New Zealand Groundwater Atlas: 3D Groundwater Models around New Zealand (A Review)

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GLOSSARY

Aquifer: an underground geologic layer that contains significant quantities of water and has sufficient internal flow of water to be productive

Bias: the difference between the probability-weighted average of all possible values for a modelled parameter and the true value of the parameter being estimated (ie a systematic [built-in] error that makes all values wrong by a certain amount)

Boundary condition: mathematical representations of the conditions of all areas of the model, including inputs, outputs, initial condition, processes occurring around the edge of the model and any time-dependent changes in these terms

Calibration: the process of adjusting model inputs and parameters to match model outputs to desired values, for example historic observations

Conservation equation: a mathematical formula that balances inputs, outputs and changes in internal storage of a term (eg energy or mass); the sum of these terms should be zero

Darcy's Law: a groundwater flow governing equation, commonly expressed as:

$$Q = -KA\frac{dh}{dL}$$

Where Q is discharge (L^3/T, eg m^3/s), K is hydraulic conductivity (q.v.), A is the area through which flow is occurring (L^2, eg m^2) and dh/dL is the gradient of hydraulic head (q.v.)

Discretisation: division of a model domain into small spatial and/or temporal parts that are mathematically solvable

Domain: the extent of the area represented by a model, for example a river basin

Drawdown: decrease in the water level in an area of an aquifer due to the withdrawal of water, especially pumping from wells

Element: a small area or volume within a model domain, in which equations are solved

Error: the difference between a measured value and a true value, where the true value can be known

Flux: the action or process of flowing in or flowing out (describing the magnitude and direction of flow)

Governing equations: the set of mathematical formulas that the model solves at each time and point in space

Head (hydraulic): elevation of groundwater relative to a chosen level

Hydraulic conductivity: a parameter that describes the rate of flow of water in a geologic layer (the ease with which a water can move through pore spaces or fractures). Units are length/time, for example m/day

Iteration: a mathematical approach implemented within a numerical model, in which a series of approximations are used to achieve a best solution

Model domain: the space (area and thickness) and time represented within the model

NWT: National Water Table, a model that calculates a New Zealand-wide water table surface

Node: a spatial point within a model, at or around which equations are solved

Observation: a quantifiable measurement that can be used as a target for matching in a calibration

Parameter: a numerical input that defines characteristics of the model and can be adjusted by the user or calibration software

Porosity: a measure of the volume of void space within the total volume of a geological mass

PET: Potential Evapotranspiration: The amount of evapotranspiration if ample water is available, that is no water deficit

QMAP: the digital geological map of New Zealand, provided at the scale of 1:250,000

Reach: a section of a stream or river along which similar hydrologic conditions exist, for example discharge, depth, slope

Recharge: rainfall or surface water that recharges to groundwater, also called ‘groundwater recharge’ or ‘drainage’

Saturated: all porosity within an area is filled with water

Scenario: a model simulation conducted to evaluate the response of a system to changed inputs

Sensitivity: a measure of the response of a model output to a change in inputs

Steady state: a numerical model that does not have time-dependent changes

Stress period: a duration of time in the model for which boundary conditions are held constant. Multiple timesteps may be contained within a single stress period

Timestep: a period represented in the model, for which transient model equations (ie any governing equation that has a term for time) are solved

Transient: a numerical model that has time-dependent changes

Truncation: mathematical error introduced by equation simplifications, for example where an infinite series is represented by only the first few terms

Uncertainty: a measurement of the possible variation of model inputs and/or outputs based on available information. The ‘true’ value is not known but is assumed to be within this range of values

Unsaturated: porosity within an area contains a mixture of water and air; not all pore space is filled with water.

EXECUTIVE SUMMARY

The New Zealand Ministry for the Environment contracted GNS Science (GNS) to carry out a desktop review of groundwater models in New Zealand as part of the national-scale New Zealand Groundwater Atlas programme. For this purpose, we collected reports for 3-dimensional (3D) geological, hydrogeological and numerical models produced by numerous consultancies, research organisations and regional councils nationally. Models exist for many of the agriculturally productive regions of New Zealand that utilise groundwater; these have been designed for different applications. The practice of building prediction-specific models has led to the creation of models at many different scales, using a variety of software packages. Much of this modelling is potentially useful for decision support of limit setting, with the caveat that it is essential to ensure that models are built to be prediction-specific. Repurposing of models to new applications risks inducing bias in model outputs which can compromise model utility for decision support.

A wide variety of scales in space and time are used in groundwater models nationally. Many of the models are produced for basin- or catchment-scale applications, where large watersheds are simulated. These large-scale, coarsely discretised models are often suitable to support management decisions pertaining to water quantity and/or quality at the catchment scale. We highlight aspects of discretisation where caution is needed. First, the spacing of the grid affects the mathematical solutions in the models, which can often produce the largest source of uncertainty in the entire model build. It is essential to consider these effects in the model build, but it is unclear to what extent these investigations are conducted nationally. Second, scale-dependent design simplifications must be application-appropriate and their uncertainty quantified.

The requirement for prediction-specific model builds complicates evaluation of model consistency nationally. Models are built and used for many different problems, using many different tools; this is not inherently problematic. Based on our review, we make a few general recommendations for future model approaches.

- Ensure that models are fit-for-purpose for their intended, specific prediction. It is important to carefully evaluate model performance when adapting existing models to new uses.
- It is essential to quantify and report uncertainty in numerical models, especially when calibration is conducted. Methods of usefully presenting uncertainty results is needed, as are guides on how to integrate uncertainty into important decision-making.
- Additional consideration of uncertainty induced by spatial and temporal discretisation effects is necessary. We noted that few of the reviewed 3D numerical groundwater models included any mention or analysis of this effect. Grid effects are often the greatest source of uncertainty in models.
- When possible, models should be periodically re-examined and their performance for their intended purpose evaluated. Benchmarking models in this way will help evaluate their fit-for-purpose and enhance their decision support utility.

1.0 INTRODUCTION

This report reviews a collection of available groundwater models throughout New Zealand as specified in Ministry for the Environment (the Ministry) contract reference 22359. The review was undertaken by GNS Science (GNS) and Aqualinc Research Ltd (Aqualinc). Material presented in this document is motivated by the national-scale Ministry-funded New Zealand Groundwater Atlas (GWA) programme (Ministry for the Environment 2018a). The Ministry requires national-scale groundwater data sets to inform groundwater workstreams related to the Environmental Reporting Act (2015) and the National Policy Statement for Freshwater Management (NPS-FM 2014, 2017), as well as to increase public awareness about groundwater.

The scope of this work originally related to the extraction and compilation of information from 3D groundwater models related to aquifer confinement status (Ministry for the Environment 2018a). However, this scope was revised mid-way through the programme to produce a desktop review report of model groundwater models in New Zealand, to consider limit setting; consistency; resolution; how confinement has been characterised; and to provide a list of models per region.

Nationally, work has been conducted on numerous regions, basins and sub-basins around New Zealand. The NPS-FM (Ministry for the Environment 2014, amended 2017) directs regional councils to manage freshwater resources, including groundwater, for sustainable management of water quantity and quality. Consequently, much of the modelling in this review has been driven by the various regional councils (eg Canterbury, Hawke's Bay) to support management decisions, optimise the way their freshwater resources were managed and to assess sustainable limits for both quality and quantity. Many regions have employed numerical models in support of these studies. The approaches of each council have been different regarding the type of modelling, what objectives were to be fulfilled by the modelling work and who undertook the work (ie regional councils themselves, consultancies in New Zealand and abroad, universities in and out of New Zealand and the Crown Research Institutes).

In this report, we explain the method undertaken to conduct this review and provide a summary of general observations concerning model types and approaches. Next, we summarise the model coverage of each region. Then, in accordance with the contract deliverables, we evaluate the consistency or variability of models between regions, comment on model resolution, evaluate the coverage of models that are applicable for limit setting and comment on representation of confinement in the extant models. We limit our review to subsurface models, noting that modelling of recharge is an extensive topic that merits a separate, extensive review. However, we do consider models that examine managed aquifer recharge when focus is devoted to the groundwater system. In addition, we do not give an evaluation of geothermal reservoir models and other numerical models that are ancillary to groundwater resource investigations.

2.0 OVERVIEW

2.1 Model Types

Broadly, our review encompassed several different types of models, including conceptual models, (hydro)geological models and numerical models. Distinctions between these types are not always clear and many of the reports reviewed included multiple types of models. Conceptual models (Figure 2.1) can be generalised as a hypothesis for how a groundwater system works, based on known stratigraphy, field samples, expert judgement and other available data. In some cases, analytical solutions or eigen models[1] may be applied to support the conceptual model or as a mid-ground between the conceptual model and a full 3D numerical model. Geological models (Figure 2.2) include spatial representation of geological units, evaluation of stratigraphy, geophysical data and general consideration of the geological sensibility of the system (in relation to groundwater flow), but do not include direct numerical solutions of the groundwater flow equations. Spatial outputs from geological models (such as elevation of geological layers) often serve as a basis for numerical models. Numerical models (Figure 2.3) are defined by a discretised domain, boundary conditions, hydraulic stresses (eg recharge; pumping) and the solution of conservation equations (ie fluid flow equations). A list of models by region is described in Appendix 1. This list and the review material herein, was primarily compiled in July 2018.

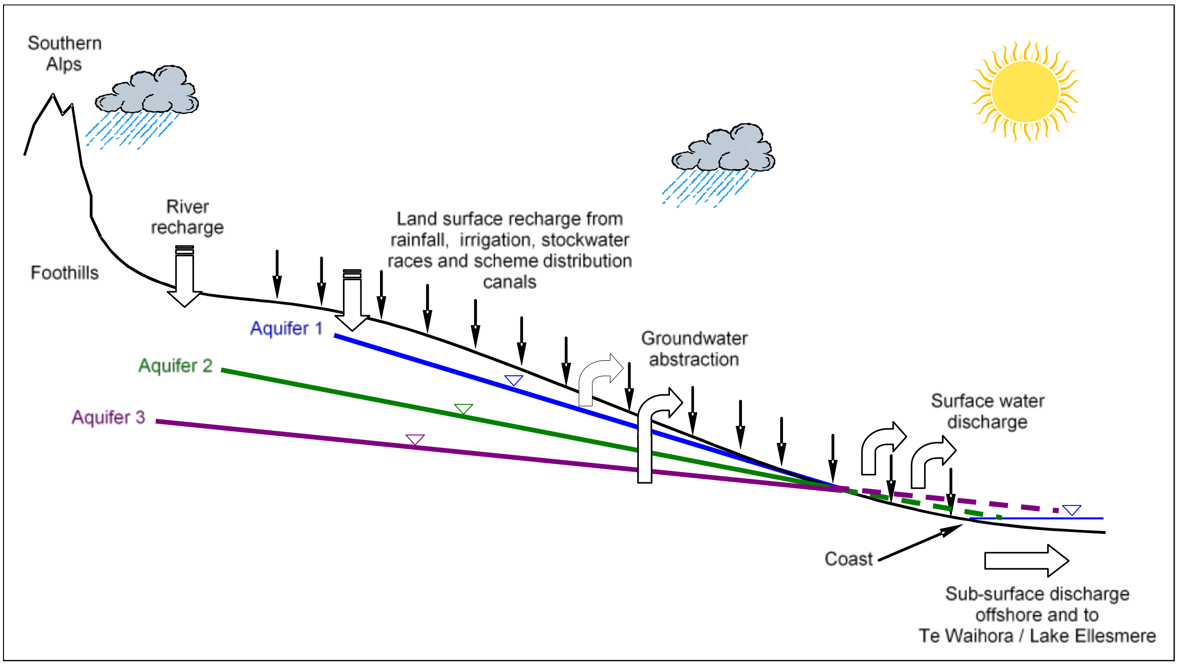

Figure 2.1 Example conceptual model of key hydrological processes influencing the Canterbury Plains aquifer system (reproduced from Weir 2018).

[1] A one-dimensional simplified representation of the aquifer system for solving groundwater flow equations based on hydrologic inputs (see Bidwell 2002). These are often developed using spreadsheets.

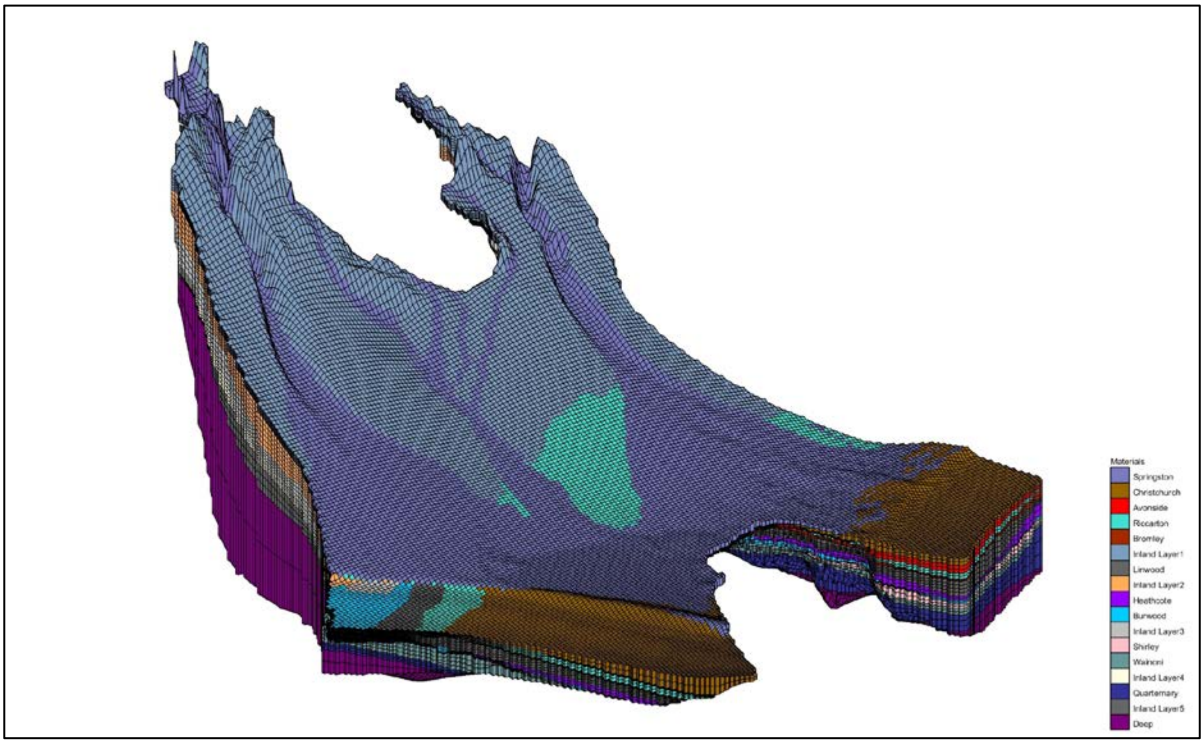

Figure 2.2 3D Geological model block diagram of Canterbury Plains (reproduced from Weir 2018).

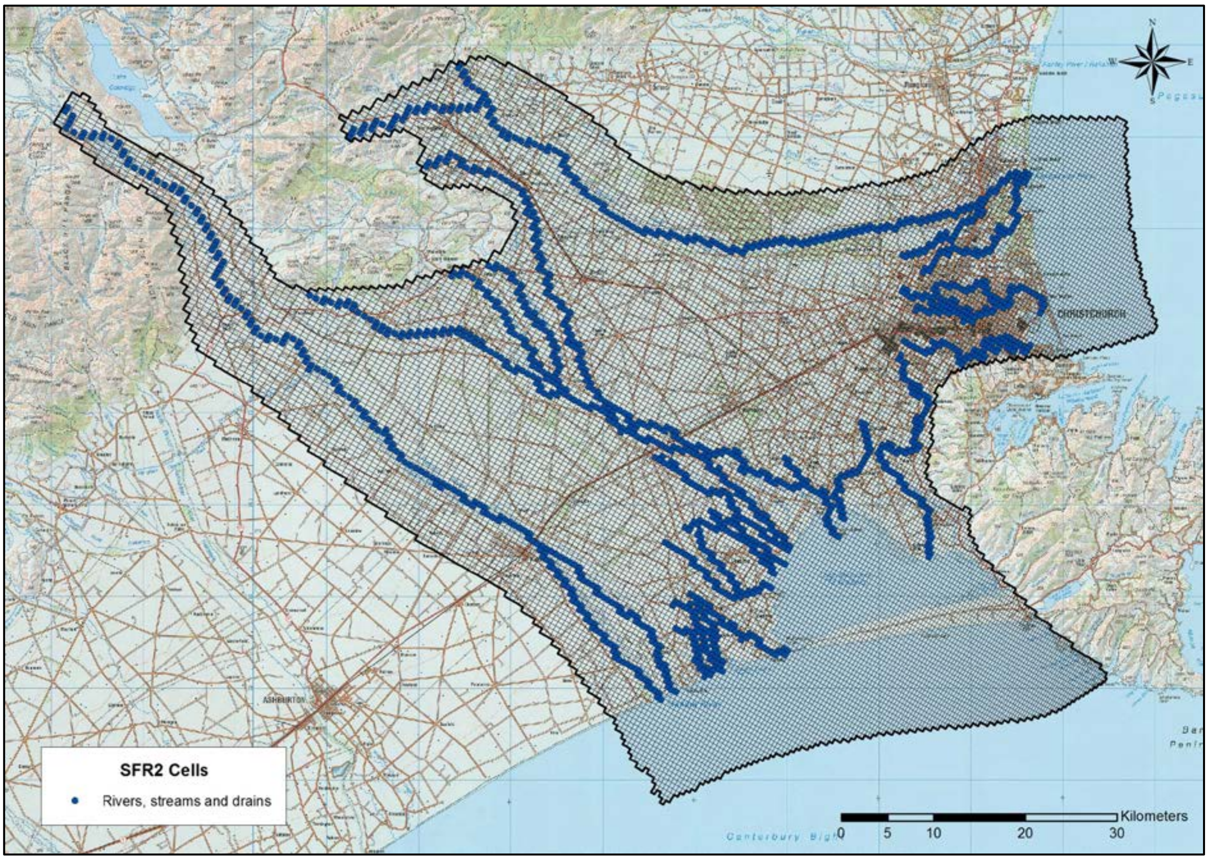

Figure 2.3 Map view of Canterbury Plains model grid, highlighting river cells (reproduced from Weir 2018).

2.2 Numerical Groundwater Models

2.2.1 Model Software

Most of the numerical groundwater modelling we reviewed was conducted using either the finite difference software suite MODFLOW (McDonald and Harbaugh 1988; Harbaugh 2005; Niswonger et al 2012; Hughes et al 2017), primarily MODFLOW-2005 (Harbaugh 2005) or MODFLOW-NWT (Niswonger et al 2012), or else a finite element model such as FEFLOW (Diersch 2013). Other less-common software packages are also used. Distinctions between the software packages include the means of discretisation, numerical approach to solving the groundwater flow equations and achieving solution convergence and ease of model access (eg open source vs. licensed). Each software package has advantages and disadvantages. This review does not advocate for any one method. All are extensively benchmarked, supported, updated and are commonly applied to the considered applications.

2.2.2 Modelling Process

In general, the constructed 3D numerical models follow similar methods, with specific modifications depending on the application, hydrogeological setting and location of the model. First, a region of interest is identified. This can be nationwide (eg Westerhoff et al 2018), a large region (eg Rawlinson et al 2016, Weir 2018), an individual river basin (eg Johnson et al 2019), monitoring of an area of interest (eg Behar et al 2019), or a small sub-catchment. Numerical porous flow simulators can even be applied to bench-scale or field experiments (eg Bourret et al 2017).

Once a region and purpose is identified, a numerical grid or mesh (eg Figure 2.4) is built which *discretises* the domain into *nodes* or *elements*. A discussion of discretisation is provided in Section 4. Next, parameters are assigned for various hydrologic properties (eg storage, porosity, hydraulic conductivity, chemical diffusivity, capillary functions etc) and these are assigned to the relevant nodes or elements. Finally, *boundary conditions* in space (linked to the presence of rivers, chemical or thermal inputs and other phenomena) and time (eg seasonal changes in infiltration), along with other phenomena such as well abstractions, are assigned. These boundary conditions specify the initial state of the model, any time-dependent changes during the course of the simulation and the connection between the model domain and the world outside of the model domain. Once the model is built, it solves a set of governing equations, which typically include conservation of flow and mass, such as:

$$\frac{\partial A_m}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{f_m} + q_m = 0, \qquad \text{Equation 1}$$

Where *A* is water quantity, ***f*** is the mass flux, *q* is the source or sink term and *t* is time (for transient models). The subscript *m* denotes water mass; some models might include terms for energy, air mass, or other quantities. The 'del' operator $\boldsymbol{\nabla}$ indicates the gradient in each direction; that is, each node or element takes on a solution value based on the surrounding nodes. Models can be transient (inflows and outflows vary over time) or steady state (everything is constant).

Water flow is represented commonly using a formulation of Darcy's law:

$$Q = -KA\frac{dh}{dL} \qquad \text{Equation 2}$$

where *Q* is water discharge (L^3/T, eg m^3/s), *K* is hydraulic conductivity (L/T, eg m/s, specified as a model input), *A* is the cross-sectional area of the boundary between grid blocks or elements (L^2, defined by the mesh) and dh/dL is the hydraulic head gradient (dimensionless, calculated in each iteration or timestep in the model).

The process of solving the model equations is not always easy and numerical models are, by definition, approximations to mathematical equations rather than exact solutions. Conceptually, the mass conservation equation aims to balance water inputs, outputs and internal changes in storage (if the model is transient) for each location in the model. Numerical models accomplish this by calculating an initial solution, determining whether the conservation equation is sufficiently satisfied and then using solver algorithms to refine the estimated solution until the conservation equation is sufficiently satisfied (ie until mass is sufficiently conserved at all locations. This mathematical approach means that a true conservation of mass (where the sum of all water inputs, outputs and changes in internal storage equal zero) will never be achieved. To address this, a *convergence criterion* is defined where if the model achieves a residual total mass change less than this value the mass conservation equation is considered solved (ie the equation is sufficiently satisfied). Thus, some amount of numerical error is always present in the model. In many cases, the constructed model is unable to achieve convergence and will crash; when this occurs, adjustments must be made to produce a functional model that runs to completion. For complex model domains, considerable effort is often needed to achieve convergence, which can include some simplifications that increase uncertainty in the model outputs.

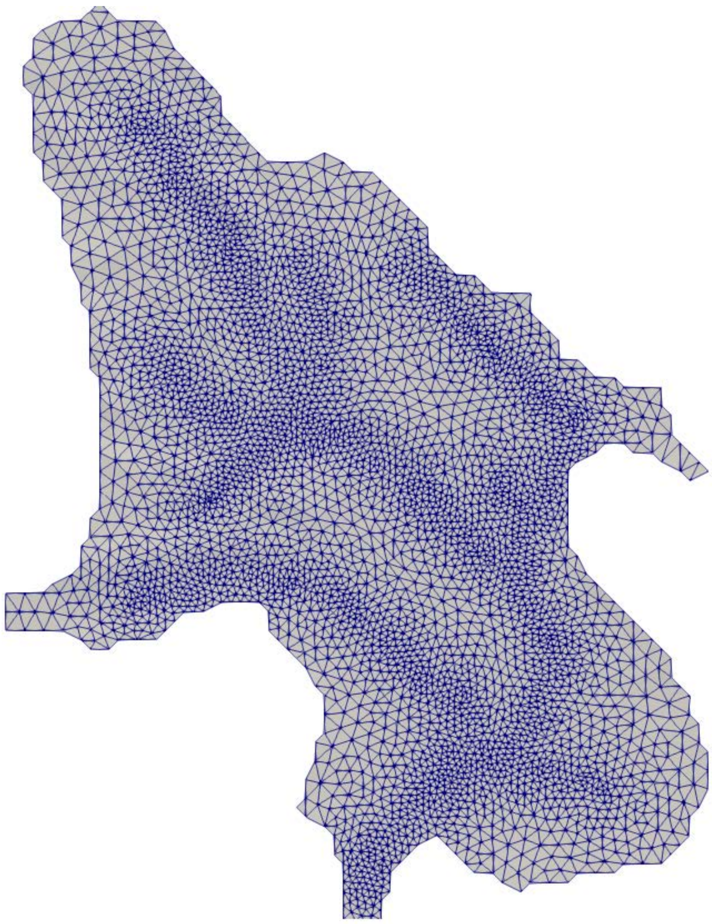

Figure 2.4 Sample numerical mesh for groundwater models. Each triangle is an *element*, with distinct parameters such as hydraulic conductivity. Model equations are solved at each element based on values in each element and in adjacent elements.

2.2.3 Model Calibration and Uncertainty

Following construction and initial running of the model, the user then has the choice to *calibrate* the model. In the calibration process, model results are compared with observation data such as measured groundwater levels in wells. Although the specifics vary and model calibration is a complex and rapidly evolving topic, the general calibration approach consists of several steps. First, the model is constructed based on available information about the system. Then, a set of *observations* are input, which consist of collected data such as water level in wells, temperature, nitrate concentration and so on. A set of *parameters* are chosen and, when possible, constraints applied to the possible range of these parameters. Example parameters might include the hydraulic conductivity at each point of the model, groundwater abstraction volumes or locations etc. The model is run with a set of parameters and the match of modelled to observed data is determined. Parameters are then adjusted, the model run again and a new fit to data measured. Commonly, an assessment is made of the *sensitivity*[2] of observations to model parameters. Highly-sensitivity parameters are specific to each model and are calculated during the calibration process. Eventually, a set of parameters is reached that produces a satisfactory match to observed data. Calibration can be done manually or using a software package (most commonly the PEST software, Doherty 2003). Determining model parameters necessary to fit data (history matching) is *inverse modelling*, in which the model is modified to match known data. This is differentiated from *forward modelling* in which a model is constructed with a set of known or chosen parameters to examine the outcome of a specified scenario (eg the response from future groundwater abstraction). A common practice is to build a model, calibrate it to previously known data to establish parameter estimates and then modify some inputs (eg changing abstractions) to suggest the future response of the system under a *scenario*.

When properly conducted, model calibration gives a useful output of parameters for chosen model applications and is useful for scenario modelling. However, caution is essential in the process because multiple sets of parameters can result in the same level of calibration; that is, calibration results are *non-unique*. For example, an observed nitrate concentration at a location could be produced by a nearby, relatively small source, or a more distant, large nitrate source. Either simulated nitrate source might meet calibration requirements, but these different calibration solutions would have very different implications for management decisions. Additional information can help improve this calibration. Introduction of further parameters increases the *solution space*, or range of possible solutions that can match observations. It is critical to choose a parameter set in calibration that is appropriate for the desired prediction; the chosen parameter set varies between models, predictions and settings. Common parameters of interest in groundwater models include, but are not limited to, hydrologic characteristics such as hydraulic conductivity, storage, unit thickness, infiltration, abstraction and nitrate loading.

The combination of model simplifications, calibration non-uniqueness, the inability to sample all areas of a groundwater system and other factors means that all groundwater models contain *uncertainty*. In inverse models, a range of possible parameters can meet calibration requirements. In forward models, many different outcomes are possible from the range of possible parameters. Quantifying and handling these uncertainties is essential when models are used to support decisions and techniques in the field are rapidly evolving. A comprehensive overview of uncertainty quantification is beyond the scope of this review,

[2] Essentially, changing a model parameter will induce a change in the outcome of some prediction of interest; the greater the change in prediction output, the more sensitive that prediction is to the chosen parameter.

but an acknowledgement of the presence of uncertainty is important in many aspects of the following discussion. Neglection of uncertainty can result in misplaced confidence in management decisions when models are used for decision support. For example, when calibration is conducted, a single set of parameters chosen and a subsequent scenario model is run, this simulation might suggest that a management decision will not result in hazardous outcomes; the management decision may be taken and a hazardous outcome occurs (a *false negative* outcome, where the model incorrectly predicts no problem will arise). Had a different set of parameters been determined in the calibration, this result might have been avoided. Uncertainty analysis in such a context can help establish the range and probability of different outcomes, allowing for a more informed management decision.

2.2.4 Model Suitability

Evaluation of model quality and suitability for purpose is challenging because all models contain simplifications and trade-offs. Consequently, model suitability depends on the desired application. Nationally, many different challenges and applications have been considered resulting in a broad variety of modelling work. Different model characteristics must be used for different applications. For example, a fundamental choice is to define the area under consideration and how to discretise the model domain. Improvements in the numerical precision, capturing of fine resolution and model detail, must be balanced against model run time and computer data file sizes. As a result, the modeller may select a relatively coarse resolution (eg hundreds of metres or one kilometre) to represent a large region. The resulting model may be suitable for applications at the regional scale (such as basin-wide water balance) with a coarsely-discretised regional model, but not for local-scale management decisions (such as maximum pumping rates to prevent stream depletion). The local scale decisions would require a finer discretisation (eg a few metres). Conversely, a finely-discretised model may require a long run time (many hours or days) if applied at a large scale, making its application to regional studies challenging.

2.3 3D Geological Models

A 3D geological model is generally composed of a series of geological layers that are assembled by taking into account their relative chronology and structural relationships. For hydrogeological purposes, they are typically built from a sequence of simplified geological layers, often referred to as 'model units'. These correspond to an aggregation of individual geological formations and groups relative to groundwater flow.

2.3.1 Model Unit Definition

These model units are decided by the modellers and decisions will be based on both hydrogeological characteristics and the available data, while taking into the account the purpose of the model. The definition of the units to be modelled is a key step in the modelling process. Once defined, the top and bottom surfaces of the model units are used to generate model unit volumes. Within New Zealand, the most commonly used geological modelling software packages are Leapfrog Geothermal/Geo and EarthVision.

Typically for geological models that have been developed recently in New Zealand, the QMAP surface geological maps (Heron 2014) and topographic models (Columbus et al 2011) are used to generate model unit polygons at the ground surface. This places a restriction on the expected resolution of the model, with a 250 m or larger horizontal resolution expected. Available geological sub-surface information is then used to: 1) identify geological formations in the model area and 2) group all relevant geological formations and groups into model units.

The upper and lower surfaces of each model unit is then constructed through surface interpolation between all available scattered data points for a unit. Geological modelling software also typically allows for different types of geological processes (eg erosion, deposition and intrusion) which can be used as input parameters to constrain the interpolation. Local edits can also be added to constrain the interpolation in areas with little data. Finally, the surfaces' relative chronology can be defined and surfaces assembled to produce a 3D model.

2.3.2 Source Data Sets and Uncertainty

Typical data sets available to create geological models include:

- Topographic data
- Bathymetric data
- Geological maps
- Geological cross-sections
- Well logs
- Interpreted geophysical data.

Each of these data sets is subject to uncertainties, which are transferred to the geological model. Uncertainty in the vertical location of model unit boundaries (ie model unit tops and bottoms) may be comparatively small for where model units are exposed at the ground surface (only linked to the uncertainty of the geological maps). Layers below the ground surface will have more uncertainty due to fewer measurements and interpretations from this data.

The spatial distribution of data is an important contributor to model uncertainty. The amount of information available for a model unit provides constraints on the possible ranges of its extent (laterally and vertically). A model unit can be well constrained if, for example, it is penetrated by many drillholes, or it can be poorly constrained due to a lack of drillholes.

Another contributor to model uncertainty is the uncertainty of the measured data itself. Additional uncertainty may be introduced through the interpolation algorithm used to interpolate the model unit surfaces and the resolution chosen for the model surfaces. A surface that is created through one interpolation method can differ from those produced by other interpolation techniques. For example, the surfaces with directional trends that guide the interpolation within Leapfrog Geothermal require significant testing and adjustment by the modeller to create interpolation surfaces that honour the data locations whilst remaining geologically sensible. The more input data points that are available, the lower the uncertainty in the resulting model.

2.4 Model Review Approach

The review is weighted heavily by the reporting that accompanies the model, as these reports contain the conceptualisation and design of the model. Running, visualisation and comprehensive quality evaluation of each model individually was deemed out of the scope of this work. Some models could not be included in this review due to:

- inability to obtain models reports as they were not publicly-available
- the model being built for applications that were far outside the scope of this review, such as petroleum or geothermal models
- limited or unspecified supporting documentation.

Overall, models could be found for most, but not all, of the main regions in New Zealand. A wide variety of model scales were explored, the majority of which were designed for water balance and allocation considerations at the scale of watersheds, basins, or regions. A smaller number of models included transport modelling, wellhead security, nitrate contamination, river/groundwater interactions and managed aquifer recharge. In addition to numerical models, several regional geologic models and a number of conceptual models were found for some regions and individual basins. A breakdown by regional councils follows.

3.0 MODEL COVERAGE

The following coverages relate to 3D geological, hydrogeological, or numerical models or preparatory work retrieved from a literature review in July 2018. Confidential reports were not included. Most regions of New Zealand have at least some areas modelled (Figure 3.1). Due to lack of spatial data (eg shapefiles) for some regions, we were unable to develop a map showing model boundaries within some regions.

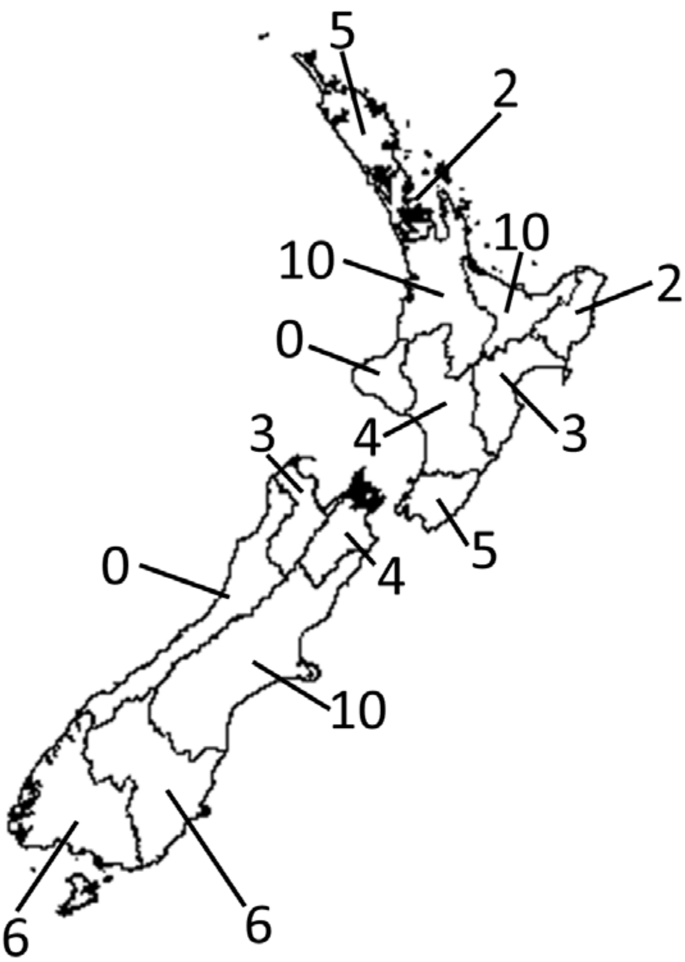

Figure 3.1 Number of basins modelled within each region.

3.1 Auckland

Two reports were available for the Auckland unitary authority, but one is a short abstract that we were unable to evaluate for model specifics (Zhan and White 1995). A recharge study for water management was conducted in the Kaawa aquifer and some of the volcanic aquifers in the region (Viljevac et al 2002).

3.2 Bay of Plenty

Ten aquifers have been studied in the Bay of Plenty region, with 14 reports produced. Western Bay of Plenty has three reports – a conceptual/hydrogeological model (White et al 2009) and water balance groundwater flow model (Zemansky et al 2011), as well as a geological model for the wider Western Bay of Plenty-Matata area (Tschritter et al 2016b). Lake Rotorua catchment has a steady-state groundwater model for baseflow (Daughney et al 2015), a conceptual model based on water-age dating (Morgenstern et al 2015) and a nutrient evaluation report that includes hydrologic descriptions (White et al 2007); in addition, a geological model has been developed for the Rotorua Geothermal Field but with some implications for water resources (Alcaraz 2014). Whakatane Central Business District has one geological model as part of an earthquake land damage assessment (Begg et al 2015b). Rangitaiki Plains area has a conceptual model with groundwater budget and a subsequent allocation assessment (White et al 2010a; White and Tschritter 2015). Lake Tarawera has a 3D geological model (Tschritter and White 2014) and an assessment of nitrogen discharge from groundwater to lakes and streams (White et al 2016). Finally, Opotiki-Ohope has a preliminary allocation assessment for groundwater and surface water (White et al 2013).

3.3 Canterbury

The Canterbury Region has been extensively studied, with 14 reports produced covering 10 catchments. One report (Scott and Moore 2008) describes a regional groundwater model analysis but lacks details about aquifer units or parameters. Groundwater/surface-water interactions were studied in the shallow catchment of Coopers Creek (Peaver et al 2017) and the Te Waihora/Lake Ellesmere catchment (Williams 2013). Recharge and hydrogeological modelling was conducted by Thorley et al (2010) for the Rakaia-Ashburton Plains aquifer. Callender et al (2005) built a geological map for Christchurch and the eastern Canterbury area with a focus on groundwater and an additional geologic map was prepared by Barrel and Strong (2012) for the South Canterbury region, with the intent of building a subsequent groundwater model. A numerical model was built by Begg et al (2015a) for the city of Christchurch. Two GNS projects are examining uncertainty for the Waimakariri area and were ongoing at the time of the review. A steady-state groundwater model of the Waimakariri and Rakaia river area was previously built as well (Scott and Thorley 2009). Aqualinc has produced two models for the area between the Rangitata and Waimakariri rivers (Aqualinc 2007a), one model for the area between Rakaia and Waimakariri rivers (Weir 2018) and one model for the Opihi-Tempuka-Orari-Pareora region (Flintoft and Weir 2017).

3.4 Gisborne

Two basins are described in four reports for the Gisborne unitary authority. Two of these reports (Rajanayaka 2011; Zemansky et al 2012) were literature reviews with recommendations and did not include models. Conceptual models were developed by Golder Associates (2014a, 2014b) as part of a feasibility study for managed aquifer recharge in the Poverty Bay area.

3.5 Greater Wellington

Eight reports were located covering five catchments in the Greater Wellington region. Numerical models have been built for the Ruamāhanga catchment for water management and water quality purposes (Moore et al forthcoming; Blyth et al 2018), Kāpiti Coast (Gyopari et al 2014), Wairarapa Valley (Jones et al 2006; Gyopari and McAlister 2010a, 2010b, 2010c) and Waiwhetu Aquifer (Phreatos Limited 2003). In addition, a regional model was built for the Lower Hutt area (Gyopari 2014) and a conceptual model and numerical developed for the overall Wairarapa groundwater basin (Jones et al 2006). Capture zone delineation studies were conducted by Toews and Donath (2015) for community supply wells throughout the Greater Wellington region.

3.6 Hawke's Bay

For Hawke's Bay, seven model reports were identified for three areas. Williamson and Diack (2018) examined the Tutaekuri, Ngaruroro and Karamu catchments for interactions between surface-water and groundwater. Likewise, a groundwater/surface-water model was developed to support abstraction evaluations for the Poukawa Basin (Cameron et al 2011). The Ruataniwha basin has had numerical modelling work done for water balance (Murray et al 2002; Baalousha 2010), nitrate transport (White and Daughney 2004; Baalousha 2013) and flow modelling by Weir et al (2013, updated in 2019). A geological model (Lee et al 2014) and MODFLOW numerical model (Rakowski and Knowling 2018) have been developed for the Heretaunga Plains.

3.7 Manawatu-Wanganui (Horizons)

Four models were located in four basins for the Manawatu-Wanganui region. Eigen models were developed for the Turakina/Rangitikei zones (Thomas and Woodhouse 2015) and for Horizons Regional Council (Weir 2018). A 3D geological model was developed for the Upper Manawatu and Mangatainoka catchments in Tararua (Rawlinson and Begg 2014).

3.8 Marlborough

Work conducted in Marlborough unitary authority includes 13 reports in four areas. The Wairau Plains aquifer has been extensively covered, including geological modelling (White and Tschritter 2010), three-dimensional modelling and chemistry to develop a conceptual model (Raiber et al 2012) and calibrated numerical modelling (Aqualinc 2004; Rajanayaka 2008; Raiber et al 2012; Wilson and Wöhling 2015; Wöhling et al 2018). Scenario modelling of groundwater responses to climate change (Weir and Davidson 2016) has also been undertaken for this area. In addition, sustainability reports were produced for the Rarangi shallow aquifer (Wilson 2007) and Wairau/Riverlands aquifers (Wilson 2008).

3.9 Nelson/Tasman

The Nelson and Tasman unitary authorities have been the subject of 15 reports or papers covering three catchments. However, many of these reports were model revisions or report/publication pairs covering the same model. The greater Motueka area has fine-resolution 3D finite element models (Hong et al 2005; Hong et al 2010) as well as modelling of abstraction scenarios (Gusyev et al 2012). The Motueka-Riwaka plains area has been extensively modelled by Aqualinc and Lincoln Environmental since 2001. The Waimea Plains has an aquifer model (White and Reeves 1999), a groundwater–surface water interaction model which has had numerous updates (Hong 2000; Hong 2003; Hong and Thomas 2006; Hong 2007), followed by some more specific scenario modelling for different land-use decisions (Hong and Thomas 2008; Hong et al 2009; Weir 2007). An evaluation of water resources was undertaken by the District Council in Tasman for the Takaka management area as well (Thomas and Harvey 2013), including hydraulic eigen modelling and transport mixing (Weir and Fenemor 2017).

3.10 Northland

Five models were retrieved for five catchments in the Northland region. Conceptual and numerical models were built for the Russel area (Sinclair Knight Merz 2002), Awanui Artesian aquifer (Sinclair Knight Merz 2007) and Aupouri Aquifer (Wilson and Shokri 2015). A detailed conceptual and numerical model was built by Zhao and Williamson (2017) for the Motutangi-Waiharara aquifer. A calibrated water balance model has also been built for the Whatitiri and Maunu-Maungatapere aquifers (Sinclair Knight Merz 2010).

3.11 Otago

Research identified 10 separate reports covering six aquifers and/or basins. Cromwell Terrace (Rekker 2012a), Wanaka Basin (Dale and Rekker 2011), Bendigo and Tarras (Houlbrooke 2010), Lower Taieri (Rekker and Houlbrooke 2009), North Otago Volcanic (Rekker et al 2008) and Ettrick Basin (Otago Regional Council 2006) aquifers are covered by geological concepts and some numerical modelling, primarily for water balance and allocation purposes. In addition, South Dunedin Coastal Aquifer was examined for the effects of sea-level rise on inundations (Rekker 2012b). This last model is currently under revision at GNS as part of a broader ongoing research effort concerning sea-level rise effects. Furthermore, Aqualinc and NIWA have developed numerical flow and transport models for the Kakanui catchment.

3.12 Southland

Southland Region studies include six reports in six management units. Edendale is addressed by a pair of reports, covering first a conceptual/geologic model and design of numerical model (Thomas 2012a) and then model calibration and a contamination transport simulation (Thomas 2012b). The Mataura watershed (Phreatos Limited 2007), Northern Southland (Wale et al 2005) and Aparima (Johnson 2019) are subjects of water balance models. In addition, a broader regional model was developed including a geological conceptual model and finite element model (Tschritter et al 2016a; Rawlinson et al 2016).

3.13 Waikato

Extensive work has been conducted in the Waikato region, with 10 basins covered in 14 reports. One report denoted requirements for future conceptual model development (Rawlinson 2014) regionally. Western Lake Taupo has been the subject of a previous flow and transport model (Toews and Gusyev 2012) and additional work is currently undertaken by GNS for this area. A groundwater flow model has been developed for the Puekawa Basalt Aquifer (Thornburrow 2017). Waihi Basin was included in the PhD dissertation of Ling (2003), with both a conceptual and a geological model developed. Toews and Moreau (2014) developed delineations of groundwater protection zones. Additional protection/capture zone[3] delineation has been done for the Putaruru area (Gusyev et al 2011). Water balance modelling for water budgets has been done at Waipa (Knowling et al 2016) and the Hauraki Plains (White et al 2018). In addition, extensive work on model uncertainty has been conducted based on the Hauraki Plains model (White 2018). Aqualinc has developed multiple versions (ongoing development) of numerical flow and transport models of the upper Waitako Region (Weir et al 2013), as well as the sub-catchments of Reporoa, Waipapa and Little Waipa.

[3] Modelling conducted to identify the region that provides groundwater to a location; contaminants within this zone can transport to, for example wells or surface water takes.

3.14 West Coast and Taranaki

No modelling studies were identified in the West Coast and Taranaki regions. Allis et al (1997) examined groundwater in support of oil and gas exploration efforts but, as their model was for a different application, it was excluded from this review.

3.15 National

An integrated National Water Table (NWT) model was developed by Westerhoff et al (2018), which implements a 3D numerical groundwater model to develop a nationwide water table elevation based on refinement of the global Equilibrium Water Table (EWT). This model aims to provide sufficient detail for national-scale overview of groundwater in a simplified conceptual system.

4.0 RESOLUTION IN 3D NUMERICAL GROUNDWATER MODELS

4.1 Spatial Discretisation

4.1.1 Concepts

Spatial discretisation in numerical models carries several important implications for function and fitness-for-purpose for different applications. Fundamentally, models are discretised into either a set of points on a grid, with the numerical solution determined locally at a point (a finite difference solution, for example, MODFLOW), or over an area or volume with determination of the solution for the entire area (2D) or volume (3D) represented by an element (a finite element solution, eg FEFLOW). Hybrid approaches, such as control-volume finite element (CVFE) methods, are possible and implemented in the most recent version of MODFLOW 6 (Hughes et al 2017), but at the time of this review have not been widely used for groundwater modelling nationally.[4] Mathematically, the CVFE method uses similar equations to the finite difference approach for solving Darcian flow but allows for varying volumes to be represented by each node, at the expense of additional memory usage compared with a finite different model (see Zyvoloski 2007). Modelling using control volume approaches may be utilised more in the future as MODFLOW 6 becomes more widely used and as downscaled applications are considered that require more sophisticated numerical mesh geometry.

Beyond the choice of numerical method, model grids or meshes can also be characterised based on the uniformity of their discretisation. Three approaches are common. A *uniform*, *structured* grid (Figure 4.1a) or mesh has identical spacing between nodes or element vertices throughout the domain. For some model applications, higher detail may be desired in certain areas. In these cases, the grid can be refined (and made *non-uniform)*, but this refinement is applied through entire rows of columns of cells throughout the model (Figure 4.1b). A drawback of this approach is that the higher resolution is also applied outside of the area of interest, increasing node numbers and computational burden.

Finite element and CVFE meshes can be structured (Figure 4.1c) or unstructured (Figure 4.1d). With *unstructured* meshes, the node spacing and element volumes vary throughout the domain. Unstructured meshes are common in finite element modelling and the ability of unstructured meshes to represent complex geometries is one motivation for recent development of CVFE models which combine the simpler finite difference mathematics with great flexibility in the numerical mesh. The mesh can be coarsened to reduce the number of elements in areas of little variability. Techniques in adaptive mesh refinement (eg Gable et al 2006) allow for balancing between the number of nodes and the level of precision required at various locations but can be harder to handle for some post processing compared with structured grids.

[4] CVFE models are employed more commonly in geothermal applications, including the MBIE-funded Waiwera project (Croucher et al 2018), but geothermal models were not included in this review.

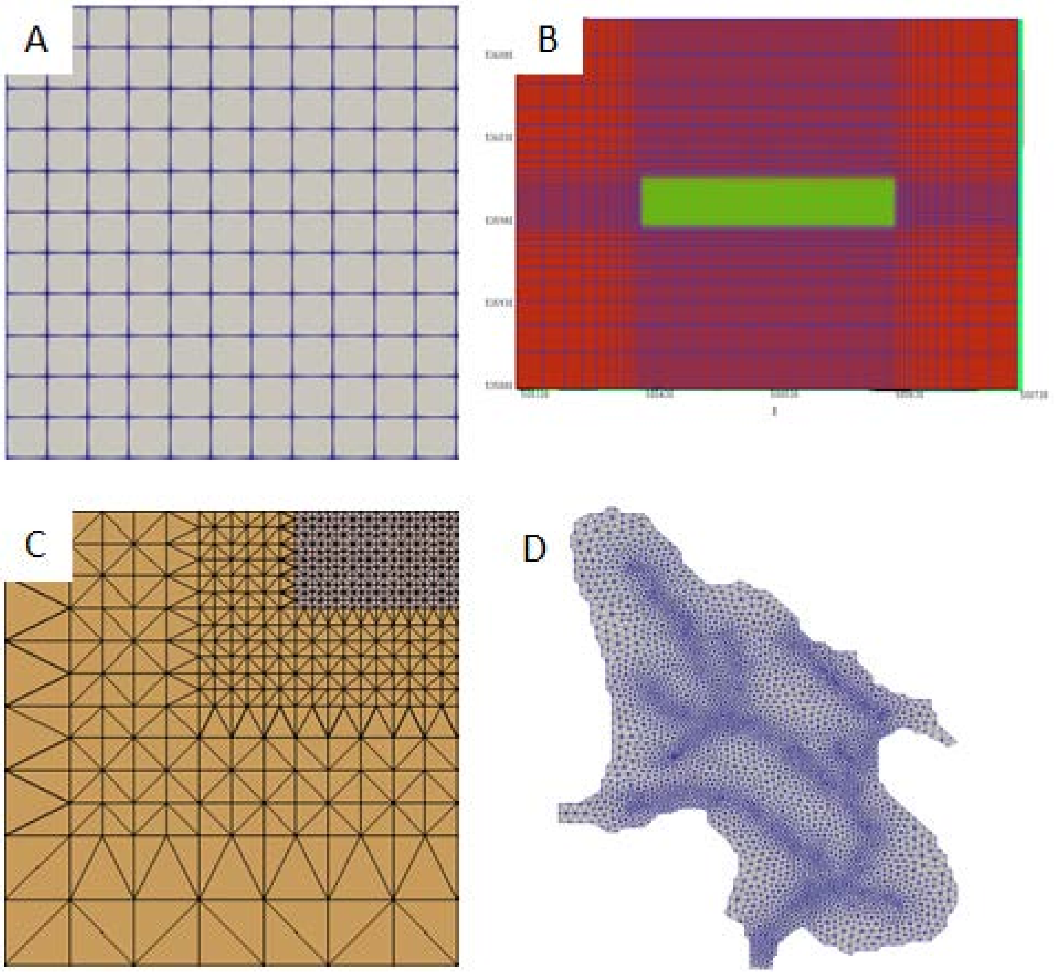

Figure 4.1 Example model discretisations. (A) Structured, uniform finite difference grid. Node spacing is equal throughout. (B) Structured, non-uniform finite difference grid (Stauffer et al 2017). Node density is increased along some horizontal and vertical strips of cells, allowing for high resolution in the centre of the model where interest is focused. (C) Structured, octree finite element mesh, adapted from Johnson et al (2019). Adaptive mesh refinement techniques are applied to allow for high node density in areas of interest while node numbers are reduced elsewhere. (D) Unstructured finite element mesh. Mesh refinement is applied (in this case) to allow for increased node density near rivers.

4.1.2 Horizontal Resolution and Discretisation Errors

Several reports do not describe the spatial resolution. In those that do, a wide variety of scales have been used. A list of models by discretisation type and, on uniform grids, scale follows.

Uniform structured grids

- 2000 m (Weir and Moore 2012)[5]
- 1000 m (Thorley et al 2010; Weir and Moore 2012; Flintoft and Weir 2019)
- 500 m (Jones et al 2005; Rajanayaka 2008; Baalousha 2010; Weir and Moore 2012)
- 250 m (Wale et al 2005; Knowling et al 2016; Moore et al forthcoming; Johnson 2019)
- 200 m (Phreatos Limited 2007; Rekker and Houlbrooke 2009; Thomas 2012a; Hemmings et al 2018a; Wöhling et al 2018; Weir et al 2013)

[5] Weir and Moore (2012) trialled grids from 2 km to 100 m, but the computational burden was too large for the computer (at the time) to manage for cell sizes below 500 m.

- 100 m (Namjou et al 2006; Otago Regional Council 2006; Gyopari 2014; Wilson and Wöhling 2015; Peaver et al 2017; Rakowski and Knowling 2018, Weir 2018)
- 80 m (Toews and Gusyev 2012)
- 50 m (Rekker 2012a)
- 25 m (Sinclair Knight Merz 2002).

Non-uniform structured grids

- MODFLOW models with variable scales (Viljevac et al 2002; Sinclair Knight Merz 2007; Wilson 2007; Rekker et al 2008; Wilson 2008; Houlbrooke 2010; Wilson and Shokri 2015; Weir 2018)

Variable-grid finite element models

- Finite element models (Hong and Thomas 2008; Sinclair Knight Merz 2010; Tutulic 2011; Daughney et al 2015; Thornburrow 2017)

Equations used in models are sensitive to the cell or element sizes, independent of the parameters in those cells. This *discretisation error* or *truncation error* (Zyvoloski 2007) occurs because the partial differential equations that govern the model are approximated as algebraic equations, particularly as the first few terms of an infinite Taylor series (Wasantha Lal 2000; Eça and Hoekstra 2014). As only the first few terms of the infinite series are calculated within the model, the mathematical result is *truncated*. Practically speaking, the finer the cell resolution, the closer the results will be to an equivalent analytical solution. Formally, discretisation effects can be explored by producing different model grids of comparable hydrogeologic units and evaluating the change in model outputs or calibration results between models (eg Bower et al 2005; Weir and Moore 2012). Model outputs and calibration results can vary greatly during these explorations and in some cases the grid can be the greatest source of uncertainty in the model (Zyvoloski and Vessilinov 2006). Consideration of grid effects is, therefore, important when building decision-support models. Ideally, as resolution increases (ie model cell size decreases), the changes in model results will decrease. Reductions in computational error can often be offset by the extra computational burden required to run the finer-resolution model and increase parameter simplification uncertainty (see Section 4.3). At a regional scale, the increased computational burden of extra calculations is generally considered an impediment to producing high resolution models, especially in cases where thousands of separate model runs may be required.

Discretisation errors are not widely considered nationally in the reviewed models, although a few reports acknowledged them. For instance, Wöhling et al (2018) mentioned that a grid sensitivity study was undertaken but did not go into detail. Weir and Moore (2012) attempted a grid convergence study but found the model crashed due to the number of cells when modelling a large area at a fine scale. In most cases, the horizontal resolution is likely based on expert judgement and what has been applied in previous model domains, or when aligning groundwater models with other data sources such as the national surface mapping project QMAP (Rattenbury and Isaac 2012) which has a 250 m resolution. It is possible that grid convergence analysis is sometimes conducted but not clearly documented in supporting writing. Often this is part of model development but is not routinely reported. Enhanced focus on this subject may be useful in the future because uncertainty induced in model results or calibration outputs due to grid effects can be greater than other sources (Zyvoloski and Vesselinov 2006).

4.1.3 Parameter Simplification

Spatial representation of model units and their associated parameters is a critical choice in model design with important implications for model use and effectiveness. Discretisation of a domain carries an assumption of homogeneity at some scale (eg within an element or grid block), effectively lumping all material inside that space into a single set of parameters. Where there are details within these homogeneous blocks that are important to the prediction but obscured by this lumping process, uncertainty is induced in the model (eg White et al 2014). This can occur both horizontally and vertically (eg the decision to combine or split layers can induce uncertainty, Knowling et al 2019). Impacts of this uncertainty on model usefulness vary depending on the decision under consideration and the level of confidence required in model outputs. For example, decisions affecting public health may require much greater confidence than a general regional water balance.

Consideration of uncertainty and how to handle it in the model and in decision-making appears to be applied inconsistently nationally. An additional source of parameter uncertainty is the sparseness of data. Although numerous wells may be present in a domain (for example), there is still an enormous area of unsampled basin beyond those points. Parameter simplification, truncation/discretisation error, boundary conditions and data sparsity are competing influences in the model domain. Also, building a numerical model with high spatial resolution to limit discretisation error can sometimes magnify the importance of parameter uncertainty because an increased number of cells have parameters assigned without guidance of local measurements. Detailed investigation of these influences is essential for producing useful decision-support models.

4.1.4 Topographic and Water Table Elevation Resolution

Another important choice in model discretisation is the representation of topography and elevation of subsurface layers, where coarse-resolution inputs can obscure small-scale features. The smoothing of topographic features can have significant impacts when considering phenomena such as contaminant transport pathways (eg Zheng 1994; Thomas et al 2017). 15-metre resolution elevation models are available nationally for New Zealand (Columbus et al 2011) and methods such as LiDAR can provide even finer resolution where available. However, most of the models in this review have much coarser elevation data than this (in some cases up to 1 km or larger grid blocks).

Related to the issues of the elevation model is the spatial representation of groundwater levels. Because a model cell can only contain a single head or saturation value, coarse model grids tend to induce a smoothing effect in regions of high water-table curvature (eg drawdown near wells). As with other spatial resolution considerations, this simplification may not be problematic for basin-scale applications but is more important when considering such topics as stream depletion near wells (here, a coarse discretisation will tend to result in underestimation of drawdown).

4.2 Temporal Resolution

4.2.1 Steady State Models

Steady state models represent a single, long-term condition of the modelled region, essentially representing the system if assigned water inputs and outputs are held constant forever. Several different applications are possible for steady state models. When observations have been collected for many years, a steady state model can in some cases be considered a reasonable approximation of the system (eg Moore et al forthcoming). Steady state models can also serve as the ‘control’ model for scenario models, where relative changes in model outputs or uncertainty are evaluated in comparison to a base scenario. Calibration of models in this context is often conducted against the long-term average value of observations. In addition, steady state models are commonly used to define the initial conditions for subsequent transient modelling. Most of the reviewed 3D numerical models included a steady state model as part of the work flow.

4.2.2 Transient Models

By definition, transient models include time-varying inputs and outputs. The term *time step* (or *timestep*) refers to a modelled elapsed time, while the term *stress period* refers to the duration within which model stresses (eg pumping/water abstraction) are held constant. For example, a model might represent seasonal variations where precipitation is modified (ie the stress period updated) at 6-month intervals, but with model results calculated at one-month intervals (time steps) within each stress period. Time steps in models can be variable and are handled differently in different software. For complex models, especially if heat or chemical transport is involved, model convergence may be challenging, but small-time increments can often achieve convergence where larger time steps cannot. Some model software packages therefore include the option to vary time step size dynamically (ie if a solution is easily achieved, the time step size is increased; if convergence is not achieved, the time step size is reduced and the calculation restarted). The timescale of stress periods (how often model inputs change) is the more relevant comparison in most cases.

The transient models reviewed cover a wide variety of time scales. Seasonal (Baalousha 2010) and monthly (Sinclair Knight Merz 2002; Sinclair Knight Mertz 2005; Thomas 2012; Wilson and Shokri 2015) models were found. At the shortest time intervals, some models might consider one or more weeks (eg Phreatos Limited 2007; Rekker et al 2008; Dale and Rekker 2011) or days (eg Hong et al 2010). All transient models developed by Aqualinc incorporate daily stress periods with sub-daily time steps.

A few notes of caution are necessary when using transient groundwater models, especially in conjunction with other simulators (eg atmospheric, soil water balance, or surface water models). First, conversion between models of different timescales can be challenging. Except under unusual circumstances, groundwater typically responds slowly to stressors compared with surface water or atmospheric effects. Uncertainty is induced when high-variability, short-term inputs are amalgamated into a single value for long-term models (for instance when hourly precipitation is averaged into month-long single values). Also, time-variability of observations can compound uncertainty. For example, attempting to represent fine-scale water table variability in a coarse grid can induce uncertainty in calibration results. Transient models are also commonly used when conducting history matching (calibration), whereby model parameters are tweaked to attempt matching historical time series data. In this case, care must be taken to ensure that input data used for history matching is proper for the desired model application.

4.2.3 Scenario Models

A common practice in the numerical groundwater models reviewed is to construct an initial steady state model and then use it as a basis for subsequent scenario modelling. Scenarios are represented by a change to the calibrated system. For example, the modeller might construct and calibrate a steady state model and then develop a scenario of increased abstractions or reduced precipitation and run a forward model to predict what might happen.

More commonly, inverse modelling is used to produce a suite of model parameters and then forward modelling applied for subsequent scenarios. Great care must be taken to ensure that the data used in calibration and the resulting parameter set are appropriate for the prediction of interest.

5.0 MODEL CONSISTENCY

An evaluation of model consistency is challenging, because there is a huge variety of modelling work being undertaken for many purposes. Furthermore, different modellers have different preferred approaches, software packages and tools. Even the terminology used in modelling can vary greatly; for example, the terms *Darcy flux, specific discharge, volumetric flux and fictitious velocity* all refer to the same general concept of directional water flow through a porous medium (Stauffer 2006).

As noted in modelling guidelines for Australia (Sinclair Knight Merz and the Australia National Water Commission 2012), an essential step in the modelling process is to determine the purpose for which the model is to be used and then build the model accordingly. A single model is often not fit for all possible groundwater modelling purposes. In the context of the New Zealand models we reviewed, the model approaches depend greatly on client priorities, resources, the time of model construction (eg software version and capabilities) and the approaches of the experts building the models. Some model builds have also been ongoing for a long time, so turnover of research personnel has naturally occurred, which has led to changes in preferred approaches and priorities. However, there is clear continuity in some regions; for instance, Waimea Plains area has had numerous studies and model revisions (Hong et al 2005; Hong and Thomas 2006; Hong 2007; Hong and Thomas 2008; Hong et al 2009; Hong et al 2010, Weir et al 2013), as has the Motueka area; but this is not the case in all basins.

5.1 3D Geological and Hydrogeological Models

The geological models we reviewed considered a wide variety of scales, ranging from multi-region studies (eg Zemansky et al 2012) to portions of individual rivers (eg Gyopari et al 2014a, 2014b, 2014c). Techniques used in these studies also vary greatly. For example, geochemical techniques (eg Raiber et al 2012) and geophysical techniques (eg Barrell and Strong 2012) may both be used but are not included in all reports. Other data sources include well logs, geological maps and structural geological mapping (eg Rawlinson and Begg 2014). Differences also clearly exist depending on the local geology; for example, the interpretations and considerations are different for volcanic aquifers (eg Viljevac et al 2002) compared with alluvial aquifers (eg Thorley et al 2010). In addition, the outputs from these models also vary depending on the model purpose. This is particularly distinct where the model is specifically for use in future numerical groundwater models, versus more general geological understanding. In the former case, model units might be grouped by similar hydraulic characteristics (eg Barrell and Strong 2012) while the latter may group by related geological formations (eg Begg et al 2015b).

In summary, model consistency for geological and hydrogeological models varies depending on the scale, types of aquifers, purpose and methods deemed most suitable for constructing the model. Methods, outputs and interpretations vary depending on project aims, available data and expertise of the modellers. Further variability will likely continue as new methods are developed and applied (eg aero-electromagnetic surveys, Sørensen and Auken 2004).

5.2 3D Numerical Groundwater Models

Great variability exists in the 3D numerical groundwater modelling employed nationally. This is not a condemnation of existing work, because it is essential that model design be prediction- and catchment-specific. As noted previously, many different concepts need to be considered in modelling.

An immediate and fundamental distinction between models is the choice of software package (eg MODFLOW or FEFLOW). Each software package has advantages and disadvantages and this review does not advocate for any preferred choice. Certain aspects of modelling (such as discretisation – Section 7) vary depending on the software package choice. In general, the models all use software packages that have been extensively tested and benchmarked, so this is unlikely to compromise model quality.

An additional and unavoidable source of inconsistency between models relates to the time over which modelling efforts have been conducted and the consequential updates and changes to model functioning over that time. MODFLOW, for example, was first designed in the 1980s (McDonald and Harbaugh 1988) but has had subsequent releases in 1988 (McDonald and Harbaugh 1988), 1996 (Harbaugh and McDonald 1996), 2000 (Harbaugh et al 2000), 2005 (Harbaugh 2005), 2011 (Niswonger et al 2012) and the current MODFLOW 6 released in 2017 (Hughes et al 2017). Therefore, in the past 20 years, MODFLOW modelling might use any of several different release versions, as well as any of many application-specific modules, interfaces and visualisation tools. Likewise, computing power has increased greatly, allowing for more complex modelling with more nodes or elements, at higher resolutions (both spatially and temporally) and with more parameters and processes captured.

Model applications are variable both nationally and within regions. Many of the reviewed 3D numerical groundwater flow models are designed to calculate water balances to support decision-making in limit setting applications at the basin scale (eg Viljevac et al 2002; Scott and Thorley 2009; Gyopari and McAlister 2010a, 2010b, 2010c; Rekker and Houlbrooke 2009; Zemansky et al 2011; Williams 2013; Daughney et al 2015; Knowling et al 2016; Rakowski and Knowling 2018; Johnson 2019). Other models focus on examining interactions between groundwater and surface-water, for instance to ascertain stream depletion as a result of pumping (eg Hong et al 2010; Williams 2013; various Aqualinc models). A few studies have been carried out to assess managed aquifer recharge (eg Hong 2007; Golder Associates 2014a, 2014b). Several models have focused on contaminant transport or wellhead security (eg Callander et al 2005; Gusyev et al 2011; Thomas 2012a, 2012b; Toews and Moreau 2014; Motueka, Upper Waikato, Takaka), which require more specific attention to the specific pathways of groundwater flow as opposed to overall regional water balance.

5.3 Summary

In summary, the 3D numerical models implemented nationally are highly variable in design, application and output. This is generally a positive fact, because the models are typically developed for specific applications, rather than trying to apply one model template to many different applications (which may produce biased results) (Knowling et al 2019). Modelling decisions are difficult to generalise. Model upscaling and downscaling is a challenging topic, requiring careful examination and caution is necessary to avoid or characterise bias introduced in model outputs when considering scales.

6.0 CHARACTERISATION OF CONFINEMENT IN MODELS

Model evaluation of confinement is handled distinctly in geological and numerical models. Broadly, we define a confined aquifer as any saturated layer where the groundwater level is above the top of the aquifer and therefore where pumping will decrease pressure but not lower the water level in the aquifer (Figure 3.1). Based on this definition, the characterisation of aquifer confinement in geological models depends on the presence and continuity of both a confining layer and a saturated porous medium beneath that layer.

This characterisation is based on a number of different factors depending on circumstances. Stratigraphic characterisation is commonly employed based on surface mapping, geophysical techniques and drill cores. Isotope tracers (eg indicating groundwater age) can also identify the presence of confined aquifers via the presence of water of different ages within each confining layer (eg Morgenstern et al 2015). In many cases, aquifer confinement may be incomplete (semi-confined), where leakage can occur (eg Hantush and Jacob 1955), or else portions of the aquifer are confined while other areas are unconfined.

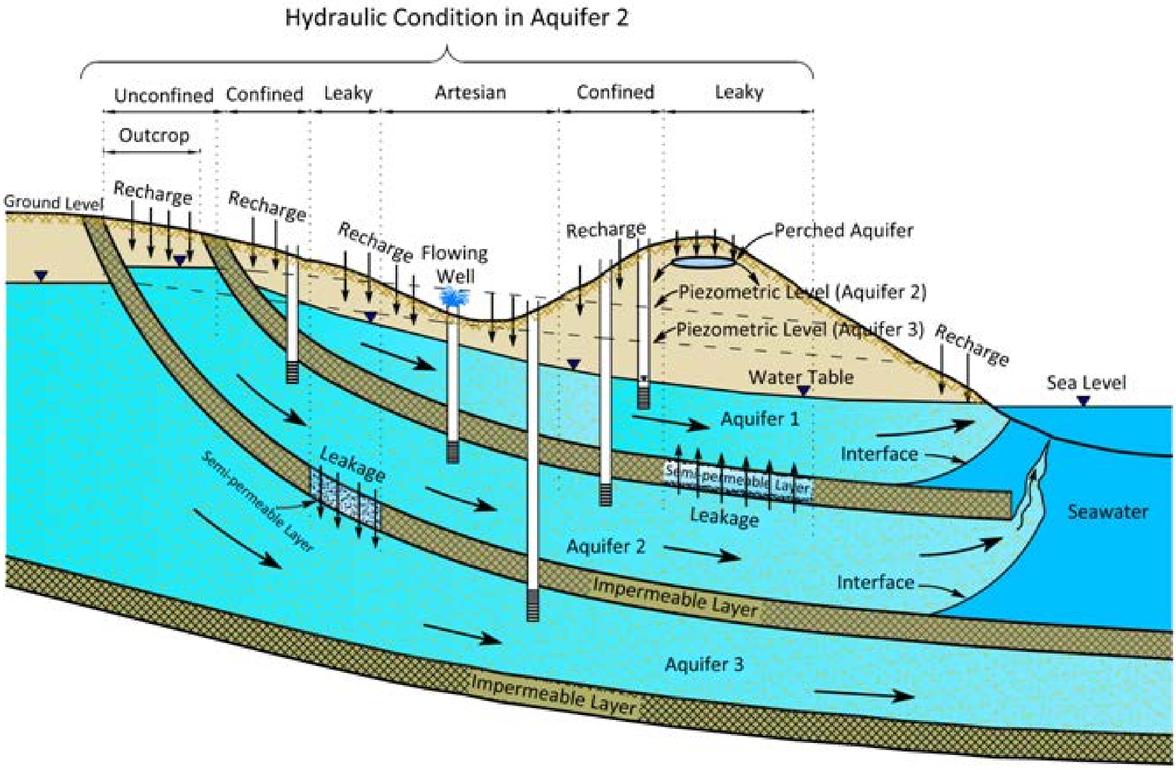

Figure 6.1 Schematic of aquifer confinement, leakage, or partial confinement, from Bear (1979).

In numerical models, confinement is either explicitly defined by the modeller based on the system conceptual model, or it can be determined from the stratigraphy and parameterisation. Both MODFLOW and FEFLOW have the option to explicitly define areas as confined. In addition, a permeable layer underlying an impermeable layer may result in confinement. Importantly, specification of a layer as confined in numerical models does not indicate that the unit has an 'impermeable cap'; rather, it affects the numerical behaviour of the modelled layer.

In the mathematics of the model, layer confinement definition has two implications. First, certain different parameters are used depending if the aquifer is confined or unconfined. Second, aquifer confinement affects the governing equations used in the model. In the fully saturated region, flow calculations based on Darcy's Law is used. If the cell becomes unsaturated (partially dry), the presence of air in the groundwater system changes water flow, so additional terms may be used that represent these effects (eg Brooks and Corey 1964; van Genuchten 1980). A confined aquifer, by definition, is saturated, so these functions are not used. Generally, the unsaturated zone has been simplified in the models and is represented by a single infiltration parameter. However, for applications such as managed aquifer recharge and reactive transport modelling, consideration of the unsaturated zone (also called the *vadose zone*) is sometimes important because flow rate and residence time can vary depending on saturation. In cases where contaminants decay over time, their retention in the unsaturated zone can reduce and/or delay loading to the saturated zone.

Based on the numerous model reports, a summary of aquifer confinement by region is presented in Table 6.1. Some regions have numerous confined aquifers present. In these cases, there is usually also a shallow unconfined aquifer present.

Table 6.1 Summary of the presence of confined aquifers by region.

Region	Basin/Aquifer	Model Confinement Type
Auckland	Northern Strat. Growth Area	Unconfined
	Waitemata	Semi-confined
Bay of Plenty	Whakatane	Unconfined
	Lake Rotorua	Complex; unconfined area of interest
	Lake Tarawera	Multiple confined aquifers
Otago	Cromwell Terrace	Unconfined
	South Dunedin	Unconfined
	Wanaka	Unconfined
	Bendigo and Tarras	Unconfined
	Lower Taieri	Partially confined
	Ettrick Basin	Unconfined
	North Otago Volcanic Aquifer	Unconfined
	Kakanui	Unconfined
Southland	Edendale	Unconfined
	Riversdale and others	Unconfined
	Northern Southland	Unconfined
	Regional	Partially confined
Tasman	Upper Motueka	Unconfined
	Waimea	Unconfined and confined (different depths)
Waikato	Lower Waikato Catchment	Confined at depth
	Waipa Catchment	Unconfined
	Matamata well field	Leaky confined
	Waihi	Unconfined at top; partially confined at depth
	Putaruru and Blue Spring	Assumed confined
	Hauraki Plains	Partially confined
	Upper Waikato	Unconfined and confined

Region	Basin/Aquifer	Model Confinement Type
Canterbury	Coopers Creek Catchment	Unconfined
	Rakaia/Waimakariri rivers	Partially confined
	Christchurch City	Confined in east, leaky/unconfined in west
	Eastern Canterbury	Partially confined
	OTOP	Unconfined and confined (different depths)
	Waimakariri-Rangitata	Unconfined and confined (different depths)
Gisborne	Poverty Bay	Confined and leaky confined
Greater Wellington	Ruamahanga	Multiple confined
	Kapiti Coast	Confined
	Wairarapa Valley	Partially confined
	Lower Hutt	Confined
Hawke's Bay	Heretaunga	Confined in east, partially confined in west
	Ruataniwha	Partially confined; confined and unconfined (different depths)
	Poukawa Basin	Partially confined
Manawatu	Upper Manawatu and Mangatainoka	Confined
Marlborough	Wairau	Confined and unconfined (different depths)
	Riverlands	Confined
	Rarangi	Unconfined
Northland	Aupouri	Confined to leaky confined
	Maunu-Maungatapere-Whatitiri	Partially confined
	Awanui Artesian	Confined
	Russell Township	Partially confined

7.0 APPLICABILITY FOR LIMIT SETTING

7.1 Current Use of Models for Limit Setting

7.1.1 Quantity Limits

Many of the extant 3D numeric groundwater flow models are water balance models designed to represent water inputs, abstractions and outflows. In this regard, many regions have at least some amount of modelling that is applicable to groundwater quantity limit setting (ie allocations). Many of these models are aquifer- or catchment-specific. Interactions between adjacent catchments are not always captured and it is unclear in many cases to what extent these interactions occur. National-scale models (such as NWT, Westerhoff et al 2018) can help identify possible interactions in the shallow subsurface. A greater challenge is determining whether cross-basin interactions are occurring at depth, which requires data collection and an understanding of the geology beneath the visible land surface.

7.1.2 Quality Limits

In addition, nitrate transport models exist in several catchments and are being used to inform quality limits for the management of freshwater bodies (eg through nitrogen load limits from different land uses). Based on the existing work identified during this review, models with applicability for limit setting exist for much of the Otago, parts of Southland, a couple of basins in the Nelson/Tasman, portions of the Waikato, portions of the Bay of Plenty, Canterbury, Greater Wellington, the two major aquifers of Hawke's Bay, Marlborough and Northland. Limited efforts have been undertaken for Auckland, Gisborne and Manawatu-Wanganui. The West Coast and Taranaki lack identified transport modelling work. Even in regions with extensive modelling work, there are likely portions that have not been covered due to sparsity of data, limited abstraction of water resources and focus on other areas.

8.0 DISCUSSION AND CONCLUSION

Groundwater models in New Zealand are used for a variety of applications, with multiple methods (3D numerical groundwater models, eigen models, geological models etc), software packages (different versions of MODFLOW, FEFLOW etc), tools (eg Visual MODFLOW, Python codes, spreadsheets etc) and incorporated processes. Many different factors must be considered in the construction of a numerical or geological model and it is essential that models be designed and built to be suited for their application; caution is necessary when considering how to adapt models to new purposes. These factors complicate comparison and evaluation of existing models. Much of the land exposed to significant anthropic pressures in New Zealand has been modelled by some variety of groundwater model, with the noted exceptions of the Taranaki and West Coast regions.

The scale and applications of groundwater models range from coarse, regional models to finely-discretised models for individual communities or stream catchments. Temporal resolutions also vary from steady-state models, daily models, short-period monthly or seasonal models, through to decade-scale climate response models. Based on our review, no single model standard exists or can be meaningfully defined to cover all models nationally. Nevertheless, models exist that can be potentially useful for limit setting for many areas of New Zealand.

The review encountered a few items of note where consistency of methods could be improved nationally. Broadly, consideration of uncertainty is applied inconsistently. This is partly a product of the long duration over which models have been developed and implemented; techniques for evaluating and responding to uncertainty are continuously improving. However, where possible, it would be beneficial to emphasise and quantify model uncertainty (at least simply), especially when models are designed for decision support applications. Related to this, it is noted that few of the models appear to be updated and benchmarked against subsequent observations. As a result, it is challenging to evaluate both the quality of the models (for example, how they are performing against their intended purpose) and their usefulness and impact. From existing reporting, it is difficult to gauge how useful modelling efforts to date have been to the various regional councils, or what new efforts might be required to improve model path-to-impact. Further discussions with model owners is needed to ascertain this.

Models must be designed for their intended application. Therefore, consistency is difficult to quantify. However, some general comments regarding model methodology derived from this review are:

- Models should be designed to be prediction-specific, with careful attention to the ability of the model to represent desired processes. Adaptation of existing models to new purposes can be problematic if the earlier model is not equipped to handle necessary new information or processes. Therefore, trying to fit models into an existing, standardised framework will be counterproductive.
- It is essential to quantify and report uncertainty in numerical models, especially when calibration is conducted. Identification of important uncertainty sources is important. Detection and mitigation of parameter bias is also important to ensure that models are useful for decision support. Methods of usefully presenting uncertainty results is needed, as are guides on how to integrate uncertainty into important decision-making.

- Additional consideration of uncertainty induced by spatial and temporal discretisation effects is necessary. We noted that few of the reviewed 3D numerical groundwater models included any mention or analysis of this effect. This is especially important when considering the use of coarse national or regional models for local applications, or when linking groundwater models with other models of more rapidly-changing systems (such as weather). For example, some atmospheric models encounter difficulties with fine grids (hundreds to thousands of metres, yet these same resolutions may be coarse for a groundwater model. Attempting to synchronise model time periods may have unintended negative consequences.
- Benefit may be derived from re-examination of existing models in the context of new information (eg how well did the model predict?). This is occurring sporadically but is not ubiquitous and/or reported. Many scenarios do not eventuate by design (eg worst-case scenario models), but where benchmarking can be undertaken this would be helpful.

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APPENDICES

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APPENDIX 1 LIST OF MODELS BY REGION

Table A1.1 Auckland Region.

	Aquifer Name	Report Reference
1	Pukekohe Aquifer	Zhan X, White PA. 1995. Groundwater flow modelling of shallow Pukekohe aquifer, South Auckland [abstract]. In: *New Zealand Meteorological and Hydrological Symposium: programme and abstracts*; 1995 Nov 12–16; Christchurch, New Zealand. Christchurch (NZ): New Zealand Hydrological Society. 1 p.
2	Volcanic and Kaawa Aquifers	Viljevac Z, Murphy G, Smaill A, Crowcroft GM, Bowden D. 2002. South Auckland groundwater, Kaawa aquifer recharge study and management of the volcanic and Kaawa aquifers. Auckland (NZ): Auckland Regional Council. 85 p. (Technical publication 133).

Table A1.2 Bay of Plenty Region.

	Aquifer Name	Report Reference
1	Western Bay of Plenty	Zemansky GM, Minni G, Suh D, Hong YS. 2011. Western Bay of Plenty groundwater flow model. Wairakei (NZ): GNS Science. 57 p. Consultancy Report 2010/129. Prepared for Environment Bay of Plenty. White PA, Meilhac C, Zemansky GM, Kilgour GN. 2009. Groundwater resource investigations of the Western Bay of Plenty area stage 1: conceptual geological and hydrological models and preliminary allocation assessment. Wairakei (NZ): GNS Science. 221 p. Consultancy Report 2008/240. Prepared for Environment Bay of Plenty.
	Western Bay of Plenty Matata area	Tschritter C, Rawlinson ZJ, White PA, Schaller K. 2016b. Update of the 3D geological models for the Western Bay of Plenty and Paengaroa-Matata area. Wairakei (NZ): GNS Science. 62 p. + 1 DVD. Consultancy Report 2015/196. Prepared for Bay of Plenty Regional Council.
2	Lake Rotorua catchment	Morgenstern U, Daughney CJ, Leonard G, Gordon D, Donath FM, Reeves R. 2015. Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand. *Hydrology and Earth System Sciences*. 19(2):803–822. doi:10.5194/hess-19-803-2015. Daughney CJ, Toews MW, Ancelet T, White PA, Cornaton FJ, Stokes K, Maxwell D, Jackson BM, Tschritter C. 2015. Implementing and evaluating models of steady-state groundwater flow under baseflow conditions, Lake Rotorua catchment, New Zealand. Lower Hutt (NZ): GNS Science. 121 p. + 1 DVD. (GNS Science report; 2015/52). White PA, Zemansky GM, Kilgour GN, Wall M, Hong YS. 2007. Lake Rotorua groundwater and Lake Rotorua nutrients phase 3 science programme technical report. Wairakei (NZ): GNS Science. 402 p. Consultancy Report 2007/220. Prepared for Environment Bay of Plenty.

	Aquifer Name	Report Reference
	Rotorua Geothermal Field	Alcaraz SA. 2014. 3-D geological model of Rotorua. Wairakei (NZ): GNS Science. 30 p. + 1 DVD. Consultancy Report 2014/289. Prepared for Bay of Plenty Regional Council.
3	Rotorua, Tarawera, Upper Rangitāiki, Opotiki, Rangitāiki Plains	Tschritter C, White PA, Alcaraz SA. 2017. Update of the 3D geological models for the lower and upper Rangitaiki, Tarawera, Opotiki and Rotorua areas. Wairakei (NZ): GNS Science. 65 p. + 1 DVD. Consultancy Report 2017/22. Prepared for Bay of Plenty Regional Council.
4	Whakatane Central Business District	Begg JG, Lukovic B, Beetham RD, Nikolaison HN. 2015. A 3D geological model of the Whakatane Central Business District, Bay of Plenty, New Zealand, with estimate maps illustrating possible earthquake land damage. Lower Hutt (NZ): GNS Science. 53 p. Consultancy Report 2015/30. Prepared for Whakatane District Council.
5	Rangitāiki Plains	White PA, Raiber M, Begg JG, Freeman J, Thorstad JL. 2010. Groundwater resource investigations of the Rangitaiki Plains stage 1: conceptual geological model, groundwater budget and preliminary groundwater allocation assessment. Wairakei (NZ): GNS Science. 183 p. Consultancy Report 2010/113. Prepared for Bay of Plenty Regional Council.
	Upper Rangitāiki	White PA, Tschritter C. 2015. Groundwater resource investigations in the Upper Rangitaiki River Catchment, Bay of Plenty region. Stage 1: preliminary groundwater allocation assessment. GNS Science. 57 p. Consultancy Report 2014/283. Prepared for Bay of Plenty of Regional Council.
6	Greater Lake Tarawera catchment	Tschritter C, White PA. 2014. Three-dimensional geological model of the greater Lake Tarawera catchment. Wairakei (NZ): GNS Science. 37 p. Consultancy Report 2013/155. Prepared for Southland Regional Council (Environment Southland). White PA, Toews MW, Tschritter C, Lovett AP. 2016. Nitrogen discharge from the groundwater system to lakes and streams in the greater Lake Tarawera catchment. Wairakei (NZ): GNS Science. 81 p. Consultancy Report 2015/108. Prepared for Bay of Plenty Regional Council.
7	Opotiki-Ohope	White PA, Tschritter C, Collins DBG, Moreau-Fournier M. 2013. Groundwater and surface water resource investigations of the Opotiki-Ohope area stage 1: preliminary groundwater allocation assessment. Wairakei (NZ): GNS Science. 68 p. Consultancy Report 2012/263. Prepared for Bay of Plenty Regional Council.

Table A1.3 Canterbury Region.

	Aquifer Name	Report Reference
1	Coopers Creek catchment shallow aquifer	Peaver L, Kaelin N, Durney P, Trewartha M. 2017. Groundwater-surface water interaction in the Coopers Creek catchment. Christchurch (NZ): Environment Canterbury Regional Council. 56 p. Technical Report R17/3.
2	Te Waihora / Lake Ellesmere catchment	Williams H. 2013. Modelling of stream discharge and groundwater levels in the Te Waihora / Lake Ellesmere catchment. Nelson (NZ): Elemental Geoconsulting Limited. 48 p. Report ECMP-1.
3	Rakaia-Ashburton Plains aquifer	Thorley M, Bidwell VJ, Scott D. 2010. Land-surface recharge and groundwater dynamics: Rakaia-Ashburton Plains. Christchurch (NZ): Environment Canterbury. 71 p. Technical Report R09/55.
4	Area located between the Rakaia and Waimakariri Rivers	Weir J. 2018. Canterbury groundwater model 3. Model documentation. Christchurch (NZ): Aqualinc Research Limited. C15066-11. Prepared for MBIE Wheel of Water Research. Aqualinc Research Limited. 2007. Canterbury groundwater model 2. Christchurch (NZ): Aqualinc Research Limited. Report L07079/1. Rutter H. 2017. Earthquake Effects on Groundwater. Groundwater Modelling Results. Christchurch (NZ): Aqualinc Research Limited. C17089. Prepared for Canterbury Regional Council. Draft. Scott D, Thorley M. 2009. Steady-state groundwater models of the area between the Rakaia and Waimakariri rivers. Christchurch (NZ): Environment Canterbury. 37 p. Technical Report R09/20.
5	Christchurch City zone	Callander P, Thorley M, Lough H, Williams H, Kininmonth M, Henderson B. 2005. Groundwater flow modelling for groundwater quality assessments in Christchurch city. In: *EnviroNZ05: water matters: conference proceedings*. 2005 Sep 28–30; Auckland, New Zealand. Wellington (NZ): New Zealand Water & Wastes Association.
6	Christchurch and Eastern Canterbury	Begg JG, Jones KE, Barrell DJA. 2015. Geology and geomorphology of urban Christchurch and eastern Canterbury: digital vector data. Lower Hutt (NZ): GNS Science. 1 DVD-ROM. (GNS Science geological map; 3).
7	Waimakariri-Ashley region of Canterbury Plains	Hemmings BJC, Moore CR, Knowling MJ, Toews MW. 2018. Groundwater flow model calibration for the Waimakariri-Ashley region of the Canterbury Plains. Lower Hutt (NZ): GNS Science. 69 p. Consultancy Report 2017/221. Prepared for Environment Canterbury. Hemmings BJC, Moore CR, Knowling MJ. 2018. Calibration-constrained Monte Carlo uncertainty analysis of groundwater flow and contaminant transport models for the Waimakariri-Ashley region of the Canterbury Plains. Lower Hutt (NZ): GNS Science. 32 p. + appendices. Consultancy Report 2017/222. Prepared for Environment Canterbury.
8	Opihi-Temuka-Orari-Pareora	Flintoft M, Weir J. 2016. Opihi and Pareora limit setting: surface water–groundwater modelling. Christchurch (NZ): Aqualinc Research Limited. C16027.
9	South Canterbury	Barrell DJA, Strong DT. 2012. Geological contours for groundwater modelling, South Canterbury. Dunedin (NZ): GNS Science. 11 p. + appendices. Consultancy Report 2012/245. Prepared for Canterbury Regional Council.

Table A1.4 Gisborne Region.

	Aquifer Name	Report Reference
1	Poverty Bay Flats	Rajanayaka C. 2011. Poverty Bay Flats groundwater model development: assessment of available data and information. Christchurch (NZ): Aqualinc Research Limited. 17 p. Report H2004/1. Golder Associates. 2014a. Poverty Bay groundwater management: MAR feasibility stage 1A – conceptual model. Auckland (NZ): Golder Associates. 52 p. Report 1378110136-003. Golder Associates. 2014b. Poverty Bay groundwater management: MAR feasibility assessment and GoldSim groundwater management tool (stage 1B). Auckland (NZ): Golder Associates. 45 p. Report 1378110136-003-R.

Table A1.5 Greater Wellington Region.

	Aquifer Name	Report Reference
1	Ruamāhanga catchment	Blyth J, Cetin L, Easton S. 2018. Water quality modelling of the Ruamahanga Catchment. Wellington (NZ): Jacobs New Zealand Limited. 64 p. Baseline Model Build and Calibration Report IZ501000. Prepared for Wellington Regional Council. Moore CR, Gyopari M, Toews MW. Ruamahanga catchment groundwater modelling. Lower Hutt (NZ): GNS Science. Consultancy Report 2016/162.
2	North and South Ruamāhanga	Rawlinson ZJ, Toews MW, Gyopari M, Moore CR. 2017. Results of Ruamahanga groundwater flow and transport modelling for the Ruamahanga Whaitua Committee: business as usual (BAU), silver and gold scenarios. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 40 p. GNS Science consultancy report 2017/101. Prepared for Greater Wellington Regional Council.
3	Kāpiti Coast groundwater system	Gyopari MC. 2014. Lower Hutt Aquifer Model revision (HAM3): sustainable management of the Waiwhetu aquifer. Wellington (NZ): Greater Wellington Regional Council. 224 p.
4	Wairarapa Lower Valley groundwater catchment	Gyopari MC, McAlister D. 2010a. Wairarapa Valley groundwater resource investigation: lower valley catchment hydrogeology and modelling. Wellington (NZ): Greater Wellington Regional Council. 131 p. (Technical publication; GW/EMI-T-10/75).
5	Wairarapa Middle Valley catchment	Gyopari MC, McAlister D. 2010b. Wairarapa Valley groundwater resource investigation: middle valley catchment hydrogeology and modelling. Wellington (NZ): Greater Wellington Regional Council. 371 p. (Technical publication; GW/EMI-T-10/73).
6	Wairarapa Upper Valley groundwater catchment	Gyopari MC, McAlister D. 2010c. Wairarapa Valley groundwater resource investigation: upper valley catchment hydrogeology and modelling. Wellington (NZ): Greater Wellington Regional Council. 303 p. (Technical publication; GW/EMI-T-10/74).
7	Wairarapa Groundwater Basin	Jones A, Gyopari MC, Morgenstern U. 2006. Regional conceptual and numerical modelling of the Wairarapa groundwater basin. Wellington (NZ): Greater Wellington Regional Council. 193 p.

	Aquifer Name	Report Reference
8	Lower Hutt Groundwater zone	Phreatos Limited. 2003. Revision of the numerical model for the Lower Hutt groundwater zone. Wellington (NZ): Phreatos Limited. 76 leaves. Prepared for Greater Wellington Regional Council.
9	Greater Wellington Region	Toews MW, Donath F. 2015. Capture zone delineation of community supply wells and State of the Environment monitoring wells in the Greater Wellington region. Lower Hutt (NZ): GNS Science. 63 p. (GNS Science report; 2015/06).

Table A1.6 Hawke's Bay Region.

	Aquifer Name	Report Reference
1	Heretaunga Aquifer	Rakowski P, Knowling MJ. 2018. Heretaunga aquifer groundwater model: development report. Napier (NZ): Hawke's Bay Regional Council. 182 p. HRBC Report RM18-14. Lee JM, Tschritter C, Begg JG. 2014. A 3D geological model of the Greater Heretaunga/Ahuriri Groundwater Management Zone, Hawke's Bay. Lower Hutt (NZ): GNS Science. 31 p. Consultancy Report 2014/89. Prepared for Hawke's Bay Regional Council.
2	Ruataniwha Basin	Baalousha, H. (2013). Ruataniwha Basin Nitrate Transport Modelling. Hawke's Bay Regional Council Report. 29 p. Baalousha H. 2013. Ruataniwha Basin nitrate transport modelling. Napier (NZ): Hawke's Bay Regional Council. 20 p. + appendix. EMT 13/06. Prepared for HBRIC Ltd. White PA, Daughney CJ. 2004. Regional groundwater quality and surface water quality model of the Ruataniwha Plains. Wairakei (NZ): Institute of Geological & Nuclear Sciences. 111 p. Client Report 2002/128. Prepared for Hawke's Bay Regional Council.
3	Poukawa Basin / Poukawa Stream catchment	Cameron SG, Gusyev MA, Meilhac C, Minni G, Zemansky GM. 2011. Pseudo-transient groundwater-stream interaction model for determination of the effect of groundwater abstraction on spring-fed stream flow in the Poukawa basin, Hawke's Bay. Lower Hutt (NZ): GNS Science. 76 p. (GNS Science report; 2011/07).

Table A1.7 Manawatu-Wanganui Region.

	Aquifer Name	Report Reference
1	Turakina and Rangitikei Groundwater Management Zones	Thomas N, Woodhouse C. 2015. Turakina and Rangitikei groundwater allocation. Christchurch (NZ): Pattle Delamore Partners Ltd. 68 p. Report 2015/EXT/1452. Prepared for Horizons Regional Council.
2	Upper Manawatu and Mangatainoka catchments, Tararua	Rawlinson ZJ, Begg JG. 2014. Hydrogeology of the upper Manawatu and Mangatainoka catchments, Tararua. Wairakei (NZ): GNS Science. 40 p. Consultancy Report 2014/127. Prepared for Horizons Regional Council.
3	Horizons Region	Rutter HK, KC B, Weir J. 2018. Groundwater level forecasting. Christchurch (NZ): Aqualinc Research Limited. 43 p. WL18030. Prepared for Horizons Regional Council.

	Aquifer Name	Report Reference
4	Horowhenua area	White PA, Raiber M, Della-Pasqua FN, Zarour H, Meilhac C. 2010. Three-dimensional geological model of the Horowhenua area. Wairakei (NZ): GNS Science. 61 p. Consultancy Report 2009/310. Prepared for Horizons Regional Council.

Table A1.8 Marlborough Region.

	Aquifer Name	Report Reference
1	Wairau Aquifer	Wöhling T, Gosses MJ, Wilson SR, Davidson P. 2018. Quantifying river–groundwater interactions of New Zealand's gravel-bed rivers: the Wairau Plain. *Groundwater*. 56(4):647–666. doi:10.1111/gwat.12625. Weir J, Davidson P. 2016. Wairau aquifer groundwater model: prediction of climate change impacts. Christchurch (NZ): Aqualinc Research Limited. 38 p. C16061. Prepared for Marlborough District Council. Wilson S, Wöhling T. 2015. Wairau River-Wairau aquifer interaction. Christchurch (NZ): Lincoln Agritech Limited. 49 p. Report 1003-5-R1. Rajanayaka C. 2008. Wairau aquifer model recalibration and coastal simulation. Christchurch (NZ): Aqualinc Research Limited. 43 p. Report H06030/1. Aqualinc Research Limited. 2004. Wairau aquifer management review: transient MODFLOW model. Christchurch (NZ): Aqualinc Research Limited.
	Wairau Plains	White PA, Tschritter C. 2010. Geological model of Wairau Plain, Marlborough. Wairakei (NZ): GNS Science. 191 p. Consultancy Report 2009/215. Prepared for Marlborough District Council. Raiber M, White PA, Daughney CJ, Tschritter C, Davidson P, Bainbridge SE. 2012. Three-dimensional geological modelling and multivariate statistical analysis of water chemistry data to analyse and visualise aquifer structure and groundwater composition in the Wairau Plain, Marlborough District, New Zealand. *Journal of Hydrology*. 436–437:13–34. doi:10.1016/j.jhydrol.2012.01.045.
2	Wairau and Riverlands Aquifers	Wilson S. 2008. Riverlands groundwater model and aquifer sustainability assessment. Blenheim (NZ): Water Matters Ltd. 46 p. Prepared for Marlborough District Council.
3	Rarangi Shallow Aquifer	Wilson S. 2007. Rarangi shallow aquifer sustainability report. Blenheim (NZ): Water Matters Ltd. 53 p. Prepared for Marlborough District Council.

Table A1.9 Nelson/Tasman Region.

	Aquifer Name	Report Reference
1	Upper Motueka River	Hong YS, Thomas J, Davie T. 2005. River-aquifer interaction modelling in the Upper Motueka River catchment: three-dimensional finite-element groundwater flow model. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 48 p. Client Report 2005/166. Prepared for Tasman District Council.
		Hong YS, Minni G, Ekanayake J, Davie T, Thomas J, Daughney CJ, Gusyev MA, Fenemor A, Basher L. 2010. Three-dimensional finite-element transient groundwater-river interaction model in a narrow valley aquifer system of the upper Motueka catchment. GNS Science. 77 p. Consultancy Report 2010/211. Prepared for Motueka Integrated Catchment Management (ICM) Programme; Landcare; Tasman District Council.
		Gusyev MA, Toews MW, Daughney CJ, Hong T, Minni G, Fenemor A, Ekanayake J, Davie T, Basher L, Thomas J. 2012. Modelling groundwater abstraction scenarios using a groundwater–river interaction model of the Upper Motueka River catchment. *Journal of Hydrology (New Zealand)*. 51(2):85–110.
	Motueka-Riwaka	Weir J, Thomas J. 2018. Motueka-Riwaka Plains water resources. Model upgrade. Christchurch (NZ): Aqualinc Research Limited. C17050. Prepared for Tasman District Council.
2	Waimea Plains	White PA, Reeves RR. 1999. Waimea Plains aquifer structure as determined by three-dimensional computer modelling. *Journal of Hydrology (New Zealand)*. 38(1):49–75.
		Hong YS. 2000. Waimea plains groundwater flow modelling with the STREAM package. Wairakei (NZ): Institute of Geological & Nuclear Sciences. 16 p. Client Report 2000/34. Prepared for Tasman District Council.
		Hong YS. 2003. Effects of abstraction on groundwater levels and river flows in the Waimea Plains: modelling and management scenario simulations for droughts inclusive of various Waimea East Irrigation Scheme (WEIS) pumping scenarios. Wairakei (NZ): Institute of Geological & Nuclear Sciences. 26 p. Client Report 2003/69. Prepared for Tasman District Council.
		Hong YS, Thomas J. 2006. Groundwater-river interaction model and determination of water allocation limits in an average year for the Waimea Plains, Nelson. Lower Hutt (NZ): GNS Science. 50 p. Consultancy Report 2006/140. Prepared for Tasman District Council.
		Hong YS. 2007. Groundwater-river interaction modelling for a water augmentation feasibility study, Waimea Plains, Nelson. Lower Hutt (NZ): GNS Science. 32 p. Consultancy Report 2006/200. Prepared for Tonkin & Taylor Limited.
		Hong YS, Thomas J. 2008. Upgrade of groundwater-river interaction model and the effect of river bed change on groundwater in the Waimea Plains, Tasman. Lower Hutt (NZ): GNS Science. 121 p. Consultancy Report 2008/223. Prepared for Tasman District Council.

	Aquifer Name	Report Reference
		Hong YS, Suh C-W, Thomas J, Zemansky GM. 2009. Scenario modelling: assessing the effect of shifting urban water supply well locations on the Waimea Plains. Lower Hutt (NZ): GNS Science. 75 p. Consultancy Report 2009/197. Prepared for Tasman District Council. Weir J. 2007. Waimea Plains groundwater flow model – results. Christchurch (NZ): Aqualinc Research Limited. Memorandum to Tasman District Council dated 26 June 2013. White PA, Reeves RR. 1999. Waimea Plains aquifer structure as determined by three-dimensional computer modelling. *Journal of Hydrology (New Zealand)*. 38(1):49–75.
3	Takaka	Weir J, Fenemor A. 2017. Takaka Valley groundwater modelling: technical investigations. Christchurch (NZ): Aqualinc Research Limited. C15066-03. Prepared for MBIE Wheel of Water Research. Thomas JT, Harvey MM. 2013. Water resources of the Takaka water management area. Christchurch (NZ): Pattle Delamore Partners Ltd. 38 p. Prepared for Tasman District Council.

Table A1.10 Northland Region.

	Aquifer Name	Report Reference
1	Motutangi-Waiharara aquifer	Zhao H, Williamson J. 2017. Motutangi-Waiharara groundwater model: factual technical report: modelling. Auckland (NZ): Williamson Water Advisory. 88 p.
2	Aupouri Aquifer	Wilson S, Shokri A. 2015. Aupouri aquifer review. Christchurch (NZ): Lincoln Agritech Limited. 64 p. Report 1056-1-R1.
3	Awanui Artesian Aquifer	Sinclair Knight Merz. 2007. Awanui artesian aquifer numerical modelling. Auckland (NZ): Sinclair Knight Merz. 46 p. AE02527. Prepared for Northland Regional Council.
4	Russell area	Sinclair Knight Merz. 2002. Russell groundwater modelling report. Auckland (NZ): Sinclair Knight Merz. 37 p. AE00106.01. Prepared for Northland Regional Council.
5	Maunu-Maungatapere-Whatitiri Aquifers	Sinclair Knight Merz. 2010. Maunu – Maungatapere – Whatitiri aquifers: sustainable yield assessment. Auckland (NZ): Sinclair Knight Merz. 55 p. AE03739. Prepared for Northland Regional Council.

Table A1.11 Otago Region.

	Aquifer Name	Report Reference
1	Cromwell Terrace Aquifer	Rekker J. 2012. Cromwell Terrace aquifer study. Dunedin (NZ): Otago Regional Council. 44 p.
2	South Dunedin Coastal Aquifer	Rekker J. 2012. The South Dunedin coastal aquifer and effect of sea level fluctuations. Dunedin (NZ): Otago Regional Council. 25 p.

	Aquifer Name	Report Reference
5	Wanaka Basin Cardrona Gravel Aquifer	Dale M, Rekker J. 2011. Integrated water resource management for the Cardrona River. Dunedin (NZ): Otago Regional Council. 78 p. Golder Associates. 2015. Pre–feasibility assessment: managed aquifer recharge Wanaka–Cardrona. Auckland (NZ): Golder Associates. 22 p. + appendices. Report 1534047-002.
6	Bendigo and Tarras Aquifers	Houlbrooke C. 2010. Bendigo and Tarras groundwater allocation study. Dunedin (NZ): Otago Regional Council. 59 p.
7	Lower Taieri Aquifer	Rekker J, Houlbrooke C. 2009. Lower Taieri groundwater allocation study. Dunedin (NZ): Otago Regional Council. 136 p.
8	North Otago Volcanic Aquifer	Rekker J, Houlbrooke C, Gyopari MC. 2008. North Otago volcanic aquifer study. Dunedin (NZ): Otago Regional Council. 108 p.
9	Ettrick Basin Aquifer	Otago Regional Council. 2006. Groundwater allocation of the Ettrick Basin. Dunedin (NZ): Otago Regional Council. 42 p.
10	Kakanui	Flintoft M. 2019. Kakanui-Kauru Groundwater Modelling. Christchurch (NZ): Aqualinc Research Limited. WL18011. Prepared for Otago Regional Council. Draft.

Table A1.12 Southland Region.

	Aquifer Name	Report Reference
1	Edendale Aquifer	Thomas N. 2012. Edendale groundwater model: conceptualisation and model design. Invercargill (NZ): Pattle Delamore Partners Ltd. 46 p. Prepared for Environment Southland. Thomas N. 2012. Edendale groundwater model: model calibration and contamination transport results. Invercargill (NZ): Pattle Delamore Partners Ltd. 77 p. Prepared for Environment Southland.
2	Riversdale, Waipounamu, Wendon, Wendonside, Knapdale, Longridge + part of Waimea Plains and Cattle Flat zones	Phreatos Limited. 2007. Mid-Mataura groundwater model. Wellington (NZ): Phreatos Limited. 91 p. Prepared for Environment Southland.
3	Riversdale, Longridge, Waipounamu, Wendon and Wendonside groundwater zones	Wale JP, Williamson J, Hughes B. 2005. Northern Southland groundwater model: model development report. Auckland (NZ): Sinclair Knight Merz. 68 p. AE02092.01. Prepared for Environment Southland.
4	Environment Southland's area of interest for freshwater management	Tschritter C, Rawlinson ZJ, Barrell DJA, Alcaraz SA. 2016a. Three-dimensional geological model of Environment Southland's area of interest for freshwater management. Wairakei (NZ): GNS Science. 67 p. Consultancy Report 2015/123. Prepared for Southland Regional Council. Rawlinson ZJ, Toews MW, Daughney CJ, Zammit C, Kees L, Moreau M. 2016. Fluxes and flows: groundwater flow models for the Southland region: development of calibration data sets, mesh, boundary conditions and loose-coupling to surface water. Lower Hutt (NZ): GNS Science. (GNS Science report; 2016/47).

	Aquifer Name	Report Reference
5	Aparima	Johnson PJ. 2019. Aparima Basin MODFLOW numerical model. Lower Hutt (NZ): GNS Science. 6 p. Consultancy Report 2019/105LR. Prepared for Environment Southland.

Table A1.13 Waikato Region.

	Aquifer Name	Report Reference
1	Western Lake Taupo catchment	Toews MW, Gusyev MA. 2012. Numerical groundwater flow and transport modelling of the Western Lake Taupo catchment. Lower Hutt (NZ): GNS Science. 26 p. Consultancy Report 2011/153. Prepared for Waikato Regional Council.
2	Pukekawa Basalt aquifer	Thornburrow B. 2017. Pukekawa aquifer: groundwater flow modelling. Hamilton (NZ): Pattle Delamore Partners Ltd. 98 p. Report T01580500. Prepared for Waikato Regional Council.
3	Waihi Basin / Coromandel Area	Ling L. 2003. The groundwater regime of the Waihi Basin, North Island, New Zealand [PhD thesis]. Auckland (NZ): University of Auckland. 311 p.
4	Matamata area	Toews MW, Moreau M. 2014. Groundwater protection zone delineation of Matamata supply wells. Lower Hutt (NZ): GNS Science. 28 p. Consultancy Report 2014/125. Prepared for Waikato Regional Council.
5	Upper Waikato Catchment	Weir J, Barkle G, Rajanayaka C. 2013. Estimated age in surface water and changes in nitrogen concentration in groundwater in the upper Waikato catchment. Christchurch (NZ): Aqualinc Research Limited. 39 p. H13001/2. Prepared for Ministry of Environment. Weir J, Moore C. 2012. Groundwater modelling of the upper Waikato catchment: stage 2. Hamilton (NZ): Waikato Regional Council. 96 p. Technical Report 2012/13.
	Reporoa (within Upper Waikato)	Flintoft M, Barkle G. 2017. Calibration of the Transient Reporoa Basin Model. Christchurch (NZ): Aqualinc Research Limited. C16017. Prepared for Waikato Regional Council. Draft.
7	Putaruru well field and Blue Spring	Gusyev MA, Morgenstern U, Zemansky GM, Cameron SG, Toews MW, Tschritter C. 2011. Delineation of protection (capture) zones for the Putaruru well field and the Blue Spring on the Waihou River. Lower Hutt (NZ): GNS Science. 31 p. Consultancy Report 2011/137. Prepared for Waikato Regional Council.
8	Waipa catchment	Rawlinson ZJ. 2014. Waipa River Catchment: requirements for conceptual groundwater model development. Wairakei (NZ): GNS Science. 79 p. Consultancy Report 2014/147. Prepared for Waikato Regional Council. Knowling MJ, Rawlinson ZJ, Moore CR. 2016. A preliminary groundwater model of the Waipa catchment. Lower Hutt (NZ): GNS Science. 17 p. Consultancy Report 2016/134LR. Prepared for Waikato Regional Council.

	Aquifer Name	Report Reference
9	Hauraki Plains	White PA, Raiber M, Tschritter C. 2018. Geological model and water budget of the Hauraki Plains, Waikato region. Wairakei (NZ): GNS Science. 63 p. Consultancy Report 2015/232. Prepared for Waikato Regional Council. White JT. 2018. A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions. *Environmental Modelling & Software*. 109:191–201. doi:10.1016/j.envsoft.2018.06.009.
10	Tokoroa	Toews MW, Lovett AP. 2015. Preliminary groundwater protection zone delineation of Tokoroa municipal supply wells. Lower Hutt (NZ): GNS Science. 32 p. Consultancy Report 2015/184. Prepared for Waikato Regional Council.

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