Nitrate assessment for the interzone source area catchment

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Summary

Nitrate-nitrogen concentrations in the deeper parts of the Christchurch aquifer system are relatively low at present, with a maximum concentration of 2.6 mg/L recorded. This is much lower than the drinking water limit of 11.3 mg/L. Nitrate concentrations in the shallower parts of the system are also generally low beneath most of the city, although high concentrations have been recorded in some areas (e.g. downgradient of the former Islington Freezing Works). Nitrate concentrations are trending upwards in Environment Canterbury's deep long-term monitoring well in the Russley area; but are still very low (less than 1 mg/L nitrate-N).

In 2016-2017 Environment Canterbury investigated the potential for groundwater and nitrate in the Waimakariri zone to travel into the Christchurch aquifer system. Our investigation concluded that groundwater nitrate concentrations beneath the city are likely to increase due to inflows from the Waimakariri zone.

In this report we have used the collaboratively-developed groundwater model from the 2016-2017 study to evaluate potential nitrate concentrations in the Christchurch aquifer under a number of different illustrative management scenarios. The nitrogen load reductions for one of these scenarios (50% reduction) is similar to some of the scenarios being explored for other parts of the Waimakariri zone. It is important to understand that these scenarios do not represent a proposed set of options for nitrogen management; their aim is to provide information that can potentially be used to aid discussions with partners, stakeholders and the community as the Waimakariri Water Zone Committee progress towards a set of nitrate management recommendations for the zone.

Modelling studies which explore the future outcomes of current processes and natural resource usage are always burdened with some degree of uncertainty. We have endeavoured to understand and quantify this uncertainty as far as possible within the constraints of this project. Our modelling results are therefore presented in terms of the probability that a given nitrate concentration could occur.

Our modelling suggests that there is a 50% probability that nitrate concentrations will increase by more than 4.5 mg/L at any location within the main urban area of the city and a 75% likelihood that concentrations will increase by more than 3.5 mg/L. These concentration increases and likelihoods are sufficiently high to prompt consideration of implementing nitrate management options for the area projected to drain into the Christchurch aquifer system (referred to as the interzone area in this report). However, outside of areas of the aquifer impacted by localised nitrate contamination (e.g. Islington Freezing works), concentrations remain below the drinking water limit of 11.3 mg/L in all locations across the city, even under the highly conservative 99% confidence model results. The model results also show that there is a possibility (albeit low likelihood) that nitrate concentrations might ultimately increase by less than 2 mg/L, even if no specific action is taken for land within the interzone area.

Our results suggest that implementation of Good Management Practice alone is highly unlikely to curb the projected nitrate increases. We explored a hypothetical scenario under which nitrate concentrations in water draining from the interzone area is reduced by 50%, and another scenario under which nitrogen losses from this area are reduced to 8 kg/ha/year. This latter scenario is referred to as the dryland farming scenario, since an 8 kg/ha/year N loss rate aligns with typical modelled values for this land use. Median modelled nitrate concentrations are low under both these scenarios; nitrate-N concentrations are also projected to be at less than 50% of the drinking water limit (i.e. 5.65 mg/L) under the conservative 95% confidence model results for both scenarios.

Whilst nitrate concentrations could start to increase in the next few decades as a result of inflows from the Waimakariri zone, and may in fact already be slowly increasing beneath the city, groundwater age modelling results suggest that any increases are likely to occur gradually. We would not expect the full increases projected by our modelling to occur within the next 100 years.

The economic impact modelling results provided in this report provide useful information on the effects of implementing a range of N load reductions on the local farming economy. Results are provided for a scenario under which the N load reductions are applied only to dairy and dairy support farming, and for another scenario under which reductions apply to all farming.

This report, in its current format, is only intended to provide information to the Zone Committee prior to commencement of a targeted engagement process. A limited number of additional nitrogen mitigation scenarios could potentially be run prior to targeted engagement if required.

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1 Introduction and document structure

1.1 Background

Groundwater investigations undertaken in 2016-2017 concluded that groundwater in the Waimakariri Canterbury Water Management Zone (CWMS) zone is likely to flow under the Waimakariri River and into the Christchurch aquifer system. The Waimakariri Water Zone Committee is exploring options for nutrient management in their zone, in order to "play their part" in maintaining the high quality of water in the Christchurch aquifers.

1.2 Introduction

The purpose of this report is to:

- Provide a brief overview of current nitrate concentrations in the Christchurch groundwater system
- Briefly explain why our investigations concluded that Waimakariri zone groundwater and nitrate are likely to flow towards Christchurch
- Provide the results of nitrate modelling for the Christchurch aquifer under four scenarios:
    - Current land management practice continues
    - Good Management Practice (GMP) as defined in the proposed Plan Change 5 of the Land and Water Regional Plan (LWRP) is fully implemented
    - Two hypothetical scenarios under which nitrogen losses from the interzone area are a) reduced by 50% and b) reduced to 8 kg/ha at some point in the future (referred to as the Dryland Farming scenario in this document).
- Explain the timescale over which nitrate from the Waimakariri zone is likely to travel toward Christchurch
- Provide economic modelling results to show the impact of reducing nitrate loads in the interzone source area

2 Current nitrate concentrations in Christchurch

2.1 Current nitrate concentrations

Groundwater quality monitoring results from within the Christchurch TLA area (Table 1) show that whilst high nitrate concentrations have been recorded at some locations in the shallow part of the aquifer (mainly in the area downgradient of the former Islington Freezing Works), average nitrate concentrations have not exceeded 2.6 mg/L in the deeper parts of the aquifer.

Table 1 Nitrate-N concentration statistics for Christchurch groundwater

Depth range	Median	Mean	95th percentile	Max
< 30 m	2.5	3.4	7.6	27
30 – 80 m	2.4	2.3	6.1	7.3
>80 m	0.3	0.6	1.6	2.6

Looking at data for the deeper parts of the aquifer spatially (Figure 1 below) we can see that nitrate concentrations beneath central and eastern Christchurch are very low, with a maximum concentration of 0.5 mg/L. Higher concentrations have been recorded in some wells to the north of the city,

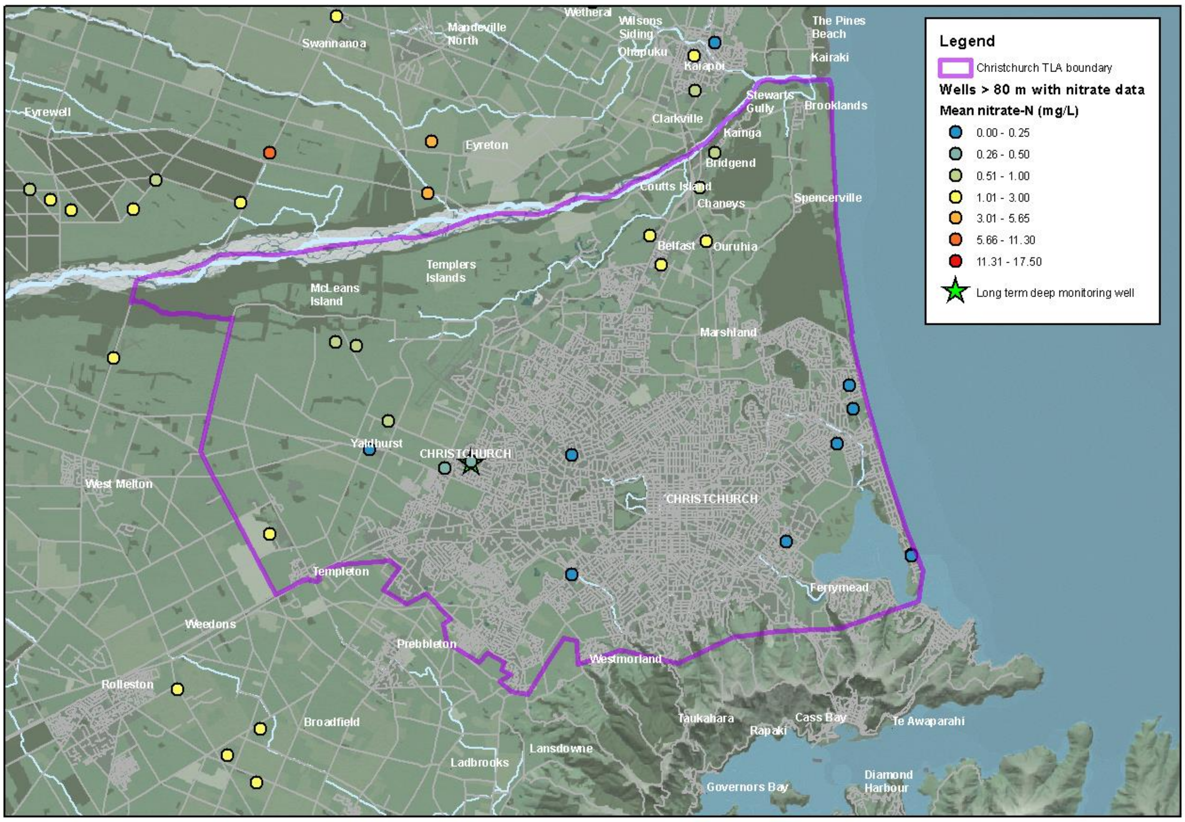

Figure 1 Measured mean nitrate-N concentrations in wells > 80 m deep since 2008

Spatial plots of nitrate concentrations in the shallower parts of the aquifer are provided in Appendix 1 (Figure 13 and Figure 12).

2.2 Nitrate trends

Groundwater nitrate concentrations in the deep Christchurch aquifer system have been monitored in our long-term deep monitoring well at Russley (see Figure 1 for well location) since 1995[1]. Monitoring results plotted in Figure 2 show that nitrate concentrations are increasing over time, but remain very low.[2]

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[1] Two wells have been monitored: Well M35/6791, screened from 188 – 200 m depth, was monitored from 1995 to 2013, when the well was decommissioned by CCC. Monitoring has continued in nearby well M35/6040 (screened from 170 – 176 m depth) since that time.

[2] Statistical analysis of these data undertaken by GNS found a Sen slope of 0.0044 mg/L per year over the 1995-2015 time period, with a p-value of 0.0045 (i.e., statistically significant at the 95% confidence level) for the Mann-Kendall test, seasonally adjusted, excluding outliers located outside a 4 times the median absolute deviation interval.

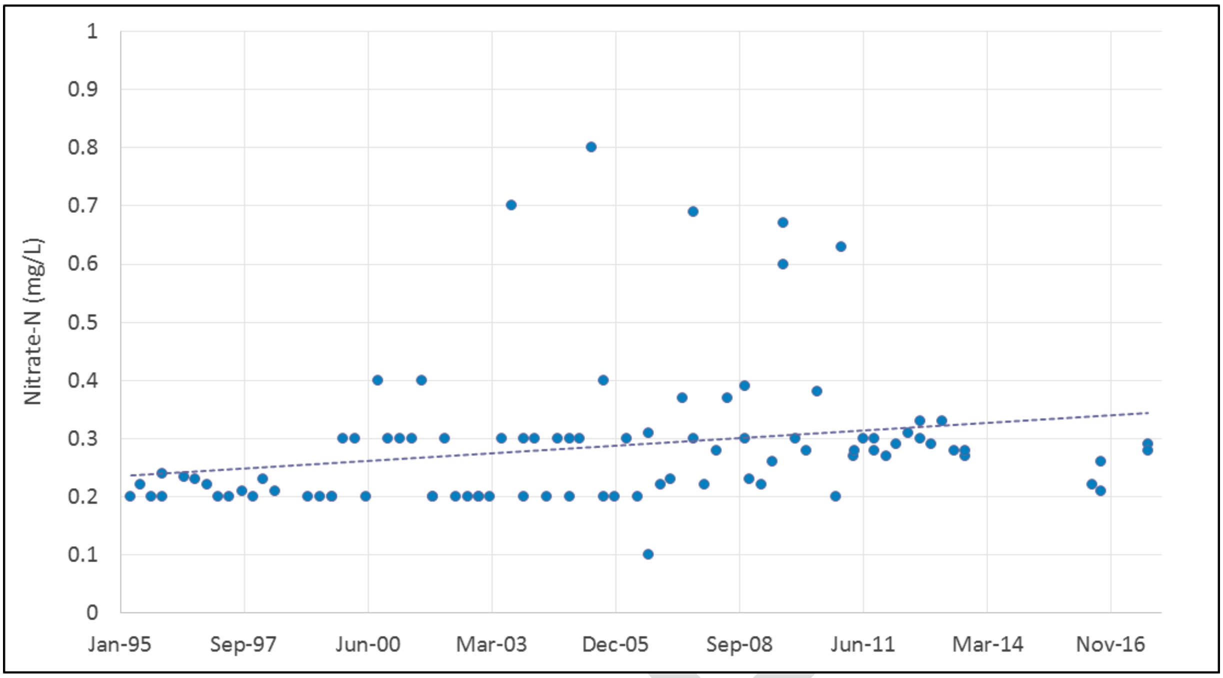

Figure 2 **Nitrate-N concentrations in the deep aquifer system beneath Russley, west of Christchurch**

3 Investigation of the connection between the Waimakariri and Christchurch aquifer systems

3.1 Background

The potential for groundwater from north of the Waimakariri to travel beneath the Waimakariri River and into the Christchurch aquifer has been identified by a number of previous studies. Stewart et al. (2002)[3] concluded that the geochemistry of groundwater samples collected from deep wells and a spring in northern Christchurch suggested a recharge source to the north of the Waimakariri River. Environment Canterbury commissioned PDP to explore this issue in 2014; this report also identified the potential for groundwater to flow under the Waimakariri River. Evaluation of this potential flow path using more comprehensive and rigorous scientific methods was therefore identified as a key component of the science work for the Waimakariri CWMS zone.

Numerical groundwater models are widely recognised within the scientific community as the best tool for exploring the complicated three-dimensional groundwater flow questions which cannot be addressed using analytical methods and expert judgement alone. Because the question of groundwater flow beneath the Waimakariri River falls firmly into this category, we initiated the Waimakariri zone groundwater modelling project in 2015. We worked collaboratively with a group of external groundwater experts throughout the project to make sure that all available expert knowledge was incorporated into the model design, construction and calibration (also known as optimisation).

Three separate groundwater models were developed for the Waimakariri zone between 2015 and 2017. The first model projected that nitrate from the Waimakariri zone would be transported into the

[3] Stewart M., Trompetter V. and van der Raaij R. 2002. Age and source of Canterbury Plains Groundwater. Environment Canterbury Technical Report No U02/30.

Christchurch aquifer system, but we had a low level of confidence in this model because it was unable to replicate measured groundwater levels and stream and river flows in some areas. A new model was then built by GNS and calibrated against measured groundwater level and stream and river flow data. This model was able to replicate measured data much more closely, and on that basis we were more confident in the results. This model again projected that water and hence nitrate draining from part of the Waimakariri zone is likely to be transported into the Christchurch aquifer. The model still had some significant limitations and data gaps, however. Given the potential significance of these model results to land and water management in the Waimakariri CWMS, Environment Canterbury decided to extend the timeframe for the Waimakariri zone Land and Water Solutions programme to allow for additional field work and a significant rebuild/refinement of the numerical model in the second half of 2017.

3.2 2017 Investigation scope

Our 2017 investigation aimed to answer three questions:

1. What is the likelihood that nitrate from the Waimakariri zone will be transferred into the Christchurch aquifer system?
2. If such inter-zone transfer is occurring, what effect will it have?
3. What level of confidence do we have in our answers to questions 1 and 2?

Because the previous groundwater models had some significant limitations in answering these questions, we designed and implemented a major field investigation and modelling project. The aim of the investigation was to answer questions 1 and 2 above with as much certainty as possible within reasonable time and budgetary constraints. We engaged an expert panel to assist us in answering question 3.

3.3 Assessment method

At the start of the interzone transfer investigation we posed the following null hypothesis[4]:

"Nitrate from the Waimakariri Zone will be transported beneath the river at problematic concentrations"

We designed an investigation to test this null hypothesis. The two main components of our investigation method were:

I. Evidence-based approach: a comprehensive, collaboratively developed groundwater model founded on expert judgement, calibrated with empirical data and evaluated using an advanced uncertainty analysis technique,
II. Expert judgement-based assessment.

The groundwater model is the main tool we used to answer the research questions outlined above, and from a scientific perspective it undoubtedly provides the most robust assessment. The expert judgement assessment was incorporated as a contingency plan, to guard against the possibility of difficulties in the modelling process and associated delays in delivery of results. Despite the subjectivity and potential biases associated with expert judgement, and its significant limitations in answering a science question of this complexity and contentiousness, general agreement between groundwater modelling and expert judgment assessments provides a greater level of reassurance than groundwater modelling alone.

[4] A null hypothesis in statistics is the hypothesis that is assumed to be correct unless there is suitable evidence to reject (or disprove) the hypothesis. For this investigation we were trying to prove that nitrate from the Waimakariri Zone was not being transported under the river at problematic concentrations

3.4 Investigation method

The component parts of the investigation and assessment process (undertaken between July and November 2017) were:

1. Identify critical gaps in information required to answer the study questions
2. Appoint an expert panel to provide advice on and review of our methods and findings
3. Meet with panel to discuss and agree upon critical gaps, investigation scope and method
4. Design and implement an extensive field investigation programme
5. Design and build new version of Waimakariri groundwater model
6. Convene an expert panel workshop to obtain views from the panel on inputs to the model (to ensure the model can explore all conceptual models and parameters envisaged by the experts)
7. Parameterise and calibrate a single groundwater model using expert panel knowledge[5] in combination with the extensive archive of groundwater level, stream flow and aquifer property data held within our databases
8. Issue memos and convene meetings with expert panel to explain and seek agreement upon changes that needed to be made to the model for it to fit with observation data
9. Analyse all available data, including information obtained from the field investigation programme, and summarise in a series of memos for review by the expert panel
10. Hold an expert judgement workshop (27/10/17) using a formal elicitation framework to provide quantitative expert judgement-based estimates of the likelihood of interzone transfer. The expert panel were not shown any of the model results prior to this elicitation to ensure that they were not influenced by the modelled outcomes.
11. Finalise the model optimisation process to create a single model which both encapsulates all expert knowledge *and* matches field observations within acceptable margins.
12. Implement an advanced uncertainty analysis modelling process, which explores areas of the aquifer system in which we have no or limited information or expert knowledge, and creates thousands of different iterations of the groundwater model (referred to from here on as the suite of models), which both encapsulate expert knowledge *and* fit observation data, to provide a tool by which poorly understood parts of the system can be explored via a range of model predictions.
13. Run model simulations at steady-state to assess the likely increase in nitrate concentrations associated with under-river transfer. Modelling assumed zero nitrate concentrations for all land south of Waimakariri River at this stage.
14. Translate expert judgement estimates of under-river transfer into nitrate concentration increases in Christchurch wells based on modelled nitrate concentrations in Waimakariri zone.
15. Present model optimisation and uncertainty analysis results to the expert panel and elicit their views on how they weigh their expert judgement against the modelling outputs, plus other questions relating to confidence in the suite of models. Experts were not shown the model results for nitrate until they had provided their views on the ability of the model to reliably predict interzone transfer.

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[5] The groundwater model provides a receptacle for expert knowledge on the study area. We therefore worked closely with members of the expert panel to elicit their conceptual understanding of the groundwater system, and then incorporated this understanding and their expert knowledge into the model.

The expert panel comprised individuals from a range of backgrounds all of whom have extensive experience in the study area. They were:

- Four research scientists with previous and/or ongoing long-term research projects in the area (Scott Wilson & Jens Rekker [Lincoln Agritech], Lee Burberry [ESR] and Paul White [GNS])
- Two consultants who between them provide consultancy services to the majority of the Waimakariri zone farming community (John Talbot [Bowden Environmental], who works for many individual farmers and Peter Callander [PDP] who advises Ngai Tahu Eyrewell Forest Farming and Waimakariri Irrigation Ltd)
- ECan Groundwater Science staff (Carl Hanson, Zeb Etheridge[6])

This recent phase of the investigation built upon several years of collaborative science work including:

- Conceptual model development project (Matt Dodson): this project gathered and documented the range of views held by a broad group of experts on the key elements of the Waimakariri zone hydrological system. The study identified critical knowledge gaps, which were subsequently addressed through a series of investigations.
- Collaborative development of the first and second iteration groundwater models: regular workshops were held with Peter Callander over a 12-month period to agree upon the key aspects of the model design, conceptual basis, inputs and assumptions.

Whilst the method outlined above addressed the groundwater flow and transport side of the question, estimates of the rate of nitrogen loss from land in the Waimakariri zone are equally important in assessment of nitrate concentrations in Christchurch groundwater. Our process to estimate nitrogen losses and the uncertainty around those loss estimates was broadly:

- Overseer modelling of losses rates from representative farms.
- Upscale results to Waimakariri zone using community-validated soil and land use mapping
- Compare modelled nitrogen loss rates to measured data (groundwater and stream nitrate concentrations). Revise modelling inputs to bring model results in-line with measured data.
- Appoint OVERSEER® nitrogen modelling expert panel to quantify uncertainty around modelled nitrogen loss rates
- Meetings and discussions with experts to agree upon how best to break nitrogen loss modelling down into components for which uncertainty could be estimated
- Analysis of uncertainty by individual experts using formal elicitation framework
- Workshop with panel to review elicitation results and agree upon combined group estimate for eight soil/land use classes, and degree of correlation between classes

The nitrogen modelling expert panel comprised: Linda Lilburne & Melissa Robson (Landcare Research), Alister Metherell (Ravensdown), Leo Fietje & Ognjen Mosilovich (Environment Canterbury). We presented the methodology and findings of the nitrogen modelling uncertainty at the 2018 Fertiliser and Lime Research Centre conference, and produced a scientific paper which documents this information.[7]

3.5 Investigation results and key messages

The expert panel agreed unanimously that at least some groundwater from the Waimakariri zone is likely to flow under the river and into the northern Christchurch aquifer. Some members of the panel believed that central and southern Christchurch could also be affected, but others did not. All members

[6] Provided expert judgement in first two workshops, facilitated final workshop

[7] Etheridge, Z., Fietje L., Metherell A., Lilburne L., Mojsilovich O., Robson M., Steel K., Hanson M. 2018. Collaborative expert judgement analysis of uncertainty associated with catchment-scale nitrogen load modelling with OVERSEER®. In: Farm environmental planning – Science, policy and practice. (Eds L. D. Currie and C. L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 31. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 14 pages.

of the panel inferred that any increase in nitrate associated with under-river flow is likely to be lower in the southern part of Christchurch.

We translated expert panel estimates of flow under the Waimakariri River into nitrate concentration estimates by making some assumptions about the source area within the Waimakariri zone. The groundwater model nitrate results and the nitrate results we extrapolated from the expert panel assessment outputs were reasonably well aligned overall, but differences regarding the specific areas of nitrate concentration increase existed.

The experts generally had medium/high confidence that our suite of model results encapsulate the true outcome in regard to impacts on nitrate concentrations in Christchurch. The results from all models show some increase in nitrate concentrations in Christchurch wells; it was therefore inferred that the experts had medium-high confidence that there will be some increase in nitrate concentrations due to inter-zone transfer.

We therefore concluded that it is no longer reasonable to assume that the Waimakariri River forms a hydraulic barrier between the Christchurch water supply aquifer and land use in the Waimakariri zone.

Given that groundwater flow rates in the deeper Christchurch aquifer are low, with groundwater ages in the decades to hundreds of years range, we concluded that under-river transfer was unlikely to affect nitrate concentrations significantly in the near future. Any significant increase is likely to occur on a decadal time scale. This is discussed further in Section 5.

We distilled the findings of the 2017 investigation into the key messages in Table 2 below.

Table 2 Key messages from 2017 investigation

Message	Certainty
Any increase in nitrate concentrations in Christchurch wells is likely to occur over several decades, or longer. No significant effects are expected in the near future.	High Strong evidence General consensus
We can no longer assume that the Waimakariri River forms a hydraulic barrier between land use in the Waimakariri zone and the Christchurch water supply aquifer.	Medium/high Strong evidence Broadly accepted
Nitrate concentrations in deep northern Christchurch wells are likely to increase due to inflows from the Waimakariri zone.	Medium/high Strong evidence Broadly accepted
Nitrate concentrations in deep central and southern Christchurch wells may increase due to inflows from the Waimakariri zone.	Medium Some evidence Lack of consensus

3.6 Modelled interzone source area

The 2017 study did not evaluate the interzone source area due to time constraints; we have therefore undertaken this work for this current report. We used the Modpath particle tracking utility to delineate the interzone area, and ran particle tracking simulations for the suite of 165 models (or model realisations) which met our calibration criteria. The methodology used to delineate these zones and the results of the delineation have been peer reviewed by external experts[8]. The experts were satisfied that the approach we used and the resultant zone delineations provided the best results that could be achieved within the constraints of this project. We have plotted the results of the particle tracking and zone delineation in Figure 3 below. We have provided two delineation outlines:

[8] Scott Wilson, Lincoln Agritech and Lee Burberry, ESR

- High likelihood outline: some or all of the water infiltrating through the land within this area is very likely (90% probability) to flow into the Christchurch aquifer system according to model results
- High to moderate likelihood outline: some or all of the water infiltrating through the land within this area is very (90% probability) or moderately likely (50% probability) to flow into the Christchurch aquifer system, according to model results

The difference between these two outlines is relatively small, but could be of significance to local farms.

It is important to note that not all of the water infiltrating from land within the delineated boundaries is expected to flow towards Christchurch, only some proportion of that water. Some of the water will be abstracted by wells within the Waimakariri zone, and some will follow pathways to Waimakariri zone spring-fed streams. The interzone source area therefore overlaps with the recharge areas we have delineated for some of the streams and wells within the Waimakariri zone. It is not possible[9] to delineate those parts of the Waimakariri zone in which a certain minimum proportion of the water is likely to drain towards Christchurch.

A number of the model realisations (less than 50% of the 165 total) indicate that some of the water infiltrating from land outside of these boundaries could flow into the Christchurch aquifer system. We have not included these areas within the delineated source zone because our analysis suggests that there is a low likelihood of this wider area contributing a significant proportion of its infiltration to Christchurch.

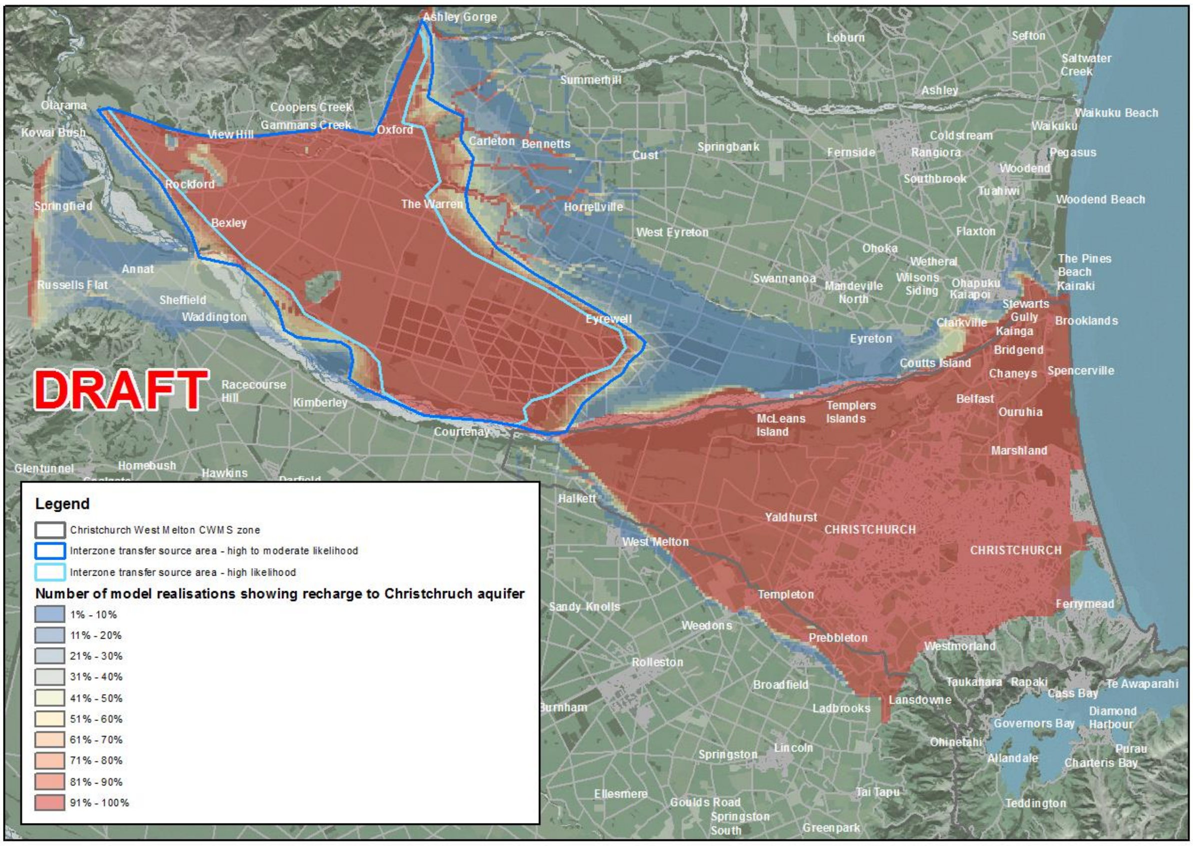

Figure 3 Interzone transfer source area

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[9] Within current time and information constraints - it may be possible in the future.

The model projects that infiltration from land in the Springfield and Russells Flat area is likely to flow into the Christchurch aquifer system. The pathway for this is likely to be via the Waimakariri River. Any nitrate in this drainage water will be diluted significantly in the river.

It is noteworthy that the western boundary of the Christchurch-West Melton CWMS zone aligns closely with our groundwater modelling results. The CWMS zone boundary was based on analysis of shallow aquifer groundwater level data, and represents an inferred groundwater divide between the Christchurch and Selwyn Te Waihora aquifer systems. Although our recent groundwater modelling was based on a larger dataset and more recent information, the similarity of groundwater divide locations inferred from these two sets of information shows that our understanding of flow pathways in the shallow Christchurch aquifer system has not changed significantly.

Some of the irrigation and stockwater race network outside of the delineated source areas (e.g. in Carleton/Bennetts area) are included within the high likelihood modelling results. This is a function of the modelling method, and can be ignored.

4 Nitrate-N modelling scenarios, method and results explanation

4.1 Model scenarios

We use model scenarios to explore what might happen in the future under a given set of assumptions. The scenarios we explored for this report as summarised below. All scenarios provide estimates of nitrate concentrations under steady state conditions, when groundwater nitrate concentrations have equilibrated with the land use and land management practices assumed under that scenario. The concept of steady state and how long it may take for this to eventuate are discussed in Section 5.

Table 3 Model scenarios

Scenario name	Description	Purpose
Current Practice	Current management practice	Estimates nitrate-N concentrations/loads at steady state, when water quality equilibrates with current land use and management practices
GMP	Good Management Practice	Assess the benefits of implementation of industry-agreed good management practices on nitrate-N discharges
50% reduction[10]	Assumes nitrate-N <u>concentrations</u> in water infiltration from land within the interzone area are reduced by 50%	Provide estimates of nitrate-N concentrations in the Christchurch aquifer under an arbitrary 50% reduction scenario

Scenario name	Description	Purpose
Dryland farming[10]	Explores potential nitrate concentrations under a hypothetical scenario under which the average nitrogen losses from the interzone source area is reduced to 8 kg/ha/year	Provide an indication of whether a nitrogen load reduction of this order is likely to maintain nitrate concentrations in the Christchurch aquifer at their current measured concentrations.

For all scenarios we applied an average nitrogen load of 8 kg/ha/year to land within the Christchurch-West Melton zone. This is based on OVERSEER® modelling work undertaken by Environment Canterbury (Leo Fietje) in 2017 to address questions raised by the Christchurch-West Melton zone committee.

4.2 Modelling uncertainty

Modelled nitrate concentrations are an estimate of what the true nitrate concentration will be under a given scenario, and are subject to uncertainty. We analysed and accounted for this uncertainty as far as practically possible in our modelling method, as explained in Section 3.4. Modelling results are therefore presented in terms of the percentage likelihood that the true value will be less than the modelled value. The 50th percentile is the middle point in the range of our modelling results, for instance. There is a 50% probability[11] that the true nitrate concentration will be higher than this modelled value and a 50% probability that the true nitrate concentration will be lower. Further explanation is provided in Table 4 below.

Table 4 Explanation of model percentiles

Model results percentile	Probability that actual nitrate concentration will be **lower**	Probability that actual nitrate concentration will be **higher**
5th percentile	5%	95%
Median	50%	50%
95th percentile	95%	5%
99th percentile	99%	1%

4.3 Model results

We divided the Christchurch district into six spatial areas (Figure 4) for this report: north east, central and eastern, south, western, north western and the main urban area. The purpose of this somewhat

[10] These scenarios assumed no reduction of land surface recharge beyond GMP. While there would likely be a reduction of land surface recharge, particularly associated with the Dryland farming scenario, it is unlikely to significantly alter the results of this modelling.

[11] Our estimates of the probability that a certain outcome will occur are in themselves also subject to some uncertainty because we do not have enough information to precisely quantify the level of uncertainty around all inputs to the model and the structure of the model. Nitrate attenuation is possible in some parts of the Christchurch aquifer system, and this has not been considered in our modelling because we cannot currently quantify it or determine whether it is likely to be a significant factor. Uncertainty about uncertainty is referred to as *second order uncertainty*. We do not discuss this second order uncertainty in this document, but it is important to be aware that when we say there is a 90% probability for a given model result, for instance, the true level of certainty could be less (or greater) than the estimated probability.

arbitrary delineation is to provide an indication of how modelled nitrate concentrations vary spatially across the city. Our modelled nitrate concentration ranges for these areas account for the following:

- The spatial variability of model nitrate concentrations within the area
- Uncertainty in the OVERSEER® modelling of nitrogen leaching rates from the soil profile
- Groundwater modelling uncertainty

We have also presented the model results for three depth zones: shallow aquifer, indicative of the Riccarton Gravel formation, mid-depth aquifer (broadly the Linwood Formation) and deep aquifer (the unnamed aquifers beneath the Wainoni Gravel aquifer). Model results for the main Christchurch urban area are summarised in Table 5 by depth zone and model scenario.

The model results for all scenarios and depths for the main Christchurch urban area suggest that within this area:

- Nitrate-N concentrations of up to 4.7 mg/L are possible under the median model results
- Nitrate-N concentrations are highly likely (95% probability) to stay below 8 mg/L
- There is a very low probability (1%) that nitrate concentrations will exceed 10 mg/L

These concentrations are all below the drinking water limit of 11.3 mg/L, even under the highly conservative 99% confidence model results. On this basis we do not expect groundwater nitrate concentrations outside of those areas of the aquifer impacted by localised nitrate contamination (e.g. Islington Freezing works) to exceed the drinking water limit as a result of inflows from the Waimakariri zone.

Table 5 Nitrate modelling results summary for main Christchurch urban area

Statistics	***5th percentile***	***Median***	***95th percentile***	***99th percentile***	**Notes**
Shallow aquifer nitrate-N (mg/L)					
Current Practice	0.3	3.4	7.5	9.1	Shallow aquifer ≈ Riccarton Gravel
GMP	0.5	3.7	7.9	9.4	
50% reduction	0.3	2.5	5.1	5.9	Mid aquifer ≈ Linwood Gravel
Dryland farming	0.3	1.7	3.7	4.3	
Mid aquifer nitrate-N (mg/L)					
Current Practice	0.6	3.8	7.1	8.6	Deep aquifer ≈ unnamed formation, lower Quaternary gravels (>120 m)
GMP	1.3	4.1	7.4	9.0	
50% reduction	0.4	2.3	4.0	4.8	
Dryland farming	0.3	1.3	2.4	3.2	
Deep aquifer nitrate-N (mg/L)					
Current Practice	1.8	4.5	7.0	8.1	
GMP	2.7	4.7	7.3	8.5	
50% reduction	1.2	2.6	3.6	3.9	
Dryland farming	0.6	1.3	1.9	2.3	

Modelled nitrate concentrations for the GMP (Good Management Practice) scenario are slightly higher than Current Practice. This is because current irrigation practice within the Waimakariri Irrigation Limited (WIL) command area is believed to be very inefficient, meaning that large volumes of irrigation water (sourced from the Waimakariri River) are likely to drain to the aquifer from irrigated land on light soils in this area. Although this drainage carries nitrogen into the groundwater, it still provides dilution of the leached nitrogen. Improved irrigation efficiency can therefore cause groundwater nitrate concentrations to increase in some instances. This has been observed in many of our groundwater quality monitoring wells across the region in areas where border dyke irrigation fed by surface water takes has been replaced by more efficient spray irrigation.

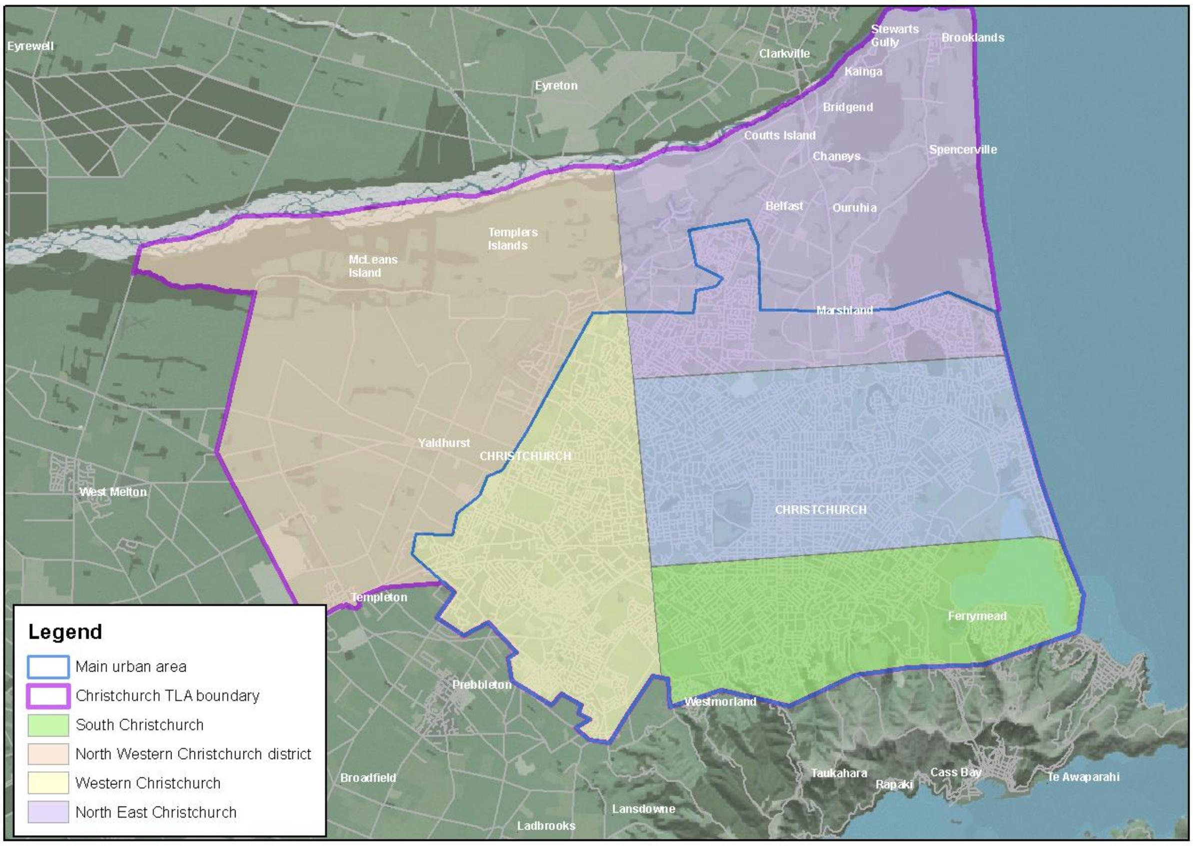

Figure 4 Christchurch area delineation for model results reporting

Model results for the GMP scenario for the north east, central and eastern, south, western, north western are shown in Figure 6 (shallow part of aquifer), Figure 7 (mid depth aquifer) and Figure 9 (deep aquifer). The modelled nitrate concentration ranges in these areas are similar to those within the main Christchurch urban area. Nitrate concentrations are slightly lower in the shallower parts of the aquifer; this is probably due to higher dilution with Waimakariri River water and greater percentage of land surface recharge sourced in the lower intensity Christchurch West Melton Zone in this part of the system. Concentrations are also lower in the western and northern parts of Christchurch for the same reason.

It has not been possible to assess whether nitrate concentrations in the spring-fed streams could be impacted by interzone transfer within the constraints of this project and our current knowledge. We consider that the likelihood of significant impacts is relatively low because the northern spring-fed streams (Avon River/Ōtākaro and Ōtukaikino) are predominantly recharged by losses from the Waimakariri River, which provides for very high dilution of any nitrate-contaminated water. There could also be significant nitrate attenuation of groundwater discharging to the lower reaches of the spring-fed streams, since water flowing upwards into the streams from the deeper aquifer may pass through the various layers of organic rich sediment (e.g. peat) which are present in the Christchurch aquifer system. Further investigations and research, probably taking several years, would be required to determine whether there is any risk to the spring-fed streams from interzone transfer.

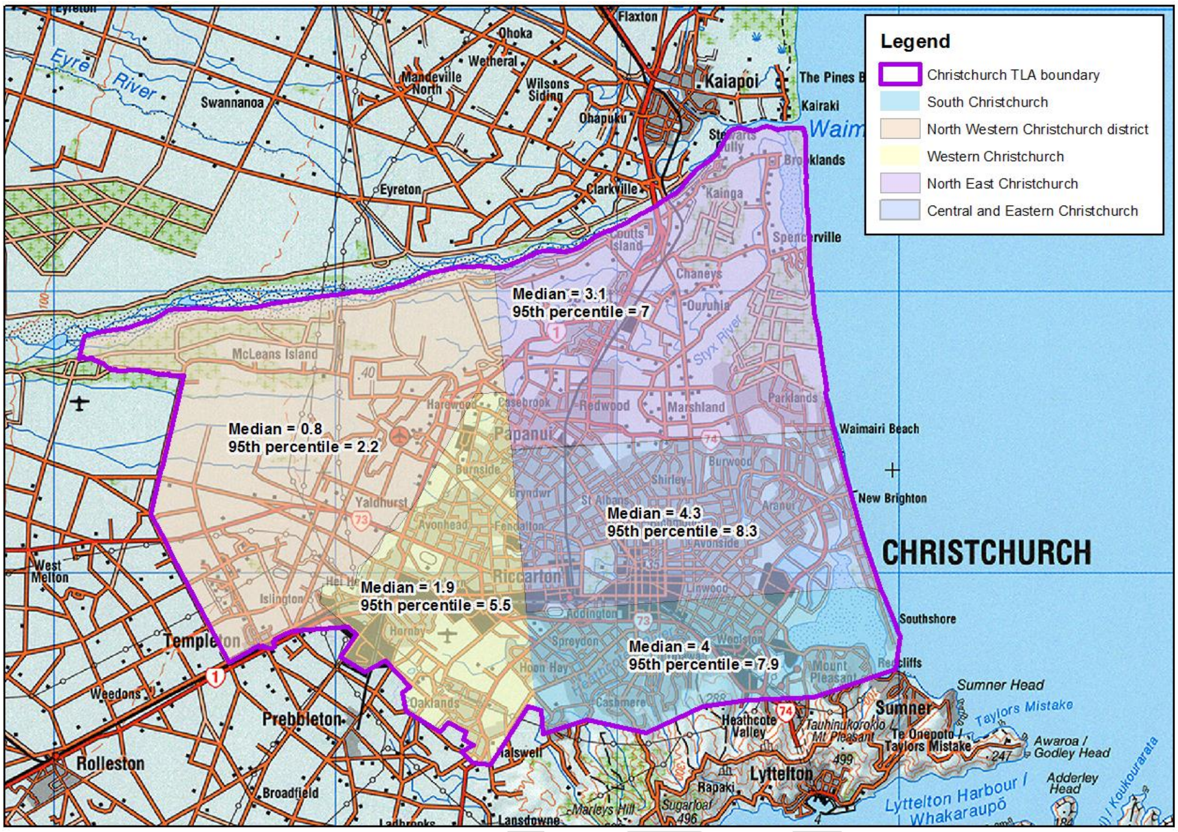

Figure 5 **Model nitrate concentrations for shallow aquifer under GMP scenario**

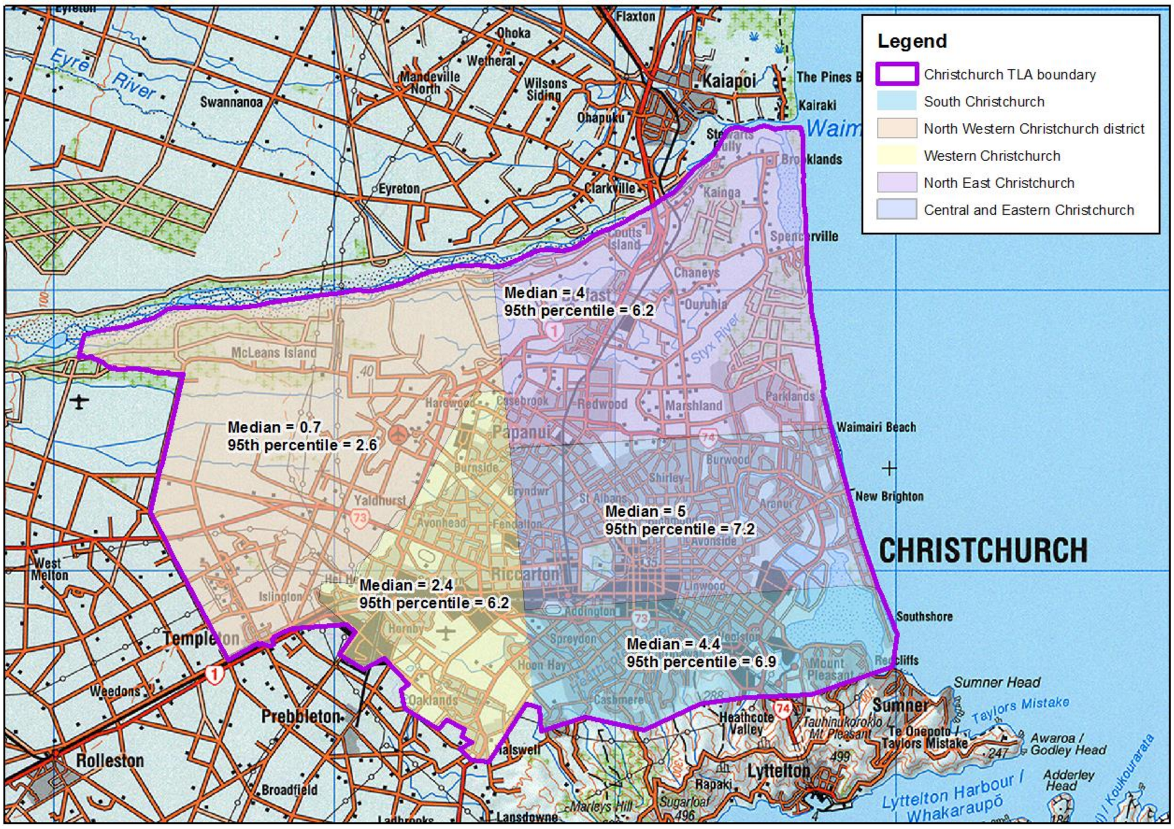

Figure 6 **Model nitrate concentrations for mid aquifer under GMP scenario**

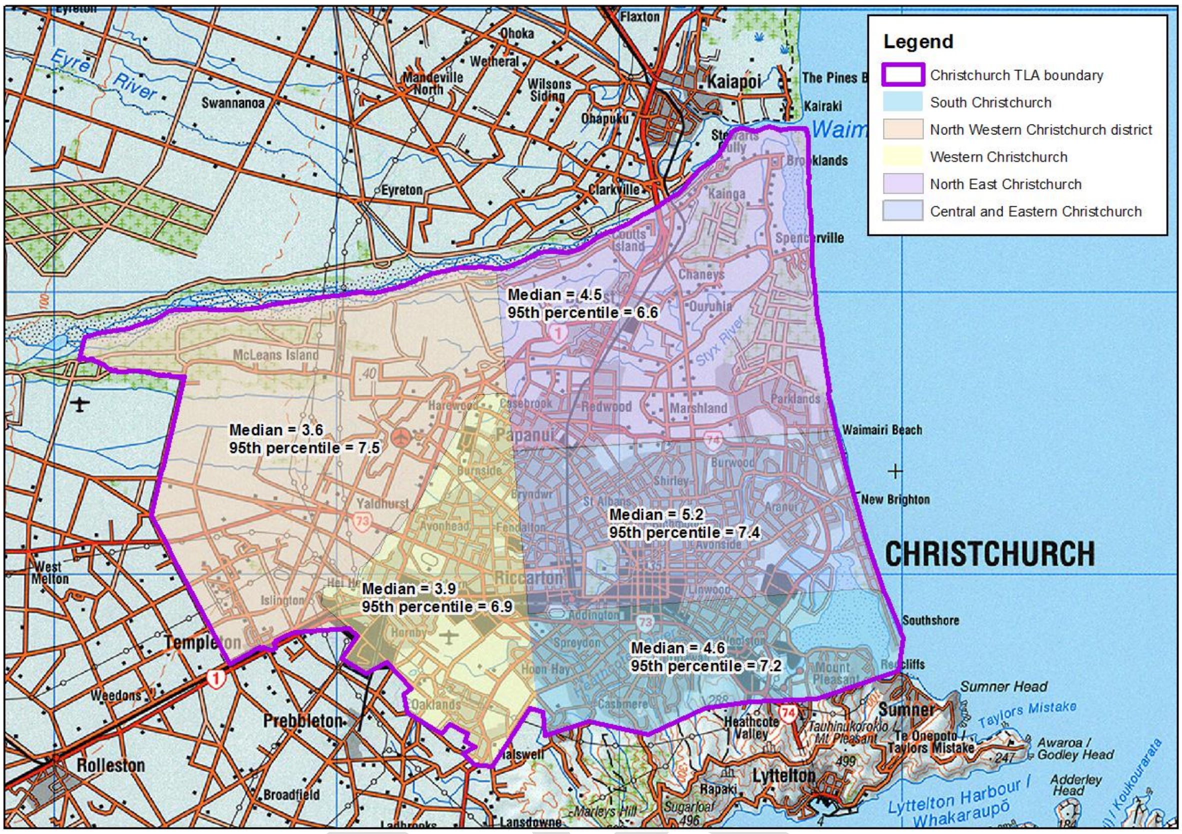

Figure 7 Model nitrate concentrations for deep aquifer under GMP scenario

Model results for the hypothetical dryland farming and 50% reduction in soil drainage nitrate concentration scenarios (Table 6) indicate that, overall, the current high quality of groundwater in the Christchurch aquifer system could be maintained under either scenario.

Average[12] measured concentrations are higher than model values for the shallow and mid depth aquifer due to historical nitrate contamination from the Islington Freezing Works, which is not included in the groundwater model. If this contamination source was included in the groundwater model, average modelled concentrations in the shallow aquifer would exceed the measured concentrations in the area of the freezing works contamination.

Model nitrate concentrations are higher than current measured values in the deep parts of the aquifer system in percentage terms under both scenarios, but we do not consider these changes from current measured concentrations to be significant in relation to drinking water quality.

Table 6 Summary of mean current measured and hypothetical nitrate loss reduction scenario model nitrate-N concentrations[13] (mg/L)

Aquifer depth	Current measured	50% reduction scenario	Dryland farming scenario nitrate-N
Shallow aquifer	3.4	2.5	1.7
Mid aquifer	2.3	2.4	1.3
Deep aquifer	0.6	2.6	1.3

[12] Results have been averaged both spatially and over time

[13] Mean model values – averages spatial variability and average of results from the 165 model iterations

5 Timing of modelled nitrate increases

5.1 Groundwater age concepts

Analysis of groundwater age data can provide useful information on the timing of nitrate concentration changes predicted by modelling. Groundwater drawn from a well or discharging to a spring-fed stream usually comprises a mixture of water, however, some of which has moved more slowly through the finer-grained, less permeable parts of the aquifer and is therefore older, and some of which has travelled more quickly through the most transmissive parts of the aquifer (e.g. the open framework gravels of former river channels). This often gives rise to misunderstandings and misuse of groundwater age estimates for determination of lag times between land use change and its full effects being seen in measured water quality. It is useful to consider groundwater age in the following terms:

- Young fraction: this is the percentage of water in a well or stream sample which is less than a certain age (e.g. one year). If a water sample has a high fraction of water less than a few years old we would expect nitrate to start to arrive at that location fairly quickly.
- Mean residence time, or mean age: this is the average age of water in a stream or well sample. This is the metric most commonly used when discussing groundwater age. Again, a young mean residence time would indicate that the effects of land use change on measured nitrate concentrations should start to be seen relatively quickly.
- Maximum age: this is the age of the oldest fraction of water in a sample. Knowledge of the maximum age allows us to understand how long it will take for nitrate concentrations in a stream or well to equilibrate with nitrate discharges from the land.

Whilst mean groundwater age can be evaluated with a reasonable degree of certainty if enough samples have been collected over a long period, determining the age distribution (e.g. young fraction and maximum age) is more challenging. Age distribution is typically estimated via mixing models; the choice of model and assumptions made when using that model can result in a wide range of estimates of the age distribution of a water sample. Groundwater age concepts are discussed further in Section 5.3 below.

5.2 Christchurch groundwater age investigations

Stewart (2012) evaluated age tracer data for the Christchurch aquifer system and concluded that prior to groundwater abstraction, the rate of turnover of water in the system was probably quite slow (i.e. mean age was quite old). By the 1970's mean groundwater ages in the deep system had become relatively young right across Christchurch (with mean ages of 60–70 years) indicating mainly lateral inflow of young water driven by groundwater abstraction. Mean ages have gradually increased since then, showing increasing upflow of much older water from depth. By 2006 a steep age gradient (from 300 years to 1400 years) had formed across Christchurch from west to east, suggesting that a large body of much older, deeper water is stored on the seaward side of the system where the deep aquifers are blind[14]. This offshore reservoir is expected to yield good quality water for many years, but eventually it is likely to be replaced or bypassed by younger (a few hundred years old) water which comprises a mixture of Waimakariri River water and land surface recharge from the inland plains (Stewart, 2012).

Our groundwater modelling suggests that nitrate will be transported downwards into the deep aquifer in the Waimakariri zone, and from there flow laterally towards the Christchurch aquifer. The model indicates that nitrate will be transported from the deep Christchurch aquifer upwards into the mid-depth and shallow parts of the aquifer system, driven by the upward hydraulic gradient in the artesian aquifer system. This means that knowledge of the groundwater ages in the deep aquifer will provide the best

[14] i.e. the aquifers are believed to terminate offshore, which limits the rate of throughflow

understanding of how long it will take for nitrate from the Waimakariri zone to travel into the Christchurch aquifer, assuming that the model results prove to be correct.

Stewart's conclusion that the very old water currently being drawn from the deep aquifer in the eastern and central parts of the system is likely to be replaced or bypassed by younger water, a few hundred years old, therefore provides useful information on how long it might take for nitrate concentrations in the Christchurch aquifer to increase as a result of land use intensification in the Waimakariri zone, but do not provide any insights into how long it would take for the full impact of this (i.e. when the full concentration increases projected by our modelling would occur).

5.3 Groundwater age distribution

Figure 8 below plots modelled age distributions for water samples collected from 115 and 220 m deep wells to the west of Christchurch. The plots show results from three different mixing models: an Exponential Piston Model (EPM) and two Binary Mixing Models (BMM). The mean residence time (MRT, i.e. mean age) estimates are variable because the analysis is based on a single sample. Collection of more samples (5-10 years after each other) would reduce uncertainty over the mean age.

Model results suggest that if land use intensification had occurred in the recharge area for these wells 20 years ago, for instance, we should have seen 30% of the nitrate concentration increase associated with that intensification by now in the 115 m deep well if either of the BMM results are correct. However, we would not expect nitrate concentrations to have increased at all yet if the EPM results are correct. We would expect the full effects of intensification to have occurred (i.e. steady state conditions) after 50 years if the EPM results are correct, but would not expect this to happen within 100 years if either of the BMM results are correct.

For the 220 m deep well, we would expect around 20% of the nitrate concentration increase associated with intensification 20 years ago to have occurred by now if either of the BMM results are correct but would not expect to have seen any change in concentrations based on the EPM results. Steady state conditions are not expected to occur within 100 years under any of these model results, but in all three cases we would expect to have measured 70-80% of the full nitrate concentration increase associated with the intensification within this timeframe.

These results do not represent the full spectrum of potential age distributions in these wells or other wells in the Christchurch aquifer system. We are currently working with GNS to improve our understanding of groundwater ages in the Christchurch aquifer systems using the results of an age tracer monitoring programme undertaken in 2017. Nonetheless, these results do provide some useful insights into the timing of possible nitrate increases.

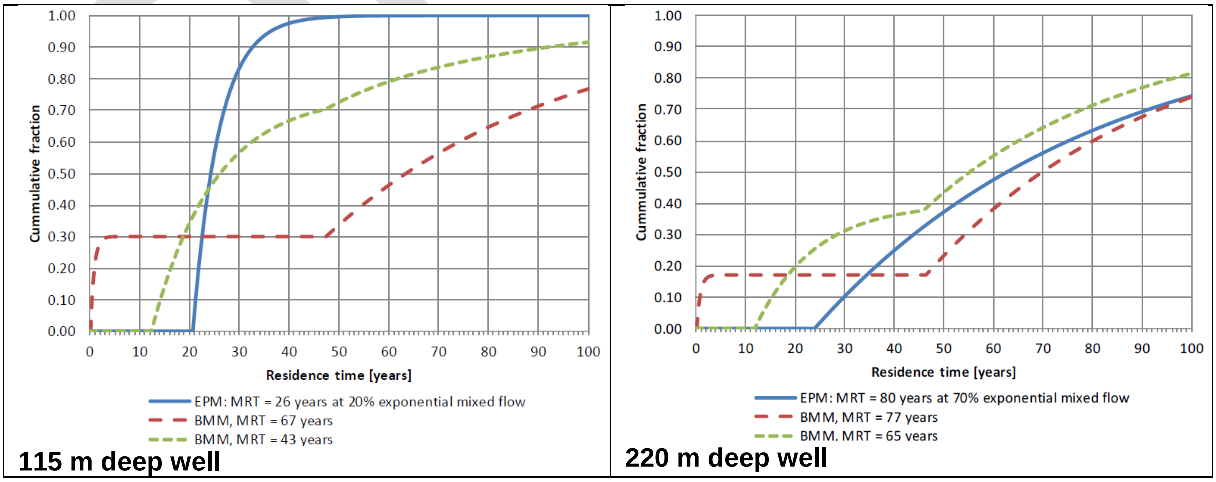

Figure 8 Age distribution for two deep wells west of Christchurch (see text for explanation)

Considering the information above in the context of measured and modelled nitrate concentrations in the Christchurch aquifer system:

- Our modelling results are consistent with the current interpretation of the age tracer data (e.g. the fact that we do not see high nitrate concentrations at depth can be explained by the expected lag in the system.)
- If our modelling results are correct, the increasing nitrate concentration measured in the deep Russley wells (Figure 2) represents the first arrival of nitrate in this area of the Christchurch aquifer system from the Waimakariri zone. Concentration increases in the Russley wells seem to start in 1999/2000; this may be in response to land use intensification which started 20-30 years prior to that time (i.e. in the 1970's-1980's), or it could be in response to land use intensifications in the 1990's, depending on which (if any) of the mixing model results are correct.
- The mean groundwater age in the deep aquifer beneath central and eastern parts of Christchurch is older than that in the Figure 8 wells (located west of the city). We would expect a wider distribution of ages as we move eastwards, with increasing distance from the inferred recharge zone north of the Waimakariri River. Whilst nitrate concentrations could start to increase in the next few decades, and may already be increasing beneath the city, mixing model results for the 220 m deep well west of Christchurch suggest that any increases are likely to occur gradually. We do not expect the full increases projected by our modelling to occur within 100 years.

6 Economic modelling method, scenarios and results explanation

6.1 Modelling approach and mitigation scenarios

6.1.1 Approach

Economic modelling has been undertaken to evaluate the impact of reducing nitrogen loss rates in the interzone source area on the local farming economy.

The economic modelling uses operating profit as an indicator of the economic outcomes, but also reports the reduction required of landholders, and the land use change needed for a range of nitrogen load reduction rates where mitigation is not feasible or economic based on current knowledge of on-farm nitrate mitigation options and their effectiveness, and also assuming no augmentation or other intervention options.

The operating profit is reported with and without the capital implications of land use change. The modelling assumes that forestry will be substituted in place of land uses to achieve the target N load reductions where mitigation is no longer feasible, and the modelling also reports an operating profit for situations where forestry is not feasible because of concerns about the implications for recharge of groundwater and flows in surface water bodies[15]. We used forestry for this illustrative modelling for simplicity and because a market for forestry production is in place. Substitution with other land uses (e.g. horticulture) may be possible but would require more complicated modelling. The operating profit figures for each land use are derived from the work with farmer stakeholders and include depreciation.

Profitability by land use and soil is shown in Table 7 below.

[15] Planting of forestry could reduce aquifer recharge and hence reduce spring fed stream flows and groundwater levels. No work has been undertaken in the Waimakariri zone to determine the magnitude of such effects.

Table 7: Operating profit ($/ha) by land use and soil type

	Soil category				
Land use	**XL**	**L**	**M**	**H**	**VH**
IRRIGATED					
Dairy	$2,462	$2,462	$2,462	$2,108	$2,108
Dairy support	$761	$761	$761	$761	$761
Arable	$783	$783	$783	$783	$783
Forestry	$0	$0	$0	$0	$0
Sheep and beef intensive	$662	$662	$662	$662	$662
Sheep and beef extensive	$109	$109	$109	$109	$109
DRYLAND					
Dairy	$2,462	$2,462	$2,462	$2,108	$2,108
Dairy support	$405	$405	$405	$405	$405
Arable	$438	$438	$438	$438	$438
Forestry	$0	$87	$105	$125	$125
Sheep and beef intensive	$325	$325	$325	$325	$325
Sheep and beef extensive	$109	$109	$109	$109	$109

6.1.2 Mitigation scenarios

A curve for mitigation of nitrogen (N) losses was derived for dairy land use only. This was estimated based on information generated with the Waimakariri farmer stakeholder group, and from information provided by Dairy NZ. The mitigations investigated by the Farmers Panel generally fall into the category of changes that can be made to existing farm systems, without making major adjustments involving infrastructure or significant changes to the farm system. These mitigations achieved up to ~10% reduction in N losses, with a cost to profitability in the order or 0 – 10%. These mitigations are referred to as the Farmers Panel mitigations. The Dairy NZ mitigations (referred to as the Systems Change mitigation) extended on this and investigated a wider range of mitigations including options that involve infrastructure such as feedpads, generally giving up to ~30% reduction in N losses. The modelling assumes that beyond this point land use change is required to achieve further reductions, which is potentially a conservative assumption because other mitigations such as housing of dairy cattle may potentially reduce losses further at a lower cost[16]. However, the implications of housing dairy cattle on a large scale have not been investigated, and it is considered that the assumptions and data available here are sufficiently robust to provide the indicative estimates of economic impacts for this stage of decision making.

The data used to estimate the costs of mitigation, and the curve generated and included in the modelling are shown in Figure 9. Note that positive numbers indicate a reduction in profit.

[16] Although it should be noted that the point of inflection in the results curve suggests that at the 30% mitigation level, under the assumptions used here, the cost of land use change is less than the cost of further mitigation.

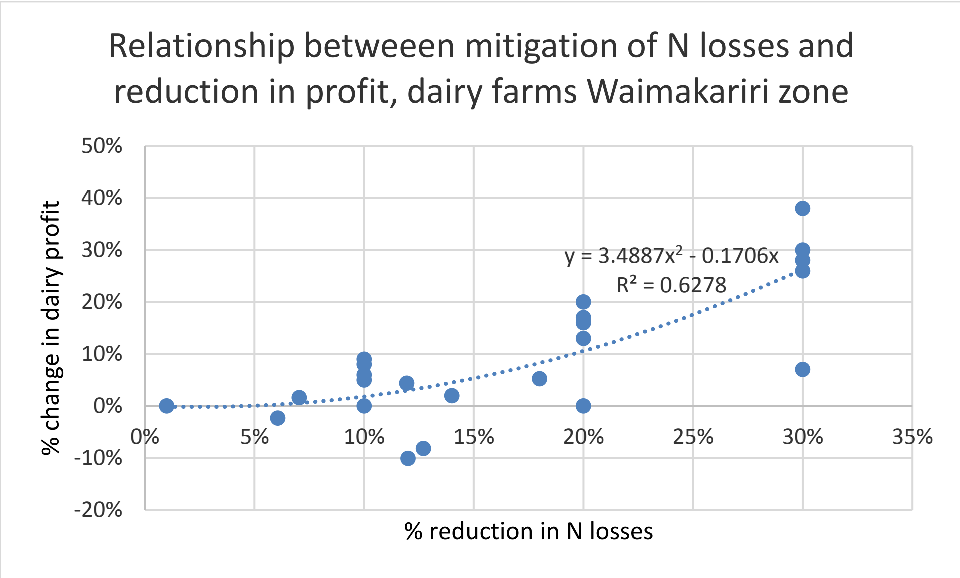

Figure 9 Reduction in profit for reduction in N losses, dairy operation

The Farmers Panel also investigated potential mitigations for sheep and beef and arable. No specific mitigations were found for mitigating beyond GMP for these land uses. This reflects that:

- Sheep and beef land uses tend to be lower intensity and have lower levels of inputs, which provides fewer opportunities for mitigation. GMP as defined in the Matrix of Good Management (MGM) already includes the major sets of mitigations available.
- Arable run at GMP reflects a very efficient system where nutrients are captured by product, and the any reduction in losses will tend to have a direct reduction in yield because they require a reduction in inputs. Because of the high levels of fixed costs, and the small margins in cropping, it is not likely to be worthwhile to take this approach.

Dairy support was included with dairy, which perhaps overestimates the potential for mitigation, but reflects the need to treat them together because of the fluid nature of the potential options for grazing within or external to the dairy farm boundary. The cost of mitigation for dairy support areas was not included in the Farmers Panel or Dairy NZ analysis above, although some of the operations included different components of dairy support within them. The cost of mitigating nutrient losses from dairy support land was modelled by simply assuming a linear reduction in profit with reduction in nutrients, which will over or underestimate the cost of mitigation depending on what replaces the dairy support within the operation.

Managed Aquifer Recharge (MAR) may ultimately prove to be a feasible option to address elevated Nitrate-N concentrations in water infiltrating from land in the interzone source area. However, detailed investigations, modelling, concept design and feasibility analysis would be required before this mitigation option could be proven. This work would take a number of years to complete.

6.1.3 Approaches to achieving catchment limits

The modelling adopts two indicative approaches to achieving reductions of between 5% and 50% in the total N load from the modelled interzone source area:

- The first applies an even reduction to all land uses in the catchment. Up to 30% this results in dairy and dairy support undertaking mitigation to reduce their N losses, while sheep and beef and arable, which have limited options for mitigation beyond GMP, move land into forestry to achieve the reduction. The profit outcomes for this approach are reported as changes in Operating Profit (OP), changes in OP after the capital costs of transition, and changes in OP assuming that additional forestry is not possible in the catchment because of water constraints and the land is left fallow.

- The second approach targets reduction to dairy and dairy support only. This results in on-farm mitigation occurring for the lower levels of reductions (depending on the proportion of dairy in the catchment). Beyond this dairy is substituted for forestry, to achieve targeted reductions in N loads. The results of targeting dairy only are shown as operating profit only.

6.2 Economic modelling results explanation

The results from this modelling of the costs of reducing nutrient loads should be seen as indicative. The modelling uses available information, the information on mitigation developed through the farmers stakeholder group, and information provided by Dairy NZ. The profitability figures for land use can be highly variable, and the differential between land uses can vary similarly. This modelling adopts a limited range of financial returns and N losses, and this means that the modelling is reasonably simplistic in the context of the true likely complexity. For example, a market based approach would in theory result in mitigation being directed towards the locations and land uses where it could be achieved at the lowest cost, but market mechanisms for trading nutrient emissions are not well developed in NZ, and face a number of practical implementation problems as well as some social and cultural opposition. Despite these caveats the analysis is sufficiently robust to identify the likely scale of costs and the difficulties of achieving some of the percentage reductions assessed in the analysis

The results plots (Figure 10 and Figure 11 for the high likelihood and high to moderate likelihood zone delineations) show the following:

Proportion of N load by land use – this graph shows what proportion of the N load is from manageable and non-manageable sources, as well as how much the intensive land uses and dairying contribute to the total N loss. This information is useful to understand why the costs of mitigation vary by source area, because the distribution of land uses in the catchment is a primary driver of the costs of achieving N reduction targets.

Reduction in N losses required from landholders relative to reduction in catchment N loss - Because not all land use in the catchment is productive, and because losses from some of the productive land (i.e. forestry) cannot be reduced, the reductions required of landholders is greater than the reduction required for the catchment overall to achieve the target. For example, if a 50% reduction is required for the catchment, and only 80% of the catchment is capable of reducing its losses, then that 50% reduction is concentrated on the smaller area. In this example the landholder who can reduce their losses must achieve a 62.5% (50%/80%) reduction in their losses in order for the catchment to achieve a 5% reduction. This graph shows by how much the landholder reductions exceed the catchment reductions.

Profit with reduction in N loss – the operating profit derived from all land uses in the catchment for different levels of reduction in N loss.

Change in land use with mitigation of N loss – where mitigation is not available within an existing land use, the model changes land use to one with a lower loss rate (forestry). This graph shows the change in land use area required as a percentage of the total area of that land use within each catchment for a range of % N loss reduction rates.

6.3 Economic modelling results

Modelling results for the moderate to high likelihood delineation interzone source area (Figure 10) indicate that:

- 74% of the land use in this area is dairy and dairy support
- A 50% total reduction in N load from this catchment, for example, would require dairy and dairy support farmers to reduce their N losses by ~65%

- The operating profit for this area is estimated at ~$44M. A hypothetical 50% N load reduction targeted on dairy and dairy support only would reduce total profit by around $24M, i.e. 55%.
- The area of dairy and dairy support land would need to be reduced by around 50% under a hypothetical 50% N load reduction scenario

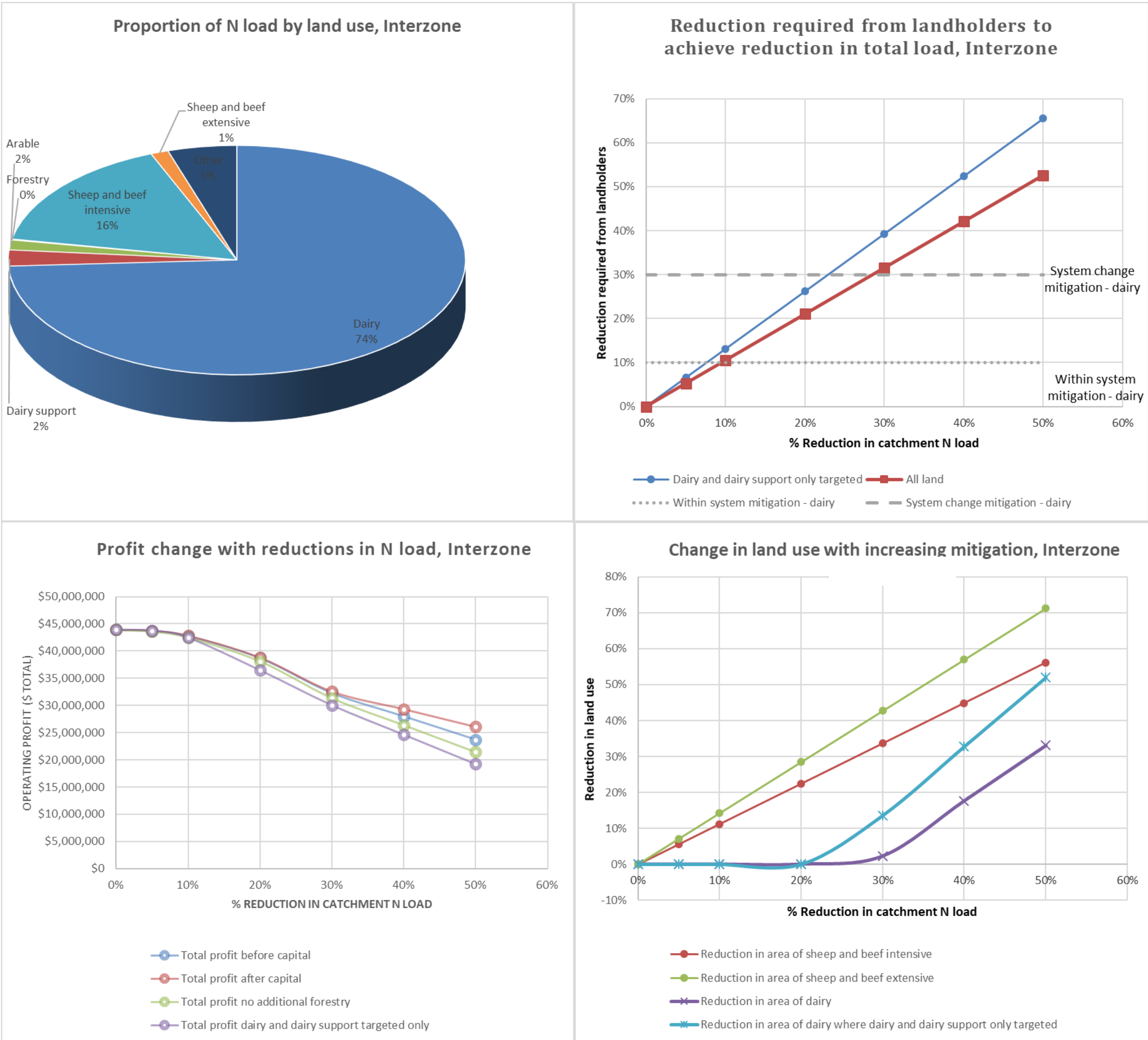

Figure 10 Economic impact modelling results for moderate to high likelihood zone delineation

Modelling results for the high likelihood delineation interzone source area (Figure 11) indicate that:

- 73% of the land use in this area is dairy and dairy support
- A 50% total reduction in N load from this catchment, for example, would require dairy and dairy support farmers to reduce their N losses by ~65%
- The operating profit for this area is estimated at ~$35M. A hypothetical 50% N load reduction targeted on dairy and dairy support only would reduce total profit by around $20M, i.e. 57%.
- The area of dairy and dairy support land would need to be reduced by around 50% under a hypothetical 50% N load reduction scenario

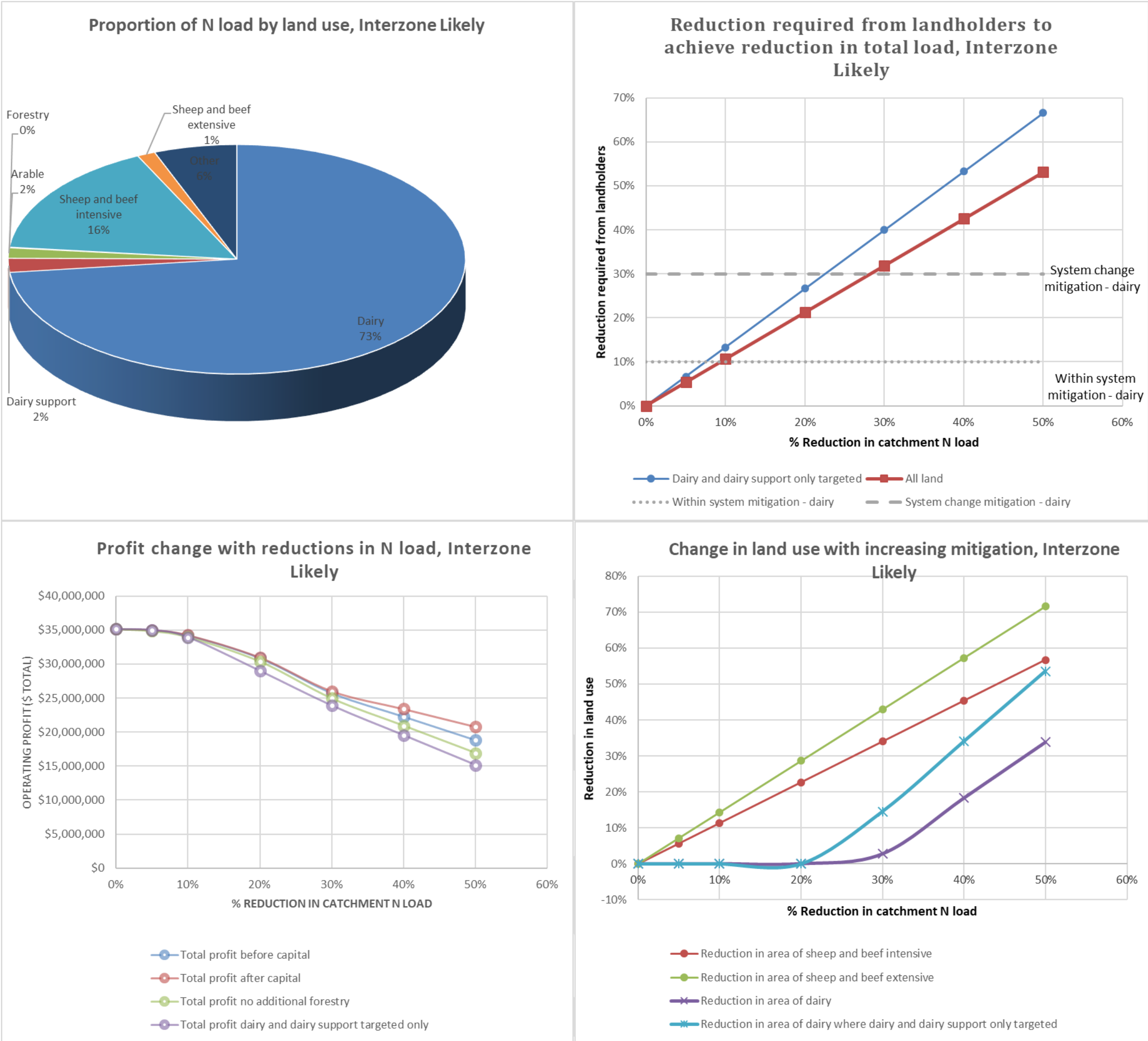

Figure 11 Economic impact modelling results for high likelihood zone delineation

7 Appendix 1: Spatial nitrate concentration plots

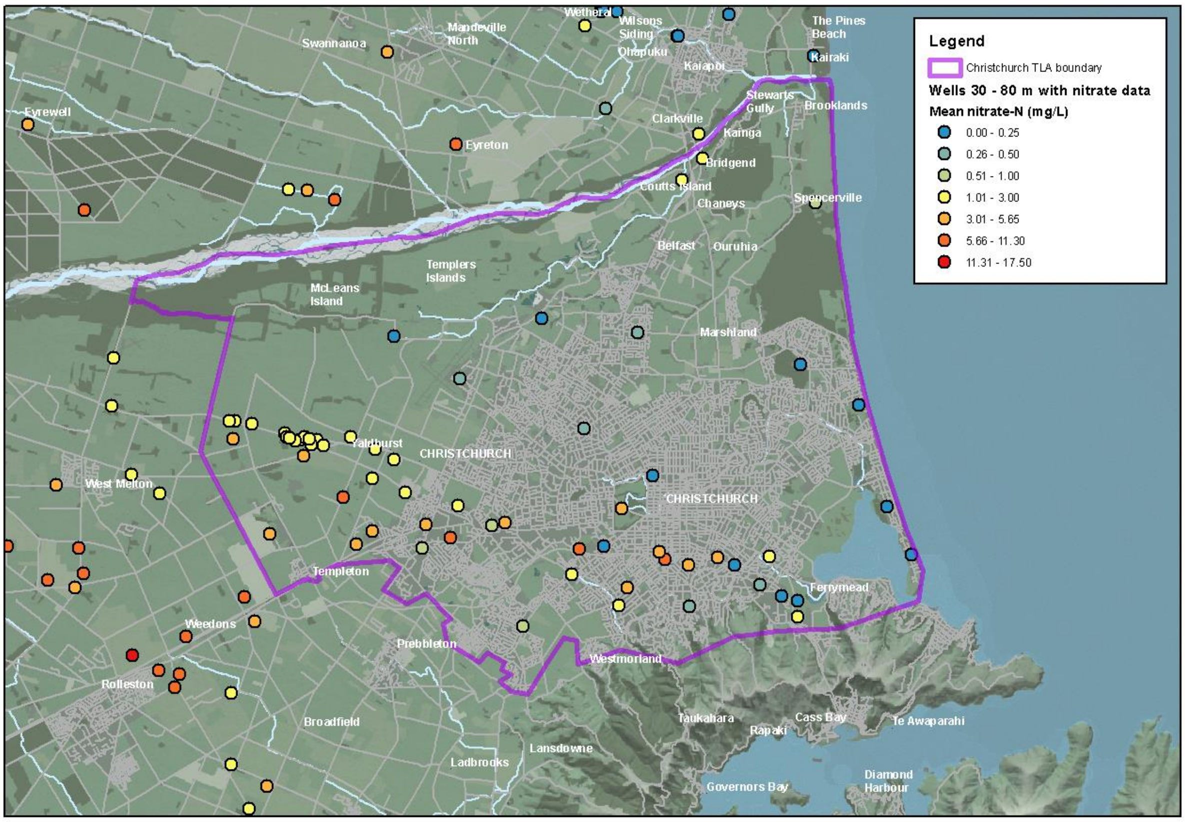

Figure 12 Measured mean nitrate concentrations in wells 30 - 80 m deep since 2008

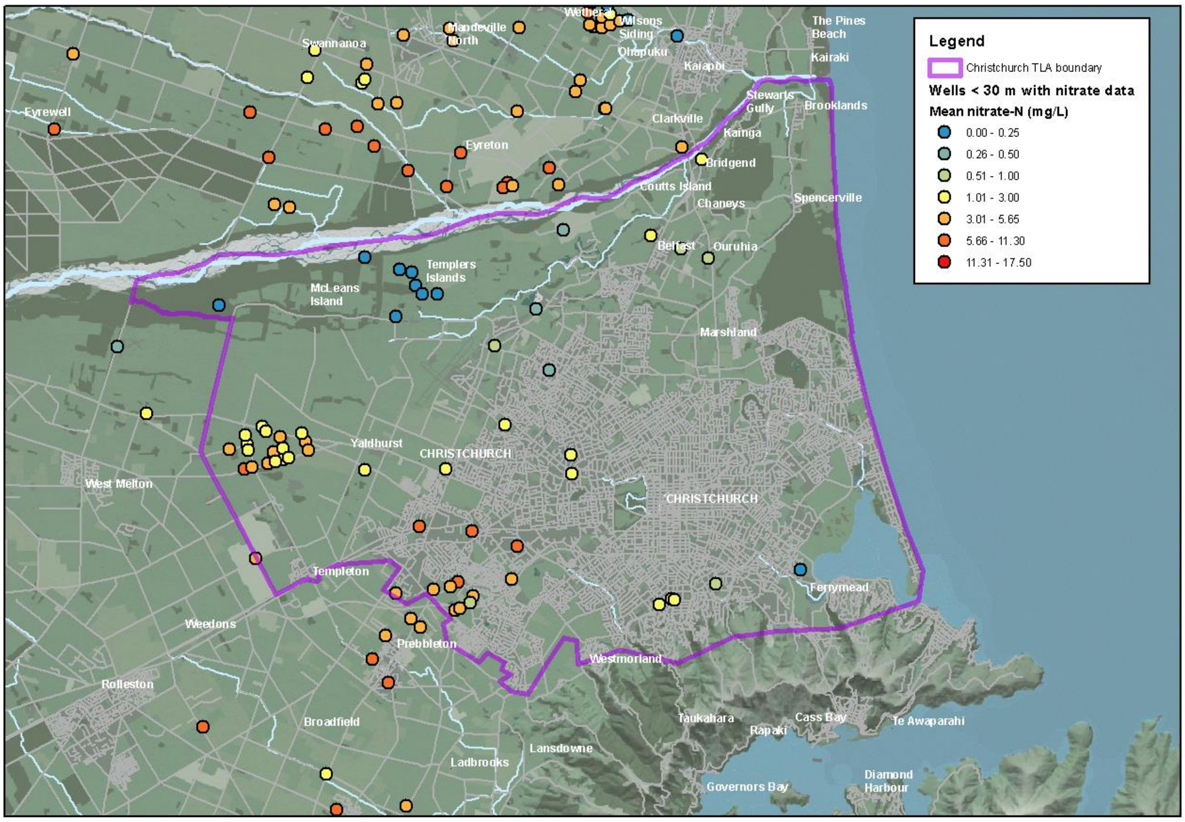

Figure 13 Measured mean nitrate concentrations in wells < 30 m deep since 2008