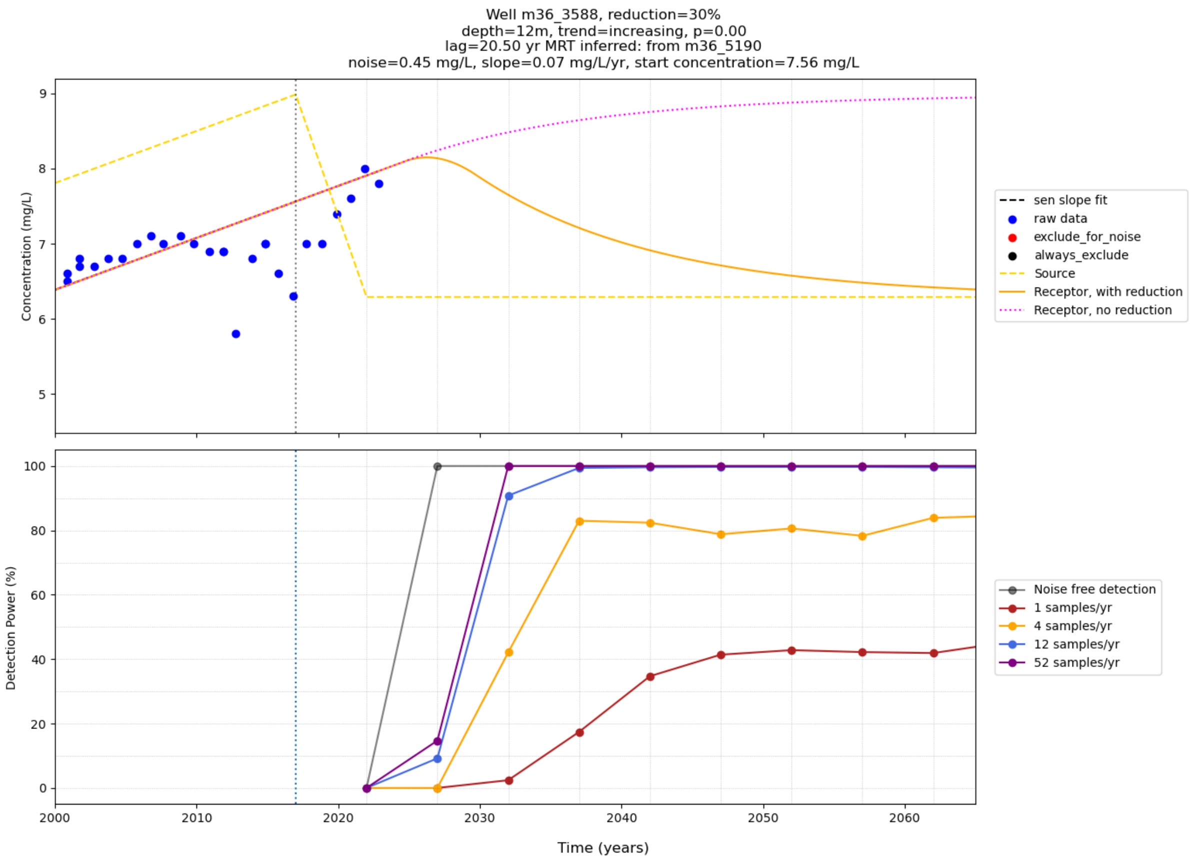


Figure 3.1: An example of the individual site detection power plots

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

3.1.1 Plateau Sites: Sites Where NO_3-N Concentrations Will Not Decrease Under the assumed Pathway

Some sites will not show a statistically robust decreasing trend under the assumed pathway. We refer to these sites as plateau sites. An example of a plateau site is shown in Figure 3.2. Well L35/0205 is a plateau site because the steep increasing trend in concentration in combination with the significant WAD-MRT suggest that the source and receptor concentration are at a significant disequilibrium. Therefore, the rather minor reductions (10%) in the assumed pathway will simply lower the eventual steady state concentration (e.g., gold vs fuchsia lines), but will not reduce the concentration below the observed initial concentration (sen slope fit in 2017).

Table 3.1: Percent of the groundwater network that will level off but never show a decreasing trend in the receptor at a theoretical reduction level at the source

Reduction	Plateau sites
5%	57%
10%	48%
20%	33%
30%	9%

These plateau sites can cause a significant challenge in detection of nitrate leaching reductions. Our knowledge of equilibrium nitrate concentrations in the absence of nitrate loss reductions is poor. This makes it difficult to understand the cause of any difference between a future observed steady state concentration (once concentration levels off) and the predicted steady state concentration (e.g., the fuchsia line in Figure 3.2). The differences could be due a number of factors (see Section 1) as well as, on the ground actions not actually being implemented and/or inaccuracies in the estimate of steady state concentration. These sites will require more sophisticated statistical analysis (for instance a counter-factual approach) to determine whether the PC_1 nitrate loss reductions have been effective.

Figure 3.3 shows the location of these plateau sites and the required reduction to yield a decreasing NO_3-N slope in the receptor. Note we did not include the surface water features here as there is too much uncertainty surrounding their WAD-MRT. For the red shaded sites nitrate concentrations would only expect to decline in the well if the average nitrate loss reduction in the monitoring well capture zone is greater than 5% otherwise the NO_3-N concentrations will plateau at a lower level than if no reductions had occurred. If an average nitrate loss reduction of 10% is assumed, nitrate concentrations in the fuchsia, gold and blue shaded sites would all plateau at some point in the future, with no measurable decrease occurring. Table 3.1 shows the percent of the groundwater network that will not show a decrease in NO_3-N concentrations at a given reduction level in the source. For example, 57% of the groundwater network will not show a decrease in NO_3-N concentrations if the source is reduced by 5%. This suggests that the PC_1 reductions may not yield steady state concentrations below 2017 concentrations for a significant portion of groundwater network; however this is not necessarily a failure of PC_1 as concentrations were expected to continue to increase after the implementation of PC_1, but to achieve an average concentration of <8.5 mg/l.

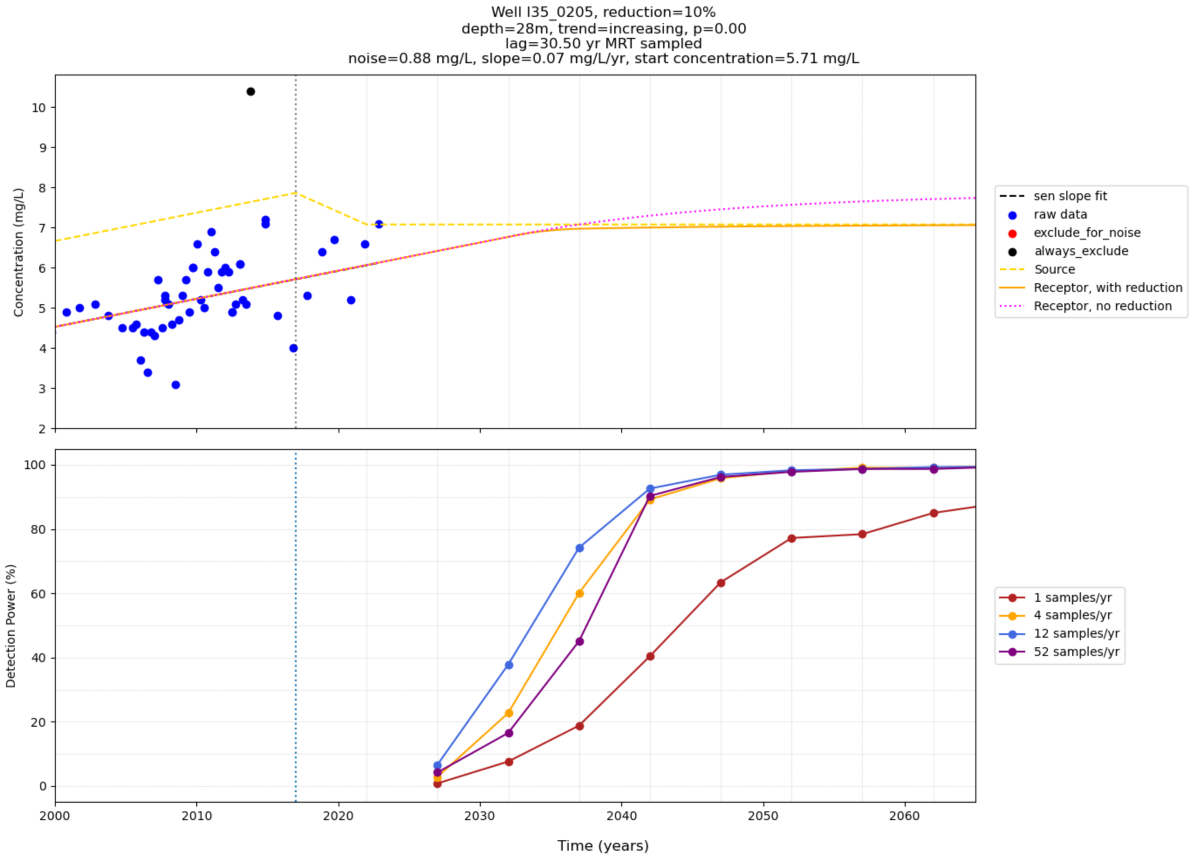


Figure 3.2: An example of a Plateau Site

KSL	**Project**: Selwyn Waihora Detection Power **Client**: Environment Canterbury **Date**: 19/02/2024

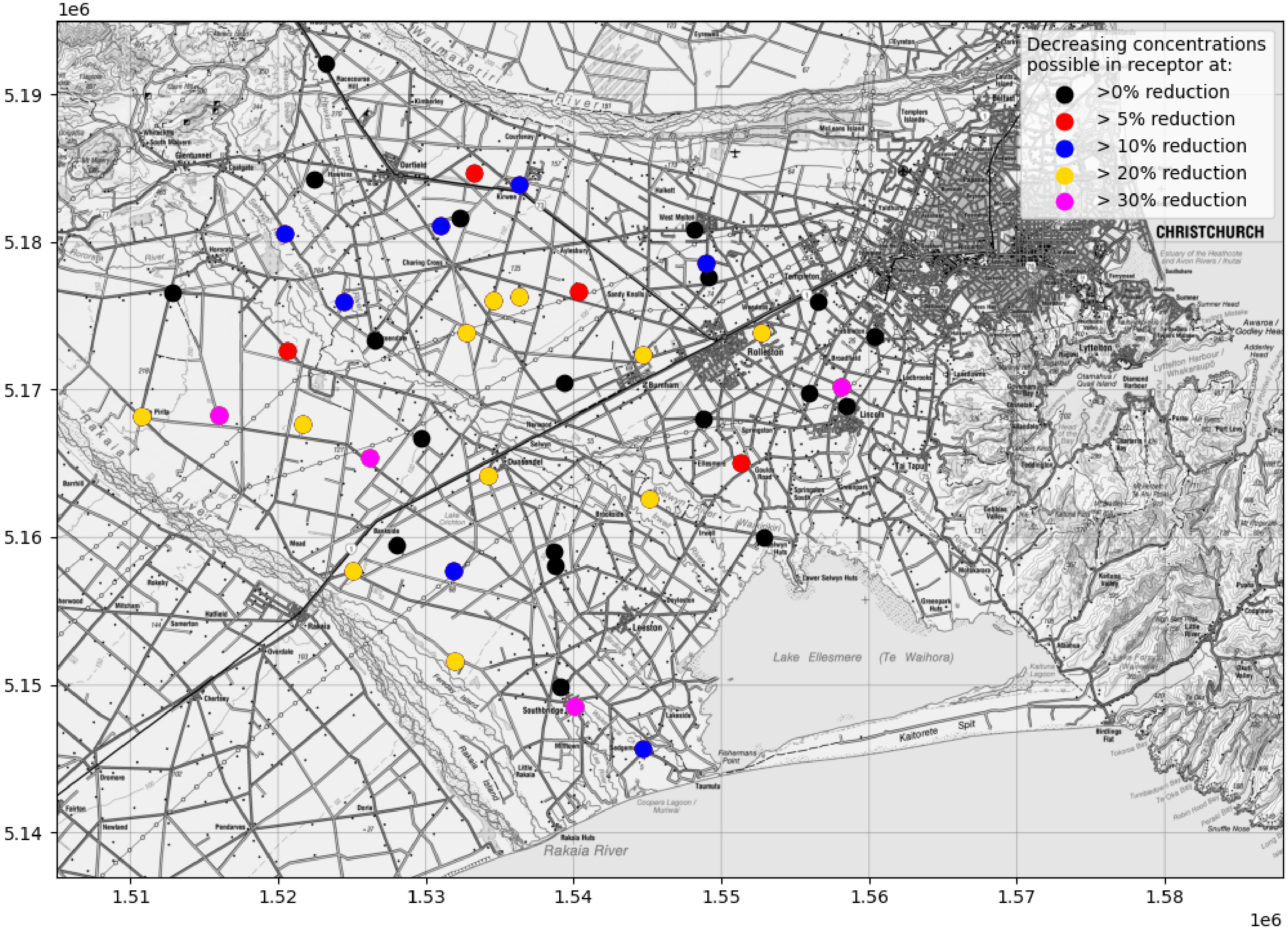


Figure 3.3: The NO_3-N reductions needed at a given site to yield a negative slope rather than a lower steady state concentration (wells only)

3.2 Mean Residence Time, Steady State Concentration, and Detection Power

Our use of a set of indicative WAD-MRT values for surface water features demonstrates the impact that uncertainties in the age distribution impacts both detection power of a receptor, and its steady state NO_3-N concentrations. Figure 3.4 demonstrates the impact of the assumed WAD-MRT on the estimation of the steady state NO_3-N concentration in Harts Creek. Harts creek is a small spring-fed tributary of Te Waihora (Lake Ellesmere) on the southwestern side of the lake. There a substantial historical record of increasing NO_3-N concentrations, but there are no data on the age of the water within the creek. Our simple source concentration modelling (see Section 2.3) and the measured nitrate concentration data prior to 2017 suggest that the peak steady state concentrations in the receptor (without reductions) could range between 7.6 to 12.0 mg/l NO_3-N depending on the WAD-MRT assumed. This large range is significant from a water resource management perspective — the maximum possible value is beyond the drinking water limit. Concentrations in spring fed streams above the drinking water limit would imply that water supply wells in the steam catchment are, on average, likely to exceed the limit. In addition, the nitrate loss reductions required to achieve the national bottom line nitrate concentration in the stream vary widely between these two estimates, which has important implications for farming in the stream catchment (though as noted this threshold postdates PC_1).

Box 3.1: Counterinuitive Results

Some of the results here are counterintuitive; for instance, in Figure 3.4 the detection power is higher with a WAD-MRT of 10 years than with a WAD-MRT of 5 years. Additionally, for some receptors (not pictured) the detection power increases and then subsequently decreases with increasing sampling duration.

This odd behaviour is due to the statistical method used. Fundamentally we are fitting a Mann-Kendall test to the data and specifying success as $p<0.05$. A rapid change (low lag and/or a swift implementation period) pared with infrequent sampling can lead to the receptor reaching steady state before the statistical test can confidently detect the reduction. The ensuring long flat period, where the true receptor concentration is not changing, leads to a higher p-value in the statistical test and therefore lower detection power. In these instances another statistical test (e.g., a counterfactual approach), maybe a more robust method to detect the change. This is discussed in Section 3.4.

The uncertainty in the likely maximum peak concentration in this receptor could be significantly constrained with one or more relatively cost-effective age tracer samples. It is also worth understanding that in surface water features WAD-MRT may not be a static value, but may vary with stream flow with higher flows, where runoff is a higher percentage of the flow, having a younger WAD-MRT than base flows where more of the stream flow is likely derived from older groundwater.

The WAD-MRT is also a significant factor for detecting PC_1 NO_3-N reductions. If the WAD-MRT is relatively low (5-10 years) then it would be feasible to detect PC_1 reductions by 2032 with the current (monthly) or slightly higher sampling frequency. A higher WAD-MRT of 20 years would significantly reduce detectability and with a WAD-MRT of 30 years, the PC_1 nitrate loss reductions are unlikely to result in a decrease in NO_3-N concentrations (see Section 3.1.1) relative to their 2017 concentrations. Note that the counterintuitive result that the detection power with WAD-MRT of 5 years is lower than that of WAD-MRT 10 years are discussed in Box 3.1.

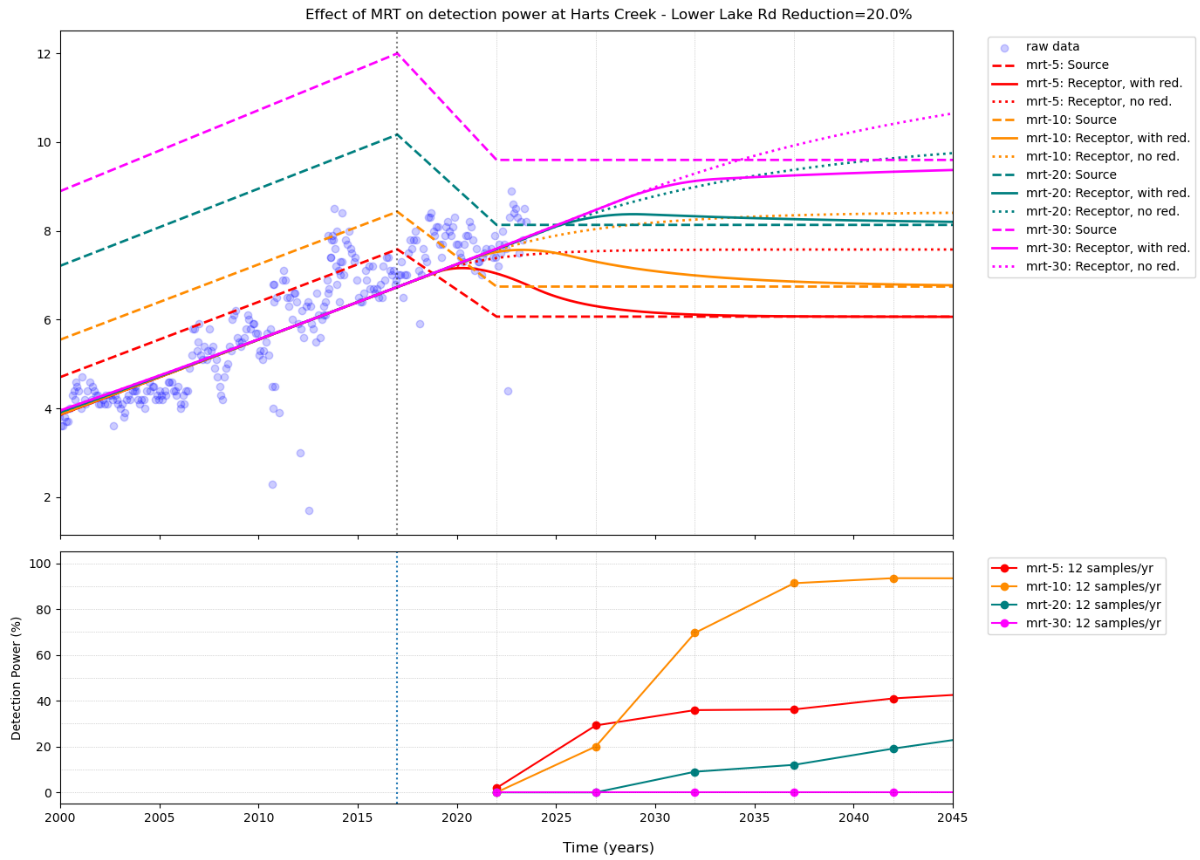


Figure 3.4: The impact of assumed WAD-MRT on the steady state NO_3-N concentrations and the potential to detect PC_1 reductions (red.)

For example, if WAD-MRT to the river site is less than 5 years, a decreasing trend would be observed, but if the MRT is 30 years then legacy nitrate will still be in transit and concentrations continuing to increase before they plateau.

KSL

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

3.3 Network Level Detection Power

Figure 3.6 shows the sampling duration required to detect PC_1 nitrate loss reductions (assuming a 20% reduction) with 80% probability using quarterly sampling. The black dashed line in Figure 3.7 shows the percentage of the network which can detect PC_1 reductions assuming that the true receptor concentration (i.e., with no noise) is known. This analysis includes the effects of lag, but excludes the obscuration of the reductions by NO_3-N variability / noise and therefore represents the upper limit of change detection potential for very low (zero) noise sites or at very high sampling frequencies. Figure 3.5 provides a geospatial representation of Figure 3.6 and the 20% subplot of Figure 3.7. In combination these figures shows that the vast majority of the groundwater network will not be able to detect PC_1 reductions with quarterly sampling. Increasing the sampling frequency can significantly increase the detection power of the network, but the detectability is constrained by the lag component - time needs to pass before we can identify the reductions.

Box 3.2: Historical mean well sampling frequency

- **Annually - Biannually**: 27 sites
- **Biannually - Quarterly**: 10 sites
- **Quarterly +**: 9 sites
- **46 sites total**

These results are consistent with the observation that very few monitored wells in the catchment currently have a statistically significant reducing trend (only 3 of 46 sites in this study, and only 9 of 102 sites for which we were originally provided data by ECAN). Given our results, the lack of reducing NO_3-N concentrations cannot distinguish whether or not PC_1 reductions have been successfully implemented. If we assume a full 20% NO_3-N reduction in all the source zones, then of the 46 groundwater sites in this study, only 30 sites will have any decreasing NO_3-N concentrations(see Section 3.1.1). At current quarterly sampling rates, it will likely take until 2062 before 15 sites (50% of those that we modelled as having decreasing NO_3-N concentrations) will have a statistically significant reduction in NO_3-N concentrations. Increasing to weekly or monthly sampling would improve the detection power of the network, and we could expect detection in those 15 sites by 2042 and 2037, respectively. However, any increase in sampling frequency would require a proportional increase in resource for the monitoring programmes.

Figure 3.7 shows the effect of different reductions on detection power with a quarterly sampling frequency. Note that these figures exclude the plateau sites (see Section 3.1.1 and Table 3.1). If we assume 10% reductions on average in the source zone, then:

1. Nearly 50% of the network wells will never measure a decreasing NO_3-N concentration.
2. With quarterly sampling we would not expect to see evidence of a 10% reduction (via a decreasing trend) in more than 10% of the remaining network and not until after 2050.
3. Increasing sampling frequencies to monthly or weekly would significantly improve the probability of detection these changes(Figure 3.8). Note that increasing sampling frequency will not impact the plateau sites.

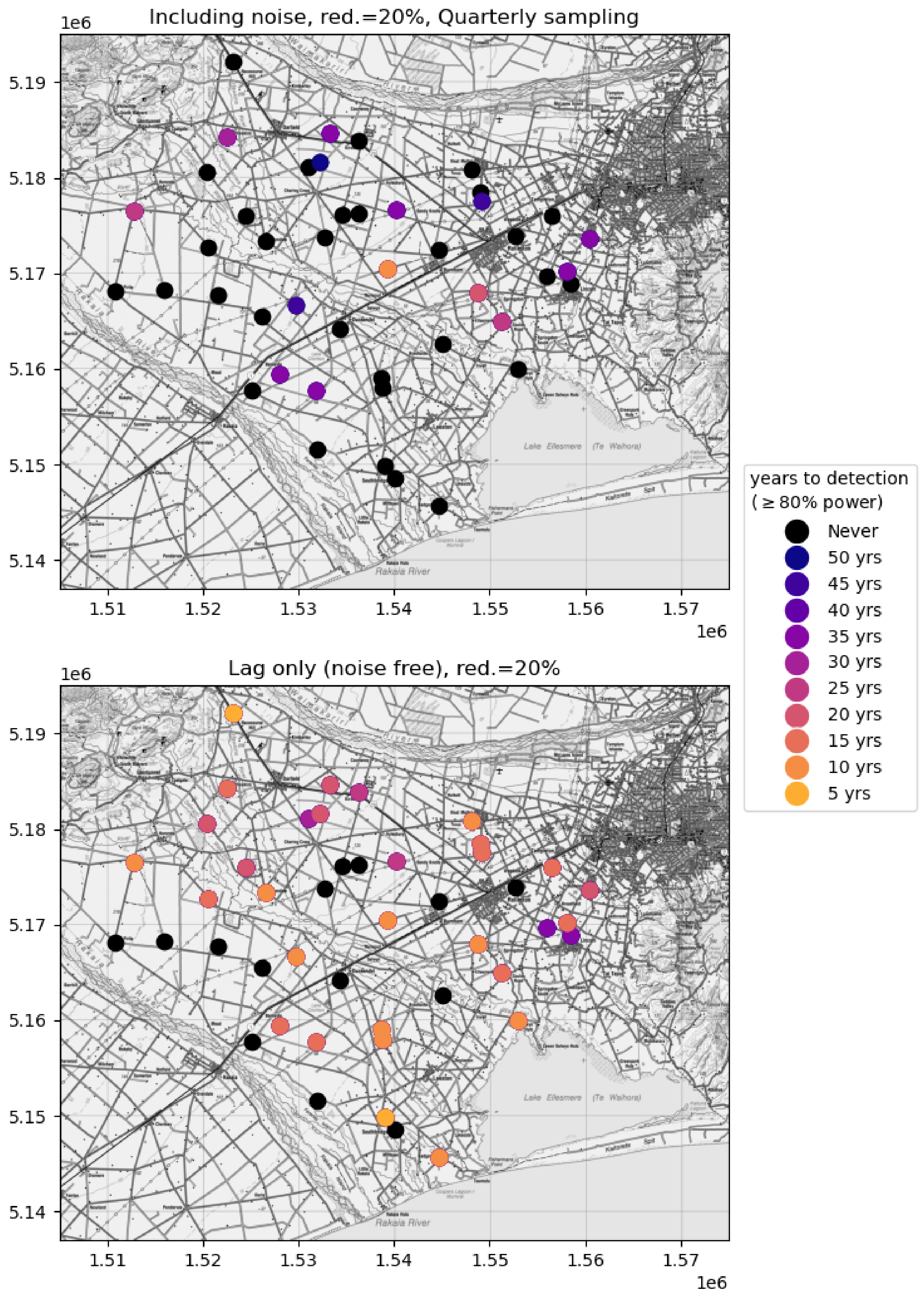


Figure 3.5: Sampling duration until the probability of detecting a reduction is $\geq 80\%$

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

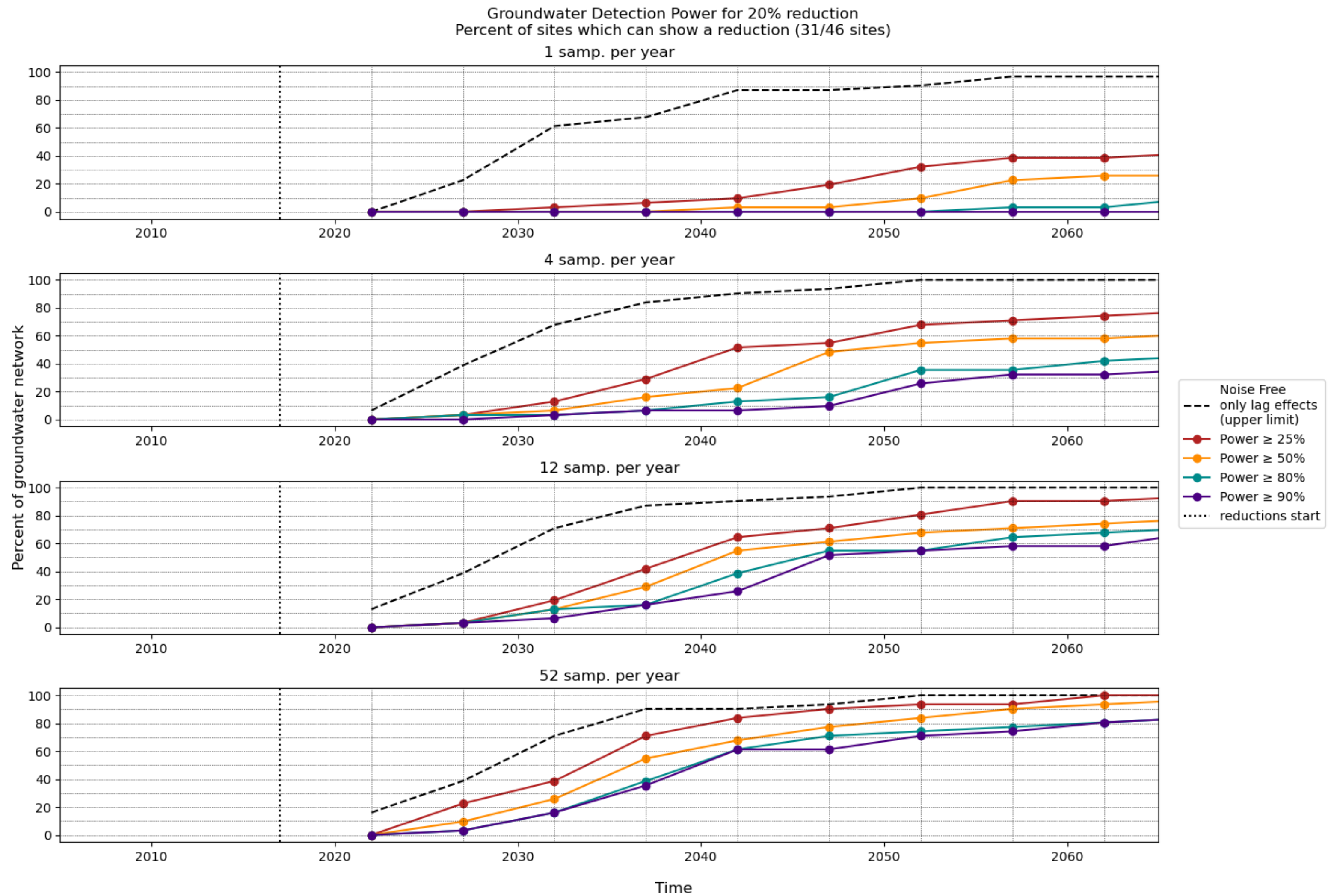


Figure 3.6: The proportion of the groundwater network whick is likely to detect the full PC_1 reductions (20%)

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

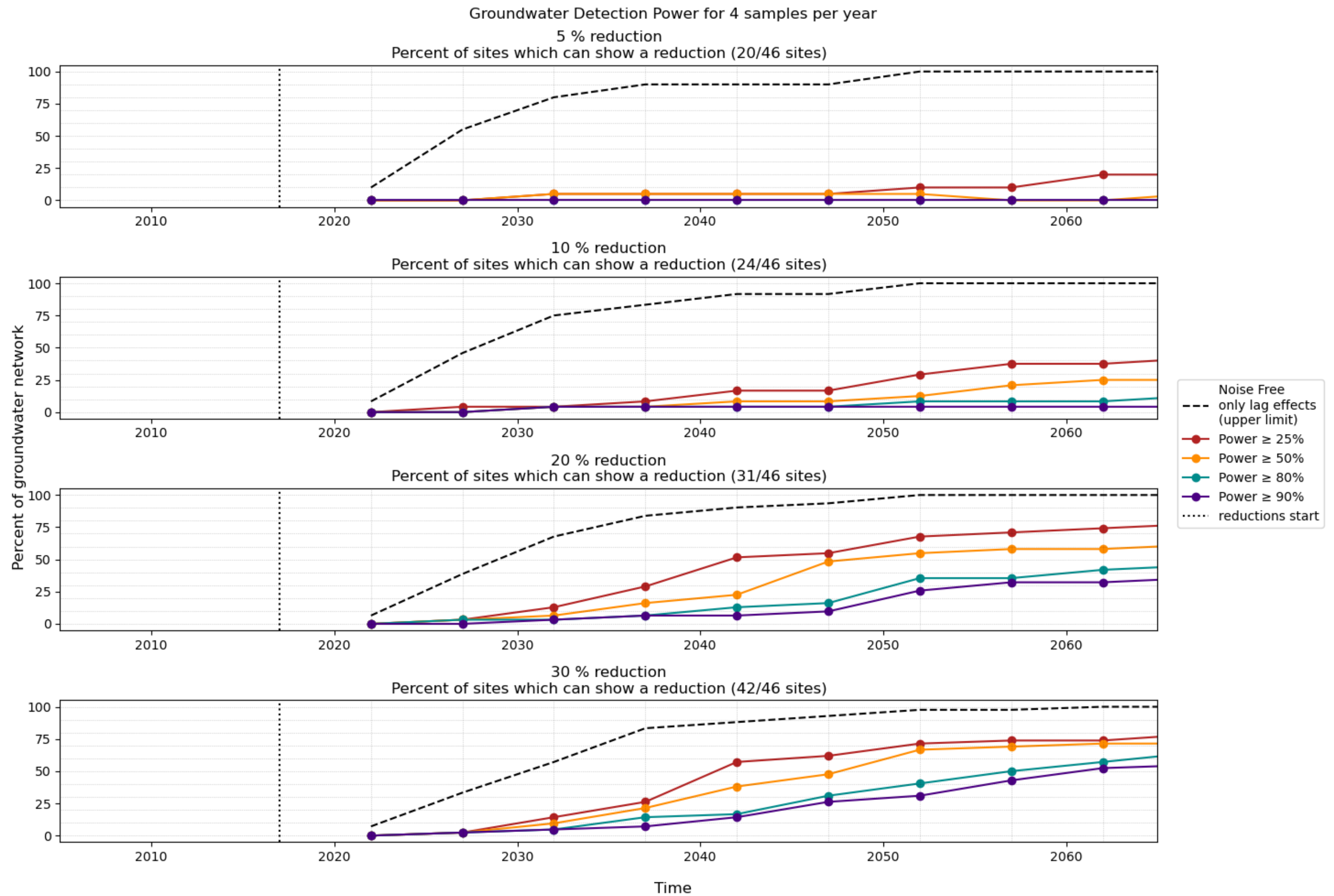


Figure 3.7: The propotaion of the groundwater network which is likely to detect reduction at the current quarterly sampling frequency

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

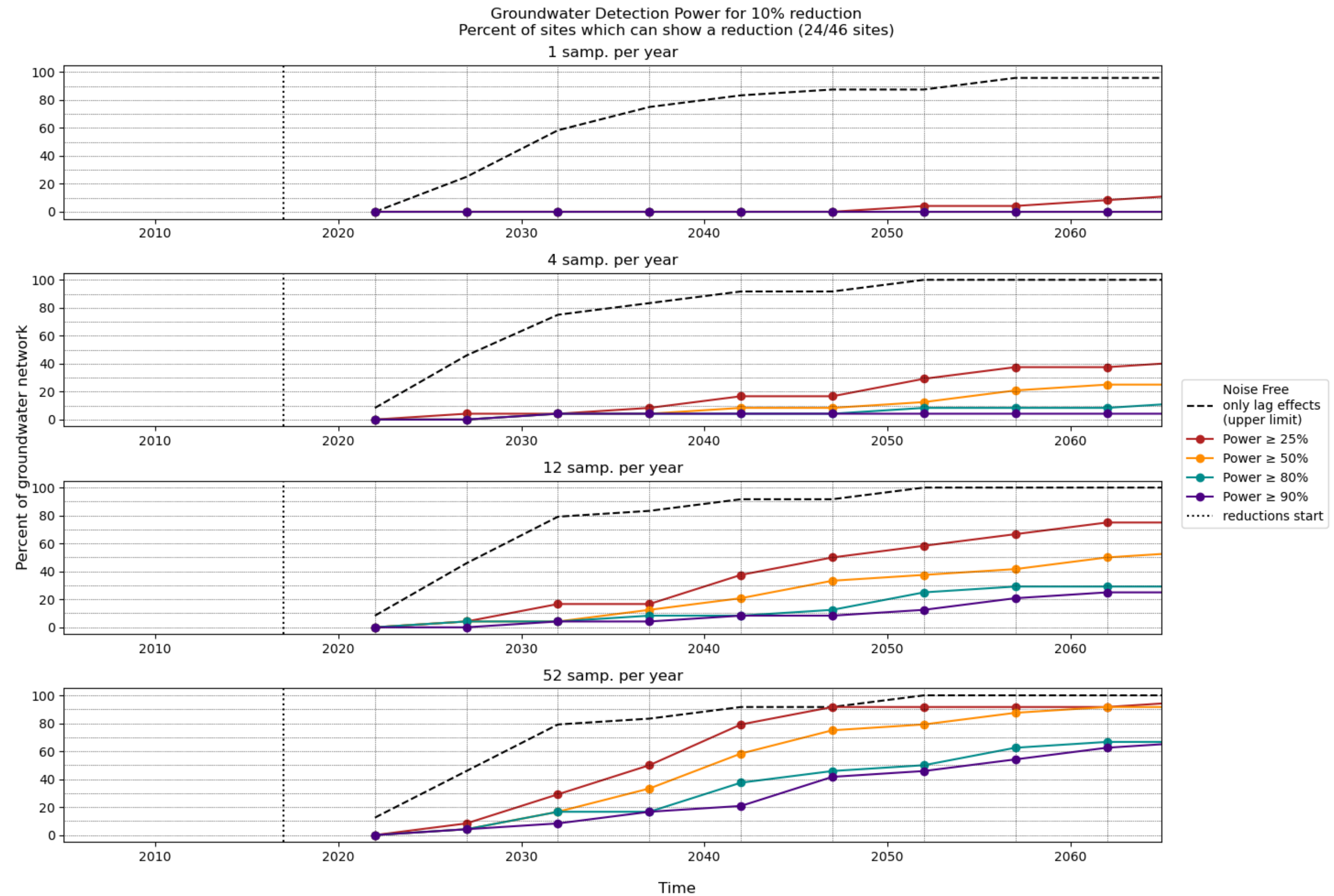


Figure 3.8: The proportion of the groundwater network which is likely to detect the full PC_1 reductions (10%)

Project: Selwyn Waihora Detection Power
Client: Environment Canterbury
Date: 19/02/2024

3.4 The Benefits of a Future Counterfactual Approach

The analysis presented here is designed to answer the question: "How long will it take to detect *any* reduction in NO_3-N at our existing receptors?" This is a useful question, but it is not the only question that can be asked. For example, we could ask: "How long will will we need to monitor to determine whether a 20% concentration reduction has occurred?" or "How long before we can determine whether or not we are on track for at least a 10% NO_3-N reduction?". These questions require a different statistical approach — a counterfactual approach. Essentially, the question answered by a counterfactual approach is: "How long until we are confident that pathway 1 (e.g. no reduction) and pathway 2 (e.g., 10% reductions) are significantly different?". A counterfactual approach has not yet been implemented in the groundwater detection power calculator (Dumont, 2023b), but it is being developed and will be available by mid 2024. It is worth noting that any uncertainty in the source concentration (i.e., at the base of the root zone), which is typically uncertain, is more likely to yield additional uncertainty in the counterfactual detection power. This is because the absolute difference between two pathways is important under a counterfactual approach whereas only the relative change is necessary for the 'reduction' detection power approach presented in this report.

Finally, it should be noted that neither the approach presented here nor the counterfactual approach can reliably determine whether a specified concentration reduction has occurred: a steady state receptor nitrate concentration at the time the reduction is implemented would be required for this. Depending on the distribution of the water age, it can take significantly longer than the WAD-MRT for a receptor to reach steady state with current land use.

3.5 How to Improve the Detection Power of the Existing Network

Our results suggest that the current monitoring programme is unlikely to detect whether the PC_1 NO_3-N reductions have been implemented successfully in the short to medium term under the current monitoring frequency. It may be possible to reduce the monitoring duration required to detect change via bespoke monitoring at new sites with a low WAD-MRT and low signal/noise ratio. Of course sufficient sampling, and thus time, would be required at any new site. Although reducing NO_3-N concentrations in any new site would provide confidence that NO_3-N concentrations are going in the right direction (down), the results could not prove that the changes were due to PC_1 because these reductions have, theoretically, already been implemented. Some young groundwater could already be approaching steady state with respect to the PC_1 nitrate loss reductions. This means that, depending on the WAD-MRT, a zero change in concentration could be consistent with successfully implemented PC_1 reductions.

Instead, we suggest that the best approach to improve the unambiguous detection of PC_1 reductions is to:

1. Increase the certainty of the WAD-MRT estimates in groundwater detection network; only c. 30% of groundwater sites had a WAD-MRT assessment (e.g., via tritium). The remaining 60% were estimated from nearby wells, which introduces a significant amount of uncertainty. Further age assessments would significantly improve the certainty of the network's detection power and allow increased frequency sampling to occur at sites which are likely to detect the change.

2. Increase sampling at selected sites that this analysis (or additional analysis with additional WAD-MRT assessments) show a suitably high probability of detecting PC_1 reductions.

3. Similar to 1. the surface water network has a significant amount of information about the catchment and acts as an integrator of water quality from a much larger sample of land within the Te Waihora catchment. This alleviates some of the challenges of the spatial representativeness of the groundwater network (Etheridge et al., 2023); however the utility of this information is thwarted by the lack of WAD-MRT assessments. Understanding the age distribution and the relationship between the age distribution and river/stream stage/flow would unlock the power of these sites and support design of an optimized and integrated water quality monitoring programme.

4. Finally, more sophisticated statistical analysis could be used to extract more information from the existing data and significantly reduce the time required to determine whether the PC_1 plan rules and associated land management actions are successfully reducing nitrate concentrations.

Importantly, the current network is used for more than just change detection. In some cases these alternative uses are directly in conflict with change detection. For instance, if the purpose of the network is to provide a broad understanding of the state of the aquifer, then it is essential to monitor deep bores with longer lags to provide an accurate picture of that portion of the aquifer. These bores by their very nature will never be ideal for rapid change detection. Our suggestions are specifically for improving the detection power of the network for the purpose of detecting PC_1 reductions or similar actions in the future. A monitoring programme must be fit for the specific purpose for which they are designed and we cannot comment on the overall quality of the network.

4 Limitations

This work has a number of limitations:

- Many of the WAD-MRT estimates are based on estimates from nearby wells. This introduces a significant amount of uncertainty into the WAD-MRT estimates.
- The WAD-MRT estimates are based on a simple 1D mixing models and are therefore uncertain.
- We have not included any signal decomposition in our analysis of the NO_3-N noise. More complex modelling of the observed NO_3-N concentrations could significantly improve the detection power of the network; however this likely requires more frequent sampling than is currently available.
- We have assumed that the source concentration has a single monotonic trend. This is unrealistic and may yield an under or overestimate of the steady state concentration.
- Our assessment of the quality of the monitoring programme is solely based on the use case of detecting PC_1 or similar reductions. The network has many more uses, and we cannot comment on the overall quality of the network.
- We have not assessed the spatial representativeness of the network, which was beyond the scope of this project.

5 Conclusions

We conclude that:

- The lack of observed reductions in NO_3-N across the Selwyn Waihora catchment is not inconsistent with full implementation of PC_1 reductions. Monitoring results to date, interpreted with simple tools (e.g, Mann Kendall or multipart Mann Kendall tests), provide no information on whether PC_1 has reduced nitrate concentrations in the catchment.
- With a full 20% reduction in NO_3-N loads in the source area only 66% of the groundwater wells assessed are likely to show decreasing NO_3-N concentrations at any point in the future. The reductions in the other 33% will simply achieve a lower steady state concentration than would have occurred in the absence of nitrate loss reductions.
- If we assume an average reduction of 10% then we would only expect to see decreasing NO_3-N concentrations in 52% of monitoring wells.
- With the current monitoring programme, the current quarterly sampling regime, and an assumed full 20% reduction; only 15 of the monitoring wells are likely to show a decreasing NO_3-N trend by 2062, increasing sampling frequencies to monthly or weekly would allow detection of the reductions in these 15 wells by 2042 or 2037, respectively.
- The lack of WAD-MRT (water age distribution and mean residence time) assessments in the surface water bodies precludes a robust assessment of the detection power of these sites. We have therefore produced estimates of the detection power for these sites under an assumed range of WAD-MRT values. The results highlight the importance of obtaining water age data for surface watercourses to understand whether actions undertaken to reduce nitrate concentrations have been successful.
- Assessments of WAD-MRT in surface water features would also help to constrain the likely maximum future NO_3-N concentration when the full effects of past land use reach the stream and the steady state concentration when water quality equilibrates with current nitrate losses from the soil profile.
- Statistical power limitations associated with the current groundwater monitoring frequency is likely to constrain detection of nitrate loss reductions to the same degree as hydrological lags. Both factors must be considered together when drawing conclusions from nitrate monitoring results. Failing to do this would equate to high risk of statistical error. If the monitoring program detects a trend when none is present (Type I error), fails to detect a real trend (Type II error), or estimates a trend that is opposite to the one present (Type III error), any management decisions based on the monitoring results could undermine rather than support the management objectives.
- The current monitoring programme is not well suited to the detection of reductions in NO_3-N concentrations in the Selwyn Waihora catchment; however the network serves multiple purposes some of which are counter to high detection powers (e.g., characterising the state of the deep aquifer system). Note we have not assessed the spatial representativeness of the monitoring network in this analysis as it was beyond the scope of this project.

6 Recommendations

Based on the work presented here we recommend the following to improve the likelihood of detecting reductions in NO_3-N concentrations in the Selwyn Waihora catchment. Note that our recommendations are specific to change detection and may not apply to the other purposes of the monitoring programme.

- The monitoring design framework presented in Etheridge et al. (2023) should be applied to the Selwyn Waihora catchment. We are aware of a recent network review which may have already addressed some of the issues we have identified.
- Water age sampling and WAD-MRT assessments should be undertaken for a prioritised set of monitoring sites to better constrain the detection power and the likely maximum NO_3-N concentration in streams and groundwater wells that will arise from current and past land use.
- Spring fed streams should be assigned a high monitoring priority due to their sensitivity and role as integrators of the catchment water quality over a broader area than individual monitoring wells.
- WAD-MRT assessments should be highly prioritised for the spring fed streams.
- Once the WAD-MRT assessments are complete, the detection power of the surface water features and any groundwater monitoring locations with new WAD-MRT values should be re-assessed.
- Increasing the sampling frequency is essential to improve the detection power of the monitoring programme. We recommend that targeted sites undergo higher frequency monitoring in order to meet detection timeline requirements. Once higher frequency data is available the detection power of these sites should be re-evaluated to ensure that the novel data does not change the detection power.
- Additional monitoring wells which target young waters may be useful; however there is a risk that new young wells may already be at or near steady state which would confound the detection of PC_1 reductions. The network should be reviewed and bespoke monitoring locations should be developed prior to any further mandated reduction in nitrate losses.
- More sophisticated statistical analysis could and should be used to extract additional information from the existing data.

References

Camargo, J. A., Alonso, A., and Salamanca, A. (2005). Nitrate toxicity to aquatic animals: a review with new data for freshwater invertebrates. *Chemosphere*, 58(9):1255–1267. Publisher: Elsevier. 1

Dumont, M. (2023a). komanawa.gw_age_tools. https://github.com/Komanawa-Solutions-Ltd/gw_age_tools. 2.3

Dumont, M. (2023b). komanawa.gw_detect_power https://github.com/komanawa-solutions-ltd/gw_detect_power. https://github.com/Komanawa-Solutions-Ltd/gw_detect_power. 2.3, 3.4

Dumont, M. (2023c). komanawa.kendall_stats. https://github.com/Komanawa-Solutions-Ltd/kendall_multipart_kendall. 2.3

Dumont, M., McDowell, R., and Etheridge, Z. (2024). Determining the likelihood and cost of detecting reductions of nitrate-nitrogen concentrations in groundwater across New Zealand. In submission. (document), 2.3, 2.3, 3.1

Etheridge, Z., Dumont, M., and Charlesworth, E. (2023). Water quality monitoring for management of diffuse nitrate pollution. https://github.com/Komanawa-Solutions-Ltd/gw_detect_power/blob/main/supporting_documents/Water_quality_monitoring_for_management_of_diffuse_nitrate_pollution_Final.pdf. (document), 3, 6

Horak, C. N., Assef, Y. A., and Miserendino, M. L. (2019). Assessing effects of confined animal production systems on water quality, ecological integrity, and macroinvertebrates at small piedmont streams (Patagonia, Argentina). *Agricultural water management*, 216:242–253. Publisher: Elsevier. 1

Knottenbelt, M. (2023). Annual groundwater quality survey, 2022. Environment Canterbury Science Report R23/07, https://api.ecan.govt.nz/TrimPublicAPI/documents/download/4868857. 1

Knottenbelt, M., Wilkins, B., Tregurtha, J., and Kreleger, A. (2023). Groundwater monitoring network review. Environment Canterbury Science Report R23/35, https://api.ecan.govt.nz/TrimPublicAPI/documents/download/4966091. 1

McDowell, R., Noble, A., Pletnyakov, P., Haggard, B., and Mosley, L. (2020). Global mapping of freshwater nutrient enrichment and periphyton growth potential. *Scientific Reports*, 10(1):3568. Publisher: Nature Publishing Group UK London. 1

Ministry for the Environment (2020). National Policy Statement for Freshwater Management 2020. 1

Rahman, A., Mondal, N., and Tiwari, K. (2021). Anthropogenic nitrate in groundwater and its health risks in the view of background concentration in a semi arid area of Rajasthan, India. *Scientific reports*, 11(1):9279. Publisher: Nature Publishing Group UK London. 1

Scott, L. (2023). personal communication. 1

Wagenhoff, A., Clapcott, J. E., Lau, K. E., Lewis, G. D., and Young, R. G. (2017). Identifying congruence in stream assemblage thresholds in response to nutrient and sediment gradients for limit setting. *Ecological Applications*, 27(2):469–484. Publisher: Wiley Online Library. 1

A Summary table of data

Table A.1: Overview of data used in this study.

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
Boggy Creek - Lake Rd mrt-10	stream	0.00	2.03	158	2003-2023	1.1, 5.3, 8.6	decreasing (0.03)	7.82	1548313	5153967	10.0 (0.62)	MRT inferred: sw age 10	None
Boggy Creek - Lake Rd mrt-20	stream	0.00	2.03	158	2003-2023	1.1, 5.3, 8.6	decreasing (0.03)	7.82	1548313	5153967	20.0 (0.62)	MRT inferred: sw age 20	None
Boggy Creek - Lake Rd mrt-30	stream	0.00	2.03	158	2003-2023	1.1, 5.3, 8.6	decreasing (0.03)	7.82	1548313	5153967	30.0 (0.62)	MRT inferred: sw age 30	None
Boggy Creek - Lake Rd mrt-5	stream	0.00	2.03	158	2003-2023	1.1, 5.3, 8.6	decreasing (0.03)	7.82	1548313	5153967	5.0 (0.62)	MRT inferred: sw age 5	None
Doyleston Drain - Drain Rd mrt-10	stream	0.00	2.27	273	1992-2023	0.1, 3.3, 6.8	decreasing (0.01)	8.85	1547960	5153366	10.0 (0.62)	MRT inferred: sw age 10	None
Doyleston Drain - Drain Rd mrt-20	stream	0.00	2.27	273	1992-2023	0.1, 3.3, 6.8	decreasing (0.01)	8.85	1547960	5153366	20.0 (0.62)	MRT inferred: sw age 20	None
Doyleston Drain - Drain Rd mrt-30	stream	0.00	2.27	273	1992-2023	0.1, 3.3, 6.8	decreasing (0.01)	8.85	1547960	5153366	30.0 (0.62)	MRT inferred: sw age 30	None
Doyleston Drain - Drain Rd mrt-5	stream	0.00	2.27	273	1992-2023	0.1, 3.3, 6.8	decreasing (0.01)	8.85	1547960	5153366	5.0 (0.62)	MRT inferred: sw age 5	None

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
Halswell River - River Rd mrt-10	stream	0.00	0.61	366	1992-2023	2.0, 3.0, 4.0	decreasing (0.00)	11.89	1561843	5163081	10.0 (0.62)	MRT inferred: sw age 10	None
Halswell River - River Rd mrt-20	stream	0.00	0.61	366	1992-2023	2.0, 3.0, 4.0	decreasing (0.00)	11.89	1561843	5163081	20.0 (0.62)	MRT inferred: sw age 20	None
Halswell River - River Rd mrt-30	stream	0.00	0.61	366	1992-2023	2.0, 3.0, 4.0	decreasing (0.00)	11.89	1561843	5163081	30.0 (0.62)	MRT inferred: sw age 30	None
Halswell River - River Rd mrt-5	stream	0.00	0.61	366	1992-2023	2.0, 3.0, 4.0	decreasing (0.00)	11.89	1561843	5163081	5.0 (0.62)	MRT inferred: sw age 5	None
Harts Creek - Lower Lake Rd mrt-10	stream	0.00	0.78	359	1994-2023	3.8, 5.5, 8.1	increasing (0.00)	12.47	1546793	5150435	10.0 (0.62)	MRT inferred: sw age 10	None
Harts Creek - Lower Lake Rd mrt-20	stream	0.00	0.78	359	1994-2023	3.8, 5.5, 8.1	increasing (0.00)	12.47	1546793	5150435	20.0 (0.62)	MRT inferred: sw age 20	$\leq 10\%$
Harts Creek - Lower Lake Rd mrt-30	stream	0.00	0.78	359	1994-2023	3.8, 5.5, 8.1	increasing (0.00)	12.47	1546793	5150435	30.0 (0.62)	MRT inferred: sw age 30	$\leq 20\%$
Harts Creek - Lower Lake Rd mrt-5	stream	0.00	0.78	359	1994-2023	3.8, 5.5, 8.1	increasing (0.00)	12.47	1546793	5150435	5.0 (0.62)	MRT inferred: sw age 5	None
LII Stream-Pannetts Rd mrt-10	stream	0.00	0.50	369	1994-2023	2.7, 3.3, 4.2	increasing (0.01)	12.82	1555716	5161859	10.0 (0.62)	MRT inferred: sw age 10	None

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
LII Stream-Pannetts Rd mrt-20	stream	0.00	0.50	369	1994-2023	2.7, 3.3, 4.2	increasing (0.01)	12.82	1555716	5161859	20.0 (0.62)	MRT inferred: sw age 20	None
LII Stream-Pannetts Rd mrt-30	stream	0.00	0.50	369	1994-2023	2.7, 3.3, 4.2	increasing (0.01)	12.82	1555716	5161859	30.0 (0.62)	MRT inferred: sw age 30	None
LII Stream-Pannetts Rd mrt-5	stream	0.00	0.50	369	1994-2023	2.7, 3.3, 4.2	increasing (0.01)	12.82	1555716	5161859	5.0 (0.62)	MRT inferred: sw age 5	None
Lee River - Brooklands Farm mrt-10	stream	0.00	0.75	166	2002-2023	2.0, 3.2, 4.7	increasing (0.00)	7.98	1542233	5143921	10.0 (0.62)	MRT inferred: sw age 10	None
Lee River - Brooklands Farm mrt-20	stream	0.00	0.75	166	2002-2023	2.0, 3.2, 4.7	increasing (0.00)	7.98	1542233	5143921	20.0 (0.62)	MRT inferred: sw age 20	$\leq 10\%$
Lee River - Brooklands Farm mrt-30	stream	0.00	0.75	166	2002-2023	2.0, 3.2, 4.7	increasing (0.00)	7.98	1542233	5143921	30.0 (0.62)	MRT inferred: sw age 30	$\leq 10\%$
Lee River - Brooklands Farm mrt-5	stream	0.00	0.75	166	2002-2023	2.0, 3.2, 4.7	increasing (0.00)	7.98	1542233	5143921	5.0 (0.62)	MRT inferred: sw age 5	None
Mathias Stream mrt-10	stream	0.00	0.94	64	2009-2023	0.9, 1.6, 3.8	no trend (0.23)	4.41	1536845	5139395	10.0 (0.62)	MRT inferred: sw age 10	None
Mathias Stream mrt-20	stream	0.00	0.94	64	2009-2023	0.9, 1.6, 3.8	no trend (0.23)	4.41	1536845	5139395	20.0 (0.62)	MRT inferred: sw age 20	None

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
Mathias Stream mrt-30	stream	0.00	0.94	64	2009-2023	0.9, 1.6, 3.8	no trend (0.23)	4.41	1536845	5139395	30.0 (0.62)	MRT inferred: sw age 30	None
Mathias Stream mrt-5	stream	0.00	0.94	64	2009-2023	0.9, 1.6, 3.8	no trend (0.23)	4.41	1536845	5139395	5.0 (0.62)	MRT inferred: sw age 5	None
Selwyn River-Coes Ford mrt-10	stream	0.00	1.37	859	1986-2023	1.2, 4.1, 6.7	increasing (0.00)	23.29	1552654	5161709	10.0 (0.62)	MRT inferred: sw age 10	None
Selwyn River-Coes Ford mrt-20	stream	0.00	1.37	859	1986-2023	1.2, 4.1, 6.7	increasing (0.00)	23.29	1552654	5161709	20.0 (0.62)	MRT inferred: sw age 20	$\leq 10\%$
Selwyn River-Coes Ford mrt-30	stream	0.00	1.37	859	1986-2023	1.2, 4.1, 6.7	increasing (0.00)	23.29	1552654	5161709	30.0 (0.62)	MRT inferred: sw age 30	$\leq 20\%$
Selwyn River-Coes Ford mrt-5	stream	0.00	1.37	859	1986-2023	1.2, 4.1, 6.7	increasing (0.00)	23.29	1552654	5161709	5.0 (0.62)	MRT inferred: sw age 5	None
Silverstream - Selwyn River mrt-10	stream	0.00	0.99	59	2012-2023	5.6, 7.2, 8.6	no trend (0.85)	5.54	1552142	5161895	10.0 (0.62)	MRT inferred: sw age 10	None
Silverstream - Selwyn River mrt-20	stream	0.00	0.99	59	2012-2023	5.6, 7.2, 8.6	no trend (0.85)	5.54	1552142	5161895	20.0 (0.62)	MRT inferred: sw age 20	None
Silverstream - Selwyn River mrt-30	stream	0.00	0.99	59	2012-2023	5.6, 7.2, 8.6	no trend (0.85)	5.54	1552142	5161895	30.0 (0.62)	MRT inferred: sw age 30	None

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
Silverstream - Selwyn River mrt-5	stream	0.00	0.99	59	2012-2023	5.6, 7.2, 8.6	no trend (0.85)	5.54	1552142	5161895	5.0 (0.62)	MRT inferred: sw age 5	None
Waikekewai Creek - Gullivers Rd mrt-10	stream	0.00	1.42	169	2002-2023	2.1, 4.5, 7.6	increasing (0.00)	8.12	1548263	5144174	10.0 (0.62)	MRT inferred: sw age 10	None
Waikekewai Creek - Gullivers Rd mrt-20	stream	0.00	1.42	169	2002-2023	2.1, 4.5, 7.6	increasing (0.00)	8.12	1548263	5144174	20.0 (0.62)	MRT inferred: sw age 20	$\leq 20\%$
Waikekewai Creek - Gullivers Rd mrt-30	stream	0.00	1.42	169	2002-2023	2.1, 4.5, 7.6	increasing (0.00)	8.12	1548263	5144174	30.0 (0.62)	MRT inferred: sw age 30	$\leq 30\%$
Waikekewai Creek - Gullivers Rd mrt-5	stream	0.00	1.42	169	2002-2023	2.1, 4.5, 7.6	increasing (0.00)	8.12	1548263	5144174	5.0 (0.62)	MRT inferred: sw age 5	None
l35_0009	well	125.00	2.11	34	2007-2023	6.8, 10.6, 12.7	decreasing (0.01)	2.15	1532276	5181640	45.0 (0.62)	MRT inferred: median within 5000.0m +-5.0m depth	None
l35_0171	well	54.00	0.52	34	1986-2022	1.8, 2.8, 3.4	no trend (0.06)	0.94	1522443	5184286.	19.5 (0.50)	MRT sampled	None

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
l35_0190	well	120.10	0.36	17	2007-2022	9.0, 9.5, 10.4	increasing (0.04)	1.13	1533265	5184666	45.0 (0.64)	MRT inferred: median within 5000.0m +- 5.0m depth	$\leq 5\%$
l35_0191	well	115.20	0.45	39	1986-2022	3.2, 4.0, 5.0	increasing (0.00)	1.08	1536265	5183932	43.8 (0.64)	MRT sampled	$\leq 10\%$
l35_0205	well	28.00	0.88	70	1985-2022	3.2, 5.1, 7.0	increasing (0.00)	1.88	1520408	5180579	30.5 (0.50)	MRT sampled	$\leq 10\%$
l35_0596	well	17.20	1.83	48	2005-2023	3.5, 6.0, 7.7	no trend (0.70)	2.70	1523183	5192126	7.5 (0.50)	MRT sampled	None
l35_0910	well	209.00	0.18	12	2007-2017	3.9, 4.2, 4.5	increasing (0.04)	1.19	1530980	5181111	60.0 (0.62)	MRT inferred: from nearby deep wells (100m rather than 200m)	$\leq 10\%$
l36_0003	well	11.17	2.96	59	2003-2023	6.3, 12.0, 15.7	no trend (0.16)	2.99	1512826	5176554	9.5 (0.50)	MRT inferred: median within 7500.0m +- 5.0m depth	None

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
I36_0059	well	47.20	0.37	36	1986-2018	1.6, 2.5, 4.3	increasing (0.00)	1.12	1520587	5172669	17.0 (0.50)	MRT sampled	$\leq 5\%$
I36_0089	well	68.60	0.63	38	2006-2022	6.3, 8.4, 10.0	increasing (0.00)	2.32	1536268	5176299	36.0 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	$\leq 20\%$
I36_0107	well	9.07	1.41	70	1999-2023	2.9, 4.5, 7.6	no trend (0.56)	2.96	1529689	5166674	18.5 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	None
I36_0121	well	45.70	2.16	18	2006-2022	8.0, 11.2, 14.4	no trend (0.47)	1.13	1528031	5159430	27.5 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	None
I36_0200	well	30.80	1.03	98	1986-2023	4.7, 11.6, 15.0	increasing (0.00)	2.67	1531877	5157736	20.0 (0.50)	MRT inferred: from manual interpretation	$\leq 10\%$

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
l36_0224	well	10.60	1.82	77	2004-2023	7.4, 9.7, 14.1	increasing (0.00)	4.11	1538717	5158060	8.0 (0.62)	MRT inferred: median within 10000.0m +- 5.0m depth	None
l36_0317	well	24.40	2.73	109	1986-2010	3.7, 6.8, 13.1	decreasing (0.00)	4.61	1526528	5173378	14.0 (0.50)	MRT sampled	None
l36_0319	well	85.00	0.45	27	1998-2022	3.6, 4.9, 6.6	increasing (0.00)	1.12	1526191	5165444	47.0 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	$\leq 30\%$
l36_0322	well	45.00	0.39	18	2005-2022	7.7, 9.1, 10.1	increasing (0.00)	1.06	1539331	5170474	7.0 (0.20)	MRT inferred: median within 5000.0m +- 5.0m depth	None
l36_0477	well	48.00	1.05	67	1986-2023	1.3, 3.9, 7.4	increasing (0.00)	1.83	1525062	5157762	17.5 (0.62)	MRT sampled	$\leq 20\%$
l36_0527	well	24.00	0.47	41	1986-2022	0.4, 1.1, 2.2	increasing (0.00)	1.14	1531976	5151575	23.0 (0.90)	MRT inferred: median within 10000.0m +- 5.0m depth	$\leq 20\%$

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
I36_0584	well	42.00	1.13	50	2005-2022	8.8, 11.1, 13.5	increasing (0.02)	2.93	1524424	5175996	36.5 (0.62)	MRT inferred: median within 1000.0m +-10.0m depth	$\leq 10\%$
I36_0682	well	7.60	1.78	24	1986-2010	5.1, 8.0, 12.0	increasing (0.01)	1.00	1538632	5159015	8.0 (0.62)	MRT inferred: median within 10000.0m +-5.0m depth	None
I36_0725	well	69.80	0.93	54	1998-2023	2.7, 3.9, 6.4	increasing (0.00)	2.12	1534252	5164175	22.2 (0.90)	MRT sampled	$\leq 20\%$
I36_0871	well	9.43	0.89	133	1993-2023	2.9, 5.0, 9.4	increasing (0.00)	4.49	1539075	5149880	2.5 (0.62)	MRT sampled	None
I36_1131	well	107.00	0.47	23	2000-2022	3.3, 4.1, 6.0	increasing (0.00)	1.05	1515982	5168291	51.5 (0.62)	MRT inferred: median within 7500.0m +-5.0m depth	$\leq 30\%$
I36_1313	well	120.00	0.51	22	2003-2022	1.1, 2.8, 4.6	increasing (0.00)	1.15	1510766	5168162	36.0 (0.40)	MRT sampled	$\leq 20\%$

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
l36_1543	well	65.17	0.60	22	2005-2022	6.6, 8.6, 9.9	increasing (0.00)	1.29	1532712	5173822	33.2 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	$\leq 20\%$
l36_2094	well	92.46	0.53	19	2005-2022	4.2, 6.5, 7.6	increasing (0.00)	1.11	1534519	5176083	63.4 (0.40)	MRT inferred: median within 10000.0m +- 5.0m depth	$\leq 20\%$
l36_2122	well	72.45	0.25	64	1986-2022	2.2, 3.8, 6.6	increasing (0.00)	1.78	1521607	5167679	33.0 (0.50)	MRT inferred: median within 7500.0m +- 5.0m depth	$\leq 20\%$
m35_1003	well	39.60	1.92	253	1986-2011	3.8, 6.0, 10.3	increasing (0.00)	10.11	1548975	5178543	21.0 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	$\leq 10\%$
m35_5509	well	54.00	1.67	61	1991-2023	1.7, 3.4, 6.8	no trend (0.69)	1.93	1548149	5180841	19.5 (0.62)	MRT inferred: median within 1000.0m +- 10.0m depth	None

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
m36_0040	well	59.40	1.12	16	2005-2022	7.3, 10.2, 12.2	increasing (0.01)	0.94	1540279	5176664	25.2 (0.33)	MRT inferred: median within 7500.0m +- 5.0m depth	$\leq 5\%$
m36_0153	well	14.60	1.54	29	1994-2022	6.7, 8.5, 11.0	no trend (0.49)	1.04	1558463	5168878	80.5 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	None
m36_0271	well	25.00	1.03	233	1986-2016	5.6, 6.8, 8.5	increasing (0.02)	7.82	1556516	5175951	25.0 (0.62)	MRT inferred: from manual interpretation	None
m36_0297	well	7.50	1.68	34	1978-2022	7.9, 9.6, 13.4	no trend (0.94)	0.77	1558095	5170218	27.8 (0.62)	MRT inferred: median within 5000.0m +- 5.0m depth	None
m36_0456	well	10.35	1.03	62	1991-2022	6.0, 7.2, 9.2	no trend (0.66)	1.99	1548802	5168040	12.0 (0.62)	MRT inferred: from mean of m36_5190 and Burnam bores	None
m36_0698	well	25.00	0.53	35	1986-2019	1.6, 2.4, 4.8	increasing (0.00)	1.06	1540043	5148573	22.8 (0.90)	MRT sampled	$\leq 30\%$

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
m36_2285	well	36.60	1.79	92	1986-2023	2.5, 5.6, 8.7	no trend (0.49)	2.50	1555910	5169768	75.0 (0.60)	MRT inferred: median within 5000.0m +- 5.0m depth	None
m36_3588	well	12.20	0.45	40	1986-2022	5.0, 6.8, 7.6	increasing (0.00)	1.11	1551288	5165039	20.5 (0.62)	MRT inferred: from m36_5190	$\leq 5\%$
m36_3683	well	10.54	1.39	40	1986-2022	1.4, 2.2, 5.1	no trend (0.20)	1.11	1552909	5160003	20.5 (0.62)	MRT inferred: from m36_5190	None
m36_4126	well	34.10	1.64	200	2006-2023	4.3, 6.3, 9.2	decreasing (0.00)	11.70	1549150	5177595	28.0 (0.62)	MRT sampled	None
m36_4227	well	12.00	1.06	175	1992-2023	6.8, 8.5, 10.3	no trend (0.43)	5.65	1560377	5173587	35.5 (0.62)	MRT sampled	None
m36_5248	well	32.00	0.59	122	1997-2022	5.5, 6.0, 7.2	increasing (0.01)	4.77	1552687	5173900	31.0 (0.62)	MRT sampled	$\leq 20\%$
m36_5255	well	24.00	0.33	28	1997-2022	1.6, 2.5, 3.6	increasing (0.00)	1.12	1558097	5170216	44.5 (0.62)	MRT inferred: minimum surrounding age	$\leq 30\%$

Continued on next page

Table A.1: Overview of data used in this study. (Continued)

Site	Type	Depth	NO_3-N noise	N samp.	Sampling period	NO_3-N (5th, 50th, 95th)	Mann-Kendall trend (p)	Samp. per year	NZTMX	NZTMY	MRT (f_p1)	MRT info	Plateau limit
m36_7734	well	27.33	0.60	57	1995-2022	4.1, 5.2, 6.9	increasing (0.00)	2.10	1545140	5162648	47.0 (0.62)	MRT inferred: median within 5000.0m +- 10.0m depth	$\leq 20\%$
m36_8187	well	36.84	0.51	208	1991-2022	3.4, 6.3, 9.7	increasing (0.00)	6.67	1544668	5172397	28.0 (0.62)	MRT inferred: median within 500.0m +- 5.0m depth	$\leq 20\%$
m37_0499	well	18.00	0.77	15	2009-2022	6.1, 7.3, 8.8	increasing (0.03)	1.16	1544710	5145705	16.0 (0.62)	MRT inferred: median within 5000.0m +- 10.0m depth	$\leq 10\%$
m37_0499	well	18.0000	0.76508	15	2009-2022	6.1, 7.3, 8.8	increasing (0.03)	1.157995	1544710	5145705	16.0 (0.62)	MRT inferred: median within 5000.0m +- 10.0m depth	$\leq 10\%$