IN THE MATTER OF:	Clauses 6 and 8 of Schedule 1 – Resource Management Act 1991 – Submissions on publicly notified plan change and variation – Proposed Plan Change 1 and Variation 1 to Waikato Regional Plan – Waikato and Waipa River Catchments
And:	**Wairakei Pastoral Ltd** Submitter
And:	**Waikato Regional Council** Local Authority

STATEMENT OF EVIDENCE OF JONATHAN WILLIAMSON

Block 2 Hearing Topics

Dated: 3 May 2019

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SUMMARY AND CONCLUSIONS

Summary

1 In my Block 1 evidence I concluded that:

1.1 Groundwater N "load to come" concept defined in the PC1 background documents as a load of N in groundwater derived from land surface recharge that will take many decades to discharge into the receiving environment, is contrary to the principles of groundwater redox chemistry [para 17], because old groundwater (which is responsible for the groundwater lag) has been subjected to redox reactions involving the progressive depletion of dissolved oxygen followed by nitrate conversion to benign nitrogen gas [para 19].

1.2 Recent N concentration increases in surface waters are explained by "quicker flow processes" including surface runoff and young groundwater discharges, which are relatively short or medium-term responses, respectively [para 18].

1.3 For this reason, the short-term (2016-2026) is more critical in terms of ensuring that freshwater quality is maintained or improved to meet freshwater objectives, particularly Objective 3 by 2026 (i.e. a 10% reduction of Objective 1 (the 80-year objective)).

1.4 PC1 adopts a blanketed policy approach with regard to managing water quality effects across the landscape. That is, PC1 as notified ignores the dynamic nature of the landscape's assimilative capacity. This is because the discharge footprints of land parcels vary, not only on the basis of land use, but also across differing sub-catchment physical characteristics, including the sub-surface.

1.5 Spatial variability in the landscapes assimilative capacity across sub-catchments is therefore a matter that should be considered when deciding resource consent applications.

2 Consequently, I concluded that the PC1 policy package will not have the desired effect with respect to nitrate water quality improvements without amendment so that the focus of PC1 should change in the following ways:

2.1 From targeting management of an assumed "load to come of N" to managing constituent load attached to quicker flow processes such as surface runoff and source areas of young groundwater discharges e.g. Farm Environmental Plans that target mitigation of constituent generation (all four contaminants) via quicker flow process (surface runoff and young groundwater); and

2.2 To adopt a more dynamic landscape-based approach, cognisant of the differing assimilative capacity of the landscape, will provide greater flexibility for landowners to manage their activities within the constraints of agreed freshwater objectives. It therefore follows that both environmental sustainability and economic utility of the land will be optimised (as discussed in the evidence of Mr Ford).

3 The focus of my Block 2 evidence is on:

3.1 The modelling tool that was developed by the technical team commissioned by **WPL** to inform relative environmental responses from land use change and mitigation options associated with various land management practices; and

3.2 Demonstration using model outputs of key hydrological concepts raised in my evidence, to show how different parts of the catchment will have differing timing and degree of effect from land use change, and how this science links to the provisions in PC1 as notified.

4 The modelling tool is known as the Ruahuwai Decision Support Tool (**RDST**), which comprises three main modelling components. The RDST is documented in four operational reports that are being continually refined as new data and scenarios are presented to the modelling team.

5 Each component of the RDST has been through a number of rounds of internal and external peer review, which were commissioned by WPL and/or Waikato Regional Council to ensure the models were of an appropriate level of accuracy for sub-catchment scale prediction of water quality outcomes from different land uses and land management practices.

6 The objective for the RDST was to explore and understand:

6.1 The hydrologic (surface water) and hydrogeologic (groundwater) functioning of the land and sub-surface within the Ruahuwai model domain;

6.2 The likely water quality concentration and load outcomes at a sub-catchment scale from different land use options;

6.3 To test and make informed land management and mitigation decisions.

7 In essence, the RDST enables landowners to optimise land utilisation within the agreed environmental objectives framework i.e. to meet environmental objectives and optimise land productivity concurrently.

Conclusions

8 This evidence has outlined my concerns with provisions in PC1 as notified and in particular the disconnect with modern science underpinning groundwater denitrification, and the dynamic functionality of groundwater systems and their interaction with surface water systems.

9 Keys aspects I consider need addressing through the planners include:

9.1 The “long term load to come of N” intervention logic for PC1 is incorrectly founded and unless the focus changes to management of quick flow and young groundwater responses, it is unlikely the long term 80-year Vision and Strategy will be met, and as Mr Ford will confirm, will not represent an optimal cost-benefit solution.

9.2 Failure to consider the timing of effects from land use change that may have occurred immediately prior to the PC1 notification date (October 2016) to manifest fully (i.e. effects may start occurring slowly immediately after the land use change, but the time for the full magnitude of effects to reach a new pseudo steady state will be some time later) may hinder achievement of Objective 3, unless FEPs are required immediately.

9.3 A policy approach that is flexible and recognises the assimilative capacity of land or vulnerable land areas - restricting high intensity land use in highly vulnerable areas and allowing higher intensity land use in low vulnerability areas.

EVIDENCE OF JONATHAN WILLIAMSON

Block 2 Hearing Topics

1 My name is **Jonathan (Jon) Williamson**. I have the qualifications and experience recorded in my statement of evidence filed in relation to the Block 1 Hearing Topics.

2 My statement of evidence has been prepared in accordance with the Code of Conduct for Expert Witnesses set out in Section 7 of the Environment Court of New Zealand Practice Note 2014.

INTRODUCTION

3 In my Block 1 evidence I concluded that:

3.1 Groundwater nitrogen (**N**) "load to come of N" concept defined in the Plan Change 1 (**PC1**) background documents as a load of N in groundwater derived from land surface recharge that will take many decades (i.e. up to 80 years) to discharge into the receiving environment, is contrary to the principles of groundwater redox chemistry [para 17], because old groundwater (which is responsible for the groundwater lag) has been subjected to redox reactions involving the progressive depletion of dissolved oxygen followed by nitrate conversion to benign nitrogen gas [para 19].

3.2 Recent N concentration increases in surface waters are explained by "quicker flow processes" including surface runoff and young groundwater discharges, which are relatively short or medium-term responses, respectively [para 18]. These effects should manifest and plateau by 2025.

3.3 For this reason, the short-term (2016-2026) is more critical in terms of ensuring that freshwater quality is maintained or improved to meet freshwater objectives, particularly Objective 3 by 2026 (i.e. a 10% reduction of Objective 1 (the 80-year objective)).

3.4 PC1 adopts a blanketed policy approach with regard to managing water quality effects across the landscape. That is, PC1 as notified ignores the dynamic nature of the landscape's assimilative capacity. This is because the discharge footprints of land parcels vary, not only on the basis of land use, but also across differing sub-catchment physical characteristics, including the sub-surface.

3.5 Spatial variability in the landscapes assimilative capacity across sub-catchments is therefore a matter that should be considered when deciding resource consent applications.

4 Consequently, I concluded that the PC1 policy package will not have the desired effect with respect to nitrate water quality improvements without amendment so that the focus of PC1 should change in the following ways:

4.1 From targeting management of an assumed long-term "load to come" to managing constituent load attached to quicker flow processes such as surface runoff and source areas of young groundwater discharges e.g. Farm Environmental Plans (**FEPs**) that target mitigation of constituent generation (all four contaminants) via quicker flow process (surface runoff and young groundwater); and

4.2 To adopt a more dynamic landscape-based approach, cognisant of the differing assimilative capacity of the landscape, will provide greater flexibility for landowners to manage their activities within the constraints of agreed freshwater objectives. It therefore follows that both environmental sustainability and economic utility of the land will be optimised (as discussed in the evidence of Mr Ford).

5 The focus of my Block 2 evidence is on:

5.1 The modelling tool that was developed by the technical team commissioned by Wairakei Pastoral Limited (**WPL**) to inform relative environmental responses from land use change and mitigation options associated with various land management practices; and

5.2 Demonstration using model outputs of key hydrological concepts raised in my evidence, to show how different parts of the catchment will have differing timings and degrees of effect from land use change, and how this science links to the policy provisions in PC1 as notified.

6 The modelling tool is known as the Ruahuwai Decision Support Tool (**RDST**), which comprises three main modelling components that are described in the following section of this evidence.

7 The RDST is documented in four operational reports that are being continually refined as new data and scenarios are presented to the modelling team, referenced as follows:

7.1 Mawer, J. and Williamson, J., 2019. Ruahuwai Integrated Catchment Modelling Project. Volume 1 - RDST Overview and Scenarios. Revision 3, 30 April 2019. Williamson Water & Land Advisory consultancy report prepared for Wairakei Pastoral Limited.

7.2 Zhao, H., Walton, M., and Williamson, J., 2019. Ruahuwai Integrated Catchment Modelling Project. Volume 2 – APSIM Modelling Report. Revision 2, 30 April 2019. Williamson Water & Land Advisory consultancy report prepared for Wairakei Pastoral Limited.

7.3 Zhao, H., Williamson, J., Kalbus, E., and Burgess, R., 2019. Ruahuwai Integrated Catchment Modelling Project. Volume 3 – MODFLOW Groundwater Modelling Report. Revision 11, 30 April 2019. Williamson Water & Land Advisory consultancy report prepared for Wairakei Pastoral Limited.

7.4 Mawer, J., Williamson, J., Loft, J., and Zhao, H., 2019. Ruahuwai Integrated Catchment Modelling Project. Volume 4 - SOURCE Catchment Modelling Report. Revision 4, 30 April 2019. Williamson Water & Land Advisory consultancy report prepared for Wairakei Pastoral Limited.

8 Each component of the RDST has been through a number of rounds of internal and external peer review, which were commissioned by WPL and/or Waikato Regional Council (**WRC**) to ensure the RDST reached an appropriate level of accuracy for sub-catchment scale prediction of water quality outcomes from different land uses and land management practices.

9 The peer reviews undertaken are documented in each report volume and are summarised in **Table 1** below.

Table 1. RDST peer review record.

Model	Reviewer & Date	Scope of Review	Key Review Comments	How Resolved in Subsequent Versions of the RDST
APSIM	Dr. Iris Vogler (Landcare Research, previously Ag Research) Dec-2016 through Aug-2017	Review the application of APSIM to model leaching of N and comparison to OVERSEER modelling. Review focussed on dairy models only.	1. Treatment of animal urine patches in the early versions of the model was deemed not fit for purpose, and 2. The methodologies for paddock averaging and effluent application were considered overly simple.	1. Spatially weighted, “background” and “urine patch” paddocks, incorporating patch overlap, were matched to management activities. 2. Additional simulations and seasonal constraints incorporated into the models. [Approved by reviewer on 18/08/2017].
	Drs. Sandy Elliot & Bryce Cooper (NIWA) June-2018	To provide a high-level review of the RDST its suitability for its intended purpose.	1. The APSIM model used in the RDST does not include an animal component to represent returns of nutrients to the soil via excrement. 2. The ability of APSIM to adequately represent some mitigation measures. For example, the different farm management measures could interact (synergistically or antagonistically), and the authors of the APSIM report point out that this is an area for further work.	1. APSIM does not have an animal component, but N returns from animals was addressed through the review of Dr. Vogler (1 above). 2. This is still a residual area of development for the application of APSIM Models.
	Dr. Val Snow (Ag Research) Dec 2018 – Jan 2019	Review the APSIM soil water and soil organic content parameterisation. Review focused on dairy model.	1. The model organic content was not initialised with a reasonable starting condition. 2. Certain model parameter values were default guideline values and may not be fit for the regional conditions. 3. Parameter sensitivity was not tested.	1. Model warm-up was conducted by rerunning the models until the carbon content in the soil reached a quasi-steady state, and this condition was used to initialise the soil carbon in model simulation thereafter. 2. Model hydraulic parameters were reinvestigated with available references. 3. Sensitivity test was conducted for certain parameters in the soil organic matter module and the initial water module.
MODFLOW / MT3DMS	Mr. Scott Wilson & Dr. Roland Stenger (Lincoln AgriTech) Aug 2017	Review the groundwater flow model and nitrogen transport model components of the RDST.	1. The transport of nitrogen through the vadose zone was not explicitly simulated. 2. The use of block-average hydraulic conductivity zonation is not representative of natural geological systems. 3. Development of stochastic approach to improve the understanding of the uncertainty of the model key inputs and their associated impact on the simulation variables.	1. The vertical unsaturated flow and associated nitrogen leaching was discussed in the context of regional conditions. The recharge modelling process was changed to incorporate vadose zone drainage functionality to represent the potential delay in the flow and solute transport to the groundwater table. 2. Transient model was refined by generating random points within geological units, and interpolating horizontal hydraulic conductivity and vertical anisotropy between points to each grid cell resulting in a smoothed hydraulic property distribution. 3. Sensitivity testing of the model’s key input parameters to constrain the uncertainty in the modelling results, is ongoing as of April 2019.
	Drs. Sandy Elliot & Bryce Cooper (NIWA) June 2018	To provide a high-level review of the RDST its suitability for its intended purpose.	1. N concentrations and tritium levels do not provide assurance the groundwater model represents the groundwater system accurately.	1. Transient land use changes were included in the model and further refinement of the spatial variation in decay rate improved calibration on N concentrations.
	Dr Richard Creswell April 2019	Reporting	1. Numerous useful comments.	1. Addressed in the April 2019 version of the report.

Model	Reviewer & Date	Scope of Review	Key Review Comments	How Resolved in Subsequent Versions of the RDST
SOURCE	Drs. Sandy Elliot & Bryce Cooper (NIWA) June-2018	To provide a high-level review of the RDST its suitability for its intended purpose.	1. The model does not predict transient adjustments to land use change. 2. Generation of constituents not linked to physical characteristics. 3. The percentage reduction associated with a number of the mitigation measures were considered overly optimistic in comparison to available literature. 4. Include geothermal sources as input nodes rather than modifying TN or TP generation rates.	1. Transient land use changes were included in the APSIM, MODFLOW and SOURCE models for the calibration period and scenarios. 2. Constituent generation indices and relationships developed relating EMC and DWC concentrations to physical characteristics (e.g. slope, land use, vegetation cover etc.) were implemented. 3. Mitigation factors were revised and reduced where appropriate in accordance with the literature. 4. Geothermal sources were included as input nodes.
	Phillip Jordan (HARC) January 2019	Flow and constituent calibration	1. Improve the flow calibration at Waiotapu River at Reporoa and at the Orakonui Stream gauge with the aim of reducing baseflow (to improve match to gauge data).	1. Calibration improved through a combination of refining drain levels and stream conductance in the catchments upstream of these gauges in the groundwater model, and surface water parameters refined in the SMWBM (Zmax increased to reduce peak runoff).

RDST DEVELOPMENT

10 My evidence will encompass the following subject matter on the model:

- 10.1 Model purpose and objectives;
- 10.2 Model description;
- 10.3 Model development;
- 10.4 Model calibration;
- 10.5 Scenarios considered; and
- 10.6 Demonstration of key concepts using the model with respect to highlighting why the intervention logic (“long-term load to come”) of the PC1 as notified is incorrect.

Model Purpose and Objectives

11 The objective for the RDST was to explore and understand:

- 11.1 The hydrologic (surface water) and hydrogeologic (groundwater) functioning of the land and sub-surface within the Ruahuwai model domain;
- 11.2 The likely water quality concentration and load outcomes at a sub-catchment scale from different land use options;
- 11.3 To test and make informed land management and mitigation decisions.

12 In essence, the RDST enables landowners to optimise land utilisation within the agreed environmental objectives framework i.e. to meet environmental objectives and optimise land productivity concurrently.

RDST Description

13 The RDST is a paddock to stream calculator of hydrological flow and constituent[1] mass, and therefore considers attenuation that occurs between the paddock and the stream. The RDST computations are performed on a daily basis, which permits analysis of effects from both storm events and seasonal responses.

14 The RDST covers an area of approximately 1,648 km^2 encompassing the tributary catchments of the Waikato River from Lake Taupo gates to the Lake Ohakuri tailrace (**Figure 1**). Essentially, the RDST area covers the 10 sub-catchments in the Upper Waikato River Freshwater Management Unit (**FMU**) as notified in PC1. Sub-catchment 66 is proposed to be subdivided into Sub-catchments 66A and 66B as covered in my Block 1 evidence.

15 The RDST couples three primary models, which are briefly described in the paragraphs that follow:

- 15.1 The Agricultural Production Systems Simulator (**APSIM**);
- 15.2 MODFLOW and MT3DMS within the GMS software interface package; and

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[1] Constituents are defined as benign or contaminant materials that are generated, transported and transformed within a catchment.

15.3 SOURCE.

16 ***Model Scale*** - Model inputs and model outputs occur on two different spatial scales.

16.1 The fundamental building block of the models comprises a regular grid of 300 m x 300 m (9 ha) cells or blocks distributed across the entire catchment (**Figure 2**). Model inputs including meteorological, catchment physical characteristics (soil, slope, vegetation cover density), and land use types (and associated stocking and/or nutrient intensity) are initially computed at the grid scale.

16.2 Depending on the model, data is either used directly in the models at the 9-ha scale (e.g. MODFLOW), or aggregated to a sub-catchment scale (e.g. SOURCE), of which 415 were defined within the Ruahuwai catchment area. The sub-catchments used for modelling purposes range in size from 7.2 ha to 3,206 ha (**Figure 2**).

16.3 All model outputs from the SOURCE model are computed at the modelled sub-catchment scale and in particular at the outlet of each sub-catchment.

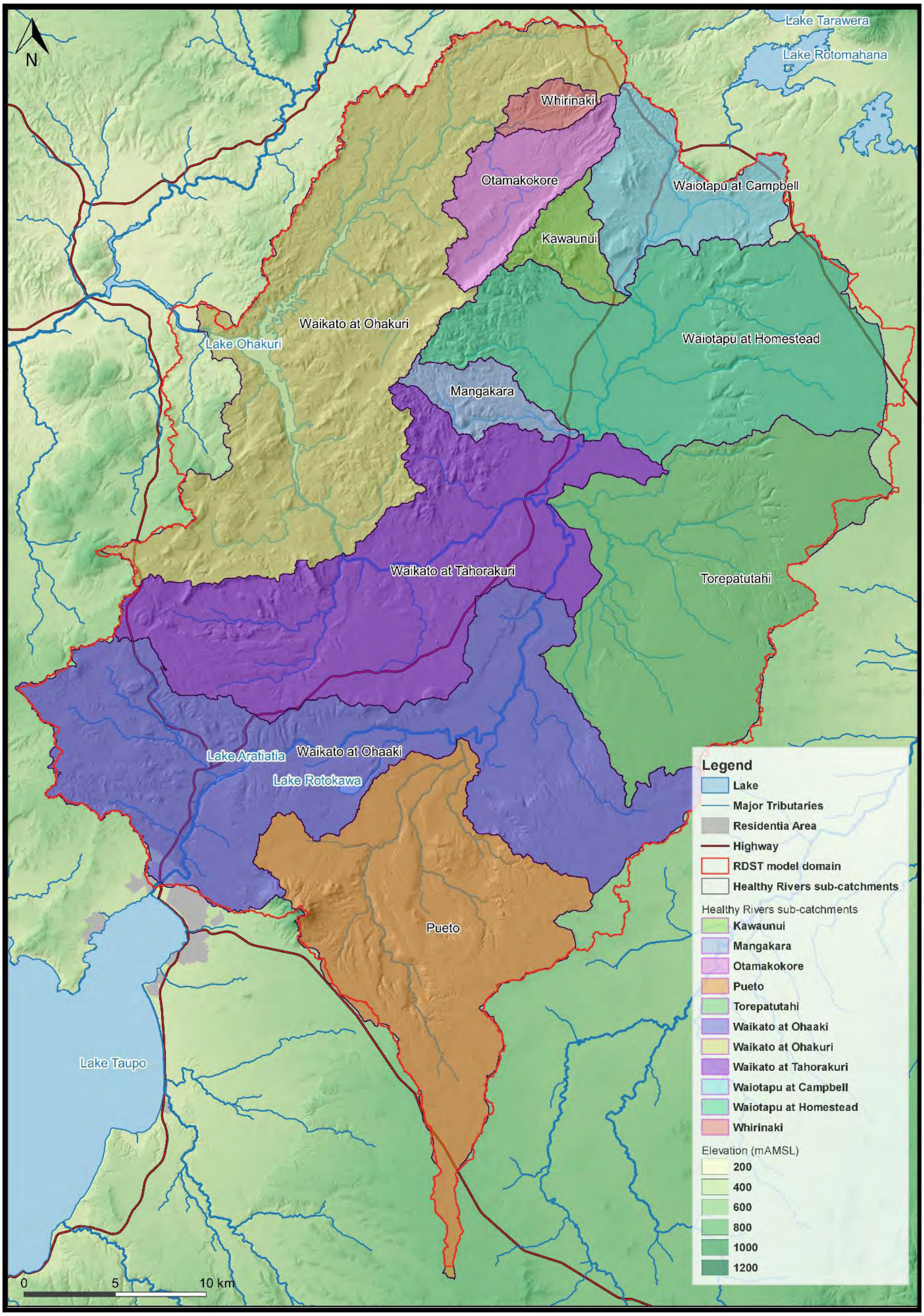

Figure 1. RDST model domain, Healthy Rivers sub-catchments and major tributaries.

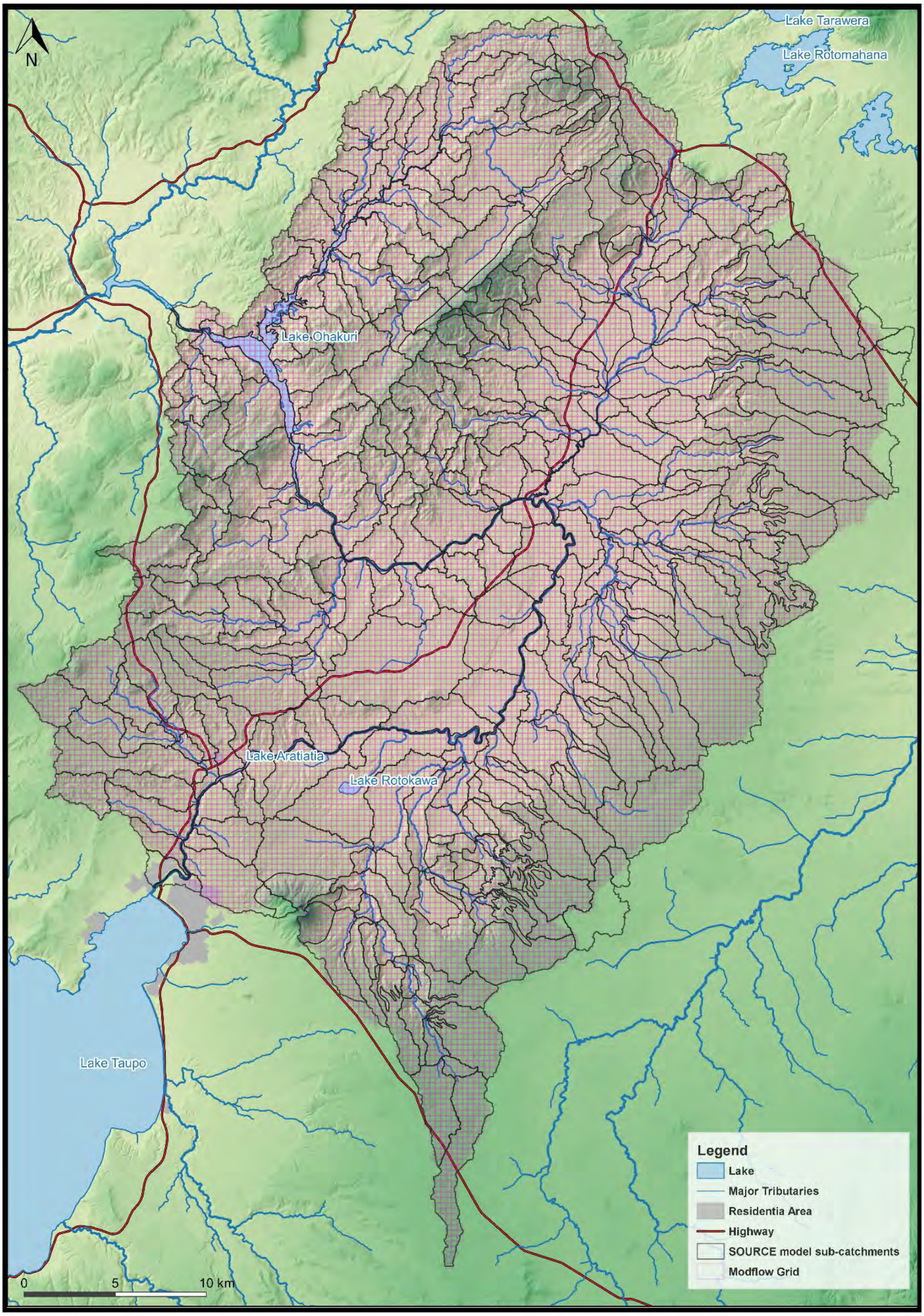

Figure 2. RDST model grid and sub-catchments.

APSIM

17 APSIM is an integrated modelling framework developed by Queensland Department of Primary Industries, CSIRO and University of Queensland for the simulation of plant growth, nutrient demands and nutrient leaching to groundwater of agricultural and horticultural systems. The model simulates hydrologic and biological processes in the soil zone and produces crop growth, soil nutrient and soil water budgets on a daily basis, including water and nutrient drainage from the sub-soil at a maximum depth of 1.5 m (Holzworth, *et. al.*, 2014).

18 APSIM models were developed in the RDST to simulate soil nitrogen dynamics related to various agricultural management regimes (land uses).

19 Current and historical land use management practices were represented by individual static APSIM models.

20 A key advantage of APSIM is the ability to perform calculations on a daily basis, which permits analysis of time-varying phenomena such as seasonal patterns.

21 APSIM has been used in a broad range of applications including:

21.1 Support for on-farm decision making;

21.2 Farming systems design for production or resource management decision making;

21.3 Assessment of the value of seasonal climate forecasting;

21.4 Analysis of supply chain issues in agribusiness;

21.5 Development of waste management guidelines;

21.6 Risk assessment for policy making; and

21.7 As a guide for research and educational activities.

22 In the RDST, APSIM models were developed for the land use types listed in **Table 2**.

Table 2. Land use types simulated in APSIM.

Forest	Fodder	Dairy Support 5 year
Lifestyle	Convert 0-2 year	Dairy 5 year
Sheep and Beef	Convert 3-5 year	Dairy 5 year Irrigation
Brassica	Convert 3-5 year Irrigation	Dairy 5 year Herd Home
Lucerne	Dairy Support 3-5 year	Dairy 5 year Herd Home Irrigation

MODFLOW / MT3DMS

23 Groundwater flow and total nitrogen (**TN**) transport models were developed and simulated using the MODFLOW and MT3DMS codes, respectively.

24 MODFLOW is the U.S. Geological Survey's modular finite-difference 3-D flow model, which is a computer code that solves the groundwater flow equation. MODFLOW is considered by hydrogeologists to be an industry standard for the simulation of groundwater flow through aquifers.

25 MT3DMS is a 3-D modular mass transport code developed and documented in Zheng (2010) for simulating transport processes such as advection, dispersion, diffusion, and chemical reactions in groundwater flow systems.

26 Regional groundwater flow, and the advection (i.e. the transfer of heat or matter by flow) and attenuation of TN in the groundwater systems of the RDST catchment were simulated within MODFLOW / MT3DMS. Groundwater discharges to surface water and their associated TN load were extracted from the groundwater model simulations and integrated with the catchment (SOURCE) model.

SOURCE

27 SOURCE is a hydrological modelling platform developed by the Australian not for profit research organisation eWater. The platform is comprised of an interface integrating various models (as plugins) and internal tools designed to simulate and extract results for all aspects of water resource systems at a range of spatial and temporal scales. The models and tools include:

  27.1 Rainfall-runoff models;

  27.2 Water demand models; and

  27.3 Constituent generation, retention, transport and decay models.

28 The fundamental architecture of a SOURCE model comprises of a series of connected sub-catchments or drainage networks. SOURCE uses nodes with connecting links that enable the user to control the route of flow and processes (hydrological and constituent) that occur along the flow path.

29 Within SOURCE, the Soil Moisture Water Balance Model with Vadose Zone functionality (**SMWBM_VZ**) was utilised as the rainfall runoff (hydrological model) plugin. The model will be described in more detail later. In summary, the SMWBM_VZ utilises daily rainfall and evaporation input data to calculate surface runoff, soil moisture conditions, percolation to groundwater and groundwater discharges at distributed sub-catchment scales.

30 Constituents generated, transported and transformed within sub-catchments represent in a project sense the key chemical components of interest in surface waters. A combination of generation indices, plugins (e.g. dSedNET for sediment generation) and external constituent generation models (APSIM) were used to simulate the generation, transport and transformation of modelled constituents.

31 Development of the following constituent models were undertaken:

  31.1 Total nitrogen (**TN**);

  31.2 Total phosphorous (**TP**);

  31.3 Total suspended sediment (**TSS**); and

  31.4 Escherichia coli (**E. coli.**).

32 The generated constituent loads were combined with flow components (runoff and baseflow) simulated by the SMWBM_VZ in SOURCE to predict constituent concentration from every sub-catchment.

Construction of Models

33 The fundamental architecture, such as structure and boundary conditions, of each component model within the RDST (i.e. APSIM, MODFLOW / MT3DMS, SOURCE) was constructed in isolation from each other up to the modelling stage where transfer of water and constituents between models was required for calibration.

34 From the calibration stage onwards, the model development became an integrated and iterative process involving the swapping of inputs and outputs until all models were satisfactorily calibrated (i.e. the various simulated features matched the observed features).

Integration of Models

35 A schematic overview of the key inputs and interactions between the three coupled models (APSIM, MODFLOW / MT3DMS and SOURCE) is illustrated in **Figure 3**.

36 The key input datasets to three models were climate data (e.g. rainfall, evaporation etc.) and catchment physical characteristics (e.g. soil properties, underlying geological properties etc.), and existing and future land use classifications (depending on scenarios being considered).

37 As indicated previously, APSIM was used to simulate the daily mass of TN leaching from the soil profile from various land use types. The SMWBM_VZ rainfall-runoff model was used to simulate for each sub-catchment the surface and sub-surface processes of stream quick-flow and groundwater recharge (percolation).

38 The groundwater model utilised to simulate the daily mass of TN leachate from APSIM and groundwater recharge from SMWBM_VZ to simulate the flow and transport (including attenuation through denitrification) of TN in groundwater.

39 The groundwater model produced outputs of stream baseflow, and baseflow TN mass, which were then imported by SOURCE.

40 The SOURCE catchment model (along with SMWBM and SedNET plugins) handled the generation of all remaining constituents other than baseflow TN (e.g. E. coli, TP, TSS). Constituent generation was undertaken on a land use basis. The load of a particular constituent from each sub-catchment was calculated as an area weighted average aggregation of all land uses within a given sub-catchment. The concentrations were calculated for the corresponding base and quick flow components of the flow regime in SOURCE.

41 The SOURCE model provides an over-arching framework allowing the integration of each of the modelling components to provide daily outputs of streamflow (base flow and quick flow) and constituent concentrations. The results were post-processed outside of SOURCE to produce plots, summary statistics, and annual constituent loads.

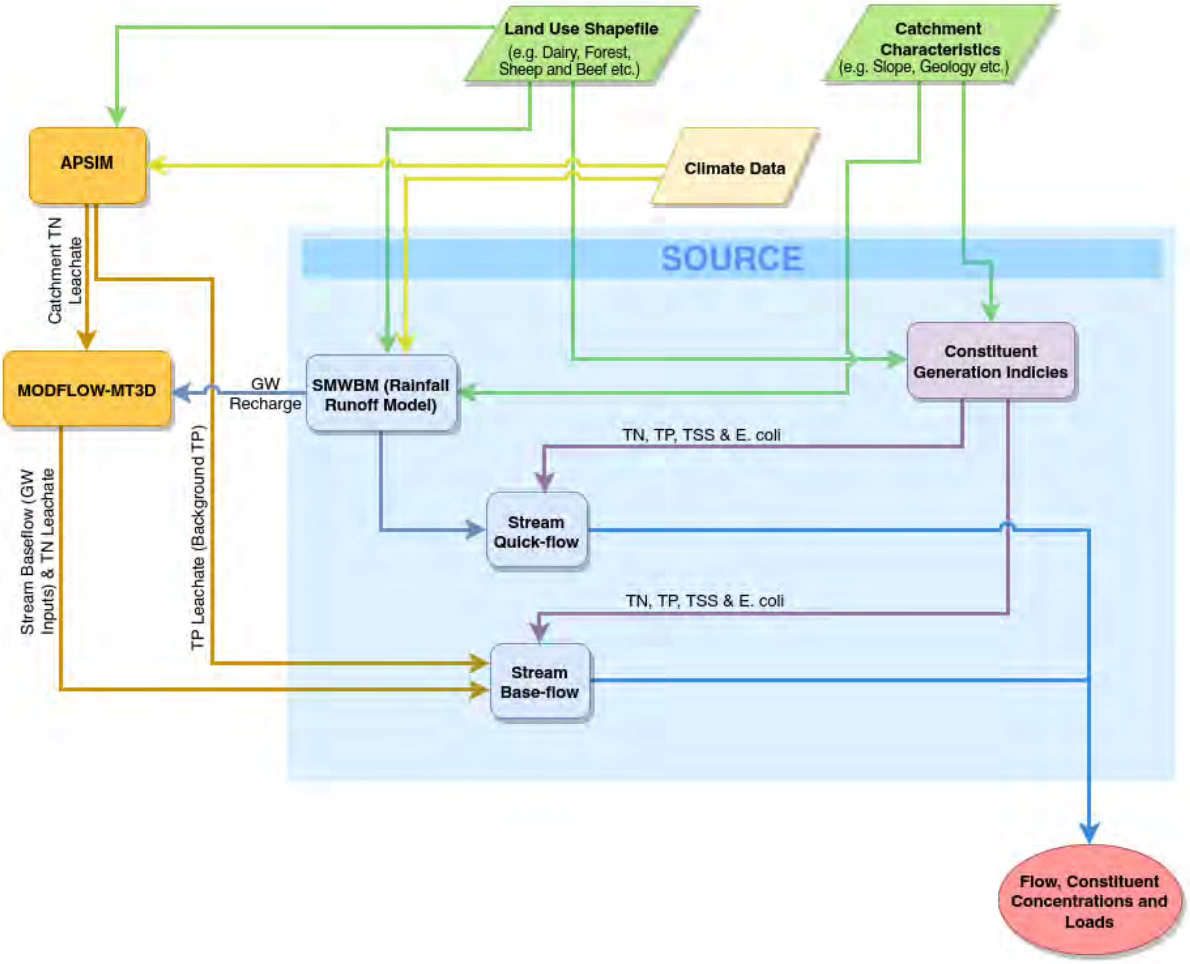

Figure 3. Schematic overview of RDST framework.

Summary:

42 This section describes the RDST model, which covers an area of 1,648 km^2 encompassing the tributary catchments of the Waikato River from Lake Taupo gates to the Lake Ohakuri tailrace.

43 The RDST is a paddock to stream calculator of flow and mass, and therefore considers attenuation that occurs between the paddock and the stream. All model outputs are computed on a daily basis, which permits analysis of effects from both storm events and seasonal responses.

44 The RDST is an integration of three primary models, including:

44.1 APSIM – simulates plant growth, soil nutrient and water cycling, and drainage;

44.2 MODFLOW/MT3DMS – simulates groundwater flow and constituent transport; and

44.3 SOURCE – simulates water movement, and constituent generation and transport in surface catchment systems.

45 The fundamental building blocks of the RDST comprise a regular 300x300 m grid over the entire RDST area and a mosaic of 415 sub-catchments ranging in size from 7.2 ha to 3,206 ha.

APSIM Model Development and Benchmarking

46 Full details of the APSIM model construction are provided in Zhao *et. al.* (2019). The fundamental features of the constructed model are described in the following paragraphs.

47 ***Soil Hydraulic Properties*** - Soil hydraulic characteristics were parameterised on the basis of well-drained pumice, which is by far the predominant soil in the region and particularly where farming activities occur. The soil was represented using 7 individual soil layers with a thickness ranging from 15 cm to 30 cm. The surface and sub-surface hydrology was simulated using a cascading water mass balance model (SoilWater) to a depth of 1.5 m.

48 ***Soil Organic Matter Module*** - The mineralisation and immobilisation of soil carbon and nitrogen were simulated using soil organic matter module representing the transfer and transformation of different forms of carbon and nitrogen. Relevant and different farm management practices (e.g. sowing, fertilisation, irrigation) were constructed for each land use model.

49 ***Land Use Type Models*** - Individual APSIM models were constructed for fifteen representative land uses, as summarised in **Table 3**.

Table 3. Summary of APSIM land use models.

Land Use	**Description**
Dairy 5 year	Established dairy land of 5 years or greater since conversion in Wairakei Estate.
Dairy 5 year – Irrigated	Established dairy land use of 5 years or greater since conversion in Wairakei Estate with irrigated pasture.
Dairy 5 year herd home	Established dairy land use of 5 years or greater since conversion in Wairakei Estate with winter feeding pad.
Dairy 5 year herd home - Irrigated	Established dairy land use of 5 years or greater since conversion in Wairakei Estate with winter feeding pad and irrigated pasture
Convert 0-2 year	Land use following clear-felling of plantation and establishment of pasture that is less than two years since conversion.
Convert 3-5 year	Land use following clear-felling of plantation and establishment of pasture that is greater than 3 years but less than 5 years after the clearing.
Convert 3-5 year – Irrigated	Land use following clear-felling of plantation and establishment of pasture that is greater than 3 years but less than 5 years after the clearing, with pasture irrigated.
Dairy support 3-5 year	Land use represents condition occurring in the later stages of the conversion process as pasture establishment and the breakdown of woody slash material advances with a dairy support management regime that is greater than 3 years but less than 5 years.
Dairy support 5 year	Land use represents conditions occurring in the later stages of the conversion process as pasture establishment and the breakdown of woody slash material advances with a dairy support management regime that is greater than 5 years.
Sheep and Beef	Land use represents sheep and beef farming
Fodder	Land use represents the winter forage crop grown in winter on the dairy and dairy support land use.
Lifestyle	Land use represents a lifestyle block with minor grazing and significant vegetation.
Brassica	Land use represents forage brassica cropping.
Lucerne	Land use represents commercial lucerne plantation
Forest	Land use represents forestry

50 ***Aggregation of Sub-Models*** - To account for the relatively higher nitrogen leaching from urine patches (reportedly up to 1,000 kg/ha/year) in dairy and to a lesser extent, sheep and beef land use, sub-models representing background, single and multiple urine patches were constructed. A weighted aggregation of the sub-models was used to represent the composite nitrogen return from dairy and sheep and beef land use. The ratios of each sub-model applied to dairy and sheep and beef are summarised in **Table 4**.

Table 4. Ratios and indicative leaching rates of APSIM sub-model applied during aggregation.

Land Use	Background		Single Urine Patch		Multiple Urine Patch	
	Ratio (%)	AALR[1] (kg/ha/yr)	Ratio (%)	AALR[1] (kg/ha/yr)	Ratio (%)	AALR[1] (kg/ha/yr)
Dairy	0.94	66	0.05	157	0.01	295
Sheep & beef	0.85	16	0.15	99	-	-

Notes: 1. Average annual leaching rate (indicative).

51 ***Climate*** - Each APSIM model developed was simulated (on a daily basis) 415 times with independent climate datasets for each simulation, over the period 01/01/1972 to 30/06/2018. Each simulation was representative of one of the sub-catchments from the SOURCE model. The climate dataset was interpolated from NIWA's 5-km grid Virtual Climate Station Network (**VCSN**), which in the Ruahuwai model domain consisted of 132 points.

52 ***APSIM Calibration (Benchmarking)*** - Calibration is the process of modifying model structure and parameters within a physically representative range until the simulated response matches observations in the field. The APSIM model was not calibrated in the conventional sense, where model outputs would be matched to field measured data. However, the key aspects of the APSIM model's accuracy were assessed through three benchmarking exercises:

52.1 Subsoil drainage from the bottom layer of the SoilWater Module was compared to sub-soil drainage or "percolation" to groundwater from a representative calibrated catchment in the SMWBM_VZ. APSIM SoilWater parameters were modified within physically realistic bounds until general agreement between the estimates from the two models were achieved, as shown in **Figure 4**.

52.2 APSIM mean annual nitrogen leaching rates for various land uses were compared to OVERSEER (**Figure 5**[2]). Typically, APSIM produced greater annual average rates of nitrogen leachate for high intensity land uses such as dairy, and sheep and beef, with similar leaching rates for the lower intensity land uses such as forestry and lucerne.

52.3 Pasture production or growth rates were benchmarked to literature values for the Wairakei region (Baars, *et. al.*, 1975), as shown in **Figure 6**.

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[2] Showing on the last 18 years for easier comparison.

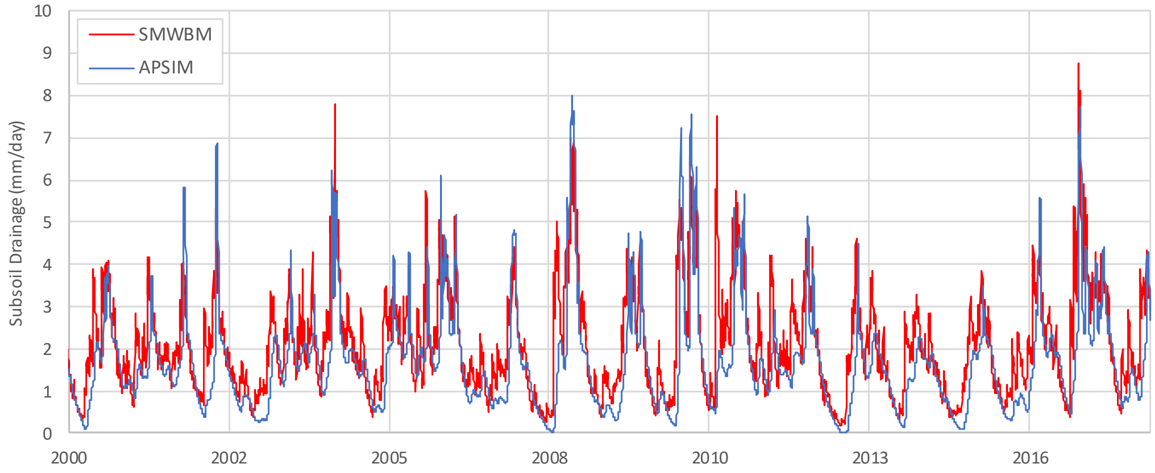

Figure 4. APSIM drainage benchmarking against SMWBM_VZ.

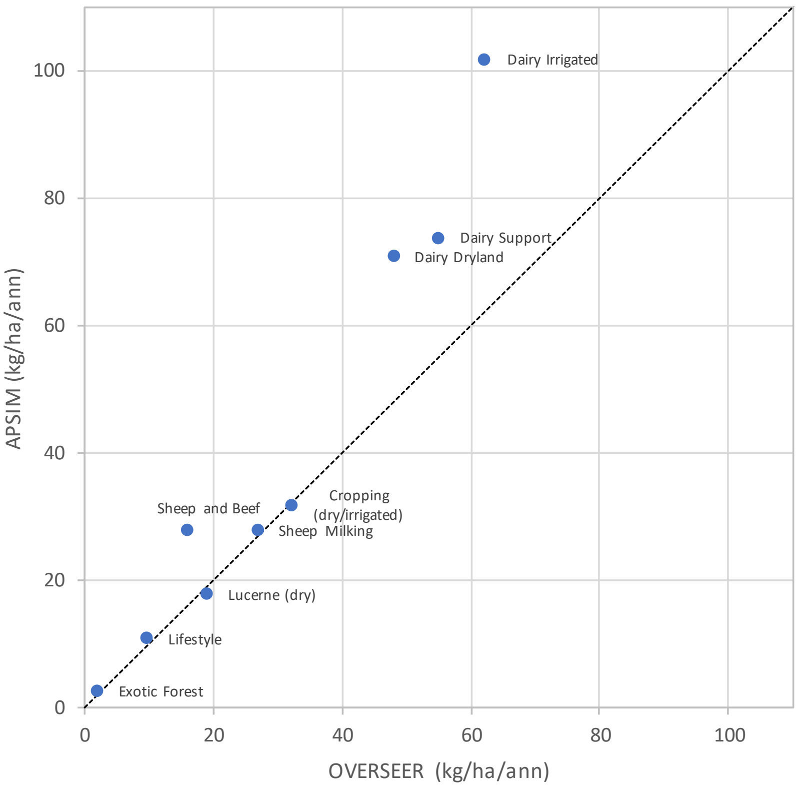

Figure 5. APSIM nitrogen leaching rate benchmarking against OVERSEER.

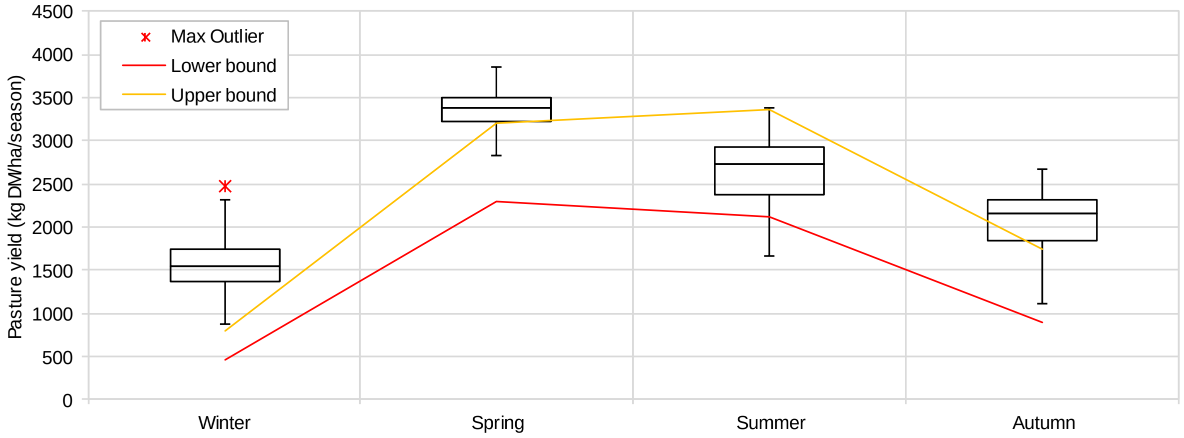

Figure 6. APSIM pasture yield (box plot) compared to literature values (lower and upper bound – Baars, *et. al.*, 1975).

53 ***APSIM Output*** - The nitrogen leachate simulated from each APSIM model was area weighted to the MODFLOW 300x300 m scale grid, and imported into the MODFLOW/MT3DMS solute transport model for groundwater flow path routing from the water table to the surface water receptors.

Summary:

54 This section describes the key features of the APSIM models constructed and the benchmarking process to confirm the model's applicability.

55 APSIM models were constructed to simulate soil water and TN drainage or leaching from the soil on a daily basis using the SoilWater and Soil Organic Matter Modules.

56 The key components of the models (drainage, leaching rates, and plant yield) were benchmarked against other tools or published information to confirm appropriateness for the project at hand.

57 Sub-models were built for 15 different land uses and each land use model was run with the climate signal from each of the 415 sub-catchments.

58 The sub-models were aggregated to the sub-catchment scale to form the land use inputs or daily sub-soil drainage mass for input to the MODFLOW model.

MODFLOW Model Development and Calibration

59 Full details of the groundwater and solute transport model's construction are provided in Zhao *et. al.* (2019). The fundamental features of the constructed model are described in the following paragraphs.

60 ***Modelling Codes*** - The groundwater numerical model was constructed utilising the MODFLOW-2005 (Harbaugh, 2005) code. The solute transport numerical model was constructed using the mass transport code MT3DMS v. 5.3 (Zheng, 2010). Both models were constructed within the GMS v10.2 graphical user interface.

61 ***Spatial Coverage and Resolution*** – covers a regional scale geographic area of 1,629 km^2 and comprises 72,340 active 300x300 m cells, defined by 18,085 cells in each of the four model layers (**Figure 7**).

62 ***Vertical Discretisation*** – the model was constructed with four stratigraphic layers, with varying geology in each. Layer 1 represents a shallow water table or aerobic mixing zone with a saturated thickness (depth below water table) of typically between 5-9 m. The base of Layer 2 defines the base of the typically unconfined layer. The base of Layer 3 represents the base of the regionally extensive Huka lake bed sediments (where present) or an arbitrary subdivision with no functionality where ignimbrite or intrusive rocks reside. The base of Layer 4 was set at a depth significantly deep enough to have limited bearing on surficial flow processes.

63 ***Temporal Resolution*** – a simulation period of approximately 46 years from January 1972 to June 2018, divided into 1,435 timesteps within 287 stress periods[3].

64 ***Groundwater Recharge*** – is the primary climate input to a saturated groundwater flow model. Recharge was assigned and varied independently within 415 discrete sub-catchments derived from the SOURCE model, as shown in **Figure 8** (see Mawer, *et. al.*, 2019).

65 ***Flow Boundary Conditions*** – are special cells in the groundwater model that are assigned conditional criteria or constraints that govern the manner in which groundwater can behave in that cell. Drains cells were defined at all perennial flowing surface waterways, with the exception of the Waikato River and its' lakes, which were assigned constant head cells (**Figure 7**). The cells are assigned elevation that represent the seepage level or typical water level in that location. The side and base of the model was assigned as a no flow boundary (i.e. water is prevented from flowing in or out of these boundaries).

66 ***3-D Grid*** - The constructed 3-D model is shown in **Figure 9**.

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[3] Stress periods are periods of time in a groundwater model where imposed stresses such as recharge, pumping rates, river stages, etc. are maintained at a constant rate. Stress period are sub-divided into multiple (typically 5-10) computation time steps.

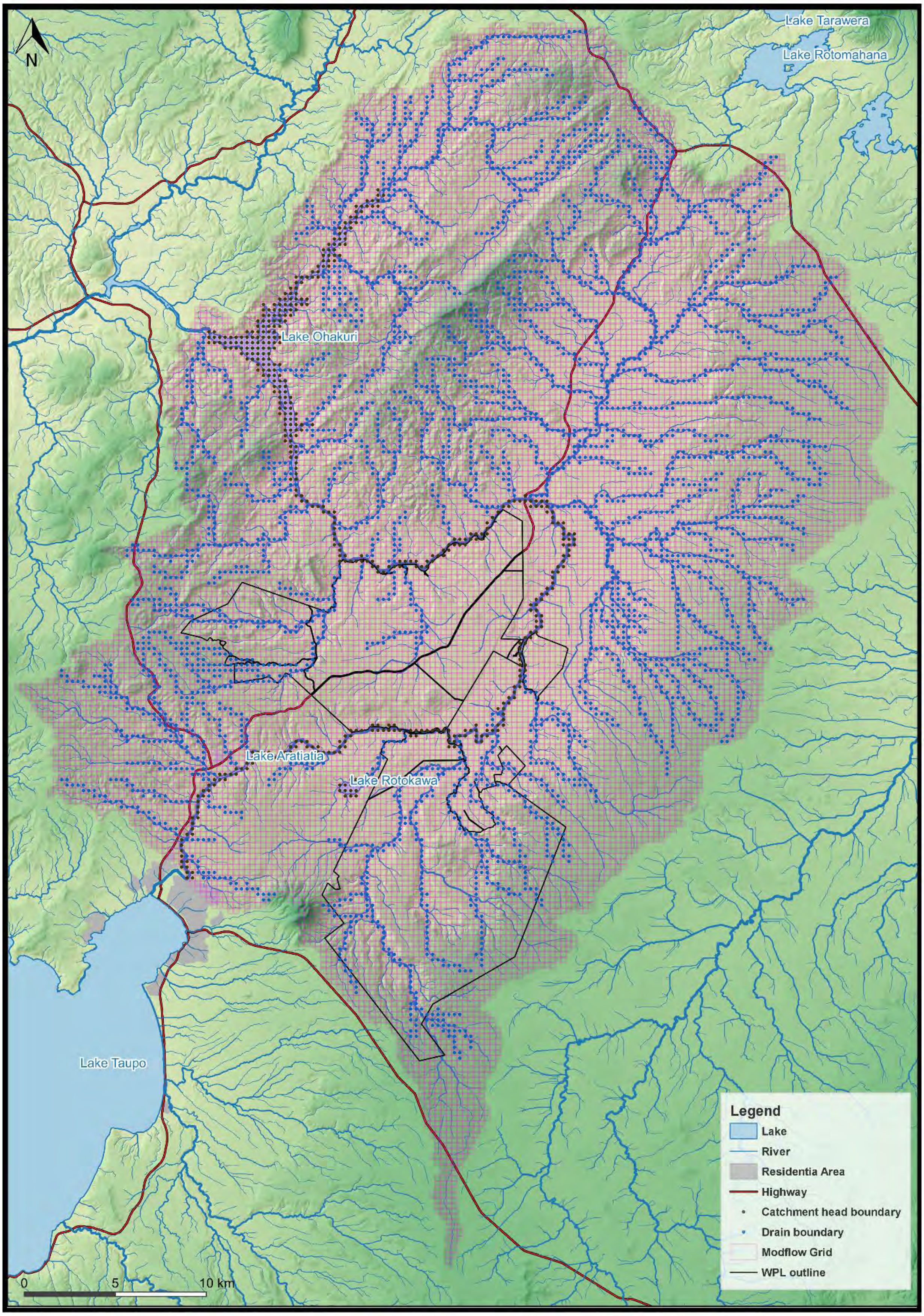

Figure 7. RDST MODFLOW grid layout and boundary conditions.

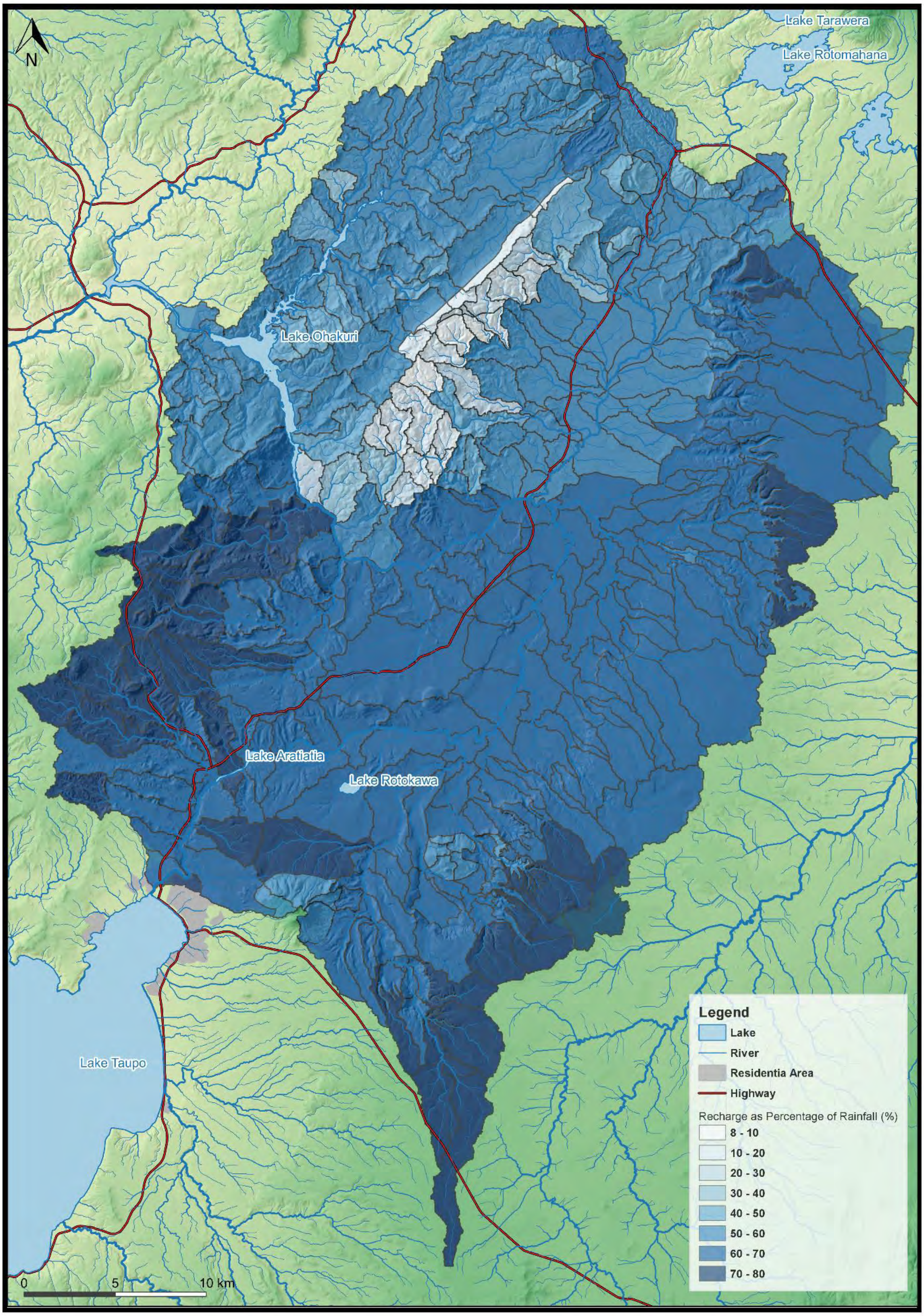

Figure 8. RDST MODFLOW recharge coverage.

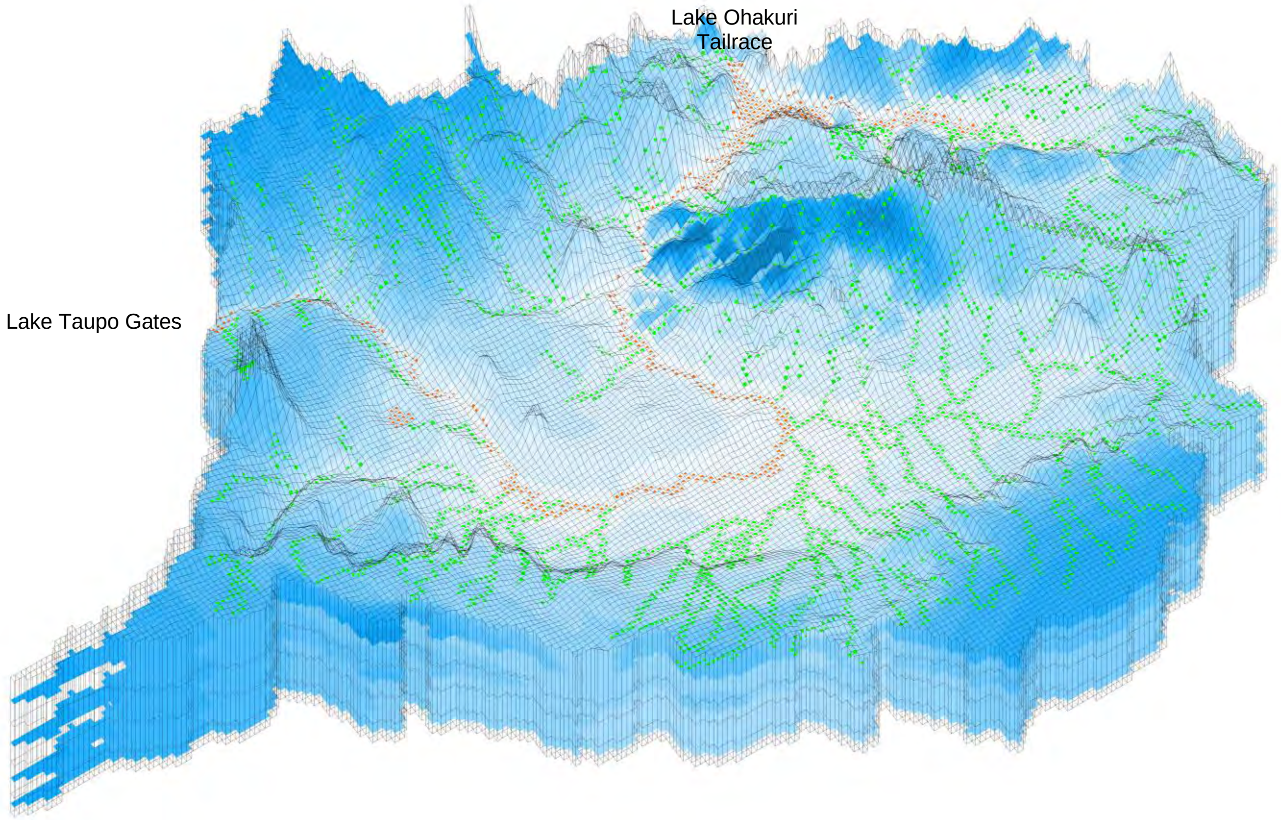

Figure 9. MODFLOW model 3-D profile.

67 ***Calibration*** – As indicated above, calibration is the process of modifying model structure and parameters within a physically representative range until the simulated response matches that observed in the field. The calibration of the MODFLOW groundwater flow and MT3DMS transport model involved multiple methods and was a multi-phased approach that occurred over a significant period of time between 2016 and 2019.

68 The methodologies used in the groundwater model flow calibration included:

68.1 ***Steady state (long-term average)*** - calibration of groundwater levels;

68.2 ***Transient (time-varying)*** - calibration of transient groundwater hydraulic head and stream baseflows;

68.3 ***Groundwater age*** - calibration through particle tracking matching to tritium groundwater age results.

69 The various phases of calibration undertaken included:

69.1 ***Manual calibration*** - via trial and error parameter changes;

69.2 ***Automated calibration*** - using the parameter estimation software PEST; and

69.3 ***Repeat of above*** **–** following new information becoming available and outcomes of linkages from simulation of the SOURCE model.

70 The observation data used in the calibration process consisted of groundwater levels from 67 bores with groundwater level ranging in elevation between 285 and 536 mAMSL, and flow records from 14 main surface water gauges. Both datasets comprised a mix of manual and automatic measurements with durations between <1 to ~15 years.

71 The calibration results for steady state hydraulic head shown in **Figure 10** provided a root mean square error (RMSE) of the head of 3.6% normalised to the range of observations (~250 m). A model calibration that achieves a RMSE value of less than 10% is considered an acceptable degree of accuracy for regional scale models (Anderson and Woessner, 1992; Groundwater Vistas, 2017).

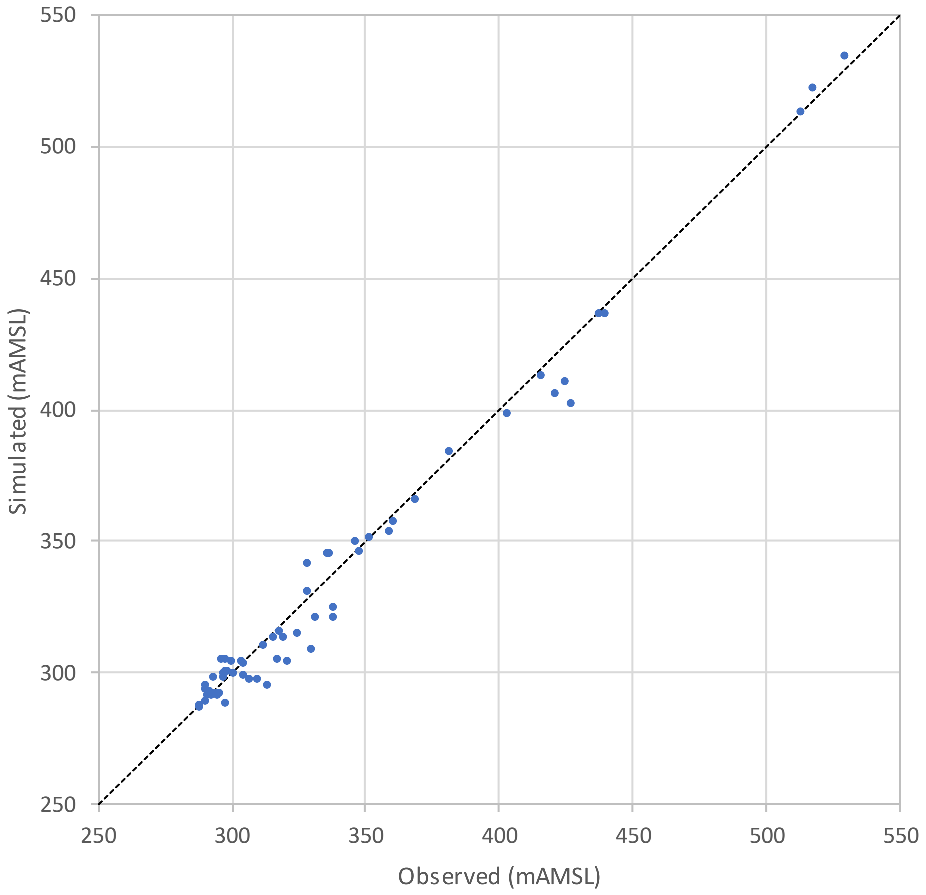

Figure 10. Steady state hydraulic head calibration match.

72 The calibration results for transient hydraulic head provided a RMSE of 4 % normalised to the range of observations (~251 m).

73 To exemplify the level of hydraulic head calibration and data available for calibration at individual sites, a selection of hydrographs are provided in **Figure 11** that range in accuracy from excellent to poor calibration.

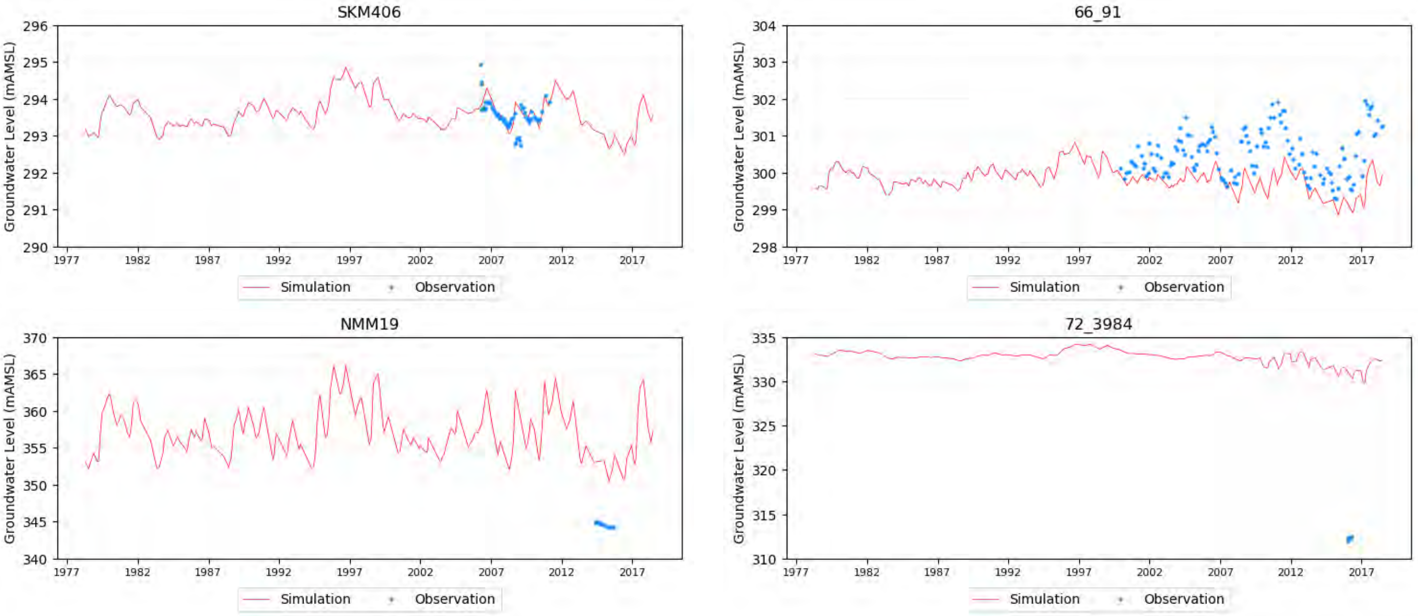

Figure 11. Transient groundwater level hydrographs demonstrating the range in model calibration at individual sites.

74 The level of groundwater baseflow calibration is discussed in the SOURCE report by Mawer *et. al.*, 2019 and within the SOURCE development section below.

75 Th groundwater model was further tested and verified through groundwater age simulations using the MODPATH[4] code and by modifying the MODFLOW groundwater flow model to simulate the transport and decay of tritium[5] using MT3DMS.

76 Tritium simulation results provided indicative agreement to observed data (see example in **Figure 12**).

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[4] MODPATH (Pollock, 2012) is a separate program that uses the output of MODFLOW to perform particle tracking. MODPATH tracks the movement of particles from a specified starting location, in either a forward or backward process, due to advection. MODPATH does not take dispersion or retardation into account.

[5] Tritium is a radioactive isotope of hydrogen with a mass approximately three times that of the usual isotope. Low concentrations of tritium exist in the atmosphere naturally, however significant amounts of tritium were released into the atmosphere during nuclear bombing tests conducted mainly in the period of 1952-1963, which led to an elevated tritium signature in rainfall globally.

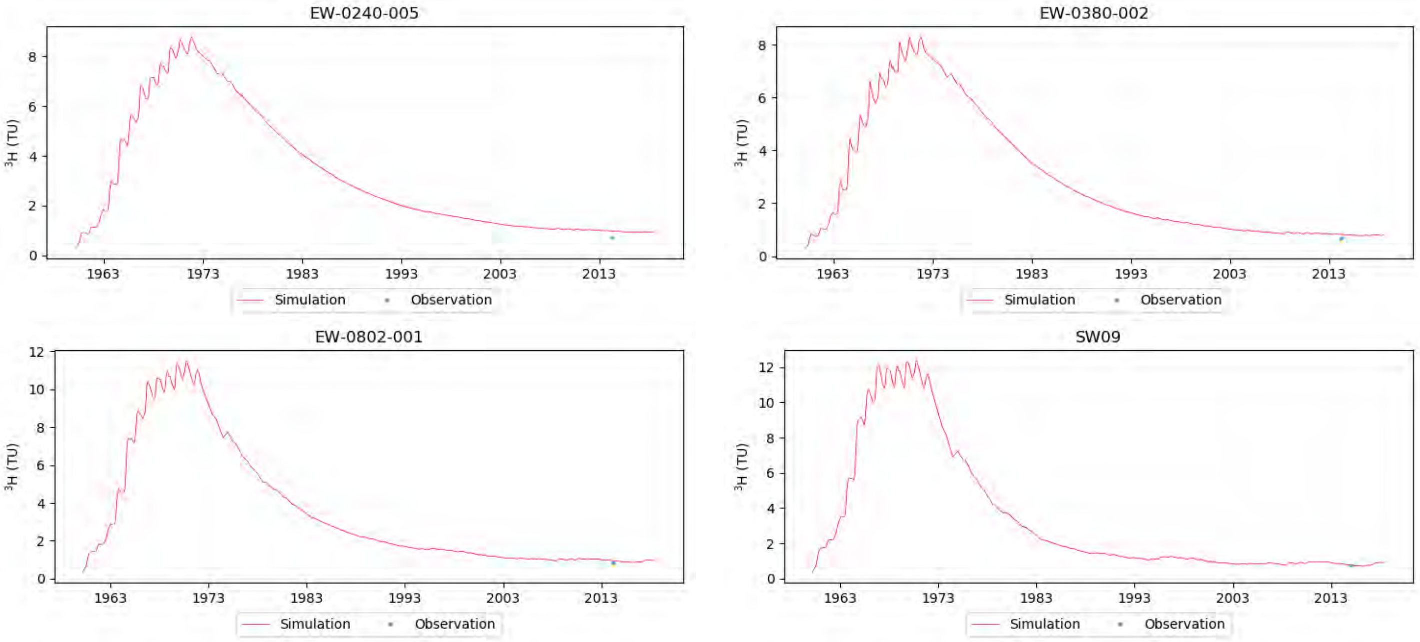

Figure 12. Example tritium simulation result for four sampling locations.

Summary:

77 This section describes the key features of the MODFLOW (2005) and MT3DMS (v.5.3) models constructed and their calibration process.

78 The MODFLOW model comprises four layers with a regular grid of 300x300m grid cells with a total of 18,085 cells in each layer and 72,340 cells in total.

79 Groundwater systems respond more slowly than surface water systems, hence the time discretisation of the groundwater model comprises 287 stress periods ranging in length from 7 days during a wet period to 295 days during an exceptionally long dry period.

80 Recharge was preconditioned using the SMWBM_VZ and assigned on the basis of the 415 SOURCE sub-catchments.

81 The MODFLOW calibration process involved both steady state and transient calibration of hydraulic head and stream baseflow, and also automated calibration of hydraulic head using PEST. The model was verified through groundwater age analysis using simulation of tritium residence time.

82 The calibration results for the transient simulation, which I place the most emphasis on, produced a RMSE of 4% normalised to the range in observations.

MT3DMS Model Development and Calibration

83 As previously indicated, the mass transport code MT3DMS v. 5.3 (Zheng, 2010) was used to simulate the concentration of TN in groundwater discharging into streams and rivers in the model domain.

84 ***Solute Transport Boundary Conditions*** – The model was used to simulate non-point source TN, using a spatially and temporally varying TN concentration loading boundary condition specified over the model domain. The TN loading concentration was calculated from the leaching rates produced by the APSIM model and percolation from the SOURCE model.

85 To reflect the gradual conversion from forest to dairy land use for the land inside the Wairakei Estate, a composite TN concentration input was produced by truncating TN concentration time series generated from four individual periods (before 2005, 2005-2010, 2010-2015, 2015-2018). **Figure 13** shows the spatial distribution of TN loading from four individual time periods.

86 ***Transport Properties*** - Transport properties, including porosity, longitudinal dispersivity, transverse dispersivity ratio and decay rate, govern the transportation of solute mass though the groundwater flow field and are summarised in **Table 5**.

87 Longitudinal dispersivity[6] and the transverse dispersivity ratio were assigned uniformly across the model domain.

88 Porosity and nitrogen decay constant properties were varied spatially across the model domain. Porosity values were specified for each hydrogeologic stratigraphic unit (**HSU**).

89 The decay rate has a spatial variation, and increases with depth, which reflects an increasing reduction potential with depth.

90 Due to a lack of local scale data, all the properties were selected from literature values. The porosity values were sourced from a previous modelling project in the region (Weir and Moore, 2011).

Table 5. Transport properties

Properties	Value
Porosity	Range from 0.1 to 0.6 depending on HSU
Longitudinal dispersivity (m)	150
Transverse dispersivity ratio (Y/Z)	0.1/0.01

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[6] Longitudinal dispersivity is used to represent the local variation in the velocity field of solute transporting in the direction of the fluid flow, by assuming a Gaussian solution to the subsurface transport (Schulze-Makuch, 2005).

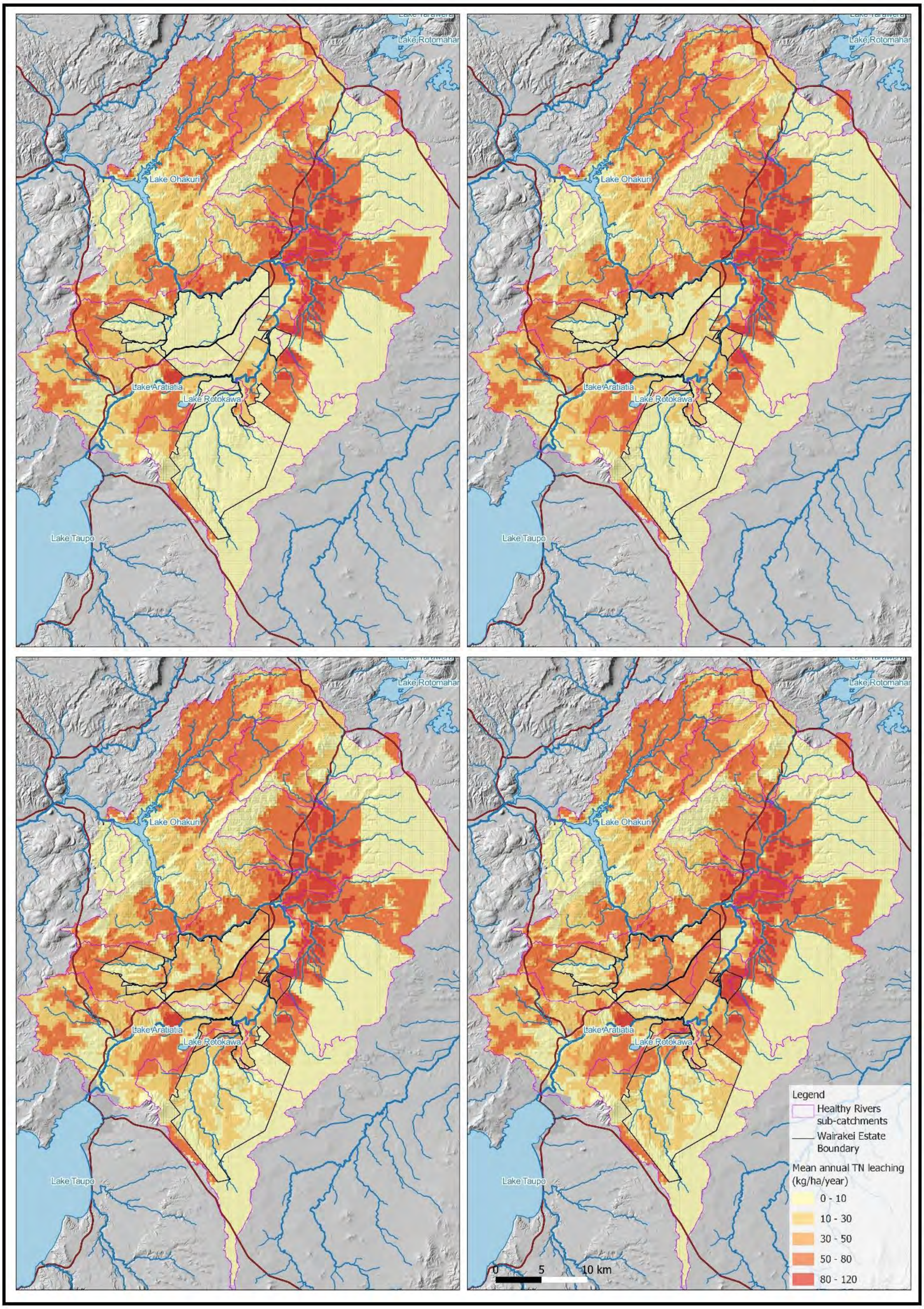


Figure 13. Spatial distribution of average annual TN loading (kg/ha/year) for four periods of time from 2005 to 2018.

91 **Denitrification** – Denitrification was simulated in MT3DMS as a first-order decay following similar approach to that of others (e.g. Schilling *et. al.*, 2014; Almasri and Kaluarchchi, 2007). The first-order decay rate, λ, is related to the half-life, $t_{1/2}$, as follows:

$$\lambda = \frac{Ln2}{t_{1/2}}$$

92 As indicated above, the denitrification potential typically increases with depth below the water table. However, it is evident from the sensitivity testing that Layer 1 and 2 dominate the mass transport dynamics of the model. This is because the water balance is dominated by these layers (i.e. most of groundwater circulation (in and out) occurs near the surface). Conceptually this makes sense because i) recharge and ii) interaction between groundwater and surface water occurs within the top of groundwater flow systems, and with progressive depth in groundwater systems, storativity and transmissivity typically decrease due to overburden pressures.

93 ***Calibration*** – The calibration of the TN transport model focused on varying the denitrification rate. This was due to the other transport properties being determined insensitive on a regional scale. During the calibration process, the denitrification rate was varied spatially, and vertically to represent the conceptual model i.e. the decay rate increases with depth to represent the progressively stronger reduction potential with depth.

94 The calibration process of matching simulated versus observed data in MODFLOW included two observed monitoring types:

94.1 Groundwater concentration recorded in bores at 47 locations; and

94.2 Surface water baseflow concentration recorded in drains and streams.

95 The calibration process comprises varying the decay rates across the four layers, while maintaining an increasing gradient in the decay rate from Layer 1 to Layer 4 to represent the change in redox conditions as groundwater generally becomes older with depth within a profile.

96 In general, Layer 1 was fixed at a very low rate of decay to reflect the oxic conditions near the water table.

97 To account for the spatial variation observed in the TN concentration of groundwater and surface water, the decay rate was also spatially varied within Layer 1 and Layer 2. The calibrated decay rates (day^{-1}) and variation in these per sub-catchment for Layers 1 and 2 are shown in **Figure 14** and **Figure 15**, while Layers 4 and 5 have constant decay rates of $6x10^{-2}$ and $7x10^{-2}$ day^{-1}, respectively.

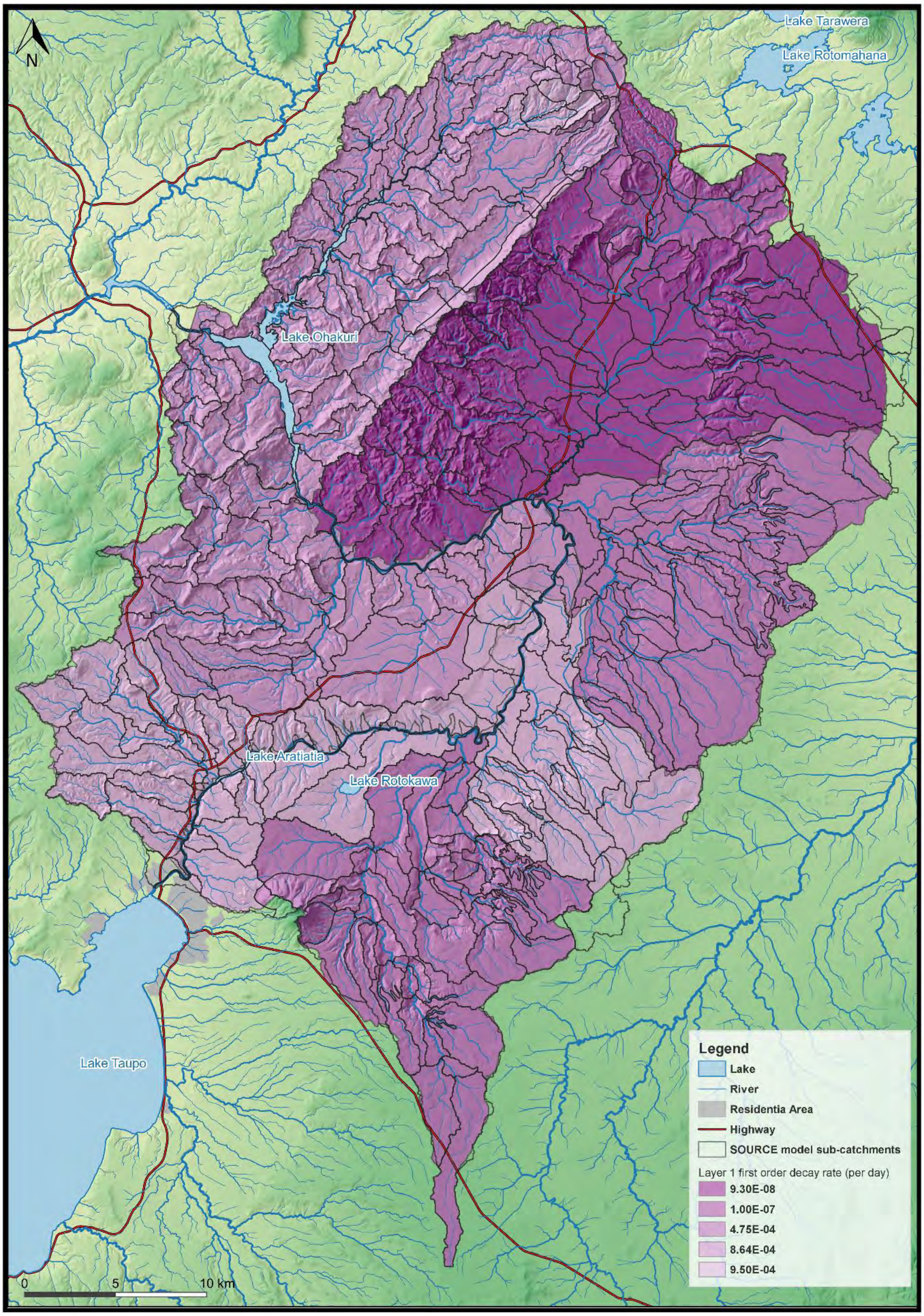


Figure 14. RDST calibrated nitrogen decay rate (/day) in MODFLOW Layer 1.

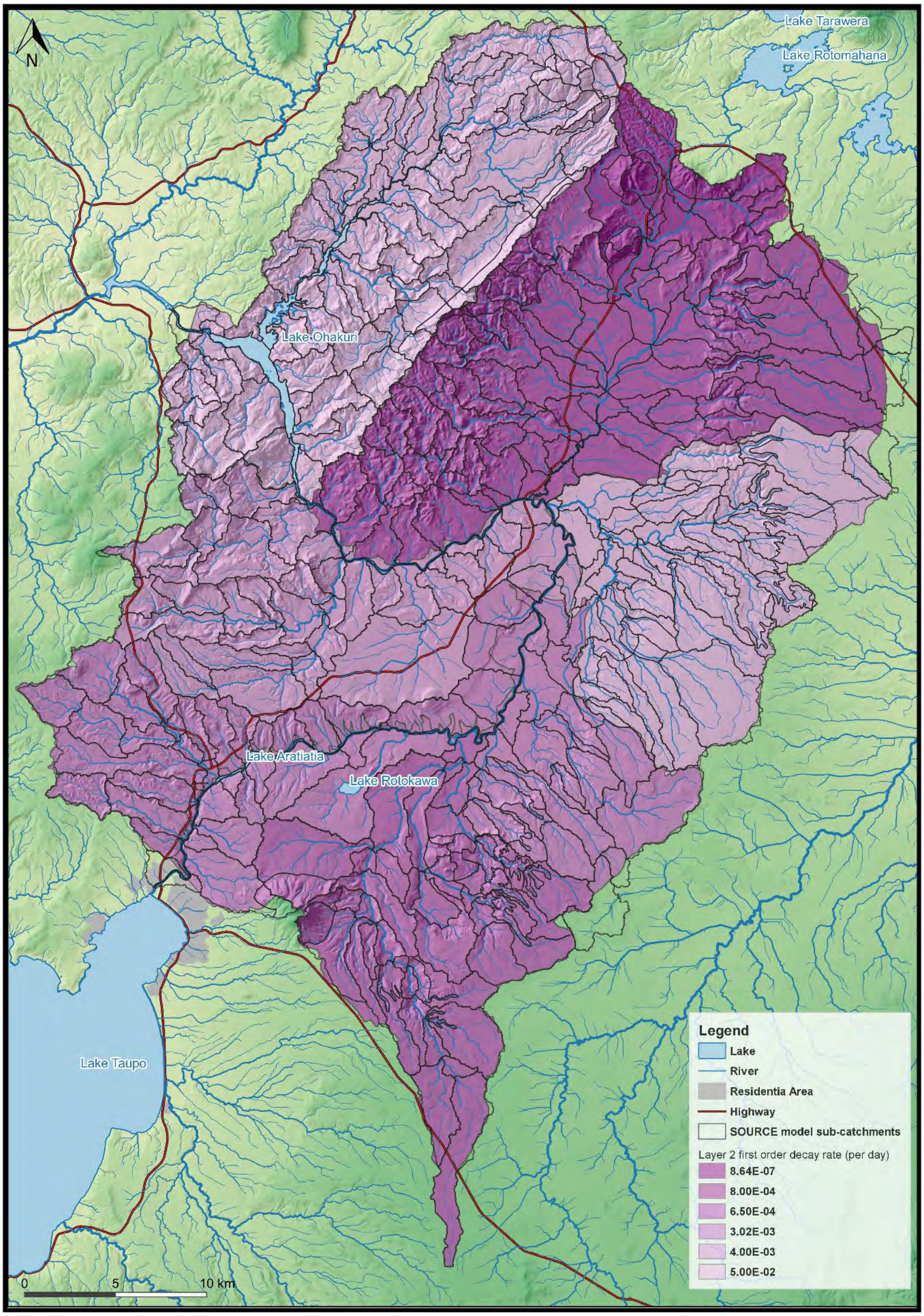


Figure 15. RDST calibrated nitrogen decay rate (/day) in MODFLOW Layer 2.

98 **Figure 16** shows four example calibration graphs of simulated versus measured groundwater concentration. The performance of TN calibration in groundwater bores was highly variable and complicated by data availability, uncertainty in the quality of the observed data, and the inability of a regional scale model to adequately simulate some responses that are governed by localised flow and loading features not included in the model.

99 The performance of the overall TN concentration calibration evaluated at surface water gauges was the focus of the integrated modelling framework and this was undertaken in SOURCE (Mawer *et. al.*, 2019) and summarised in the SOURCE section that follows.

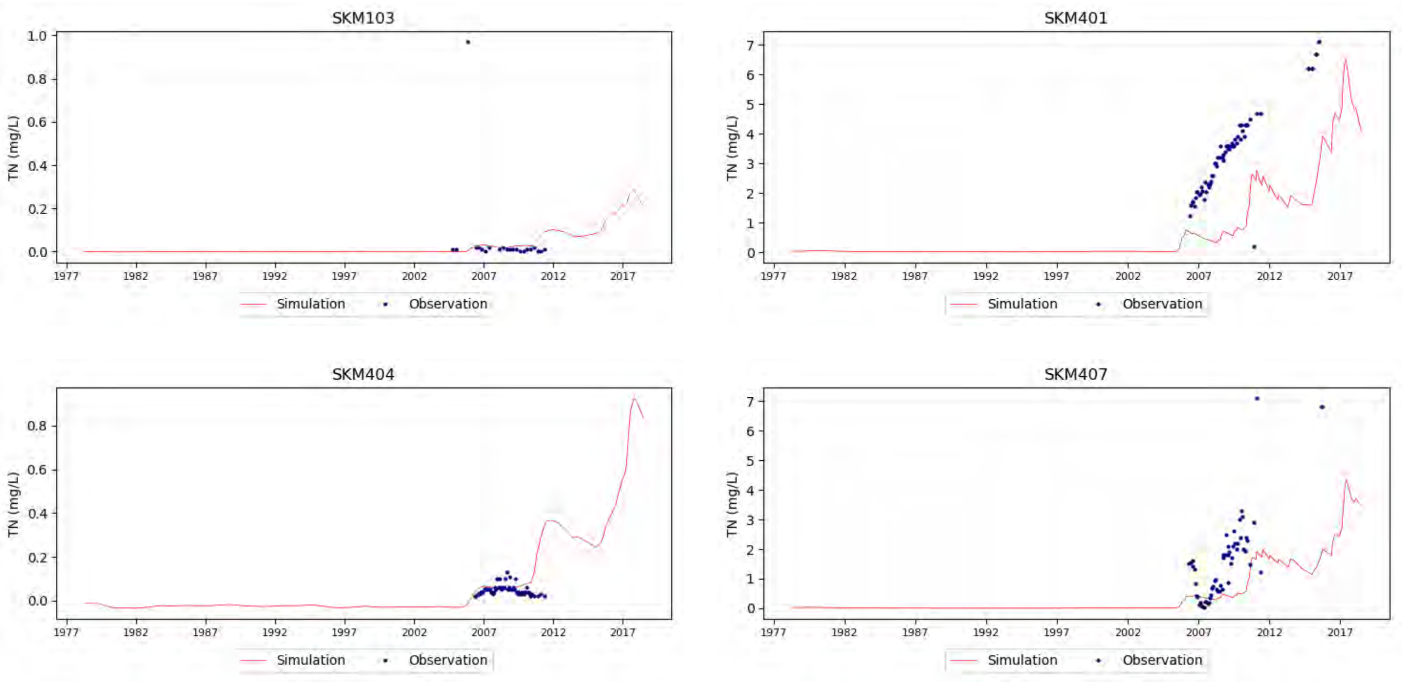


Figure 16. Example simulated versus measured groundwater TN concentration timeseries.

Summary:

100 This section describes the development and calibration of the MT3DMS model.

101 The MT3DMS model was used to simulate non-point source TN, using a spatially and temporally varying TN concentration over the model domain. The TN loading concentration was calculated from the leaching rates produced by the APSIM model and percolation from the SOURCE model.

102 To reflect the gradual conversion from forest to dairy land use for the land inside the Wairakei Estate, a composite TN concentration input was produced by truncating TN concentration time series generated from four individual periods (before 2005, 2005-2010, 2010-2015, 2015-2018).

103 The calibration of the TN transport model focused on varying the denitrification rate spatially and vertically. Vertical denitrification rates increase with depth to represent the progressively stronger reduction potential with depth.

104 The calibration process of matching transient simulated versus observed data in MODFLOW included groundwater TN concentration recorded in bores at 47 locations, and surface water baseflow TN concentration recorded in drains and streams.

SOURCE Model Development and Calibration

105 Full details of the SOURCE catchment model's construction are provided in Mawer *et. al.* (2019). The fundamental features of the constructed model are described in the following paragraphs.

106 ***Model Version*** - The model was developed using SOURCE version 4.5.0.a.7474.

107 ***Time Control*** - SOURCE models simulate on a daily time step. The simulation period for the RDST was 01/01/1972 to 30/06/2018.

108 ***Sub-Catchment Delineation*** – The SOURCE catchment model comprises a series of interconnected sub-catchments and drainage networks (**Figure 17**) that were discretised to reflect similar catchment characteristics, including geology, slope, land use, rainfall, and logical drainage pathways.

109 The objective of the sub-catchment discretisation process was to enable the application of homogenous catchment parameters in the rainfall-runoff model, i.e. as catchment scale increases, catchment parameters in a model become a blend of area weighted values, whereas as catchment resolution decreases, the parameters applied increasingly reflect local-scale variation.

110 **Figure 17** shows the 415 sub-catchments adopted for this study, and alignment with the Healthy Rivers catchments.

Figure 17. RDST model domain SOURCE sub-catchment numbering.

111 ***Boundary Conditions*** – boundary conditions utilised in the RDST SOURCE model include:

111.1 ***Confluence Nodes -*** Confluence nodes represent a natural join in a river system. Confluence nodes were used in the catchment model as they are able to combine the upstream flow from two sub-catchments before they flow into a downstream sub-catchment.

111.2 ***Inflow Nodes*** - Inflow nodes are boundary conditions that allow the addition of flow that is not generated by rainfall runoff processes into the stream network. Inflow nodes were used in the RDST to represent releases from Taupo gates and groundwater inputs to steam beds from MODFLOW.

111.3 ***Storage Nodes*** - Storage nodes are used to calculate water balances representing locations where water is stored along the river, such as dams, reservoirs, weirs and ponds, and in the RDST were used to represent Lake Aratiatia and Lake Ohakuri.

111.4 ***Supply Point Nodes*** - A supply point node identifies the location in a river where water can be extracted to meet a demand, and were utilised in the RDST to represent water permits for authorised abstraction of surface water.

111.5 ***Water User Nodes*** - The water user node represents a point in the stream network where a demand is modelled, for example a consent for irrigation. A water user node can generate orders, manage extractions and provide drainage return flows (although return flows were assumed to be minimal and were not configured in the RDST model).

112 **Figure 18** provides an image of the boundary condition configuration with the SOURCE model, showing the network of sub-catchment links and nodes.

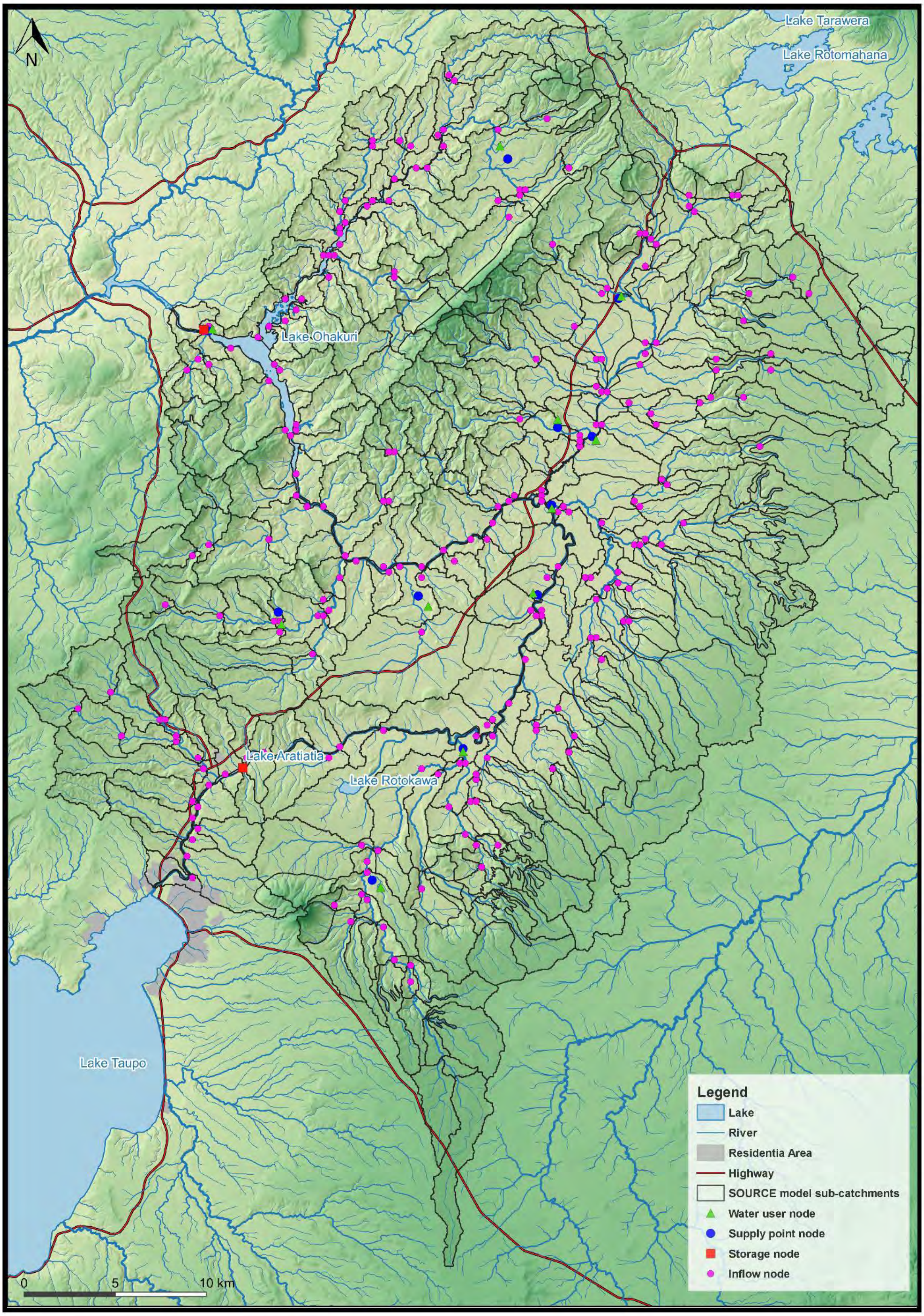


Figure 18. RDST SOURCE model boundary conditions configuration.

113 ***Soil Moisture Water Balance Model*** – The Soil Moisture Water Balance Model with Vadose Zone functionality (**SMWBM_VZ**) was utilised as the rainfall runoff model plugin within SOURCE (Williamson, 2017). The model has also been utilised on similar SOURCE modelling projects for Bay of Plenty Regional Council and Hawke's Bay Regional Council.

114 The SMWBM_VZ model allows catchment parameters to be set for each sub-catchment, transforming the SMWBM_VZ from a semi-deterministic lumped parameter model into a distributed catchment model.

115 The key input data is daily rainfall and evaporation, which are used with parameters describing the soil physical characteristics to calculate the soil moisture conditions under natural rainfall conditions, and under different irrigation management regimes.

116 While the SMWBM_VZ output is on a daily basis, to enable high flows to be assessed more accurately during raindays, computations are performed on hourly timesteps that vary in number depending on the daily rain depth. On dry days, the SMWBM_VZ defaults to a daily computation timestep.

117 A full description of the SMWBM_VZ is provided in Mawer *et. al.* (2019), whilst **Figure 19** provides a summary of the model's architecture and parameters.

118 ***Constituent Generation*** - Constituents are defined as materials that are generated, transported and transformed within a catchment and can affect water quality. Constituent models were developed to simulate each of these processes. Development of the following constituent models was undertaken:

118.1 TN;

118.2 TP;

118.3 TSS; and

118.4 E. coli.

119 Due to the differing generation mechanisms, transformations, and transport pathways from catchment to the stream network for each constituent, individual constituent generation models were developed for each of the four constituents as follows:

119.1 TN generation was simulated using a combination of the APSIM for baseflow and quickflow generation based on catchment physical characteristics and runoff.

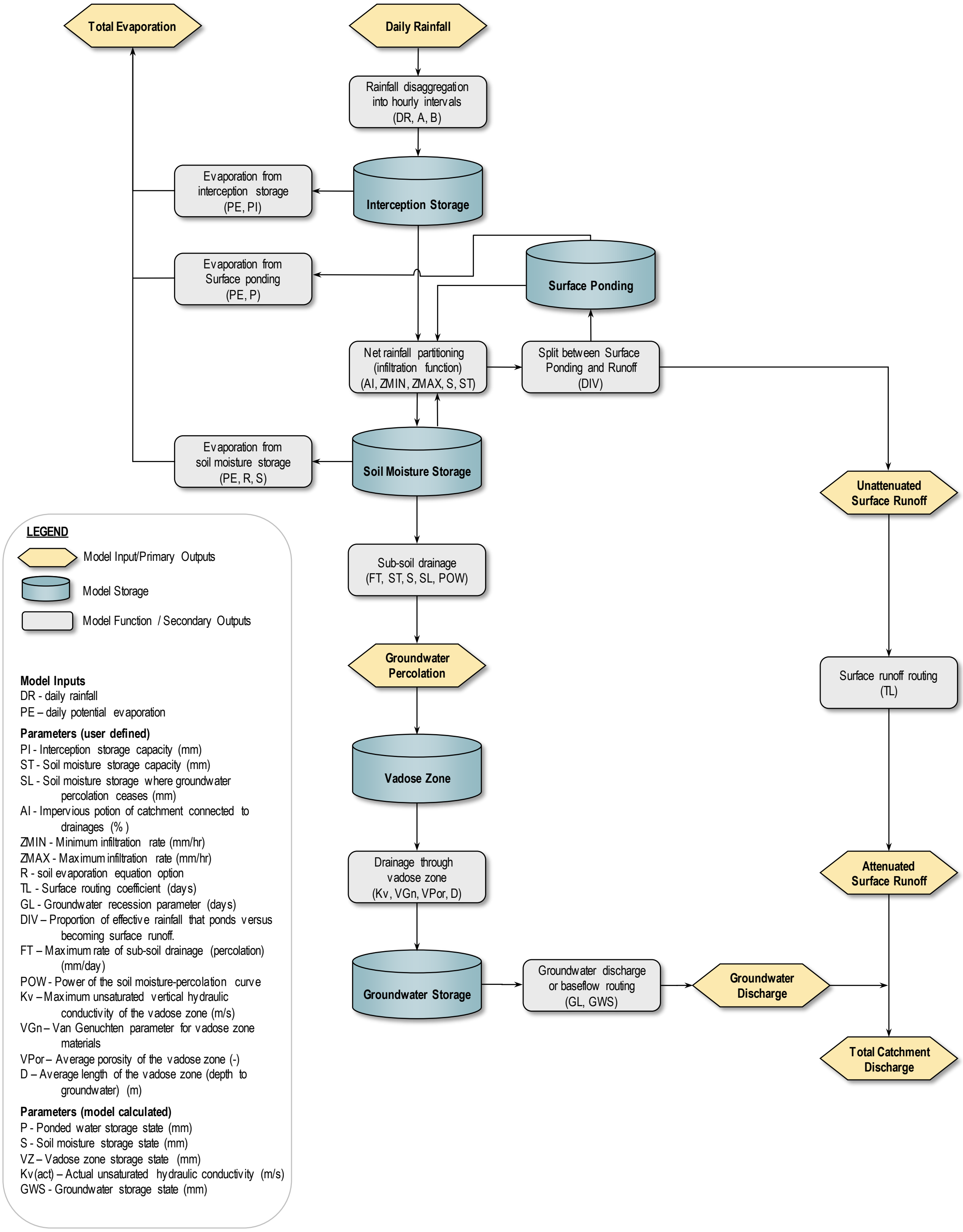
119.2 TP was generated based on catchment characteristics and runoff.

119.3 TSS was simulated using the Dynamic SedNET model.

119.4 E. coli was generated based on catchment characteristics and runoff.

120 ***Calibration*** – The calibration process of the SOURCE model involved two discrete phases, initiating with calibration of flow, followed by calibration of the four constituents (TN, TP, E. coli and TSS). The calibration process was extremely complicated and technical, hence for evidence brevity, I provide an overview only (the detail is provided in Mawer *et. al.*, (2019)).

121 Calibration of the flow and constituent components of the model followed a similar process of systematically adjusting individual model parameters and comparing simulation results against available measured data. Upstream calibration sites were targeted initially, and then progressively moved downstream once appropriate calibration was achieved.



Model Inputs
DR - daily rainfall
PE – daily potential evaporation

Parameters (user defined)
PI - Interception storage capacity (mm)
ST - Soil moisture storage capacity (mm)
SL - Soil moisture storage where groundwater percolation ceases (mm)
AI - Impervious potion of catchment connected to drainages (%)
ZMIN - Minimum infiltration rate (mm/hr)
ZMAX - Maximum infiltration rate (mm/hr)
R - soil evaporation equation option
TL - Surface routing coefficient (days)
GL - Groundwater recession parameter (days)
DIV – Proportion of effective rainfall that ponds versus becoming surface runoff.
FT – Maximum rate of sub-soil drainage (percolation) (mm/day)
POW - Power of the soil moisture-percolation curve
Kv – Maximum unsaturated vertical hydraulic conductivity of the vadose zone (m/s)
VGn – Van Genuchten parameter for vadose zone materials
VPor – Average porosity of the vadose zone (-)
D – Average length of the vadose zone (depth to groundwater) (m)

Parameters (model calculated)
P - Ponded water storage state (mm)
S - Soil moisture storage state (mm)
VZ – Vadose zone storage state (mm)
Kv(act) – Actual unsaturated hydraulic conductivity (m/s)
GWS - Groundwater storage state (mm)

Figure 19. SMWBM_VZ architecture and parameters.

122 By way of example, a schematic overview for the constituent development and calibration process is shown in **Figure 20**, noting constituent decay and transformation are only applied to E. coli and TN, respectively.

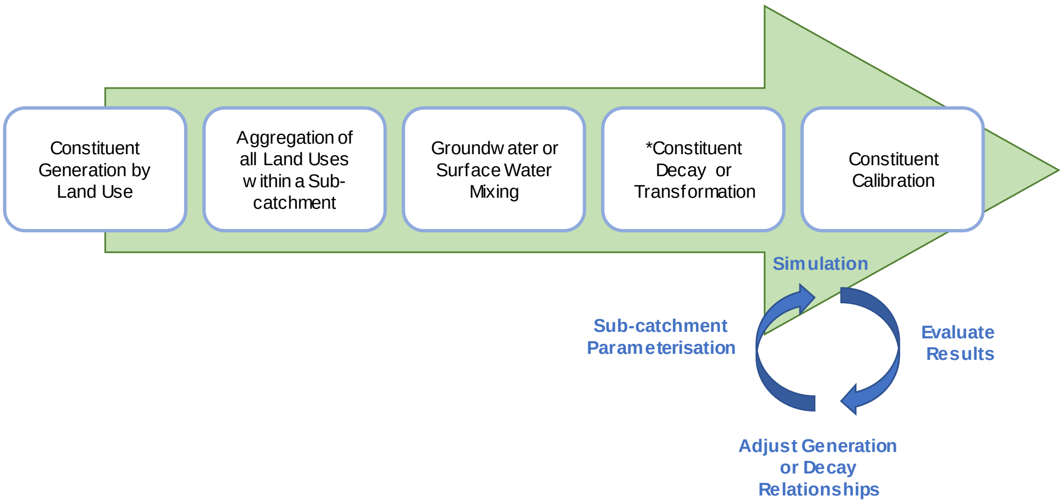


Figure 20. Constituent calibration process.

123 The approaches used to assess the accuracy of the flow and constituent calibrations included:

123.1 Flow hydrograph and constituent concentration time series plots; and

123.2 Flow duration curves, summary statistics and scatter plots.

124 Flow hydrographs, constituent time series, flow duration curves, and scatter plots provide a visual means of qualitatively assessing model calibration accuracy, while summary statistics provide more of a quantitative comparison.

125 Each calibration assessment approach has inherent strengths, weakness, and range of conditions for which they are best suited, hence each method was considered during the RDST calibration process.

126 Flow duration curves were produced for all flow monitoring sites with greater than 100 observed data points, and were calculated only on concurrent pairs of observed and modelled data points.

127 Scatter plots and associated RMSE calculations were the only statistical measures that were used in Healthy Rivers model for consideration of the model accuracy (NIWA, 2015; NIWA 2016).

128 Observed gauge information for flow calibration was available at 14 locations across the RDST area. The gaugings comprise a mixture of continuous (7 gauges) and spot readings (7 gauges), as shown in **Figure 21**.

129 Observed water quality data for calibration was available at 24 locations across the RDST model area, as shown in **Figure 22**.

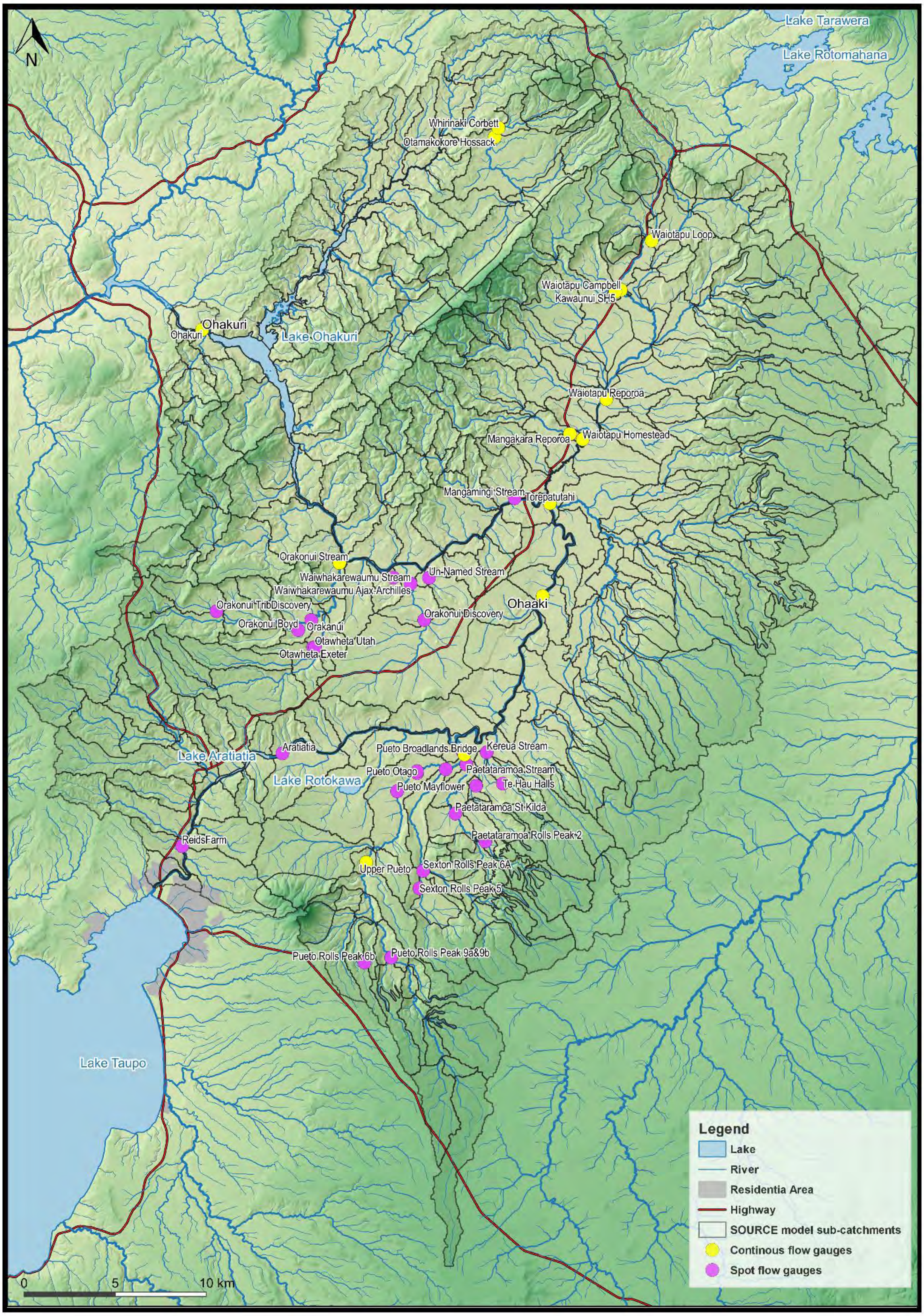


Figure 21. Available continuous and spot flow gauge locations.

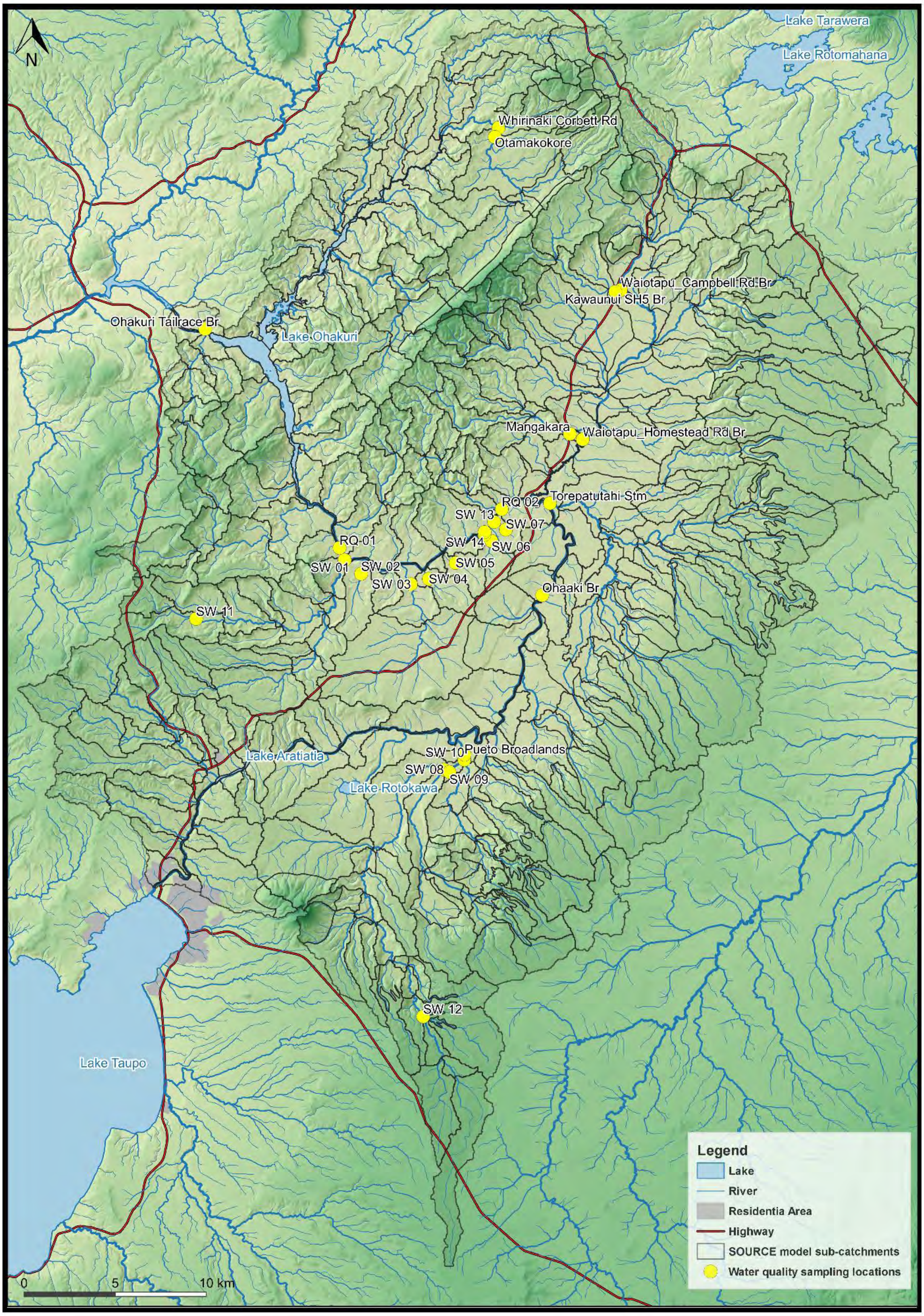


Figure 22. Available water quality sampling locations.

130 Mawer *et. al.* (2019) presents flow time series plots for all gauges, while flow duration curves and model performance metrics are only presented (to avoid statistical bias) for sites with 100 or more data points within the model period (1972-2018). In this evidence I have selected three sites to demonstrate the model's simulation ability at different scales:

130.1 Regional scale (Lake Ohakuri tailrace); and

130.2 Sub-regional scale simulation ability (Waiotapu River at Reporoa, and Pueto Stream at WPL gauge).

131 Comparison of modelled and observed flow time series, and corresponding flow duration curves at the three sites mentioned above are presented in **Figure 23**.

132 A summary overview of the flow calibration and performance at the eleven Healthy Rivers sites within the RDST domain is presented with scatter plot comparisons of the median, 5th and 95th percentile observed and modelled flows in **Figure 24**.

133 The scatter plots demonstrate the model predicts close agreement to both the observed median and 95th percentile flow statistics at all sites (with sufficient data), with only small scatter from the one-to-one line, and R^2 values greater than 0.99.

134 Comparison of modelled and observed concentration time series are provided for TN, TP, E. coli and TSS in the same three rivers[7] in **Figure 25** to **Figure 28**, respectively.

135 Scatter plots summarising the constituent calibration and performance at median and 95th percentile concentration range at the eleven Healthy Rivers sites within the RDST domain (similar to flow) are presented in **Figure 29** to **Figure 32**.

136 The scatter plots provide the following conclusions with respect to the model's overall ability to match observations for each constituent:

136.1 ***TN*** - good agreement at most sites with the regression line slope for median and 95th percentile concentrations of 0.90 and 0.82 and R^2 values for both being greater than 95%;

136.2 ***TP*** - agreement at most sites with the regression line slope for median and 95th percentile concentrations of 0.90 and 0.82 and R^2 values for both being greater than 95%;

136.3 ***E*. *coli*** – poor agreement for median concentration with slope of regression line at 0.48 and R^2 at 52%, but good agreement at the 95th percentile with an R^2 of 0.73.

136.4 ***TSS*** – there are not enough sites with data to make an overall judgement of the model's ability to simulate suspended sediments.

137 In summary, the overall performance of the RDST is considered good, with excellent results for some parameters (flow, TN, TP) and moderate results for others (E. coli). With a complicated model of a natural system focussed on multiple outputs such as this, refinements in the model conceptualisation and calibration will likely be an ongoing process. WPL's intention is to continue the work on the model as additional data becomes available, so that the model can be used assess any attribute inserted into PC1.

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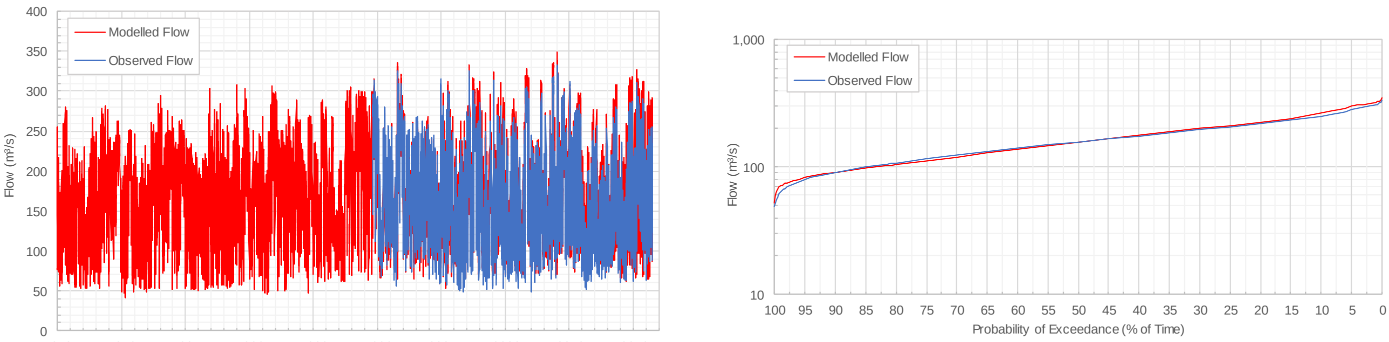
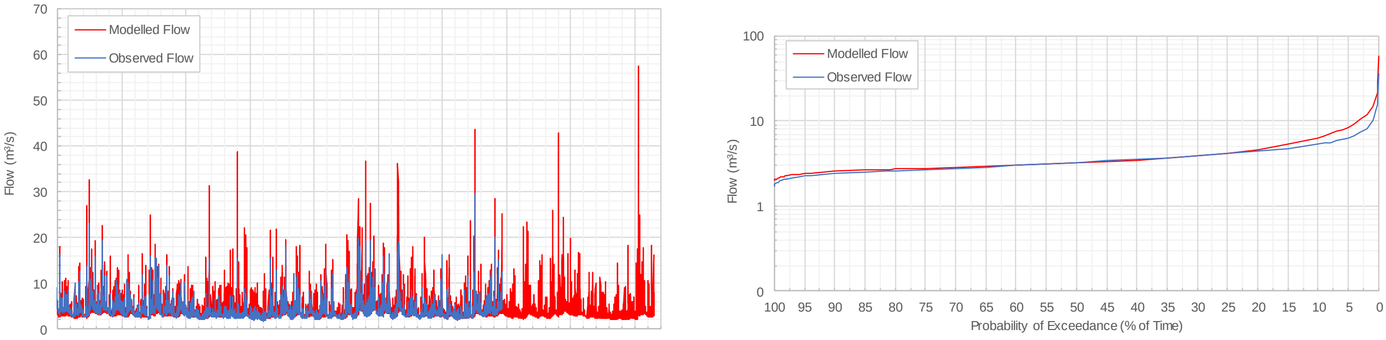
[7] Please note the location change due to data availability. For constituents, Waiotapu River at Homestead replaced Reporoa, and for the Pueto Stream, Broadlands Road replaces the WPL gauge.

Lake Ohakuri Tailrace



Waiotapu River at Reporoa



Pueto Stream at WPL gauge

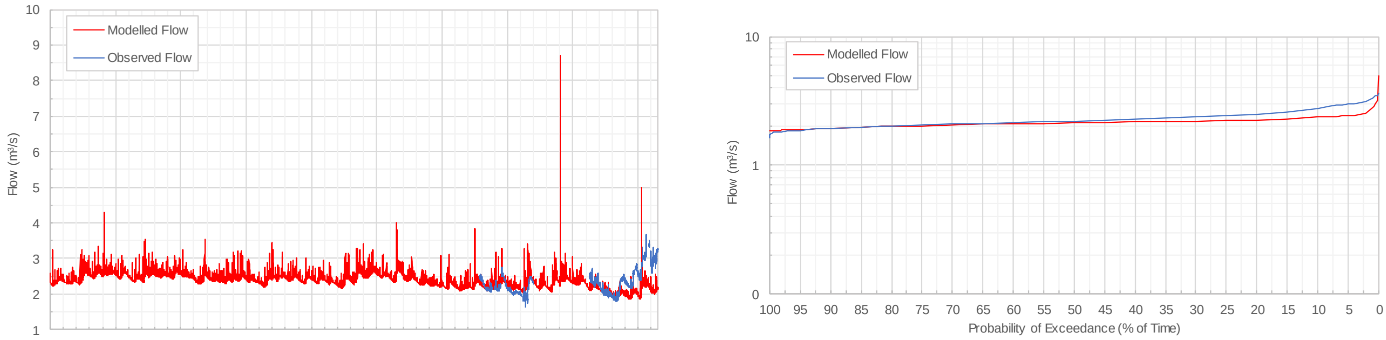


Figure 23. Flow calibration time series examples.

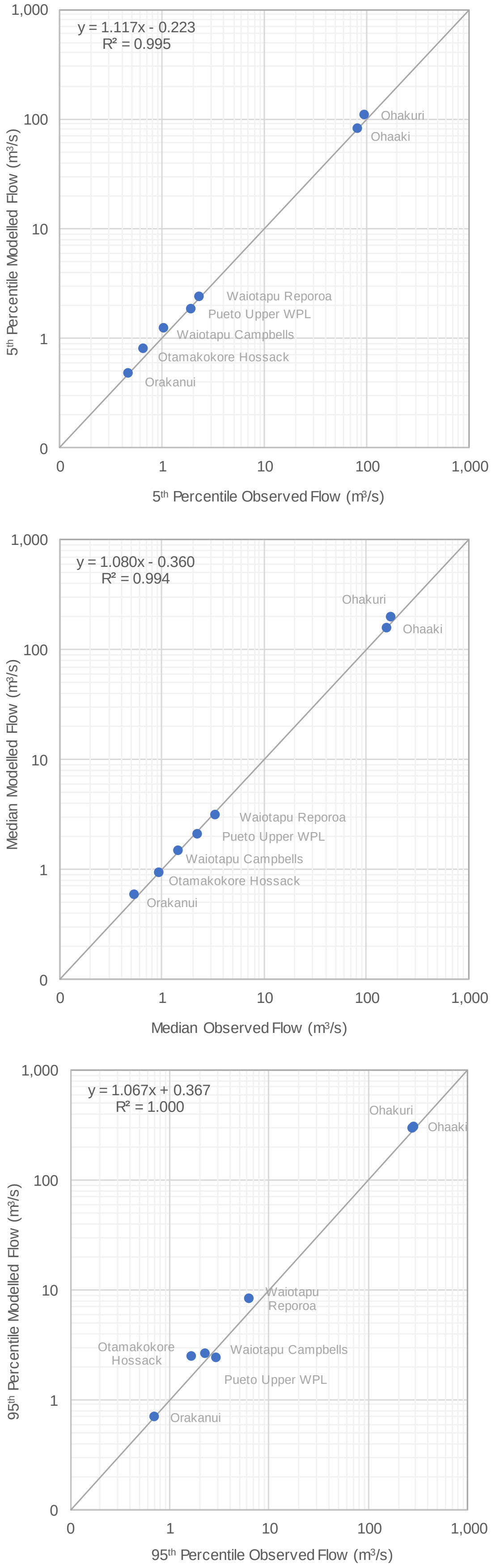
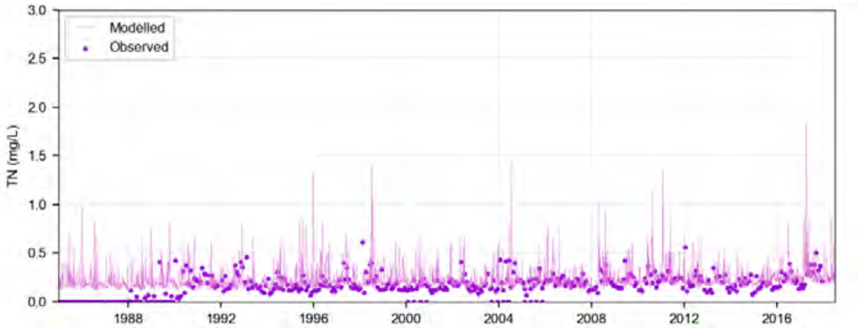
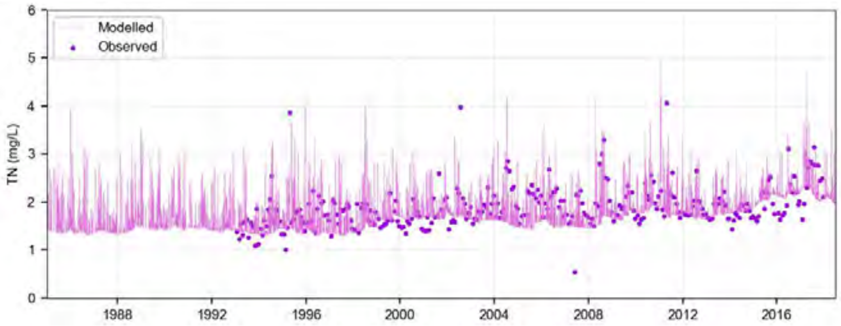


Figure 24. Scatter plot of observed and modelled 5th percentile, median, and 95th percentile flows.

Lake Ohakuri Tailrace



Waiotapu River at Homestead Road



Pueto Stream at Broadlands Road

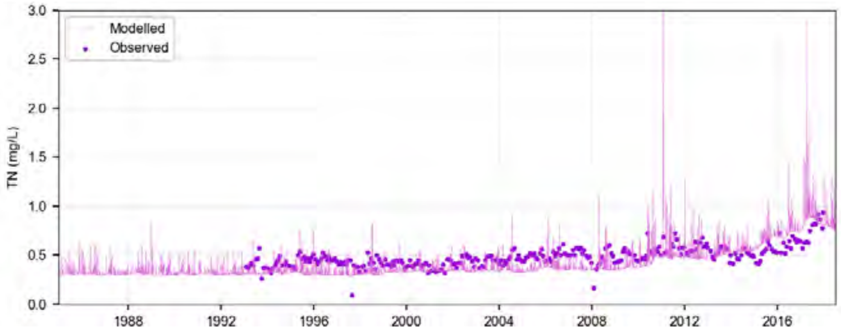
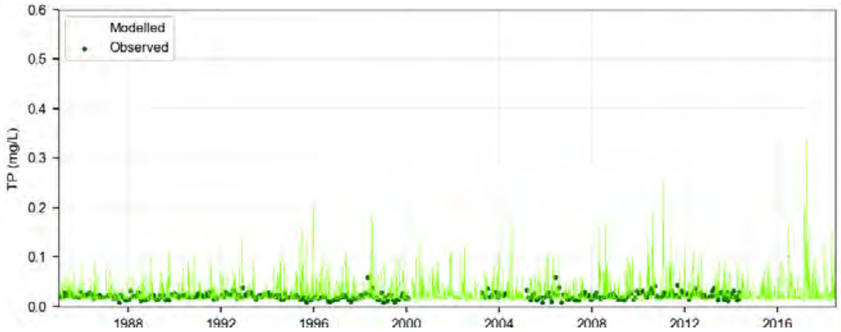
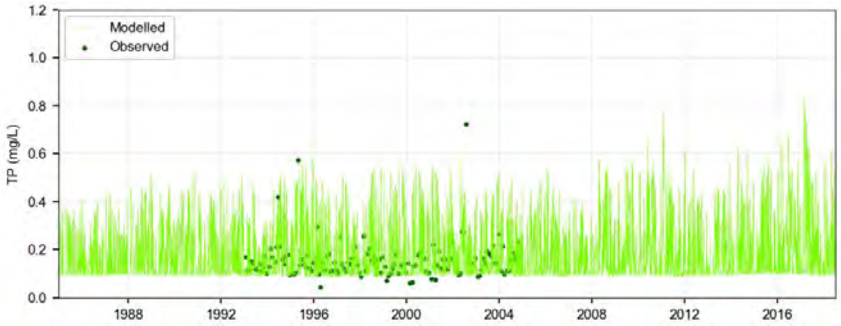


Figure 25. Constituent calibration time series examples for TN.

Lake Ohakuri Tailrace



Waiotapu River at Homestead Road



Pueto Stream at Broadlands Road

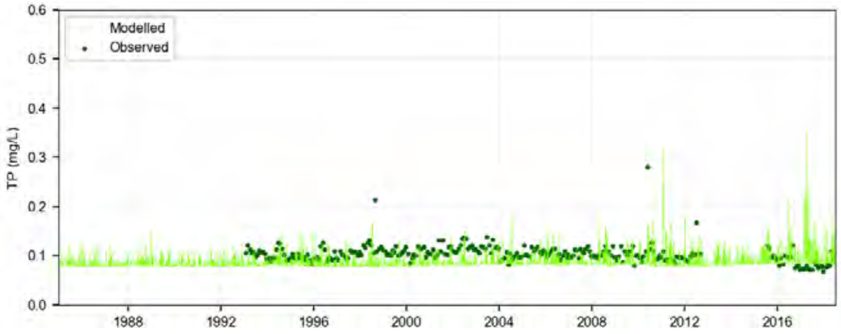
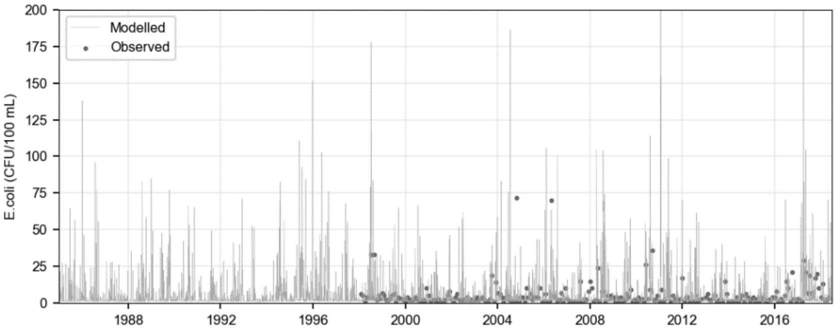
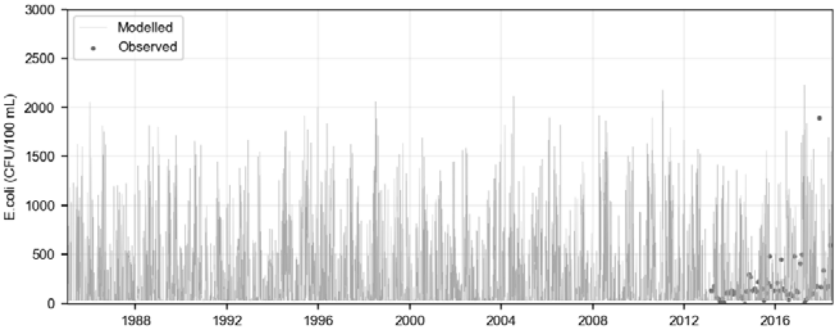


Figure 26. Constituent calibration time series examples for TP.

Lake Ohakuri Tailrace



Waiotapu River at Homestead Road



Pueto Stream at Broadlands Road

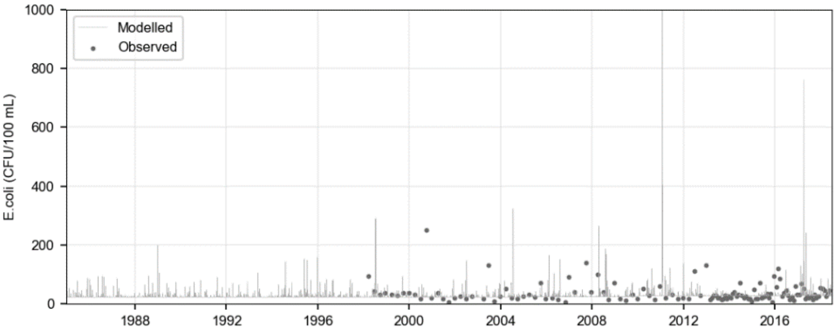
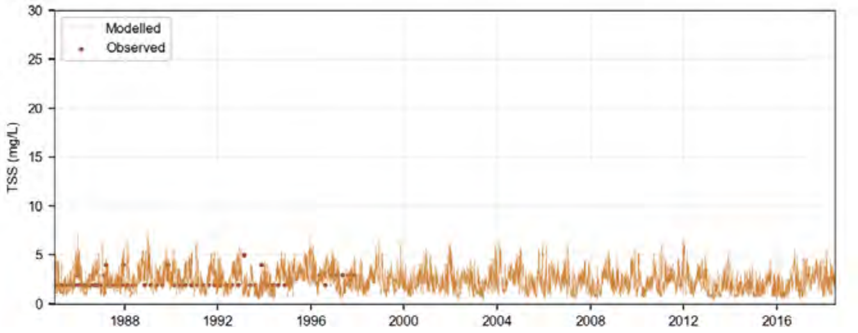


Figure 27. Constituent calibration time series examples for E. coli.

Lake Ohakuri Tailrace



Waiotapu River at Homestead Road

No data available

Pueto Stream at SW10 (up stream of Broadlands Road)

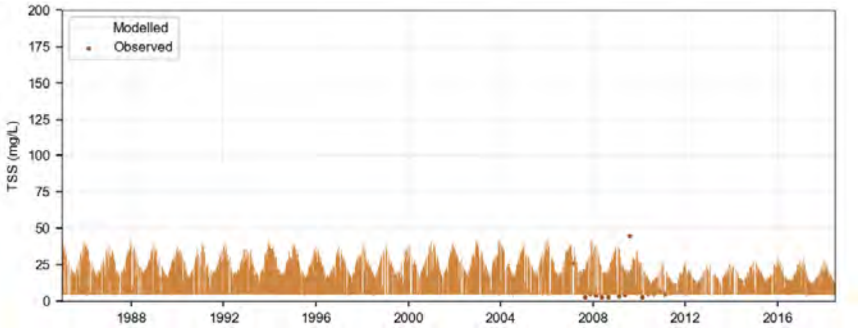


Figure 28. Constituent calibration time series examples for TSS.

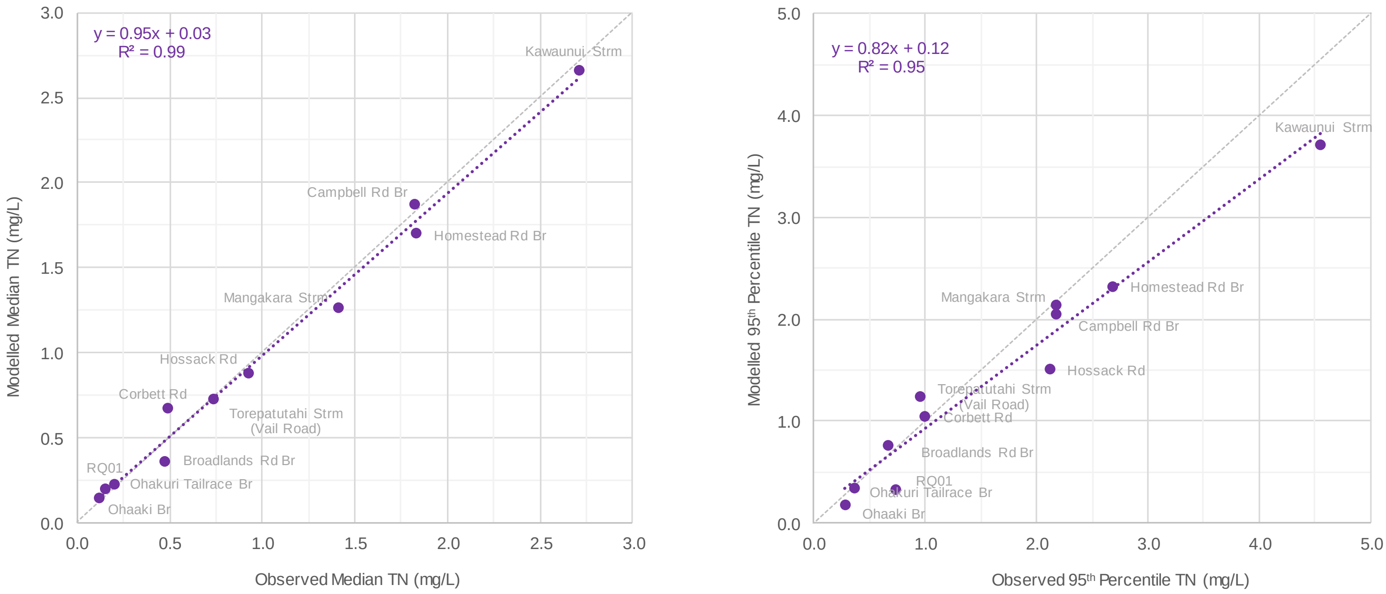


Figure 29. Scatter plot of observed and modelled median and 95th percentile TN concentration.

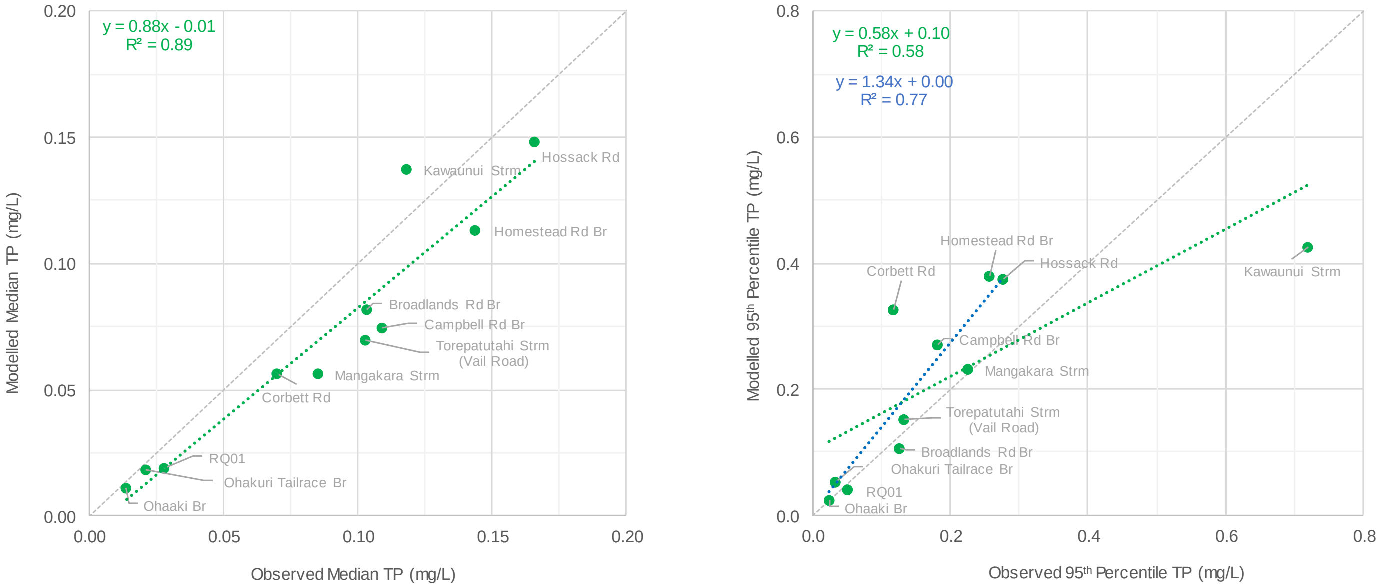


Figure 30. Scatter plot of observed and modelled median and 95th percentile TP concentration.

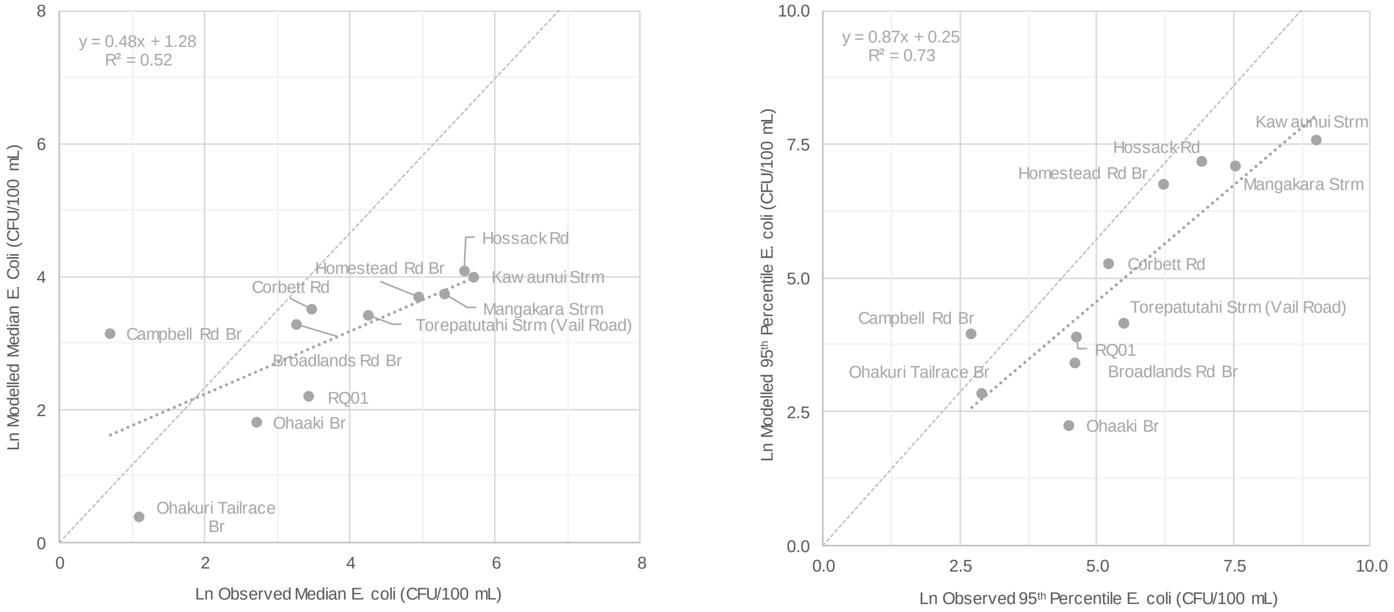


Figure 31. Scatter plot of observed and modelled median and 95th percentile E. coli concentration.

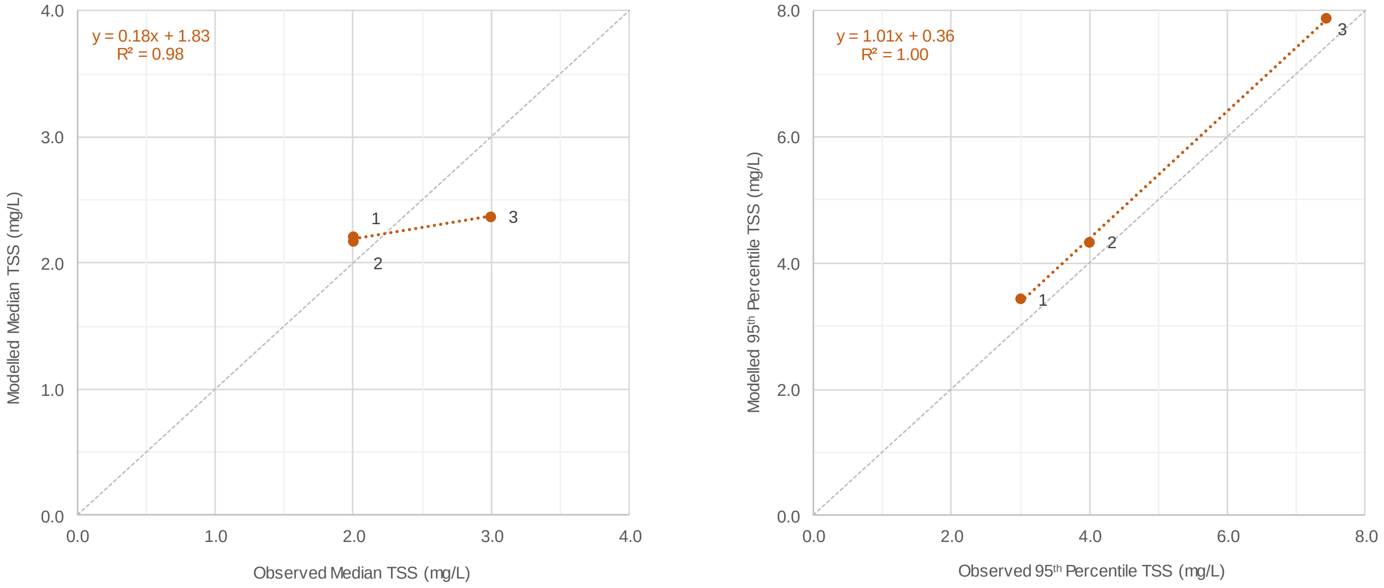


Figure 32. Scatter plot of observed and modelled median and 95th percentile TSS concentration.

Summary:

139 This section describes the construction and calibration of the SOURCE model, which was developed using SOURCE version 4.5.0.a.7474.

140 The SOURCE model simulates on a daily time step and the simulation period for the RDST project was 01/01/1972 to 30/06/2018.

141 The SOURCE catchment model comprises a series of 415 interconnected sub-catchments and drainage networks that were discretised to reflect similar catchment characteristics, including geology, slope, land use, rainfall, and logical drainage pathways. The high spatial resolution (compared to the HRWO model) enable more appropriate simulation of key physical features that play a key role in governing hydrological processes (e.g. rainfall gradients, steep land, low permeability geology, highly drainable or impervious soils, etc.).

142 Boundary conditions utilised in the RDST SOURCE model include confluence nodes, inflow nodes, storage nodes, supply point nodes, and water user nodes – all of which govern the transfer of water and constituents within the model for varying purposes.

143 The calibration process of the SOURCE model involved two discrete phases, initiating with calibration of flow, followed by calibration of the four constituents (TN, TP, E. coli and TSS).

144 The calibration process involved systematically adjusting individual sub-catchment model parameters and comparing simulation results against available measured data. Upstream calibration sites were targeted initially, and then progressively moved downstream once appropriate calibration was achieved.

145 The approaches used to assess the accuracy of the flow and constituent calibrations included:

145.1 Flow hydrograph and constituent concentration time series plots; and

145.2 Flow duration curves, summary statistics and scatter plots.

146 Observed gauge information for flow calibration was available at 14 locations across the RDST area. The gaugings comprise a mixture of continuous (7 gauges) and spot readings (7 gauges).

147 Observed water quality data for calibration was available at 24 locations across the RDST model area.

148 In summary, the overall performance of the RDST is considered good, with excellent results for some parameters (flow, TN, TP) and moderate results for others (E. coli). With a complicated model of a natural system focussed on multiple outputs such as this, refinements in the model conceptualisation and calibration will likely be an ongoing process. WPL's intention is to continue the work on the model as additional data becomes available, so that the model can be used assess any attribute inserted into PC1.

RDST Scenarios Considered

149 The calibrated model was used to assess different land use combinations and land management rules using the same systematic and repeatable data input and modelling processes, so as to enable comparison of the relative responses or changes in water quality outcomes. Full details of the scenario modelling are provided in Mawer *et. al.* (2019).

150 This section of my evidence describes the scenarios considered by the RDST to-date and how there were configured. Other members of the WPL Team including Mr Conland (environmental consultant), Dr Neale (ecologist), Mr Ford (economist) and Mr McKay (planner) will discuss the results in the context of what they mean for the PC1 provisions.

151 There were two groups of scenarios, all of which utilised the 1972 to 2018 climate series. The first group (Scenarios 1-4) compares the notified PC1 provisions, while the second group (Scenario 5-7) provides WPL's alternative scenarios. Simulation outputs from each of the scenarios were processed at the eleven Healthy Rivers monitoring sites to enable comparison with the freshwater objectives in PC1 Table 3.11-1.

152 The RDST scenarios listed as follows, were developed by Mr Conland and are described in more detail in his Block 2 evidence:

152.1 ***Scenario 0*** – ***Calibration***. This represents the calibration conditions for the RDST using the calibrated model using the five transitional periods of land use change (1972, 2005, 2010, 2015, 2016/17).

152.2 ***Scenario 1 – Do Nothing.*** This represents a 'future' where the land use as existing at the time of notification (22 October 2016) continues with no mitigations or FEP's developed in the catchment.

152.3 ***Scenario -1 – Stop Farming.*** This represents a 'future' where all land (except native forest, roads, built, and river land uses) are changed to plantation forest. In this situation geothermal inputs and point sources such as Contact Energy's power station are still included. Inflow from Lake Taupo remains unchanged (e.g. Lake Taupo catchment remains developed).

152.4 ***Scenario 2 – FEP and 'GFP' on all farms.*** This represents a 'future' where all farms in the catchment prepared and completed a FEP. This is developed following the 5 protocols developed by WPL and GFP as considered determined by OVERSEER protocols (summarised in Mr Ford's evidence). This is consistent with the first 10-year actions considered by Doole, *et. al.*, 2015.

152.5 ***Scenario 3 – FEP and 'BFP' on all farms.*** This represents a 'future' where the conditions in Scenario 2 exist, except all farms have undertaken significant mitigation steps to "Best Farm Practice" as developed by Mr Ford (in his evidence).

152.6 ***Scenario 4 – FEP and 75th Percentile limits on all farms.*** This represents a 'future' where the conditions in Scenarios 2 exist, except all farms are limited to the 75th Percentile as proposed in the planning provisions under PC1.

152.7 ***Scenario 5 – FEP then LUC limits applied.*** This represents a 'future' where the conditions in Scenarios 2 exist, except all the farms are limited to the Land Use Capability limits for productivity as developed by Mr Ford (in his evidence). The land use changes in intensity follow the direction provided by Doole, *et. al.*, 2015.

152.8 ***Scenario 6 – FEP then mitigations on Vulnerable Land.*** This represents a 'future' where farming on Vulnerable Land is avoided and mitigated in proportion to the level of nitrogen risk at the farming location.

152.9 ***Scenario 7 – FEP then mitigations plus land use changes on Vulnerable Land.*** This represents a 'future' where farming on Vulnerable Land is avoided and mitigated similar to Scenario 6 except on land with very low nitrogen risk. At these locations land use changes in terms of intensity following the direction provided by Doole, *et. al.*, 2015.

Summary:

153 This section describes the development of the nine scenarios that have currently been undertaken and reported.

FIRST 10 YEARS ARE CRITICAL

154 In my Block 1 evidence I argued that i) there is no long-term load to come of N, and ii) recent nitrogen concentration increases in surface waters are caused by "quicker flow processes" including surface runoff and young groundwater discharges.

155 Under PC1 as notified, Objective 3 seeks a 10% reduction in the 80-year target (Objective 1) by 2026. To achieve this objective, focus needs to be placed initially on source areas of constituents, which ultimately materialise in surface waters i.e. vulnerable source areas (discussed in more detail in the section on the Vulnerable Land Management Approach below).

156 Planning provisions that are premised on reducing the "load to come of N" will not be effective in 80-years' time because there will be no load arriving due to denitrification. Instead, planning provisions should focus on the short to medium-term effects of land use and land management practices.

157 Waiting until approved FEPs are required in 2026 will not achieve the interim 2026 objective (Objective 3) (nor the long-term objective of the Vision & Strategy (Objective 1) as stated above).

158 This is because the quicker flow effects for catchments that have undergone recent land use changes prior to PC1's notification date of October 2016, while partially materialising relatively quickly due to surface runoff process, will not fully materialise until sometime within the next 5-15 years (depending on the sub-catchment).

159 A case study example to demonstrate this point is the Pueto Stream catchment, where approximately 5,650 ha or 28% of the catchment has undergone conversion from forestry to pastoral systems between 2004 and 2016. The RDST was used to match the change in water quality that occurred in the stream and predict the future state if land use was maintained at the 2016 state (**Figure 33**).

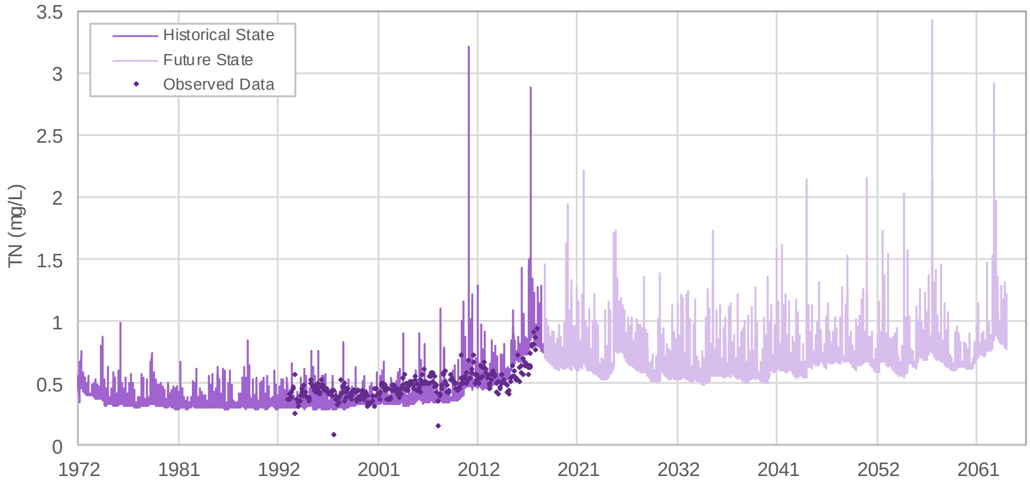


Figure 33. RDST simulation of TN in the Pueto Stream for historical (1972 to 2018) and future state (2018 to 2064).

160 While **Figure 33** presents an overview of the transition from historical to future water quality conditions (assuming no further land use change), it is difficult to adequately assess the time for effects from the land use change to fully materialise. The reason for this is threefold:

160.1 The land use change occurred progressively over a period of 12 years;

160.2 Climatic influences have a strong bearing on water quality outcomes; and

160.3 Surface water (quick flow) processes mask the groundwater effect.

161 To resolve these issues, we re-configured the modelling process in the following ways:

161.1 The land use setup was modified so that the full land use change occurred instantaneously in the middle of the 46-year model run. The middle of the run was selected so that the land use change had enough time to fully materialise before the end of the simulation;

161.2 The model was simulated with three different climate signals and one signal representing average recharge and input concentration (from 1972), so that the impact of prevailing climate at the time or shortly after the land use change could be understood with respect to the time it takes for effects to fully materialise; and

161.3 Only the groundwater baseflow component (i.e. MODFLOW outputs) was considered so that the masking effects of quick flow processes were ignored.

162 Results from the four simulations were analysed as an absolute change between the old and the changed land use. This was plotted on a time series graph, with time since land use change on the x-axis, and concentration change on the y-axis, as shown in **Figure 34**. The key observations for this analysis are:

162.1 The average time for effects to fully materialise in this catchment varies from approximately 6 to 12 years;

162.2 However, there is variability in the results dependent on the prevailing weather patterns (before and after) the time land use change was undertaken[8];

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[8] It is interesting to note the increasing concentration response shown during the last 10 years of the simulation starting in 1995, which represent the years 2008 to 2018. This increase is purely meteorological driven, as land use is maintained static in the simulation.

162.3 Where the weather patterns had been wetter than normal (1995) the effects fully materialise from the new land use appear more quickly (6 years) than if the prevailing weather conditions were drier (1972 and 1982) than normal (10-12 years).

163 The implications of the analysis results presented in **Figure 34** are that:

163.1 Without mitigations, water quality in the river in 2026 will logically deteriorate when measured against the 2010-2014 state, if land use change had occurred right up to PC1's notification date of October 2016.

163.2 If the Objective 3 targets for 2026 are to be met for the Pueto catchment (for example), approved FEPs would ideally need to be required by at least 12 years prior to 2026 to see any effect of them in 2026. While this is not practicable, it emphasises the urgent need to put FEPs in place as soon as possible.

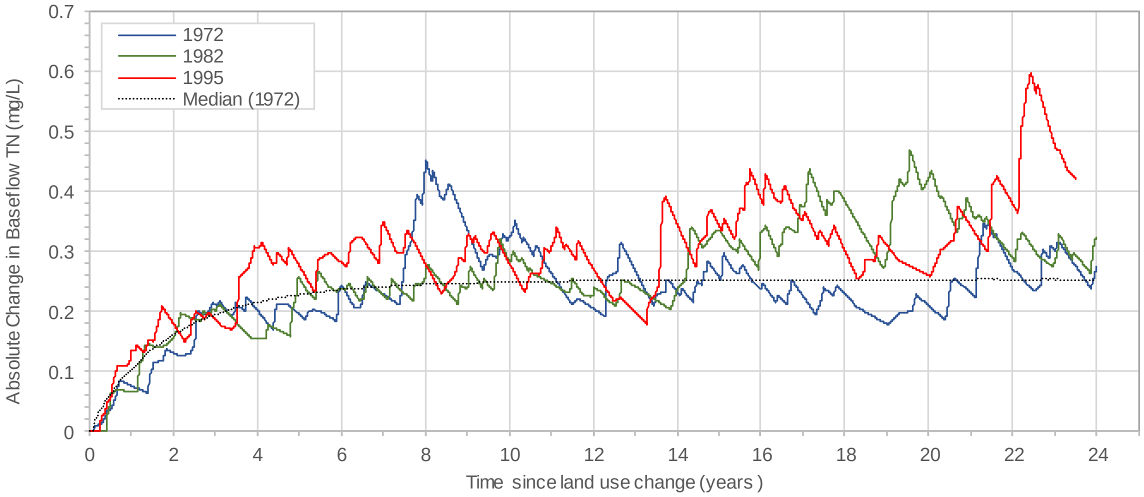

Figure 34. Impact on Pueto Stream baseflow concentration (considering groundwater only) since conversion.

Summary:

164 In this section I suggest that waiting until approved FEPs are being implemented in 2026 will not achieve the interim 2026 objective (Objective 3) nor the long-term objective (Objective 1) because the effects for catchments that have undergone recent land use changes prior to PC1's notification date of October 2016 will not fully materialise until sometime within the next 5-15 years (depending on the catchment).

165 Modelling was undertaken to demonstrate that the average time for effects to fully materialise, using the Pueto catchment as an example, was approximately 6-12 years depending on weather patterns prevailing at the time of the land use change. It is anticipated that this timeframe would be wider with consideration of a range in catchments.

166 The key implications of this are:

166.1 Without mitigations, the water quality in the river in 2026 will logically deteriorate when measured against the 2010-2014 state, if land use change had occurred right up to PC1's notification date of October 2016.

166.2 If the Objective 3 targets for 2026 are to be met, approved FEPs would likely be required by at least 12 years prior to 2026 to see any effect of them in 2026. They should be put in place as soon as possible.

VULNERABLE LAND MANAGEMENT APPROACH

167 In my Block 1 evidence, I stated that from a scientific perspective, the PC1 provisions should be amended so that land use control concepts should only be applied on areas identified as high-risk N source areas (vulnerable land). Mr McKay presents evidence on how these planning provisions should be amended. In my evidence that follows, I provide technical details on:

167.1 The modelling approach developed by my team using the RDST to map vulnerable land areas; and

167.2 A case study example demonstrating how different parts of the catchment respond differently to land use change – hence targeting vulnerable land areas will be more effective for meeting water quality objectives.

Modelling Approach for Identification of Vulnerable Land

168 Zhao *et. al.* (2019) provides details in the section entitled "Nitrogen Vulnerability Analysis", of the modelling procedure undertaken to develop the "N source risk areas" or "vulnerable land areas" map.

169 The analysis undertaken to define the relative nitrogen risk of land parcels (land vulnerability) utilised forward particle tracking in MODPATH, premised on effects being calculated at the receptor i.e. the discharge point of the groundwater flow path[9].

170 The analysis ignores groundwater mixing of waters from different flow paths because the specific purpose is to compare the relative effects from different source locations within the landscape. The analysis therefore considers attenuated TN contributions to surface water bodies.

171 Using the calibrated flow model and denitrification configuration, nitrogen risk to the surface water receptor was estimated on the basis of:

171.1 ***The length of the travel time:*** The travel time indicates the time taken for constituents to travel from source to discharge location. Based on the conceptual model, flow paths with relatively longer travel time (e.g. in the intermediate and regional groundwater flow field) are more likely to become reduced and therefore attenuated.

171.2 ***The decay profile along the flow pathway:*** Typically, groundwater becomes older with depth, and as groundwater ages it degases with respect to oxygen resulting in conditions favourable for denitrification. TN travelling through systems with more favourable denitrification conditions are more likely to be attenuated.

172 Based on particle forward tracking results and decay rate in the model cell, the quantum of denitrification (% reduction) was estimated progressively at each model cell along the groundwater flow path from source to receptor, using the following process:

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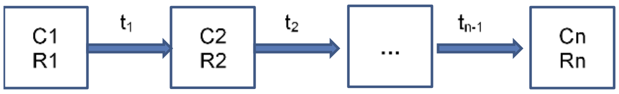
[9] As opposed to OVERSEER, which calculates load at the soil root zone and there is a presumption that this translates to a similar relative quantum of effect.



173 Where, “C” denotes the concentration at the cell, “R” denotes the decay rate at the cell, and “t” denotes the travel time between cells. The concentration at cell two “C2” is calculated following the first order decay equation as follows:

$$Ln(C2) = -R_1t_1 + Ln(C1)$$

174 This assumes that without mixing, after time t_1 with a decay rate of R_1, the TN concentration attenuates from C1 to C2 following the first order decay. Following the flow path of the particle and the decay rate in the transition cells:

$$Ln(C1) - Ln(Cn) = R_1t_1 + R_2t_2 + \cdots + R_{n-1}t_{n-1}$$

175 With the formulation discussed above, TN reduction is calculated as the reduced concentration as a percentage of the initial concentration (i.e. (C1-Cn)/C1), where C1 denotes the initial concentration and Cn denotes the concentration at the receptor for flow travelling through the cells.

176 Higher TN reduction percentage indicate a lower nitrogen risk.

177 In addition to this calculation, cells where water discharges, typically representing perennial streams, were assigned a highly vulnerable source area by default.

178 The nitrogen vulnerability map shown in **Figure 35** serves as an indication of the relative differences in natural attenuation capacity of the source area (% reduction of TN), albeit without consideration of denitrification associated with:

178.1 Soil water (perched and/or vadose zone) in poorly drained soils (i.e. peat areas); or

178.2 The riparian zone.

179 The key observations from **Figure 35** are that:

179.1 Land areas adjoining perennially flowing streams/rivers (typically 300-1,200 m from the stream) are highly vulnerable (red zones);

179.2 Land areas with shallow groundwater (e.g. Reporoa basin) are mapped as highly vulnerable, although our current methodology does not consider the denitrification in soils with high organic content, hence the land vulnerability in this zone may be exaggerated;

179.3 The land becomes less vulnerable with distance from perennial streams, which typically corresponds to higher elevation areas.

180 Conceptually, the vulnerable land area map conforms to the principle of redox chemistry, however its accuracy could be improved by increased spatial coverage (availability) and reliability of flow and TN observation datasets for calibration, and by consideration of dentification in the shallow soil profile where peat soils reside (planned for future update). Nevertheless, these limitations would not materially change the concept presented here.

181 To assist in demonstrating the role of attenuation in different parts of the catchment, the following section sets out two catchments examples.

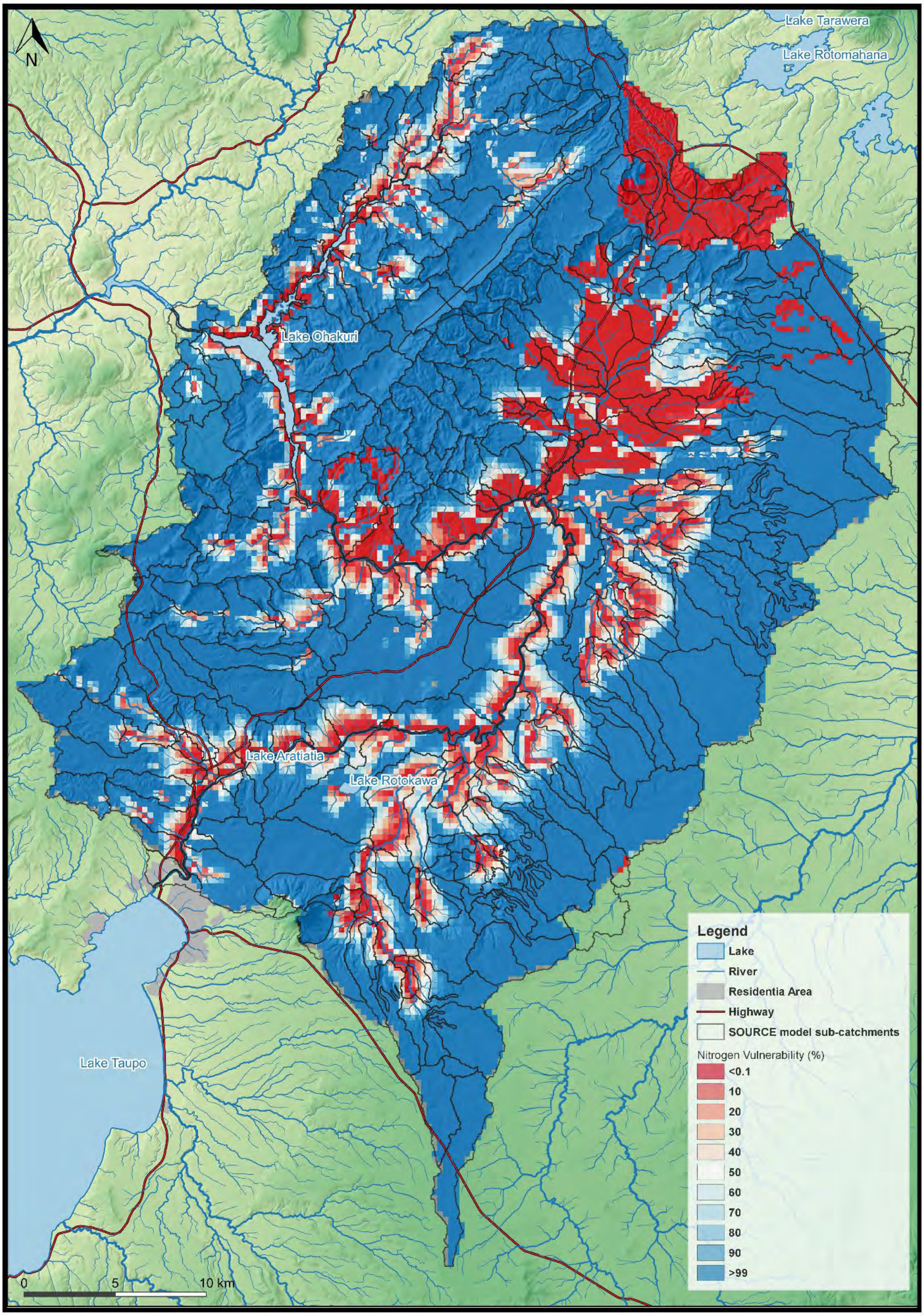


Figure 35. RDST nitrogen vulnerability map.

Effects from Different Parts of the Catchment

182 The time it takes for a land use change to fully stabilise or reach a new pseudo steady state is different in different parts of the catchment. There are two primary factors governing this:

182.1 ***Distance -*** Proximity to surface waterways and hence the receptor for surface water and groundwater flows; and

182.2 ***Groundwater denitrification potential*** – As indicated in my Block 1 evidence, where the groundwater flow path from source to surface water receptor is short and fast, attenuation of constituents in groundwater is relatively limited, whereas where the groundwater flow path is long and/or slow the opportunity for attenuation is much greater.

183 The RDST has been used to demonstrate the time it takes for a land use change to fully stabilise in different parts of the catchment. This was undertaken with the RDST where land use was independently modified to an extreme land use difference compared to the basecase model (i.e. if the basecase land use was dairy, this was changed to forestry; if forestry, this was changed to dairy).

184 The analysis was undertaken in the Pueto and in the Waiotapu catchments. Two sub-catchments were selected in each catchment for comparison – one in close proximity to the stream (catchments #251 in Pueto, #63 in Waiotapu) and one with significant distance from the stream being located in the upper headwaters, but disconnected from the stream itself (catchment #198 in Pueto, #40 in Waiotapu), as shown in **Figure 36**.

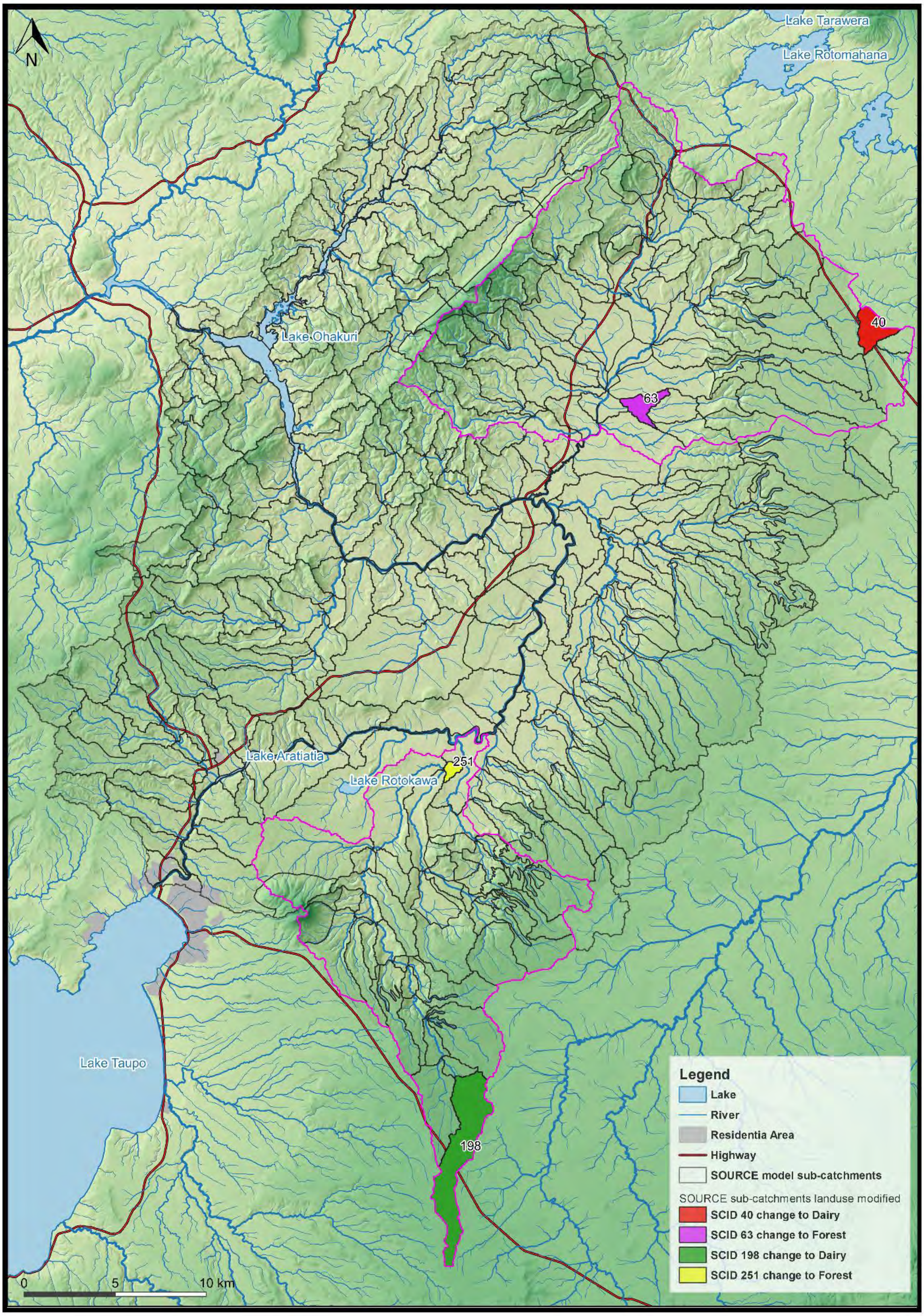


Figure 36. Four sub-catchments with land use modified to demonstrate timing for effects from different parts of the catchment.

185 **Figure 37** shows the relative absolute change in concentration of TN in the Pueto Stream with time since the land use change occurred. The key observations to note are as follows:

185.1 For the catchment in close proximity to the stream, the land use change impact starts occurring quickly and the effects have fully materialised after approximately 2 years where a new pseudo steady state is reached; while

185.2 For the catchment at significant distance from the stream, the land use change impact occurs very slowly, taking approximately 6 years for the impact of the land use to fully materialise, and the magnitude of impact is very small due to denitrification[10].

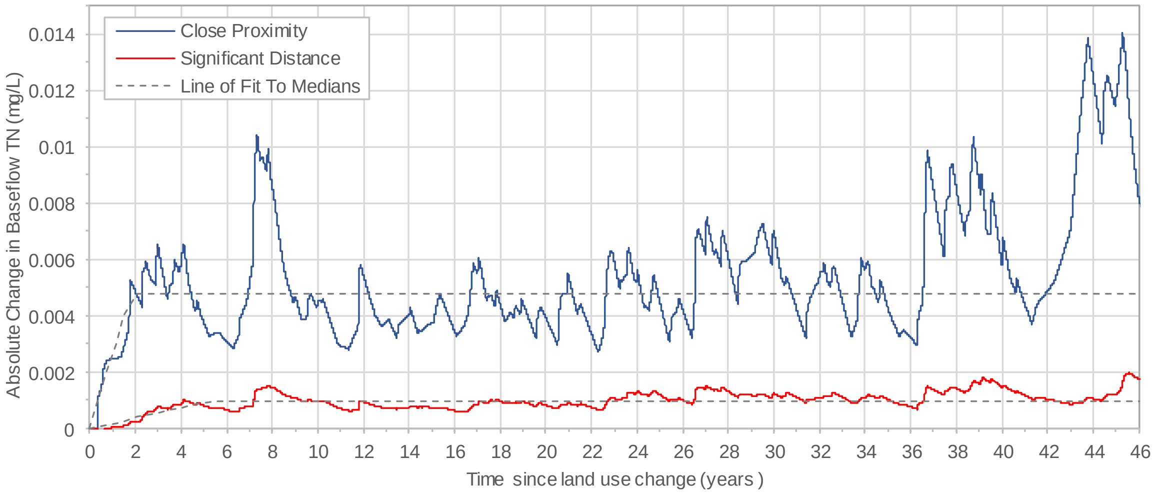


Figure 37. Timeseries showing timing of concentration change following land use change in Pueto Stream with a) sub-catchment in close proximity to a stream, and b) a sub-catchment significant distance from a stream.

186 **Figure 38** shows the relative absolute change in concentration of TN in the Waiotapu Stream at the Homestead gauge, with time since the land use change occurred. The key observations to note are as follows:

186.1 For the catchment in close proximity to the stream, the land use change impact starts occurring quickly and the effects have fully materialised after approximately 4 years where a new pseudo steady state is reached; while

186.2 For the catchment at significant distance from the stream, the land use change impact occurs very slowly, it takes approximately 15 years for the impact of the land use to fully materialise, and the key point is that the impact in this case from forestry to dairy is very small (0.001 mg/L)[11] due to denitrification.

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[10] Note: this level of impact would vary depending on the size of the catchment modified.

[11] Note: this level of impact would vary depending on the size of the catchment modified, although in this case the expectation is similar results regardless of size due to the effect of denitrification.

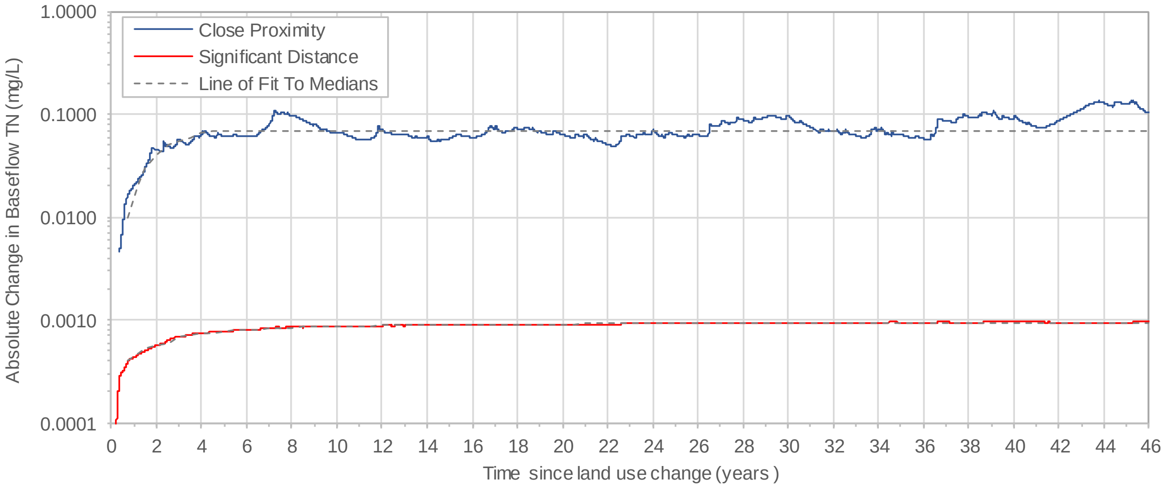

Figure 38. Timeseries showing timing of concentration change following land use change in Waiotapu Stream with a) sub-catchment in close proximity to a stream, and b) a sub-catchment significant distance from a stream (note log scale on x-axis).

Summary:

187 In this section I describe the modelling approach developed using the RDST to map vulnerable land areas, and provide two case studies demonstrating how different parts of the catchment respond differently to land use change.

188 The vulnerable land area analysis calculates at the discharge point (receptor), the percentage reduction in TN from different source areas, by considering the residence time in groundwater zones of differing reduction potential (denitrification profile).

189 The key observations from the vulnerable land area map are that:

189.1 Land areas adjoining perennially flowing streams/rivers (typically 300-1,200 m from the stream) are highly vulnerable (red zones);

189.2 Land areas with shallow groundwater (e.g. Reporoa basin) are mapped as highly vulnerable, although our current methodology does not consider the denitrification in soils with high organic content, hence the land vulnerability in this zone may be exaggerated; and

189.3 The land becomes less vulnerable with distance from perennial streams, which typically corresponds to higher elevation areas.

190 Conceptually, the vulnerable land area map conforms to the principle of redox chemistry, however its accuracy could be improved by increased spatial coverage (availability) and reliability of flow and TN observation datasets for calibration, and by consideration of dentification in the shallow soil profile where peat soils reside (planned for future update). Nevertheless, these limitations would not materially change the concept presented here.

191 The time it takes for a land use change to fully stabilise or reach a new pseudo steady state is different in different parts of the catchment. There are two primary factors governing this:

191.1 Proximity to surface waterways or length of groundwater flow path; and

191.2 Groundwater denitrification potential.

192 Two case studies were tested in the Pueto and Waiotapu catchments with the RDST to inform the time taken for land use change to materialise in different parts of the catchment. The key findings were:

192.1 For sub-catchments in close proximity to the stream, water quality effects became evident in the stream almost immediately after the land use change, and took 2 years and 4 years to fully materialise in the Pueto and Waiotapu catchments, respectively.

192.2 For the sub-catchment at significant distance from the stream, the land use change impacts occur very slowly. In the Pueto catchment, it took approximately 6 years and in the Waiotapu catchment approximately 15 years for the impact of the land use to fully materialise. However, for the distant sub-catchments the impact was negligible (0.001 mg/L) due to denitrification.

CRITERIA FOR DECISION SUPPORT TOOLS

193 The notified version of PC1 uses a single model for calculating nutrient discharges and regulatory compliance (OVERSEER).

194 A key point to note with respect to the difference between a catchment model like the RDST compared to a paddock scale model like OVERSEER, is that a paddock model cannot account for overall effects at the sub-catchment scale or impacts in the river, hence is not an appropriate regulatory tool if used in isolation.

195 In my opinion, an appropriate tool must be able to explicitly simulate (a process model) or implicitly simulate (a conceptually based model) the key physical features of systems that govern the effects that are being managed.

196 In this regard, the key features of an appropriate decision support tool (**DST**) for managing water quality outcomes in streams and rivers, as a minimum should comprise the following:

196.1 ***Temporal variability*** – ability to simulate historical and future temporal variability in land use, climate, and abstractions and discharges that may impact on river flows or water quality, particularly:

(a) Seasonal influences - which have a significant bearing on groundwater flow and constituent load responses; and

(b) Storm responses - which have a significant bearing of generation of sediment laden waters.

196.2 ***Flexible spatial scale*** – flexibility to discretise at a scale appropriate to accommodate major changes in land use, rainfall, and catchment physical characteristics such as geology, soil, slope, vegetation cover, etc.

196.3 ***Integrated models*** – the model must be integrated to the extent that it can model on a conceptual deterministic basis the key physical features of the systems (groundwater, surface water) contributing to water quality outcomes.

196.4 ***Conceptually based*** – all aspects of the model (constituent generation and transport) should be parameterised in a manner that is broadly representative of the physical behaviours occurring in the catchments of interest.

196.5 ***Physically based parameterisation*** – the model's functionality should be driven by hydrological system parameters that are representative of physical features of the systems being simulated (both surface catchments and groundwater aquifers) and readily estimated from field measurements or textbook values.

196.6 ***Physically based attenuation*** – the model must have the ability to attenuate discharges along the various transport pathways in accordance with fundamental scientific principles.

196.7 ***System storages*** – the model must have the ability to model storages (e.g. vadose zone, groundwater, and lakes) and time delays associated with storages, if these are important factors contributing to water quality outcomes in the area of interest.

Summary:

197 In this section I suggest that criteria are needed to support the possible future selection of DST's by WRC.

198 I provide my preliminary thoughts on what this criterion might be, including: temporal variability, flexible spatial scale, integrated models, conceptually based, physically based parameterisation, physically based attenuation, system storages.

CONCLUSIONS

199 This evidence has outlined my concerns with provisions in PC1 as notified and in particular the disconnect with modern science underpinning groundwater denitrification, and the dynamic functionality of groundwater systems and their interaction with surface water systems.

200 Keys aspects I consider need addressing in amended planning provisions include:

200.1 The "long term load to come" intervention logic for PC1 is incorrectly founded and unless the focus changes to management of quick flow and young groundwater responses, it is unlikely the long term 80-year Vision and Strategy will be met, and as Mr Ford will confirm, will not represent an optimal cost-benefit solution.

200.2 Failure to consider the timing of effects from land use change that may have occurred immediately prior to the PC1 notification date (October 2016) to manifest fully (i.e. effects may start occurring slowly immediately after the land use change, but the time for the full magnitude of effects to reach a new pseudo steady state will be some time later) may hinder achievement of Objective 3, unless FEPs are being implemented immediately.

200.3 A policy approach that is flexible in that it is cognisant of the assimilative capacity of land or vulnerable land areas - restricting high intensity land use in highly vulnerable areas and allowing higher intensity land use in low vulnerability areas.

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