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Groundwater REPORT

GUIDELINES FOR MODELLING SOURCE WATER RISK MANAGEMENT AREAS

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Executive Summary

This report guides the approaches for the development of bespoke groundwater Source Water Risk Management Areas (SWRMAs) by Councils and consent applicants for potable supply. Several councils currently have default zone delineation methods that use modelling techniques that are usually based on simple (generic) criteria that need improvement. A bespoke risk management area defined by a numerical model may be "better" than a default area, either in terms of the level of protection offered, or the impact on existing land-use activities. However, this is not always the case: a numerical model that is poorly conceptualised, overly simplistic, uses poor input data, or is constructed for a different purpose, may produce results that are worse than some of the more basic methods available. To understand the limitations of the results and (if required) develop a conservative (lower risk) management area, the approach taken needs to fully account for uncertainty in the data used and the model structure.

The current commonly-used approach to assessing SWRMA is to define the immediate wellhead area, a one-year travel time area[1], and the total catchment (source) area. The first of these is not usually modelled, but taken to be a radius around the source (e.g. 5 m). The one-year travel time is focused on specific land-use activities or discharges that might directly contaminate the water source, primarily microbial contamination. The total catchment source area encompasses the entire catchment that could contribute to the groundwater source.

This report considers the main modelling approaches that can be used for SWRMA modelling, and the input data required for these. Sensitivity and uncertainty are assessed, and methods to quantify uncertainty are described. The report then outlines modelling approaches and model design complexity that is relevant to different settings and situations.

[1] That is, the distance (and associated area) within which contaminants will reach the bore in one year or less.

GLOSSARY

The following terms are referred to in this document.

AEM	Analytical element modelling
DRN	MODFLOW's Drain package
ECan	Environment Canterbury
ESR	Institute of Environmental Science and Research
FOSM	First order, second moment
GDC	Gore District Council
GNS	Institute of Geological and Nuclear Sciences
HBRC	Hawkes Bay Regional Council
MAR	Managed aquifer recharge
MC	Monte Carlo
MfE	Ministry for the Environment
NCC	Napier City Council
NES-DW	National Environmental Standard for the Sources of Human Drinking Water
RIV	MODFLOW's River package
SDC	Selwyn District Council
SPZ	Source Protection Zone
SWRMA	Source Water Risk Management Area
TOT	Time of travel
TSA	Targeted stream augmentation
UQ	Uncertainty quantification
USG	Unstructured grid

1 INTRODUCTION

1.1 Project Background and Purpose

The Ministry for the Environment (MfE) commissioned Aqualinc Research Ltd (Aqualinc) to develop a report that provides guidance around the use of numerical and analytical models to establish drinking water Source Water Risk Management Areas (SWRMAs) for potable groundwater supplies. The report aims to inform the New Zealand Government's current programme to amend the National Environmental Standard for the Sources of Human Drinking Water (NES-DW). The aim was to develop technical guidelines for defining SWRMAs, to ensure consistency between different regions and between consenting authorities, water suppliers and other interested parties when generating models to assist in implementing the NES-DW.

The report outlines approaches to use in the development of bespoke SWRMAs by Regional Councils (councils) and consent applicants. It is likely that water suppliers would develop and propose bespoke SWRMAs and then councils would approve them. Several councils currently have default zone delineation methods, usually based on simple (generic) criteria. Councils generally have a requirement to improve these with time. This often includes the use of modelling techniques. There is a perception that a bespoke zone defined by a numerical model will be implicitly "better" – either in terms of the level of protection offered or in the impact on existing land-use activities. However, this is not always the case: a numerical model that is poorly conceptualised, overly simplistic, overly complex, uses poor input data or is constructed for a different purpose, may produce results that are worse than some of the more basic methods available.

Furthermore, a "default" delineation method can sometimes be overly conservative or under conservative. This can result in land-use controls that are unnecessary or inadequate to provide the necessary protection. This strengthens the need for fit-for-purpose numerical models tailored to the specific location. Based on these guidelines, models developed will be used to delineate SWRMAs, and may also be used to assess impacts of permitted activities within the SWRMAs. Models can be used to define both one-year travel times (SWRMA 2) and total catchment protection areas (SWRMA 3)[2], and this will be considered in the assessment.

Surface water SWMRA delineation is more of an exercise in spatial analysis. This project focuses on modelling and determining the sensitivity and uncertainty associated with that modelling. For these reasons, this project focuses on groundwater SWRMAs.

In terms of assessing the usefulness of modelling, it is critical to assess uncertainties associated with the modelling. MfE requires information on how the uncertainty within models is estimated, how this is communicated to stakeholders, which factors should be considered when building a model, and the influences of the different factors on the model uncertainty.

The output from this work will enable MfE to better understand the limitations of models and to support councils in the development of guidance on how to implement modelling for SWRMA delineation and associated assessment of activities within the SWRMA. The aim is to provide guidance that will enable a more coherent and consistent approach to the development of SWRMAs across New Zealand. This document discusses the required level of robustness for a given risk context and ensures that the limitations of the different SWRMA delineation approaches are understood. This work also provides guidance on the establishment of baseline criteria for defining a risk context and discusses how these criteria could be applied consistently.

We note that there is a considerable body of work that is currently being undertaken and due for completion over the next few years. We recommend that the guidelines are reviewed annually to allow for

- Inclusion of research findings, and how they can be integrated into practice
- Feedback about modelling approaches,

[2] Previously referred to as Source Protection Zone (SPZ) 2 and SPZ 3 respectively

They should be reviewed periodically thereafter.

1.2 Definition of Source Water Risk Management Areas

Three source water risk management areas are outlined below. Further details are provided in Section 1.4.

1.2.1 SWRMA 1 (Immediate Well Head Protection Area)

The immediate wellhead protection area is the immediate area around the drinking water supply intake (SWRMA 1). This area is where contaminants could have a direct impact on the supply intake, if (for example) a chemical spill near the wellhead could result in contaminants directly entering the well or bore. Activities within this area should be highly controlled (for example, no storage of any contaminating material). It has been variously defined in New Zealand as a 5-10 m (or sometimes larger) radius around the wellhead. Reality may limit the size of the zone; for example, many urban pump stations are on lots that are less than 20 m wide, and extending this zone onto properties on either side may be problematic and unnecessary.

SWRMA 2 (Intermediate area)This intermediate area (SWRMA 2)[3] focuses on specific land-use activities or discharges that might directly contaminate the water source from microbial or chemical contamination. This is the SWRMA that is of principal concern. As it is aimed at protecting against microbial contamination or rapidly degrading chemical contaminants. Within New Zealand, the area is defined as the one year time of travel (TOT). Within this time frame, it is expected that contaminants will have died off, or become degraded, sufficiently that they do not pose a risk to drinking water safety.

SWRMA 3 (Total Catchment)This area (SWRMA 3)[4] encompasses the entire capture area of the bore. It is the total groundwater catchment area from within which water may eventually make its way to the bore. Delineation of this area may be useful to attempt to understand the impacts of long-term contaminants, such as nitrate, and delay, dilution and attenuation of slowly degrading chemical contaminants can occur. However, precise understanding of transport processes through heterogeneous media, particularly over the relatively long flow and transport pathways determined for this area, will always limit the confidence in their use.

1.3 Prediction Context

Appropriate model selection is dependent on the prediction context. For SWRMA delineation, this relates to the level of risk being addressed (i.e. the risk that people could get sick; the loss of land use capability; etc.). The role of a model in this context is to both robustly quantify the uncertainty of a SWRMA zone and to reduce this uncertainty to the extent possible given any relevant available data. This should be the basis for any model design (Doherty and Moore, 2020).

Older model design guidance is based on the availability of data alone, suggesting that complex models be adopted only when there is more data to process through history matching. More recently, it has been recognised that this basis for model design is flawed as it ignores the possibility that the available data may not inform aquifer parameters relevant to the SWRMA delineation predictions being made. Similarly, it ignores the importance of incorporating parameter variability relevant to SWRMA delineation and the quantification of uncertainty, even though it may be uninformed by the available data.

The level of risk that dictates the prediction context is defined in terms of three main components:

(i) The pumping rate, which is related to the numbers of people being supplied by the drinking water supply well;

[3] Previously known as SPZ 2

[4] Previously known as SPZ 3

(ii) The characteristics of the aquifer and recharge rate; and

(iii) The extent that available relevant data may be able to reduce the uncertainty surrounding the aquifer parameters used in the SWRMA delineation model.

A prediction context may be considered reasonably simple if a well is screened in a homogeneous unconfined sand aquifer and used to supply a single dwelling. The pumping rate required to supply a single dwelling would be low, and hence difficulties in representing aquifer boundary conditions can be ignored. Even though a demonstrably conservative allowance for uncertainty would be required for a simple model, this would not relate to a large SWRMA because of the low pumping rate. Hence, only a small area of land would be affected by this necessary conservatism. In this simple context, a model may be based on expert knowledge and site characterisation information.

In contrast, a prediction context may be considered more complex where a town supply well is screened within an alluvial gravel aquifer that contains rapid, high-permeability transport pathways. In this context, the pumping rate will be larger because of the bigger population being serviced. The model will therefore need to represent more distant aquifer boundaries (such as surface features) and consider how these boundaries will change over time. The heterogeneity that allows rapid transport of pathogens in this type of aquifer will also need to be accounted for using stochastic methods, informed by expert knowledge and site characterisation information. In this more complex context, a model may also be informed by historical observations of the aquifer system using history matching methods, if this will reduce the uncertainty of the SWRMA delineation.

Different types of models are adopted in these different prediction contexts, as conceptually shown in Figure 1.

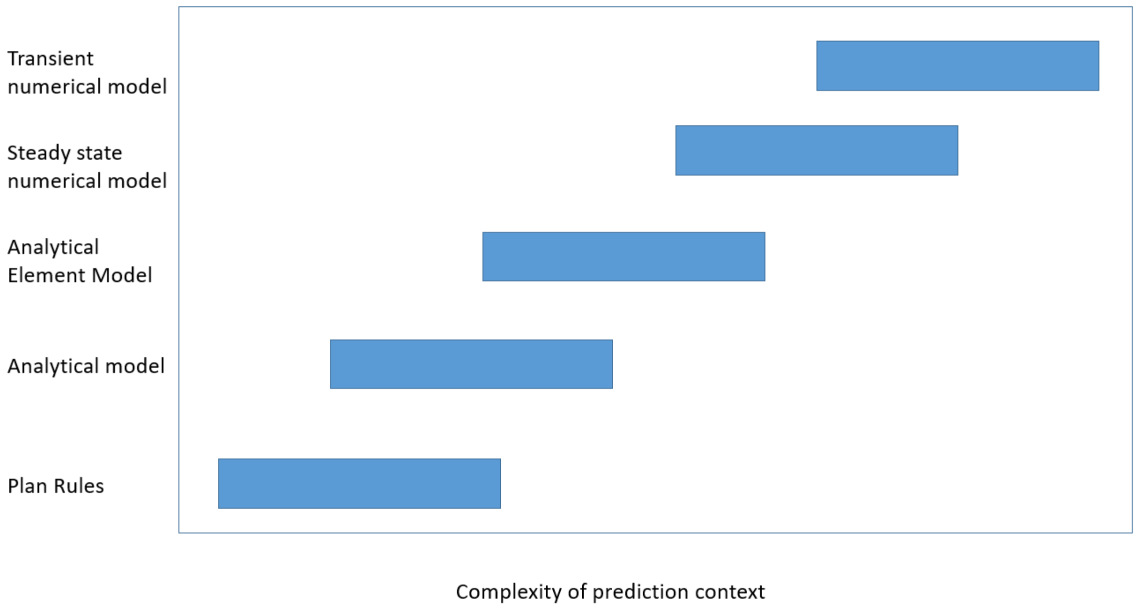

Figure 1: Complexity of prediction context

The factors that need to be considered in building a model have been identified, along with how uncertainty with each input can influence the results. These are listed below, grouped into the three components of prediction complexity identified above.

1. The number of people being supplied by the drinking water supply well, which will impact the following:
   - The pumping rate required;
   - The size of the SWRMA; and
   - The depth of the well (this will impact where the recharge area is, and the distance to the recharge area).
2. Hydrogeological context (i.e. the aquifer disposition and hydraulic characteristics) including:

- Aquifer geology (e.g. sand, gravel, karst, basalt, etc.);
- How preferential flow paths and/or heterogeneities can be incorporated within the modelling framework (for example, as occurs in alluvial deposits of variable grain size and fractured rock), and how the risk of other pathways (such as other bores; earthworks) can be accounted for;
- How variability in environmental conditions can be accounted for (e.g. cumulative pumping effects; changes in vertical and horizontal flow and gradients; earthquake impacts; floods and droughts; etc.);
- Limitations of the models in representing real-world conditions, particularly in terms of model boundaries, aquifer structure (including the degree of aquifer confinement) and the upscaling inherent in representing aquifer heterogeneity at field scales; and
- Recharge rates.

3. The availability of data to inform model parameters representing the aquifer hydraulic properties, heterogeneity and connectedness:
    - Tracer tests in similar strata (e.g. from ESR; internationally);
    - Groundwater age estimates (and other groundwater isotope tracers) indicating recharge provenance;
    - More traditional groundwater model data (such as pumping data, groundwater levels, streamflow gaugings, etc.).

Based on the complexity of the prediction as defined by the three components above, this report develops guidance for the appropriate model design and uncertainty quantification process to be applied. This includes guidance on the following modelling components:

1. Appropriateness of an appropriate SWRMA delineation model or method to use ;
2. Descriptions on how calibration or history matching standards could be applied, including how they would be defined, based on the model's intended purpose;
3. Description of how sensitivity testing and/or uncertainty analyses should be applied, including:
    a. How to describe parameter uncertainty (e.g. using parameter bounds or geostatistical methods).
    b. How to account for upscaling of aquifer heterogeneity.
    c. What method of analysis should be applied (e.g. Monte Carlo based methods; error propagation methods; etc.).
4. Discussion of how SWRMAs and the uncertainty associated with their delineation can be communicated in a consistent, practical and understandable manner.

1.4 SWRMA Mapping Philosophy

SWRMAs are increasingly being recognised as essential for managing the safety of drinking water derived from both groundwater and surface water resources. The delineated areas are either time-related capture zones, or they are total catchments of supply to pumping wells, springs or surface water takes. The establishment of such areas is essential for the proper assessment of resource vulnerability and management of risk within the protection zone. The delineation of risk management areas can be carried out via numerous approaches, from pre-defined shapes to complex models.

It is important to understand that this report applies only in the case where a decision has been made to use a modelling approach. For many small supplies, it is anticipated that a default approach (as outlined in earlier reports) will be accepted. Therefore, this report focuses on the use of models for the delineation of groundwater SWRMAs based on site-specific information (including aquifer geometry, hydraulic parameters, hydraulic gradient and boundary conditions).

Well capture zones for a groundwater source are typically determined by evaluating the corresponding isochrones: the contour lines of equal groundwater residence time. These isochrones can be calculated analytically. They can also be computed numerically, for example by back-tracking particles from a well until the required residence time is reached.

Different countries have different approaches to defining groundwater source protection areas. These approaches were evaluated by GNS (Moreau et al., 2014b) to develop the NZ guidelines. The GNS study uses the terminology ‘SPZ’. However, these are equivalent to ‘SWRMA’ in the context of this report. Moreau *et al* (2014b) recommend three zones for assessing SWRMAs in New Zealand:

- **An immediate protection area** (SPZ1, now SWRMA 1), delineated by a minimum distance of 5 m around the source. The aim of this protection area is to protect the source from the possibility of spills immediately adjacent to the wellhead being able to migrate down to the pumped horizon or directly into the well. Land-use activities in this area should be strictly controlled. This area is defined on the basis that the well is properly constructed and sited to avoid rainwater and floodwaters directly entering the well casing.
- **A microbial protection area** (SPZ2, now SWRMA 2), specifically to guard against microbial contamination. This protection is generally taken to be a one-year travel time. The travel time refers to the time it takes groundwater to flow from a given point to the source. For surface water sources, the extent of the area is based on providing an early warning of a potential contamination event and limiting the concentrations of microbial pathogens in surface water prior to abstraction and treatment. For groundwater sources, the SWRMA 2 area’s primary purpose is to limit the potential for microbial contaminants to reach the water supply in an effective state. While this area is primarily intended to provide for sufficient microbial attenuation (including filtration and die-off), it is also considered sufficiently large to provide protection against other rapidly degrading contaminant discharges or point source discharges (including accidental spills). SWRMA 1 is contained within SWRMA 2.
- **A capture area for protection from other types of contaminants** (SPZ3 now SWRMA 3). This capture area can be defined as either the total catchment contributing to the source, or it can be defined using a pre-defined travel time (e.g. 10 or 50 years). This capture area protects the well’s source area from any contaminant resulting from land-use activity that enters the groundwater system, which can then travel in the aquifer towards the source over a time period longer than one year. Within SWRMA 3, non-point source contaminants arising from general land use (e.g. nitrates), cumulative effects from small point source contaminants, and large-scale discharges, may need to be managed. This area is also intended to address persistent contaminants that may not attenuate adequately before reaching a water supply intake (e.g. nitrate; pesticides; some emerging contaminants; etc.).

Moreau *et al* (2014b) recommend that a sensitivity-type approach be adopted to delineate the microbial protection area (SWRMA 2) and the total capture area (SWRMA 3) by varying input parameters within known bounds, or by ±25% if insufficient data about the parameter distribution is available. Average or median values for input parameters can be used for a “best estimate” calculation. However, they consider that a conservative approach would be to take the extremities of risk management areas 2 and 3, obtained through sensitivity testing as the ‘worst case’ protection areas.

Other potential approaches (such as the draft guidelines by ECan, 2018) use a more risk-based approach, with the end result depending on the hydrogeological setting, degree of confinement and numbers of population served.

In delineating SWRMAs, it is important to consider the balance between human health and maintaining productive land use. Simple approaches to defining SWRMAs must use a higher degree of conservatism than more complex methods. However, where risks are high, and/or there are large populations supplied by a well, then a model that can better quantify (and where possible reduce) the uncertainty of the SWRMAs has merit.

Councils, through consultation, have indicated their interest in taking a pragmatic approach, particularly in view of the large number of sources that exist, and will require development of a SWRMA.. It may be that a practical approach would be to prioritise sources. For example, large sources supplying large populations would be a high priority, and a rigorous modelling approach with uncertainty quantification would be developed. Sources supplying smaller populations would have a lesser priority and take a simpler approach. This may include a factor of safety, envisaging that the SWRMA defined would be modified in the future. In all cases, where there are insufficient data to be able to carry out modelling and uncertainty analyses, then there is a priority to collect data, recognising that the additional cost of data collection may prove to have a major benefit in terms of reducing the size of the SWRMA. In the meantime, a simpler, or default, approach may be applied, resulting in a larger defined area.

1.5 Modelling Philosophy

By definition, decision support modelling (such as SWRMA delineation) is undertaken to assist decision making , with the aim of reducing the chances that a decision will be wrong, while at the same time estimating those chances. A wrong decision results in a course of management action that leads to an unwanted environmental, economic or human health outcome. Doherty and Moore (2017) and Doherty and Moore (2020) refer to this unwanted management outcome as a "bad thing". In this case, the "bad thing" would be the definition of a one-year capture area that is either too limited (allowing risky land use within the area), or too conservative (taking valuable land out of production). Uncertainty quantification (UQ) is a central part of any risk-based modelling. Implicitly or explicitly, risk assessment requires UQ. The level of risk also dictates which model design and UQ should be adopted. This risk-based modelling approach has been adopted for the SWRMA delineation guidance in this report.

The issue of model complexity is important in SWRMA delineation modelling. Modelling of flow and transport through hydrogeological systems is complex. SWRMA delineation must consider the movement of contaminants toward a source where dispersion, adsorption, diffusion and possibly reactions (all of which vary spatially) will strongly influence the degree to which a well is exposed to contaminants. The mathematical model, which is a simplified representation of the real world, must account for this complexity. The challenge is to make the model represent the natural system sufficiently to address the problem at hand. This model can be too simple, too complex, or can represent an effective and pragmatic balance between these two extremes.

In both simple and complex models, parameter non-uniqueness can occur: in other words, many different sets of parameters and boundary conditions can represent the same observed water levels, fluxes and concentrations. In complex models, this parameter non-uniqueness is explicitly characterised with many parameters. In simpler models, where parameters are lumped together, parameter non-uniqueness can be more difficult to ascertain. This can become a problem if a prediction is sensitive to parameter detail that is inaccessible in a simple model.

Further, whilst simple numerical models can be easy to solve, the downside is the lack of realism, and the need to adopt demonstrably conservative uncertainty limits, because of the additional manufactured model simplification error that must be accounted for. On the other hand, more complex numerical models require more effort because (a) data requirements escalate, and (b) complex models are difficult to run. These increased data needs, and the associated data uncertainty, as well as the difficulty of interpreting the results of complex models, can be counter-productive. Hence, effective modelling requires a balance between realism and practical constraints.

Finally, the importance of data can change when considering the one-year travel time or the total catchment SWRMA delineation. Porosity, hydraulic conductivity and associated heterogeneities are important for "time of travel" areas, and how they are represented in a model is scale-dependent. For the total catchment, the ratio between the pumping rate and recharge boundary conditions and spatial heterogeneity is key.

1.6 Approach to Risk

As noted above, SWRMA delineation must avoid two main risks associated with the one-year capture zone. These are a zone that is too small to avoid health risks (i.e. allowing risky land use within the area), and a zone that is too large (placing additional restrictions on land use). The desired level of confidence in avoiding these risks contributes to the selection of a SWRMA assessment approach. A simple method, with demonstrably conservative uncertainty limits, may be able to be used to avoid a capture zone that is too small, but at the potential expense of undue land-use restrictions due to the zone being too large. These conflicts may be a motivation for moving to a more complex model, thereby reducing the uncertainty and making full use of relevant field data.

There is a clear tension between defining the right SWRMA area, large enough to manage risk but small enough to not be unnecessarily restrictive . To avoid an under-sized SWRMA, and avoid any water safety issues, the area may become conservatively too large. Regardless, avoidance of an undersized SWRMA is the priority. Different degrees of risk aversion and tolerance may be adopted by different communities through the use of lower or higher levels of confidence in the modelling.

1.7 Key Terms and Concepts

There are a few terms and concepts that can be used in different ways. These are defined below.

1.7.1 Data and expert knowledge

The term ‘data’ in this report is used to refer to history-matching datasets comprised of observations of the system state, that may include concentrations, groundwater levels, flows, etc. The term ‘expert knowledge’ is used in this report to refer to site conceptualisation data such as groundwater flow directions and field estimates of hydraulic property values and heterogeneity, and data found in literature such as hydraulic property value ranges etc. Expert knowledge is used in all SWRMA delineation models. Data is incorporated into a model via a formal history matching process and can be used to reduce the uncertainty of delineated SWRMA’s.

1.7.2 Sensitivity

‘Sensitivity’ analysis is used to assess the extent to which changes in aquifer properties will change a SWRMA. It will typically demonstrate that a SWRMA model is insensitive to some aspects of the hydrological system and is more sensitive to others. SWRMA models are typically highly sensitive to changes in the chosen boundary conditions.

1.7.3 Uncertainty Quantification

Uncertainty quantification is related to, but distinct from, sensitivity analysis. The uncertainty of inputs to the SWRMA delineation model are described in terms of parameter probability distributions. These parameter distributions are propagated through the model to allow the calculation of the uncertainty in the delineated SWRMA. There are numerous methods used to quantify uncertainty, some of them very simple and approximate and others more demanding. A selection of these is described in Section 4.

1.7.4 Upscaling

‘Upscaling’ refers to the representation of hydraulic properties at dimensions that are larger than the representative elementary volume (i.e. the volume within which the properties can be considered to be uniform). Upscaling considerations for SWRMA delineation are particularly important when representing small- or local-scale features that dominate transport (e.g. open framework gravels within an alluvial system or karst features in a limestone), to the catchment scale.

One of the challenges in upscaling is determining what the upscaled parameter probability distributions should be and how they relate to the measured hydraulic properties. Rules of thumb are often applied, and upscaled properties that account for discrete transport pathways can be conditioned by empirical studies. For example, studies show that viruses are not observed to be transported further than 3 km in alluvial gravels, which can provide an upper limit to the extent of a SWRMA. Currently, research is being undertaken to support the estimation of upscaled parameter values.

2 EXISTING MODELLING APPROACHES

There have been several approaches used to define SWRMAs in New Zealand in recent years. Some examples are presented in Appendix A. Overall, the approach taken has been controlled by available models, available software, data and/or analysis time.

Moreau *et al* (2014a) outline a range of approaches that might be used to determine SPZs, including fixed radius, uniform flow equations, variable shapes, analytical element modelling and numerical modelling. The guidelines are accompanied by a second report, (Moreau *et al.,* 2014b). Both reports provide background on capture zones and brief details on modelling approaches. The current study does not replicate this previous work but progresses them based on recent modelling developments. These include:

- The use of spatial parameterisation to allow representation of relevant geological heterogeneity at a finer scale than previously;
- Software that supports the exploration of predictive uncertainty using stochastic parameter fields while maintaining the model in a calibrated state; and
- Software that supports the probabilistic analysis of contributing areas in SWRMA delineation.

The types of models used in current or past studies are assessed below to overview some of the practical issues with implementing SWRMA modelling. Of particular note is that heterogeneity (including rapid preferential flow and transport) is poorly represented in all of these approaches. In order to allow for the lack of representation of local heterogeneity, the current approach is to provide a factor of safety to attempt to accommodate the uncertainty created by this heterogeneity by adding a +/- 25% tolerance around the parameter values adopted. However, this approach is not always sufficiently conservative to account for flow and transport in these high permeability channels (see Section 2.1.2.2 for an example of this).

2.1 Types of Models Used in Current and Past Studies

Once the decision is made to use a modelling approach rather than to use pre-determined shapes, a number of variables have to be assessed. Firstly, it is necessary to consider the natural groundwater flow direction. The capture zone for a well in a uniform flow field will no longer be circular and centred about the well, but will be somewhat elongated, extending in the direction of the flow. Other information that will be needed includes the location of boundaries, recharge, and aquifer properties. Previous reports have covered the main types of models and some of their limitations. This report briefly covers the previous work and includes examples of the approaches currently used in New Zealand.

Section 5 (below) identifies suitable approaches to uncertainty analyses and modelling based on the population being served, data availability and hydrogeological complexity. In this context, uniform flow methods and analytical element modelling would be considered to be “low” model design complexity; numerical steady state would be “moderate”; transient numerical modelling could be considered to be “high” design complexity.

2.1.1 Uniform Flow Equation Method (Non-Spatial Analytical)

The non-spatial analytical approach relies on broadly conceptualising groundwater flow and the associated likely transport times within an aquifer system. The approach, although relatively simple, does require sufficient information to be able to develop aquifer conceptualisation.

The method delineates a protection area based on a well being pumped at a constant rate, and assuming known piezometric surface and aquifer properties. Stagnation points down-gradient and across-gradient are determined, beyond which water would not be drawn into the well based on analytical aquifer test properties and equations (by calculating the location beyond which the flow direction may be reversed). The up-gradient boundary is not known. However, work by Blaschke *et al.* (2016) and Lough *et al.* (2018) suggests that microbes are unlikely to travel more than 2.5 to 3 km distance in most aquifer systems. This may be a realistic upper limit for most cases in alluvial gravels. Drillers' logs may be used to inform assumptions about aquifer thickness and degree of confinement, though these need to be interpreted knowing that they have limitations in terms of their accuracy. If a vertical gradient can be derived and depth to water is known, then estimates of travel times from the ground surface to the water table can also be made.

Given calculations of flux velocity, an assumed effective porosity can then lead to estimation of the pore velocity. From that, a time of travel to the well can be calculated. Typical values of porosity and hydraulic conductivity can be obtained from various sources including Moreau *et al.* (2014a). Flow in open framework gravels (or other rapid transport pathways) can be modelled by assuming conservative parameters, particularly by using a low value for effective porosity.

Uncertainty cannot be assessed in detail, but a lack of confidence in parameter values can be allowed for by using conservative estimates of aquifer parameters and adjusting values within an appropriate tolerance limits. For example, this tolerance may be set by adjusting parameter values by ±25% as suggested by Moreau *et al.* (2014a). It may also be appropriate to use a wider tolerance range in some aquifer contexts. As a rule of thumb, the simpler the model the greater the imperative to ensure that demonstrably conservative uncertainty limits are adopted. More complex models allow more refined estimates of uncertainty. It is also useful if the variability of the piezometric surface and flow direction (within different seasons) is also assessed. If needed, any variability that is identified can be used to develop an envelope of risk management areas, with the worst-case (most conservative) area being identified by the outer limit of all overlapping areas.

These methods do not account for the effect of varying boundary conditions that may dominate the transport of contaminants.

2.1.1.1 Data Required

For the conceptual model, estimates of hydraulic conductivity, effective porosity, saturated aquifer thickness, hydraulic gradient and flow direction, pumping rates and river/stream/lake locations are typically needed. Aquifer properties (transmissivity, storativity and leakage) are required for assessments of the extent of drawdown effects from pumping.

2.1.1.2 Examples

This approach has been used in Canterbury by Aqualinc to assess one-year travel time and associated SWRMAs for several sources including Ashburton, Hakatere Huts, Waikuku Beach and West Eyreton (See Appendix A.3). They were used based on limited data available. Uncertainties were incorporated using a 'factor of safety' approach.

2.1.2 Analytical Element Modelling

In analytical element modelling (AEM), many analytical solutions are combined to solve the groundwater flow system. Unlike numerical methods, there is no discretisation of the model domain into a grid or mesh. Instead, the modeller can input hydrogeological features directly. This provides a continuous solution across the model domain, apart from the boundaries. AEMs can cover large areas whilst maintaining accuracy at local scales. They can be particularly useful for modelling local features (including cones of depression). The lack of a need for discretisation is regarded as an advantage for AEMs as there is no compromise between model resolution and computational needs. Modelling is usually carried out in 2D and does not take account of vertical changes in properties or vertical flow gradients. However, water budgets are perfectly balanced (water is not lost or gained due to a lack of numerical precision).

Different analytical elements are chosen to represent different hydrological features. For example, stream sections are modelled by line sinks and recharge areas by areal sinks. Surface waters that are not fully connected to groundwater can be modelled as link sinks with a bed resistance. Discontinuities in aquifer thicknesses or hydraulic conductivity can be modelled using line doublets.

Capture zones are delineated using backward particle tracking; that is, many numerical "particles" are released at the well and then tracked back. It is possible to delineate more than one risk management area for more than one source using this approach. AEMs require moderate modelling expertise.

Uncertainty may be assessed using packages such as PEST, but usually, low confidence in parameter values is allowed for by using conservative estimates of aquifer parameters and adjusting values within appropriate tolerance ranges that reflect parameter uncertainty. For example, parameter limits can be altered ±25% (as suggested by Moreau *et al.*, 2014b), but wider tolerance limits may be required to ensure demonstrably conservative estimates of uncertainty in some aquifer contexts (for example, in alluvial gravels). If needed, the variability in the resulting areas can be used to develop an envelope of risk management areas, with the worst case (most conservative) area being identified by the outer limit of all overlapping areas.

2.1.2.1 Data Required

AEMs require a good conceptual model, including estimates of hydraulic conductivity, porosity, aquifer thickness and saturated thickness, hydraulic gradient, pumping rates, recharge, river/stream/lake locations and bed properties.

2.1.2.2 Examples

2.1.2.2.1 Hastings

Modelling of groundwater flow for the delineation of source protection zones was conducted using the AEM method and conservative solute transport (modelled with particle tracking) near Hastings. Hawkes Bay Regional Council (HBRC) previously developed a transient groundwater flow model of the Heretaunga Plains aquifer system using a numerical MODFLOW model that was calibrated to stream and hydraulic head observations. Due to a paucity of groundwater monitoring data in the area of the bore fields, Tonkin & Taylor adopted the modelled transient hydraulic heads from the calibrated numerical model and integrated these into the AEM. It was not within the scope of works for Tonkin & Taylor's project to assess or use the HBRC numerical model for delineating SPZs directly.

AnAqSim24 was used for the derivation of SWRMAs. The software includes functions for modelling pumping wells, including the influence of hydrological features (such as rivers, recharge, and no-flow boundaries). Previous work in the Heretaunga Plains aquifer system indicated that the shapes and extent of source protection zones were sensitive to aquifer thickness, hydraulic conductivity and effective porosity. Therefore, these input parameters, as well as hydraulic gradient, were increased or decreased by 25% to accommodate uncertainty.

The Hastings SWRMA delineation work was revised by HBRC using a stochastic numerical modelling approach, which provided different areas that extended further in some dimensions and less in other areas. The difference in these areas was (in part) due to a more realistic representation of the aquifer boundaries that was possible using a numerical model.

It is important to note that the 25% tolerance applied in the AEM modelling undertaken by Tonkin & Taylor was insufficient to encompass the areas indicated by the numerical model.

2.1.2.2.2 Matamata

SWRMAs were delineated for two Matamata groundwater supply wells located near Tawari Street, Matamata, in the Waikato Region. AEMs were used to simulate steady-state 2D groundwater flow using the software GFLOW. GFLOW simulates rivers, streams, and drains using line-sink elements.

Backward particle tracking was used to define SWRMAs using pumping test data from the bore field. The length of the up-gradient zone was based on work by Pang *et al.* (2005) to estimate microbial transport distances.

2.1.3 Numerical Modelling

Numerical models can be used to simulate two- or three-dimensional flow and contaminant transport. They models can be run as steady-state (constant) or transient (time-varying) models. They are able to accommodate more complex flow and transport conditions, including spatially-variable aquifer properties (i.e. heterogeneity and anisotropy), changes between confined and unconfined conditions, multiple wells (at multiple locations and depths) and variable pumping rates. They also include non-uniform boundary conditions such as recharge, rivers, drains, no-flow, and coastlines (etc.). They are usually built over larger study areas including far-field boundaries than simpler models. They can be used to delineate multiple capture zones and can also account for interference between pumping at different locations.

Based on a literature review of SWRMA delineation in New Zealand, numerical models have not previously been developed with the specific purpose of SWRMA analysis but have been used where a model already existed. Their use also might be considered where there is a need to understand uncertainty clearly or where there is a concern about minimising the risk management area (for example in areas with high land value).

There are various types of models, most of which are subdivided into:

- 2D vs 3D;
- Steady-state (long-term average or seasonal extreme) or transient (time-varying);
- Deterministic (single model realisation based on a physical representation of reality) or stochastic (based on estimating probability distributions of potential outcomes by allowing for random variation in one or more parameters). Stochastic methods should ideally be adopted when numerical methods are used, to ensure that the uncertainty (and hence the risks) associated with the SWRMA are clearly communicated. However, this needs to be balanced against situations where there has already been considerable investment in deterministic methods and hence where other approaches to uncertainty analysis might be employed.
- Type of numerical approach: finite difference, finite element, or finite volume. The type used is often based on what software package is readily available and what the modeller is familiar with, rather than technical reasons.
    - *Finite Difference*. MODFLOW is one of the better-known packages that use the finite difference method to solve the groundwater flow equation. The domain is divided into a grid using structured, rectilinear (rectangular) grids. The finite difference solution is easy to understand and calculate, the solutions are easily mass-conservative, and the code is well documented and accepted. There are also extensions available, such as PEST (for uncertainty analysis), contaminant transport, particle tracking and zone budgeting. The main weakness is that grids cannot be efficiently refined around areas of interest (such as wells and model boundaries), and numerical layers must be continuous across the model domain. If grid refinement is required around pumping wells (as is reasonable for SWRMA analysis), the grid refinement needs to be extended across the model domain, increasing the computational load to run the model. Complex geology can also be difficult to represent, particularly where there are discontinuous or pinched-out layers, and so it is limited for modelling faults and fractures.
    - *Finite Element*. There are several finite element codes available, FEFLOW being the most popular. These use a triangular finite element mesh to represent the model domain, which allows more efficient refinement around wells and boundaries, and can more easily adapt to variable stratigraphy. Finite element methods provide a better representation of anisotropy compared to finite difference grids. However, with finite elements, local conservation of mass is not certain, and discontinuous velocities at the element boundaries can make it difficult to determine unique pathlines. Similar to finite

difference methods, model numerical layers must be continuous across the entire model domain.

- *Finite Volume.* A relatively new approach, the finite volume method is being introduced through (and since) the MODFLOW-USG (**U**n**S**tructured **G**rid) code. With finite volume methods, a cell can be connected to an arbitrary number of adjacent cells. This allows for infinite possibilities of cell geometry. The model domain can be discretised both horizontally and vertically using triangular, rectangular or Voronoi polygons. This means that the grid can be refined locally around areas of interest (such as wells and boundaries) without adding extra cells outside the areas of interest. The approach also allows for efficient representation of discontinuous layers (lenses, perched aquifers, etc.). The solution remains mass conservative and numerically efficient.

Full flow and contaminant transport models can be developed, but numerical methods are more often used to develop flow models, and then backward particle tracking is used to define a capture zone.

2.1.3.1 Uncertainty

Currently, uncertainty is usually assessed using Monte Carlo processes, often facilitated using packages such as PEST. These analyses convey the uncertainty in the SWRMA caused by the uncertainty in the model parameters. In some cases, a simpler assessment of SWRMA uncertainty is undertaken by simply adjusting values within credible limits, and/or by adopting a limited Monte Carlo assessment where only a small selection of parameter realisations from a parameter probability distribution are used. In all cases, the description of the parameter uncertainty needs to accommodate upscaling of small scale heterogeneity features that are not represented at the model grid scale. Numerical methods allow a more realistic representation of aquifer heterogeneity and its boundary conditions. Therefore, they are able to represent the uncertainty of model predictions more realistically and reduce this uncertainty by more effectively extracting information from available data. Because of this, numerical models do not need to adopt the greater conservatism that is required of simpler models that can lead to unnecessarily conservative SWRMAs.

2.1.4 Data Required

Numerical models require a good conceptual understanding, including estimates of hydraulic conductivity, porosity, aquifer geometry, saturated thickness, hydraulic gradient, pumping rates, recharge rates, and river/stream/lake locations and bed properties. Parameter variance terms and covariance matrices allow the spatial correlation between parameters with increasing separation distance to be represented in uncertainty analyses.

2.1.4.1 Examples

Two examples of the use of numerical models for assessing SWRMAs are provided below. These are the 'HAM' model in the Hutt Valley and the Canterbury groundwater model in the Selwyn area.

Furthermore, a 'state of the art' worked example is available online for the delineation of probabilistic capture zone analysis using numerical models. This comes from the Flinders University based Groundwater Modelling for Decision Support initiative and can be found at:

https://gmdsi.org/blog/worked-example-probabilistic-capture-zone-analysis/

2.1.4.1.1 Hutt Valley

This project utilised the existing 'HAM3' model with backward particle tracking to estimate time-based capture zones for 1-year, 2-year and 5-year groundwater travel times. The technical information available was previously agreed upon . It was noted that while numerical modelling is important in assessing and understanding groundwater transport, model predictions to inform policy should be treated with care. It was suggested that the use of model predictions on their own were not as robust as an 'in-concert' approach where model predictions, hydrogeological investigation, assessment of risks, and sensible use of policy together, achieve a better outcome to protect the water supply.

It was identified that uncertainty of data was key to SWRMA delineation, particularly concerning the degree of natural hydraulic confinement and potential contaminant sources at the ground surface.

2.1.4.1.2 Canterbury Groundwater Model

SDC required SWRMAs to be defined for various community supply bores including those at Lincoln, Leeston, Rolleston and Prebbleton. A similar approach was used for all sites, utilising the existing MODFLOW groundwater model (Weir, 2018). The model is a three-dimensional, calibrated, flow model, with MODPATH used for backward particle tracking. As such, only advective transport is simulated. The model used is steady-state with long-term average stresses (groundwater abstraction, land surface recharge and river flows).

2.2 Lessons Learned

Different approaches to SWRMA modelling have been taken by various organisations over recent years. Several points are worth commenting on:

- The assumption that simpler methods produce the largest capture zones may not be true. In the same way, default zones may be under- or over-conservative. For example, default zones for deep confined Canterbury wells use a 100 m radius around the well (LAWRP, 2018; Schedule 1). Numerical modelling results indicated that this approach could be over-conservative because the one-year travel time does not reach the surface at all in all cases modelled. Conversely, an unconfined well in the depth range of 10-30 m has an up-gradient limit of 1,000 m and cross-gradient width of 200 m, with a similar depth well in a confined aquifer having a 100 m radius. Both these examples have been found to be under-conservative compared to a simple, non-spatial analytical approach.
- Although more sophisticated risk-based approaches would point towards more robust methods in certain situations, and in particular may reduce the risks of unnecessarily large SWRMA's, the adoption of these approaches is often controlled by the resourcing available, including:
  - Availability of existing models – the existence of a 3D numerical model is, in itself, an advantage in terms of a more realistic representation of aquifer boundary conditions, though existing models will usually require modification for delineating SWRMA for specific wells;
  - Available budget and time; and
  - Skills and expertise that exist within the organisation, or access to skills outside of the organisation.
- Detached protection zones[5] may occur, where one year travel times may remain at depth, or even go deeper than the well screen, depending on the hydrogeological setting. The ability to model in 3D, such that this behaviour can be visualised and understood, is valuable. Consequently, 2D approaches may result in surface expression of the one-year travel time that does not occur in reality.
- The need to take into account local effects around the well, which for numerical approaches requires either grid refinement across the model or the use of an unstructured grid approach.
- UQ and sensitivity analyses have been considered as an afterthought, whereas they should be considered at the start of a modelling project as part of the method design.

[5] Where the SWRMA defined at the surface does not include the area where the bore is located

- We know UQ for SWRMA 2 is dependent on small scale heterogeneity which must be upscaled within models. Taking account of this upscaling in UQ was only considered in one of the reviewed examples.
- A good fit with the data is assumed to mean good predictive capabilities. A good fit to heads and stream flow rates provides little information about contaminant transport times. Uncertainty quantification for SWRMA based on a calibrated model's fit to heads or bulk flow rates through an aquifer is flawed; it must also take account of the aquifer heterogeneity that will not be well informed by heads and flows.
- Model design is generally opportunistic rather than considering the risk-data context. Numerical models have been used based on a misconception that they are always more sophisticated tools, rather than considering whether a current numerical model build is appropriate for SWRMA model delineation.
- Geostatistical analyses of the subsurface, which is the cornerstone of heterogeneity-focussed uncertainty analyses, was largely missing in all reviewed examples. This is needed for robust spatial uncertainty representation.

3 MODELLING COMPONENTS TO BE CONSIDERED

Numerous variables need to be considered in building a model. Uncertainty with each input can influence the results.

The main model inputs are considered here together with a discussion on the uncertainties and implications of these on model outcomes.

3.1 Model Input and Calibration Data

There are numerous inputs into flow and transport modelling that need to be estimated or evaluated. These are discussed below.

3.1.1 Flow Directions

Flow directions are obtained from hydrogeological investigations. The prevailing flow field can often be approximated by a horizontal two-dimensional (2D) flow. The formulation and numerical implementation of 2D models is usually much simpler than that of 3D. However, 3D effects may be important in practice. For instance, the evaluation of a 3D capture zone or catchment, at least in the vicinity of a well, is often required when dealing with deep wells and partially penetrating or partially screened pumping wells (as with deep alluvial aquifers where the well may only be screened over a 3 m or 6 m interval).

3.1.2 Pumping Rate

The pumping rate of the well is often the least uncertain of all the information. However, if pumping records are not available, this can be difficult to evaluate. If data are available, then a long-term rate (for example a 90th percentile) is more useful than a maximum, which may only be achieved in exceptional circumstances. However, the pumping schedule can affect the capture zone, and in some cases should be considered. A less conservative approach would be to use the median or mean rate of take. In some circumstances, metered data may not be available. Here, the consented rate of take may be appropriate as an upper limit. For very small supplies, the rate of take could be estimated based on the number of people supplied and the average water use per person.

3.1.3 Groundwater Recharge

For AEM and numerical modelling, an estimate of recharge is often needed. The groundwater recharge rates are generally only indirectly determined, through assessment of the rainfall, evaporation and transpiration rates, and subsequent flow processes in the unsaturated zone (which are affected by soil and geology types). The recharge rate is also time-dependent, and more or less spatially variable. Infiltration from rivers and streams also needs to be accounted for: infiltration/exfiltration rates between surface and groundwater can be estimated based on hydrological considerations, or sometimes through calibration of a flow model using nearby head data. Usually, both land surface and river recharge cannot be accurately assessed and may show considerable uncertainty.

3.1.4 Piezometric Gradients and Flow Directions

These data sets are generally informed from borehole and groundwater level monitoring data. The piezometric head dominates the flow directions, and transient effects can be significant. It is usually vertically averaged information. Even with high spatial- and temporal-resolution data, uncertainties remain.

3.1.5 Boundaries

Boundaries are usually defined from a regional hydrogeological and hydrological assessment, utilising bore logs, geological mapping, topographic mapping, and any other information. The boundary conditions consist of the heads at the boundary, or of the water flux through the boundary (which can be set to zero). These boundary conditions are often uncertain and this should be reflected in the uncertainty analysis along with the aquifer parameters.

3.1.6 Hydraulic Conductivity (or Transmissivity) of the Aquifer and Aquitards

This information is generally obtained from pumping test interpretation, but may also be based on textbook values and subsequent model calibration, in the absence of any other information. Hydraulic conductivity is always spatially variable due to the heterogeneous nature of aquifers, and local values derived from aquifer testing can never be extrapolated with full confidence. Spatial variability has an impact on the uncertainty of the location of the SWRMA. In addition, the scale at which the measurements have been taken has to be carefully considered: for example, step-testing samples a smaller volume of aquifer relative to constant rate testing with observation bores.

3.1.7 Effective Porosity

Effective porosity is the interconnected pore volume in sediment or rock that contributes to fluid flow. This directly affects the flow velocity and therefore the residence times, which subsequently determines the size and location of the capture zone. This information is often based on textbook values for representative sediment types. It may also be derived from tracer tests, if such data is available.

3.2 Inclusion of Preferential Flow Paths

Preferential flow paths and/or heterogeneity are highly important when modelling SWRMAs, as high permeability pathways provide a “short circuit” for contaminants to travel to the bore. The variability of effective porosity and hydraulic conductivity parameters need to be characterised and then upscaled to account for these small scale features in models used to delineate SWRMAs. How to best use available data to characterise these fine-scale rapid transport pathway features, and how best to upscale this characterisation in SWRMA models, is the subject of current research being undertaken by GNS and ESR, including within the MBIE funded Te Whakaheke o Te Wai programme.

Currently, the approach taken is usually to apply a conservatively low value for effective porosity to predict faster flow velocities than would be achieved using a bulk value. This important consideration is discussed further under uncertainty upscaling.

The current approach has been to estimate effective porosity from laboratory and field techniques, which is then used to estimate groundwater velocity using the following equation:

$$V = \frac{Ki}{n_{eff}}$$

Where: V is the groundwater velocity (LT^{-1})

K is the hydraulic conductivity (evaluated from pumping tests) (LT^{-1})

i is the measured hydraulic gradient (dimensionless)

n_{eff} is the effective porosity. (dimensionless)

Dann *et al.* (2008) carried out both pumping and tracer tests on the Canterbury Plains aquifer at the Burnham field site, Christchurch. They found that the pumping tests gave K values that represented flow through the bulk aquifer, whereas the tracer test gave K values reflecting flow through a preferential flow path (open framework gravel).

Published effective porosity values for sands and gravels are in the range of 0.1 to 0.4, though Dann *et al.* (2008)'s work on open framework gravels suggested it could be very much smaller (up to two orders of magnitude).

It is important to reflect the fraction of permeable channels within the total volume of the aquifer. In the case of the field test site for Dann *et al.* (2008), the permeable channels make up about 1% of the overall aquifer. Therefore, using the bulk porosity of the gravels (0.32) and multiplying by the fraction the channels make-up of the overall aquifer (0.01), the effective porosity is 0.0032.

Even though the main fluid flow pathways for groundwater transport are via highly permeable channels within a heterogeneous, alluvial aquifer, the effective porosity for the dominant flow path needs to be in the context of the average bulk aquifer.

Therefore, if using K calculated from pumping tests (which is a bulk aquifer K) to calculate groundwater flow velocities from complementary tracer tests, the effective porosity used in the modelling needs to reflect the fraction of high permeability pathways within the bulk aquifer. It may also then need to be adjusted depending on the degree of upscaling undertaken.

3.3 Changing Variables That Impact on the SWRMA

Conditions may change in a catchment that has a subsequent impact on the actual shape or size of a one-year travel time or total catchment area for a well. These factors are not considered when defining risk management areas but have a real-world impact on the areas. To maintain the integrity of a SWRMA and the activities that can occur within it, such factors should be evaluated on an ongoing basis. However, there is no current mechanism for doing this. The following summarises the key variables that can influence the SWRMA.

3.3.1 Variability in Environmental Conditions

Various environmental factors may change and need to be accounted for. Examples of changeable environmental conditions include seasonal changes in recharge, pumping effects, earthquake impacts, floods and droughts; (etc.). All of these may result in changes in vertical and horizontal flow and gradients, which can then impact the defined SWRMA.

For example, assessment of both winter and summer groundwater contours is beneficial to reduce uncertainty, as it reveals seasonal changes in gradients and/or flow directions. Also, if additional data becomes available, this may result in improvements in the contouring, again affecting gradients and flow directions. Re-assessment of contouring itself can result in significantly different flow characteristics. This can be seen by comparing Figure 2 and Figure 3 below. Figure 2 presents broad-scale contouring of water-table elevation near Ashburton. Figure 3 shows refined water-table contouring near the Ashburton River mouth, incorporating additional data points and river level elevation. As can be seen, the more refined contouring suggests flow towards the Ashburton River, which could indicate that the river is gaining flow from groundwater in this location. The broad-scale contouring does not suggest flow towards the river which would have been missed without contour refinement. This demonstrates the importance of using all available data, as well as the wrong conclusions that may be drawn using limited data.

Figure 2: Broad-scale contouring of groundwater levels in the lower Ashburton River area

Figure 3: More detailed contouring of groundwater levels nearer the Ashburton River mouth

3.3.2 Degree of Aquifer Confinement

Aquifer confinement is important in understanding SWRMA definition, but may not be well understood, and may vary within a risk management area. This variability can be natural (for example if the source is located close to the margin of confining layers), and it can also be human-induced (for example, wells installed through confining layers). Where there is a strong upward hydraulic gradient, this risk may be of little influence as the water will travel from deeper layers upwards to the well and not from the land surface downwards.

3.3.3 Engineering and/or Infrastructure Changes

Several other human-caused factors may impact the SWRMA. These can change the recharge patterns of the SWRMA, and/or may affect hydraulic gradients. Examples might include:

- Additional or reduced groundwater pumping, both in the assessed bore and in other bores with the SWRMA;
- Surface water races being closed and/or schemes being piped, reducing recharge;
- Recharge from new water sources;
- Changes to drainage networks; and
- Managed aquifer recharge (MAR) and/or targeted stream augmentation (TSA), including artificial injection of water into an aquifer.

4 SENSITIVITY AND UNCERTAINTY

All groundwater models, including those used for capture zone delineation, are built on incomplete knowledge. As a result, the essential parameters that determine the location and extent of well capture zones or catchment areas cannot be determined with certainty. Only limited data exists to inform groundwater model parameters: that is, it is impossible to sample aquifer properties at every point in the aquifer system, and information must be extrapolated from a few data points. Experimental and field data is also corrupted to some degree by measurement and interpretive errors. Uncertainty quantification (UQ) is, therefore, a central part of any risk-based modelling, and predictions made by a model need to be accompanied by assessments of their uncertainties. Furthermore, to avoid decision support failure, these assessments of uncertainty must be conservative; in this context, decision support failure represents an occurrence where contaminants outside of a delineated capture zone reach a drinking water supply well.

UQ is distinct from, but related to, sensitivity analysis. Sensitivity analysis describes how much a model simulated prediction will change by changing a model parameter value. More sophisticated sensitivity analyses also consider the correlation of parameters with other parameters (e.g. Satelli 2004), while others just vary parameters one by one. We use this information to design a model and UQ in a way that emphasises prediction-relevant groundwater details, to better quantify and reduce uncertainty.

Uncertainty quantification describes how uncertain a model simulated prediction is given the uncertainty in model parameter values, using the full joint probability distributions of a parameter suite. This accounts for the uncertainty of the parameter values, and any correlation between them. Depending on the model design, UQ approaches can be undertaken on the basis of prior parameter distributions (i.e. prior to any history matching), or on the basis of posterior parameter distributions (as defined by some history matching effort).

4.1 Model Design and UQ Methods

As mentioned in Section 1.3, the level of risk associated with a capture zone changes in different contexts. For example, a capture zone for a single dwelling domestic supply well has smaller risks associated with it than a capture zone for a community supply well due to the very limited rate of take and the much smaller SWRMA than a capture zone for a community supply well. Higher productivity wells screened within alluvial gravel aquifers that have rapid high-permeability transport pathways are associated with faster groundwater transport. This means that they have a more extensive likely one-year time of travel and greater risk than wells screened in pumice sands (for example). The model design and UQ must be sufficient to be able to quantify the uncertainty that contributes to these risks and reduce this uncertainty (where possible). The 'prediction context' described in Section 1.3 is used to describe the combined risk context, which includes a consideration of the availability of relevant data that can be used to reduce the uncertainty.

This prediction context dictates which model design and UQ should be adopted. In a low-risk context, an appropriately designed simple model may be deployed to delineate a capture zone, accompanied by an "engineering safety margin". An appropriately designed simple model, plus conservative predictive safety margins, allows a rapid capture zone delineation, with the only requirement being that the safety margin is demonstrably conservative. This conservatism can be difficult to verify (e.g. the differing approaches used by Tonkin & Taylor and HBRC in Hastings, where an AEM and numerical modelling approach resulted in very different one-year capture zones). The discrepancy in these results indicated that the ±25% discussed by Moreau *et al.,* (2014a) may be insufficient to meet the demonstrably conservative bar in some groundwater contexts. However, , the engineering safety margin may be so wide that the modelling is of limited use. This may then justify greater modelling complexity.

More complex models can refine a capture zone delineation through greater use of expert knowledge, (for example through the use of geostatistical analyses). If relevant data is available, it may support a level of model detail that enables a better fit with a history matching dataset and reduces the uncertainty of a capture zone delineation. Complexity also means that the uncertainty can be quantified. This is because a complex model can more accurately represent hydraulic processes and properties than a simple model, which means it is possible to explore the repercussions of less-than-full knowledge of these details. The need to ascribe a conservative predictive safety margin to the model prediction is therefore replaced with an uncertainty assessment of the capture zone that reflects all of the information available.

Increasing modelling complexity and quantification of the uncertainties associated with a model's predictions are numerically intensive tasks. They require the use of a model in partnership with uncertainty software packages, and these packages must run a model many times, which becomes an issue if the complex model takes a long time to run. They also tend to have greater issues with numerical instability than simple models. This can make the decision support process impossible. Also, paradoxically, parameterisation is often simplified in such complex models to mitigate these issues, thereby undermining the reliability of uncertainty analysis that complex models can provide.

Therefore, model design (including complexity) and UQ needs to be considered early in a decision support modelling project, to assess which prediction-risk-data context the capture zone delineation is in (e.g. Doherty 2015, Hemmings *et al*. 2020). This consideration of UQ can be conceptual or quantified. Regardless, the UQ will then be revisited and refined at the end of the modelling work.

4.2 Available UQ Methods

Current UQ methods include the following:

- Worst case analyses, which consider only the conservative end of parameter probability distributions. These may be as simple as introducing an "engineering safety margin", as long as this margin is demonstrably conservative (e.g. the conservative end of the recommended ±25% discussed in Moreau *et al*., 2014b, noting that a value greater than 25% may be required to be sufficiently conservative). A form of worst-case analysis that can represent hydraulic property heterogeneity more explicitly can be useful where there are data available that may be able to reduce the uncertainty through history matching. This process, known as hypothesis testing, relies on history matching to the data as well as a hypothesised undesirable prediction. The hypothesis can then be rejected if the parameters derived through history matching are deemed unrealistic (Moore *et al.* 2010).

- Propagation of error methods, in their simplest form, are the most common form of uncertainty analysis, whereby a mean and a standard deviation is used to express the uncertainty of a model prediction. These methods are also called first order, second moment (FOSM) methods. A more complete expression of the uncertainty is calculated on the basis of a prediction-parameter sensitivity matrix and a parameter covariance matrix. This UQ method assumes a linear relationship between parameters and predictions, allowing an analytical solution to be used, which can in some cases offer a rapid UQ option. Versions of FOSM equations that account for the heterogeneity of aquifer properties can be found in Moore and Doherty 2005, and Doherty 2015.

- Monte Carlo (MC) assessments, which allow realisations of multiple possible subsurface heterogeneities that may affect the prediction to be represented. The model is then run with each of these realisations to make predictions which are collated into a probability distribution. These methods are considered the most correct, but can be very slow to complete, particularly if history matching is used to transform a prior parameter distribution into a posterior distribution.

- Hybrid methods have been developed to address the computational burden associated with implementing MC methods within a history matching context. The most recent of these more efficient technologies is the ensemble smoother technology (White, 2018), which within a few thousand model runs can transform a prior parameter probability distribution into a posterior, with much less effort than previously.

If the resulting uncertainty analysis has a wide range, this should be a prompt for the need for further data collection.

4.3 Upscaling

All UQ approaches require a consideration of the upscaling of hydraulic properties that occurs when they are represented as parameters within a model. Upscaled values represent not only the values of the hydraulic properties, but also the connectedness of those properties relative to the direction of groundwater flow, which may differ under natural or stressed conditions. Because of this, the values of upscaled parameters often take on parameter values that fall outside the range of those measured in laboratory and field studies, where the scale of the measurement differs from that of the model parameterisation. Effective porosity is an example of this. Upscaled parameter values may also differ depending on the prediction being made, as noted in Section 4.1.

Upscaling is an area of active research, and methods are currently being developed to support analyses such as capture zone delineation in different aquifer contexts. In the absence of such studies for the New Zealand context while this research is undertaken, the use of demonstrably conservative parameter uncertainty limits should be adopted.

4.4 Building Blocks of Capture Zone Uncertainty Analysis

The seven components for capture zone delineation discussed in Section 3 fall into model structure, parameter, stress, or data categories. These are summarised in Table 1. All components have associated uncertainty, and hence need to be represented in an uncertainty analysis. Ideally, anything that is uncertain should be treated as a parameter in uncertainty quantification, due to the relative ease of quantifying uncertainty associated with model parameters. This is reasonably straightforward to do for data and model stresses. However, parameters can also usually be used to define the uncertainty associated with model structure, by simply defining those aspects of structural elements that are not uncertain as fixed structural elements, and redefining those structural elements that are uncertain as parameters. This is also discussed in Table 1.

Table 1. Components for capture zone delineation

Model component	Component	Representation of uncertainty in model
Flow geometry	Structure	Define uncertain vertical aquifer structure as a fixed model structure with multiple layers populated with model parameters.
Pumping rate	Stress	Time-varying or average rates are used. Time-varying is important where extreme events may impact the capture zone. Parameter limits, standard deviation, or covariance matrices are used to describe the uncertainty of this component.
Recharge rate	Stress	Time-varying or average rates are used. Time-varying is important where extreme events may impact the capture zone. Parameter limits, standard deviation, or covariance matrices are used to describe the uncertainty of this component.
Piezometric gradient and flow direction	Data	Time-varying or average rates are used. Time-varying is important where extreme events may impact the capture zone. Parameter limits are used to describe the uncertainty of this component.
Boundaries	Structure	Redefine model inflow and outflow boundaries as uncertain parameters. Parameter limits and standard deviation may be used to describe the uncertainty of this component.
Hydraulic conductivity	Parameter	Parameter limits, standard deviation, covariance matrices, geostatistical relationships of parameter covariance and/or juxtapositional relationships.
Effective Porosity	Parameter	Parameter limits, standard deviation, covariance matrices, geostatistical relationships of parameter covariance and/or juxtapositional relationships.

5 METHODS AND GUIDELINES

The proposed approach for SWRMA assessments is to first identify the prediction context, which depends on the hydrogeological setting, the pumping volumes and rate required to serve a particular population size, and the available data. This prediction context provides a framework within which the required level of modelling complexity can be determined before embarking on the modelling exercise itself. Once this is established, the most suitable modelling approach is then adopted, including model design, history matching and uncertainty quantification.

This framework adopts the risk-based modelling philosophy outlined at the beginning of this report. Previous methods have tended to focus solely on the available data rather than addressing the risks that SWRMA modelling seeks to mitigate.

An outline of the three main modelling approaches (uniform flow equations/non-spatial analytical, AEM, and numerical modelling) is provided in Appendix B.

There is a common need for approaches to be pragmatic. This may require that an initial approach is used with a ‘factor of safety’ to assesses sensitivity and uncertainty. This would likely lead to the delineation of a conservatively large SWRMA, and one that could be re-assessed in the future as more data becomes available and/or more time is available to complete more complex analysis. If a SWRMA is in an area with little pressure in terms of land use, then the larger, more conservative area, may be acceptable (also refer to Section 1.6).

5.1 Modelling Approach

Table 2 through to Table 4 outline the complexity to be accounted for in model design and UQ. The criteria are grouped under hydrogeological complexity, population served, and data available. These tables are combined into Table 5, which outlines a risk-based model design and uncertainty quantification framework. Some of the categories are somewhat arbitrary, and a more formal risk analysis in different hydrogeologic contexts could be useful to refine these categories. As such, these categories should be recognised as guidance, and councils may choose to modify some of the categories to fit with their local situation.

It is also important to recognise that there may be existing models which practitioners would like to use. However, the limitations of existing models need to be understood. Key issues such as grid discretisation (and the possible need to refine in the vicinity of the pumping well), boundary effects, and how to realistically upscale parameters (or downscale from a regional model) need to be considered. The focus should be on establishing that an existing model is fit for its purpose.

Table 2: Hydrogeological complexity

Category	Criteria	Complexity to be accounted for implicitly or explicitly in model design and UQ
Confinement	Artesian head criterion	Low
	No artesian heads	High
Surface Water Boundary conditions	Proximal streams/surface waters	High
	No proximal surface waters	Low
Heterogeneity	Connected high permeability pathways (Alluvial gravel, karst and fractured rock)	High
	Moderate (Sandstone and non-karstic limestone)	Moderate
	Homogeneous (Alluvial sand, pumice sand, coastal sand)	Low

Table 3: Pumping rate estimate for the population served6

Category	Pumping rate	Complexity
Small community (up to 500 people)	10-100 m^3/day	Low
Large community – Township (up to 50,000 people)	100-10,000 m^3/day	Moderate
Municipal city supply	>10,000 m^3/day	High

Table 4: Data that could be available and used to reduce capture zone uncertainty

Historical measurement Data	Information content
Tracer test in location	High
Aquifer flow information, boundary conditions, recharge rates, and how these change over time.	Moderate
Limited	Much of the model information must come from expert knowledge or site characterisation data

[6] Regional councils may want to set their own limits based on their approach to risk

Table 5: Risk-based minimum model design and uncertainty quantification framework

Pumping rate	Hydro complexity	Information content	Minimum model design complexity plus UQ
Low (Small communities)	Low – moderate	Any	Appropriately designed simple models* combined with a demonstrably conservative engineering safety margin or mean plus standard deviation to express SWRMA uncertainty. Do not history match as models are too simple, but check that the model outputs do not contradict available data or site conceptualisation information.
	High	Any	
Moderate- High (Large communities- Townships- Cities)	Low - moderate	Any	Appropriately designed simple models, ensuring that model boundary conditions are well represented. Combined with FOSM or Monte Carlo methods to express SWRMA uncertainty. If prediction-relevant data is available and using numerical models, history match to reduce the uncertainty of capture zones to the extent the data allows.
	High	High	More complex numerical model with structure appropriate to support a highly distributed parameterisation, supported by a geostatistically-based parameter covariance matrix. Use FOSM or Monte Carlo or hybrid Monte Carlo methods to quantify SWRMA uncertainty. Use history matching to reduce the uncertainty of capture zones to the extent the data allows.
	High	None	More complex numerical model with structure appropriate to support a highly distributed parameterisation. Parameterisation may be supported by a geostatistically-based parameter covariance matrix, OR using other advanced geostatistical methods to better characterise aquifer connectivity.**

*The appropriateness of a simple model is context-specific. Identifying the appropriateness of various simple model designs in anisotropic and heterogeneous aquifers is the subject of current research (Section 6).
** In their current implementation, advanced geostatistical representations of aquifer heterogeneity cannot be used in history matching contexts without corrupting the geostatistical realism, and hence these methods are best deployed where history matching is not possible.

5.2 Model Design Complexity

Model design complexity has two components: the model structure, and the model parameterisation that is supported within that structure. The model structure is fixed, while the parameterisation can vary to the extent that it needs to fit the data and to express the uncertainty associated with a prediction. In some cases, the model structure can be simple while the parameterisation is complex. Or the model structure can be complex and the parameterisation simple. Ideally, for computational reasons, anything that is uncertain is expressed by parameters (as already noted previously).

5.2.1 Model Structure

A model structure of low complexity would be equivalent to the method described in 2.1.1 for a uniform flow equation method and/or non-spatial analytical model. Model design of low-moderate complexity may be the AEM modelling approach or a simple numerical groundwater model (Section 2.1.2). Moderate-high structure complexity would be encompassed by more complex steady state or transient numerical modelling designs, with various levels of parameterisation detail and with more realistic representations of boundary conditions.

The selection of which model structure would work best depends on the prediction risk context, and whether the uncertainty of the capture zone delineation can be reduced with history matching to available data. In general, low-moderate model structure complexity is not appropriate for history matching, while moderate-complex numerical models can support the parameter heterogeneity required to enable the extraction of information from data during history matching.

However, where data with a high information content exists (such as tracer test results), a low complexity model could be tuned to ensure that the general pattern of groundwater connectivity and velocities obtained from the tracer test are respected in the low complexity model design. A more complex model could be used to extract more information from tracer test data (such as concentration reductions over time) by being able to introduce the parameter heterogeneity that fits this data. This would involve a more formal history matching process.

5.2.2 Model Parameterisation

As noted above, the degree of model parameterisation is another important aspect of model design. Highly parameterised models ensure that the heterogeneity that matters to a prediction is represented. This ensures reliable prediction uncertainty analyses, so that the truth will lie within its probability bounds without requiring an overly conservative estimate of uncertainty. Highly parameterised models also ensure that the heterogeneity information that data expresses is able to be represented, allowing a good fit to the data and a reduction of uncertainty to the extent that the data allows. In contrast, a homogeneous parameterisation can squander the information in data, essentially by not having sufficient flexibility in parameters to assimilate this data.

5.3 Model Uncertainty Analysis Complexity

The uncertainty methodologies listed in Section 4.2 (i.e. defining an engineering safety margin, using a mean plus a standard deviation, Monte Carlo methods etc) can be considered to range from low to high complexity. Where the prediction-risk context is low, then the lower-complexity UQ methods and model design can be used as long as the safety margin or FOSM based estimate of standard deviation is demonstrably conservative (including accounting for upscaling).

Where the prediction-risk context is higher and a numerical model is used, FOSM methods can still be applied. However, when using highly parameterised numerical models, which would be required in highly complex heterogeneity contexts, Monte Carlo based methods would be more effective. If prediction-relevant information is available for history matching, then hybrid Monte Carlo methods would be most suitable.

6 INFORMATION GAPS

Some major information gaps were identified in the SWRMA model delineation methods reviewed in this report. These gaps all form the subject of current research being undertaken internationally, but also within New Zealand, principally at GNS Science and ESR crown research institutes.

The first of these is the characterisation of rapid transport pathways in NZ aquifer strata, particularly alluvial aquifers where rapid transport pathways permeate the gravel strata. Both ESR and GNS Science are currently working on the geostatistical characterisation of gravel aquifer strata based on lithological logs from well drillers, as well as more targeted studies such as Burbery et al. (2017).

Secondly, methods to robustly upscale such characterisations of rapid transport pathways to field scales are required. Fogg and Zhang (2016) suggest that this challenge of determining the stochastic nature of prediction specific heterogeneity at field scales is likely the biggest stochastic contaminant hydrogeology challenge of all time. Currently, GNS Science and ESR are working on an upscaling of the rapid transport pathways that permeate NZ gravel strata.

Finally, guidance on the design of simple models for SWRMA assessments is needed to ensure that they provide a sufficiently conservative assessment to ensure water security. For example, what adjustments in a simple model design are required for anisotropic and highly heterogeneous aquifers? Such work is being undertaken by GNS as part of the MBIE funded TWOTW Endeavour research programme.

7 DISCUSSION

This report has discussed the approaches for the development of bespoke groundwater Source Water Risk Management Areas (SWRMAs) by Councils and consent applicants for potable supply. The aim is to provide guidelines for assist modelling of SWRMAs, taking into account the balance between the level of protection offered, and the impact on existing land-use activities. However, this is not always the case: a numerical model that is poorly conceptualised, overly simplistic, uses poor input data, or is constructed for a different purpose, may produce results that are worse than some of the more basic methods available. the approach taken needs to fully account for uncertainty in the data used and the model structure.

In conclusion:

- Risks increase with the size of population served (due to increased rate of take, likely more highly permeable aquifers, and more extensive area of one year TOT)
- Some aquifers can be relatively well characterised, and models will have lesser uncertainty. However, more heterogeneous aquifers will have considerable uncertainty, partly due to the fact that we can only sample the aquifer at discrete points, and we then have to extrapolate between those points.
- Because of the uncertainty, many models will need to have a “factor of safety” approach used, though we need to ensure that the factor of safety is sufficient.
- The more that uncertainty can be reduced, the more the SWRMA can potentially be reduced, thereby reducing the land use limitations in the area.
- There is ongoing research into aquifer heterogeneity and rapid flow paths, and modelling these. In light of this, and in terms of developing pragmatic approaches, these guidelines should be reviewed, to ensure that they reflect current understanding.

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Appendix A: Existing modelling approaches used in New Zealand

A.1 Hutt Valley SWRMA Assessments Using a Numerical Approach (Gyopari, 2014; Perwick *et al*., 2018)

Wellington Water Ltd operate two major drinking-water supply wellfields near the coastal end of the Hutt Valley (Waterloo wellfield and the Gear Island wellfield). These bores abstract water from the highly permeable Waiwhetu gravel aquifer. The system was modelled using the finite-difference code MODFLOW.

A.1.1 Aquifer Type, Pumping Tate, Well Depth and Population Supplied

The aquifer comprises alluvial gravels. A confining layer separates both Waiwhetu wellfields from the overlying unconfined Taita Alluvium. The aquifer supplies 45% of the total demand to Wellington. Groundwater abstraction rates were not available, and maximum consented rates were used instead. All bores are approximately 40 metres deep.

A.1.2 Uncertainty Analyses

Aquifer parameters have been assigned based on measured and estimated ranges for aquifer transmissivity and horizontal hydraulic conductivity. Vertical hydraulic conductivity has been assumed to be at least an order of magnitude less than horizontal, due to the presence of highly stratified sediment sequences and laterally-persistent silt-rich layers. The specific yield of the uppermost layer has been based on lithology. The storativity of the aquifer was derived from pumping test results.

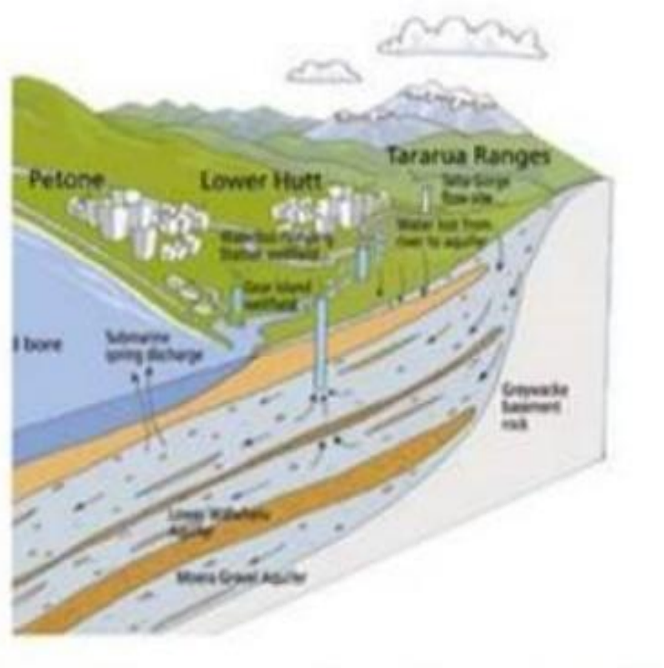
Model calibration entailed the adjustment of independent variables (parameters and fluxes) within realistic limits to produce the best match between simulated and measured data (groundwater levels, spring flows and measured river flow losses/gains). As such, the calibration process is an 'inverse approach' attained through the adjustment of parameters until relevant model outputs match observed data. Manual calibration under steady-state conditions was initially undertaken as a first step to evaluate the conceptual model. This was followed by a manual transient flow calibration phase to obtain a sense of model sensitivity, and to further test the appropriateness of the conceptual model and boundary conditions, as well as further tune the hydraulic conductivity zonation. Following completion of a manual 'pre-calibration' phase, the automated parameter estimation code PEST (Dougherty, 2008) was utilised to optimise the calibration, perform a sensitivity analysis, and provide information on the uniqueness (or robustness) of the calibration. The PEST calibration was performed for a five-year dataset (2007-2012) during which a wide range of system stresses occurred. Finally, a verification run was performed using a 20-year calibration dataset.

A.1.3 Aquifer Boundary Conditions

Rivers were modelled using MODFLOW's River (RIV) package, with channel geometry derived from cross-section surveys. Drains were modelled using MODFLOW's Drain (DRN) package to represent drainage from aquifers into drains, but not vice versa. Wellington's harbour was simulated as a constant head boundary.

A.1.4 Aquifer Confinement

The upper unconfined layer comprises Taita alluvium, whilst the Petone Marine Beds act as an aquiclude. The Upper Waiwhetu aquifer becomes semi-ham the well field. The Lower Waiwhetu gravels are confined. The principal layer boundaries were derived from a 3D geological model developed by GNS for the Lower Hutt basin (Boon et al., 2010)., conceptually shown in the figure below.



Waiwhetu Aquifer and Associated Processes

An eight-layer model was developed to allow for the stratified nature of the leaky aquifer system. The work for the SPZs also considered potential contaminant pathways, including edges of the valley floor, piercing of confining layers, and earthquakes. Whilst these do not appear to have been implemented in the model, they were considered in terms of what should be defined as a SWRMA.

A.1.5 Representation of Temporal Variability in the Piezometric Surface

A transient model was developed and hence included temporal variability.

A.1.6 Representation of SWRMAs

1, 2 and 5 year travel times were delineated.

A.1.7 Model Discretisation

A 100 m x 100 m grid was defined for the onshore portion of the model. It is not clear whether the discretisation was refined for the area surrounding the wellfield.

A.1.8 Preferential Flow Paths

Preferential flow paths can be simulated with high-resolution grids (e.g. 1 m) that represent stochastic ensembles of aquifer materials. This is computationally demanding and wasn't undertaken with these models.

A.2 Canterbury SWRMA Assessments Using a Numerical Model Approach (e.g. Weir, 2020)

SDC required SWRMAs to be defined for various bores, including those at Lincoln, Leeston, Rolleston and Prebbleton. A similar approach was used for all sites, utilising an existing MODFLOW numerical groundwater model. The model is a three-dimensional, calibrated flow model, with MODPATH used for backward particle tracking. As such, only advective transport is simulated. The model used is steady-state with long-term average stresses (groundwater abstraction, land surface recharge and river flows).

A.2.1 Aquifer Type, Pumping Rate, Well depth and Population Supplied

Alluvial gravels form the Canterbury alluvial aquifer system. The system is several hundred metres deep and works as a semi-confined system, apart from in the coastal areas where a well-defined, multi-layered confined aquifer system exists. For the majority of the Plains, the system is a heterogeneous and anisotropic mixture of gravels, sands and silts, with the majority of flow and transport occurring horizontally through open framework gravels (Dann *et al.,* 2008). Various SWRMA assessments have been carried out using an existing 3D numerical model (see Table 6).

Table 6. SWRMA assessments carried out

Source	Pumping rate (l/s)	Well depth (m)	Population supplied
Leeston	100	69, screen at 62-68	>5,000 people
Prebbleton (Shands Road)	100	173, screened at 166.5-171.5	>5,000 people
Rolleston, McLenaghan Road	75	192.5, screened at 149-152	>5,000 people
Lincoln	Unknown	89.2, screened at 82.2-88.2	>5,000 people
Dalwood Crescent, Rolleston	~80 combined	~170m	>5,000 people
West Melton	~50 combined	83 m, screened at 80-83 m. 193m screened at 183-193 m.	>2,000 people
Kirwee	~35	190	>5,000 people

A.2.2 Uncertainty Analyses

The sensitivity analyses have been generated by PEST. Due to software limitations and project timeframes, a full sensitivity analysis of the transient model could not be completed. Instead, this has been undertaken using the steady-state model with model stresses (river flows, land surface recharge and pumping) averaged over the full transient model simulation period. As this model is steady-state, the sensitivities of aquifer specific storages and specific yields could not be completed.

Model calibration is generally more sensitive to the vertical conductivities in inland layers 2 and 4 than the other parameter sets. This is because these parameters control the rate at which water infiltrates into deeper layers from inland sources (mainly rivers) that subsequently flows towards the coast. Model calibration is also relatively sensitive to parameters nearer the main rivers (the Waimakariri, Selwyn and Rakaia rivers) compared to those located further away.

For the SWRMA work, what-if scenarios were carried out to test the theoretical presence of local scale aquitard punctures, larger scale aquitard punctures, and increased aquitard vertical conductivities.

A.2.3 Aquifer Boundary Conditions

General head boundaries were used to present Lake Ellesmere, the Christchurch estuary and offshore discharge. No flow boundaries were set at the other model spatial boundaries (the model base, north, south, west and off-shore limits). Wells were used for abstraction/injection, and recharge was used to simulate land surface recharge. Stream, river and drain boundaries were represented using MODFLOW's SFR2 package. River reaches either have a specified top-reach inflow where there were interactions with space outside of the model domain, or have no specified inflow where they originated from within the domain. The SWRMA 2 areas assessed were distant from these boundaries.

A.2.4 Aquifer Confinement

Aquifer confinement at the surface is only relevant in the coastal confined area, which was outside of the area being assessed for these SWRMAs. The aquifer (outside of the coastal confined area) has been represented as a semi-confined series of aquifers, with the 'confinement' being applied through lower vertical hydraulic conductivities relative to the horizontal.

A.2.5 Representation of Temporal Fluctuations in the Piezometric Surface

Temporal fluctuations in the piezometric surface were not represented, as a steady-state model was used.

A.2.6 SWRMA Representation

The defined SWRMAs are significantly different to default areas previously applied. The default areas that were used for bores greater than 70 m depth were 100 m radius. The modelling approach suggested the one-year travel time didn't reach the surface, and so a 100 m radius was considered to be unnecessary.

A.2.7 Model Discretisation

Model discretisation was variable, with cell sizes ranging from 500 m x 500 m to 500 m x 1,000 m. Cell refinement in the vicinity of the bore was initially proposed, but was rejected as previous cell refinement work for Christchurch City Council made little difference to the SWRMA assessments, and the model was already considered to be conservative.

A.2.8 Preferential Flow Paths

Preferential flow paths were conservatively allowed for by assigning a low porosity value to replicate transport times in the open-framework gravels near Burnham, effectively resulting in rapid transport over all of the model domain.

A.3 Canterbury SWRMA Assessments Using an Analytical Approach (e.g.Hector, 2020)

Ashburton District Council required SWRMAs to be defined for various sources, including Hakatere, Ashburton Township and Tinwald groundwater supplies. Similar approaches were used for Waimakariri District Council for their Waikuku Beach and West Eyreton groundwater supplies. Assessments were based on using groundwater contours, estimates of hydraulic conductivity (vertical and horizontal), estimates of porosity, and pumping rates. Darcy's equation was applied with conservative estimates of parameters to obtain likely one year travel times. Stagnation points were estimated cross- and down-gradient to calculate distances for the protection zones.

A.3.1 Aquifer Type, Pumping Rate, Well Depth and Population Supplied

Alluvial gravels form the Canterbury alluvial gravel aquifer system. The system is several hundred metres deep, and works as a semi-confined system, apart from in coastal areas where a well-defined, multi-layered confined aquifer system exists. For the majority of the Plains, the system is a heterogeneous and anisotropic mixture of gravels, sands and silts, with the majority of flow and transport occurring horizontally through open framework gravels (Dann *et al.,* 2008).

Various bores that supply several settlements were assessed, as follows:

Bore Number	Bore Depth (m)
K37/1703 (Ashburton)	119.4
K37/1285 (Ashburton)	118.0
K37/2343 (Ashburton)	90.7
K37/3533 (Ashburton)	125.9
K37/1284 (Ashburton)	96.6
K37/3497 (Tinwald)	73.6
L37/1138 (Ashburton)	95.5
L37/1139 (Ashburton)	99.2
Bore L37/0811 (Hakatere Huts	29.7
BW23/0480 (West Eyreton)	96
BX24/0394 (Waikuku Beach)	25.2
M35/0474 (Waikuku Beach)	21.6

Settlement populations are as follows:

- Ashburton: approximately 19,000
- Upper Hakatere Huts: approximately 110
- West Eyreton: approximately 70

- Waikuku Beach: approximately 1150

A.3.2 Uncertainty Analyses

Parameter ranges were derived from available data, and then conservative values were applied. Regional hydraulic gradients were compared with local gradients derived from local data.

A.3.3 Aquifer Boundary Conditions

Where rivers are within estimated SWRMAs, these were assumed to be recharge boundaries for shallow wells (Waikuku Beach and Hakatere Huts). Estimates of stream bed conductances were used to predict the hydraulic connection of the river.

A.3.4 Aquifer Confinement

Drill logs and geological mapping were used to assess the degree of confinement. This was represented using leakage estimates from aquifer testing to characterise vertical conductivities.

A.3.5 Representation of Temporal Fluctuations in the Piezometric Surface

Temporal fluctuations in the piezometric surface were partly represented by looking at ECan's regional contours versus local contours based on data from different dates.

A.3.6 Representation of SWRMAs

The SWRMAs were significantly different to the default areas previously assessed by ECan. It was also found that the areas defined according to the different piezometric contours were significantly different to each other, partly due to different dates used, and partly due to the inclusion of different data in the two contouring approaches.

A.3.7 Preferential Flow Paths

Preferential flow paths were conservatively allowed for by assigning a low porosity value to replicate fast transport times in the open-framework gravels near Burnham, effectively resulting in rapid transport over all of the model domain.

A.4 Napier SWRMA Assessments Using an AEM Approach (Tonkin and Taylor, 2018)

Following the Havelock North contamination, Napier City Council (NCC) engaged Tonkin & Taylor to develop SWRMAs for its proposed redevelopment of public water supply bores in the Napier area. The approach taken was 2D analytical element modelling (using AnAqSim), using data from a numerical model to inform the AEM.

A.4.1 Aquifer Type, Pumping Rate, Well Depth and Population Supplied

Alluvial gravels form the Heretaunga Plains. Coarse gravels and sands act as the aquifers, with finer-grained sediments (such as clay and silt) forming confining layers. The aquifer system is dominated by recharge from river losses, plus some land surface recharge. A no-flow boundary was introduced to account for limestones and mudstones to the west of the NCC bore fields.

For this work, it was assumed that the maximum rate of take for the two existing and two new Awatoto bores is 125 l/s, from depths ranging between 74-118 m. The aquifer is understood to be confined below approximately 40-50 m depth due to overlying marine deposits. The aquifer is artesian.

The Tarradale bore field consists of one existing and 3 proposed bores, taking around 125 l/s combined from depths of around 60-70 m. The area is overlain by 10-30 m of clay, underlain by fluvial sands/gravels and clays of perhaps 50 m thickness.

A.4.2 Uncertainty Analyses

No parameter uncertainty was defined.

Aquifer thickness and hydraulic conductivity were obtained from bore logs and aquifer testing. Previous work had indicated that the definition of SWRMAs was sensitive to aquifer thickness, hydraulic conductivity and effective porosity, and these parameters, as well as the hydraulic gradient, were adjusted by ±25%. SWRMAs 2 and 3 were defined by using the maximum areas defined through the parameter variations, this being larger than the “best estimate” area.

A.4.3 Aquifer Boundary Conditions

A hydraulic boundary was included to represent mudstones and limestones to the west of Taradale. These formations are considered to have very low permeability and contribute negligible amounts of groundwater to the Heretaunga aquifer. Within the model, the formations were represented as a ‘leaky barrier’ boundary with a conductance of 0.0001/day.

A.4.4 Aquifer Confinement

Both bore fields were assumed to be overlain by low permeability confining material.

A.4.5 Representation of Temporal Fluctuations in the Piezometric Surface

Hydraulic gradients and flow directions were derived for each bore field from monthly piezometric contours for the stress periods between July 2008 and June 2015 from the HBRC numerical model. The calculated hydraulic gradients and flow directions were then aggregated into average, minimum and maximum values with a rolling average window of one, three, six and twelve months for each bore field. The individual minimum and maximum values of hydraulic gradient and modelled groundwater flow directions for each bore field and rolling average period was applied as input parameters for model scenarios. For “best estimate” capture zones and sensitivity analyses, the mean gradient and flow direction of all bores in a bore field was used. By incorporating the modelled extremes in groundwater flow directions and hydraulic gradients over several years, it was considered that temporal impacts to regional-scale groundwater flow regimes from seasonal changes and pumping are reflected in the subsequent SWRMAs.

A.4.6 Representation of SWRMAs

One-year and total catchment SWRMAs were defined. "Best estimate" and maximum capture zones were also defined.

A.4.7 Preferential Flow Paths

Regional SWRMAs were delineated by applying a uniform flow condition using groundwater levels (and associated hydraulic gradient and flow directions) derived from the HBRC numerical model outputs. The work recognised that the majority of flow was through a small percentage of the aquifer thickness, via high-permeability pathways, and that the effective porosity would be smaller than suggested by laboratory values. As a result, the bulk effective porosity was relatively low. Tonkin & Taylor gave a range of effective porosity values of 0.003 to 0.15 (source unknown), and for the purpose of the AEM approach, values of 0.015 to 0.025 were used.

A.5 Waikato SWRMA Assessments Using a Numerical Approach (Hadfield and Nicole, 2000)

Community groundwater supplies assessed in the Waikato region included 90 schools and 28 District Council managed community groundwater supplies. The model used was the ASMWIN 2D groundwater flow and transport model. This is a finite difference flow model for automatic calibration. Indicative SWRMAs were constructed for selected Waikato groundwater supplies from vulnerable unconfined, aquifers. The size and shape of each of the areas varied, predominantly due to changes in aquifer permeability and pumping rate. The parameter most open to error was considered to be hydraulic conductivity, emphasising the importance of aquifer test information.

The extent and shape of each of the SWRMAs vary predominantly due to changes in aquifer permeability and pumping rate. Attenuation and remedial zones were constructed using the ASMWIN finite difference numerical groundwater model, which requires the specification of hydraulic conductivity, hydraulic gradient, effective porosity, flow direction, aquifer thickness and pumping rate.

A.5.1 Aquifer Type, Pumping Rate, Well Depth and Population Supplied

As well as the 90 school and 28 District Council managed supplies, numerous motor camp water supplies also serve the district. School populations are typically less than 500. Other community supplies are likely to supply less than 5,000 people.

A.5.2 Uncertainty Analyses

The project report does not mention uncertainty analyses, and it appears that sensitivity analyses and/or parameter evaluations were not assessed. The work only shows what is possible, and is 'indicative' only. However, it goes into some theory of various methods for SWRMA assessment and acknowledges that arbitrary fixed radius is the most uncertain of all methods. The SWRMAs delineated are indicative and highlight the importance of understanding aquifer behaviour in considering supply protection and the potential contaminant threat.

A.5.3 Aquifer Boundary Conditions

Aquifer boundaries were not considered or described.

A.5.4 Aquifer Confinement

Aquifer confinement was not considered or described

A.5.5 Representation of Temporal Fluctuations in the Piezometric Surface

Temporal fluctuations in the piezometric surface were not represented.

A.5.6 Representation of SWRMAs

At each location, the following were represented:

- Arbitrary fixed radius;
- 100-year travel time isochron; and
- 2-year isochron.

A.5.7 Model Discretisation

It is noted that the finite difference method is being used. However, discretisation intervals are not given.

Matamata SWRMA Assessment Using an AEM Approach (Toews, and Moreau, 2014).

SWRMAs were delineated for the two Matamata groundwater supply wells located near Tawari Street, Matamata, in the Waikato Region. An AEM was used to simulate steady-state 2D groundwater flow using GFLOW. The GFLOW software was used to simulate rivers, streams, and drains using line-sink elements.

Backward particle tracking was used to define SWRMAs using pumping test data from the bore field. The length of the upgradient zone was based on work by Pang *et al.* (2005) to estimate microbial transport distances.

A.5.8 Aquifer Type, Pumping Rate, Well Depth and Population Supplied

The supply wells are screened in a relatively shallow (16 m to 22 m depth) leaky-confined aquifer. An existing resource consent allows for a combined take of 120 m^3/hr of groundwater from these wells. Pumping rates used to delineate capture zones were distributed to 60 m^3/hr for each well, as the combined consent for the Tawari Street well field is 120 m^3/hr. The Likely population served is approximately 7,000 people.

A.5.9 Uncertainty Analyses

The GFLOW model for Matamata was calibrated using groundwater elevation observations from 60 boreholes over the region, obtained from drilling records maintained by Waikato Regional Council. No parameter upscaling was undertaken.

Many of the groundwater levels may not represent ambient groundwater flow in the aquifer, because they were measured immediately after drilling, influenced by nearby pumping wells, obtained from a separate (deeper) aquifer, or have uncertainty with the coordinates and elevation. Because of this, 10 of the 60 data points were removed before calibration.

To achieve a suitable calibration, groundwater recharge rates and hydraulic conductivity values were adjusted to minimise the residuals between simulated and observed groundwater levels. This process was completed first using PEST. Additional manual calibration adjustments to model parameters were also made to the resistance terms for line-sink elements representing surface water features. The calibration was completed without any pumping, as the measured groundwater levels from the Matamata wells represent static groundwater levels prior to aquifer testing.

Several parameters were identified as being sensitive to the capture zone delineation. These were varied to produce alternative maps for capture zones. Parameters were either increased and/or decreased to yield larger capture zones than the calibrated base case. These sensitivity analyses are summarised in the table below. Here, the K+ case increased the hydraulic conductivity by 25%, while the R- and R+ cases reduced and increased the recharge rate by 25% respectively. The rationale for the 25% adjustment to parameter values is provided by Moreau *et al*., (2014b). The TB case adjusts the aquifer bottom and thicknesses to their practical limits to contain the range of specified head elevations of all the line-sinks, within the well screen elevation intervals.

Sensitivity analysis scenarios

Case name	Hydraulic conductivity [m/d]	Recharge [m/d]	Bottom elev. [m]	Thickness [m]
Base	40.0	0.0011	19.3	30.0
K+	50.0	-	-	-
R-	-	0.000825	-	-
R+	-	0.001375	-	-
TB	-	-	22.0	22.0

Dashes indicate no change from "Base" conditions.

A.5.10 Aquifer Boundary Conditions

Rivers and surface waterways were defined as line-sink elements.

A.5.11 Aquifer Confinement

The aquifer within which the production wells are screened is confined above by layers of moderately sorted silt and sand, and confined below with sandy loam to very fine sand and pumice sediments. Deeper water-bearing zones have also been identified at depths of 41 m to 47 m bgl.

A.5.12 Representation of Temporal Fluctuations in the Piezometric Surface

Temporal fluctuations have not been represented as the model is steady-state.

A.5.13 Representation of SWRMAs

SWRMAs have been delineated using backward particle tracking. The particle-tracking assigns rings of reverse-tracking particles placed near the bottom of the pump well screen. Each particle pathline has a travel time, which was used to delineate the areas for 1-, 5-, 10-, and 20-year isochrones.

A.6 Southland SWRMA Assessment Using an AEM Approach (Gusyev et al., 2011)

The Coopers and Jacobson well fields supply the town of Gore for Gore District Council (GDC). GDC commissioned GNS Science to delineate SWRMAs for the two well fields (comprising four bores in total). A groundwater model was developed using GFLOW, which is a single layer, AEM steady-state model.

GFLOW supports three-dimensional particle tracking, but employs the Dupuit-Forchheimer approximation which ignores resistance to vertical flow. Additional features include areas of differing aquifer properties, horizontal barriers with resistance to flow (slurry walls), 3D flow near a partially penetrating well, local transient flow near a well (the Theis solution), steady-state interface flow in coastal aquifers, and PEST support for parameter optimisation.

A.6.1 Aquifer Type, Pumping Rate, Well Depth and Population Supplied

The shallow aquifer is unconfined and is located within the Quaternary glacial outwash and alluvial terraces of the Mataura River. This aquifer is referred to as the Knapdale groundwater zone.

The shallow aquifer is primarily recharged through the infiltration of rainfall, but it likely also receives recharge from the Mataura River and its tributaries, to which it is believed to be hydraulically connected. The Coopers and Jacobson wells all draw groundwater from the shallow unconfined aquifer. As an unconfined, transmissive aquifer, the Knapdale aquifer is regarded as being vulnerable to potential contamination from land-use activities.

The wells have a large diameter (1,500 mm) and draw water from shallow gravels (well depth around 7 m) in the Knapdale groundwater zone.

The pumping rates for the two Coopers production wells are fairly constant throughout the year with a mean abstraction of 2,850 m^3/day and peak abstraction rate of 5,157 m^3/day (May 2002 to September 2006). Subsequently, the mean abstraction increased slightly to 3,167 m^3/day with peak abstraction of 4,056 m^3/day from January 2006 to April 2007. Abstraction rates are similar for the two wells. Water levels in well #2 vary significantly in response to the pumping schedule, which may be attributable to lower hydraulic conductivity.

A.6.2 Uncertainty Analyses

The uncertainties in the mapped capture zones were addressed by quantifying the uncertainty associated with the aquifer porosity, hydraulic conductivity and recharge values used in the model. Aggregated SWRMAs (“time of travel” capture zones) have been produced for both the Coopers and Jacobson well fields by combining all capture zones produced during the uncertainty analysis.

A.6.3 Aquifer Boundary Conditions

Aquifer boundaries have not been represented.

A.6.4 Aquifer Confinement

The wells are screened in a shallow unconfined aquifer that is susceptible to contamination from land-use activities. It occurs within the glacial outwash and alluvial terraces of the Mataura River.

A.6.5 Representation of Temporal Fluctuations in the Piezometric Surface

A steady-state model was used, so no fluctuations are modelled.

A.6.6 Representation of SWRMAs

1-year and 50-year time of travel (TOT) were delineated using backward particle tracking in the GFLOW software.

Appendix B: Modelling methods

B.1 Uniform Flow Non-Spatial Analytical Methods

The basic process for assessing SWRMAs using uniform flow, non-spatial analytical methods is to first develop the system conceptualisation. This involves the following data collection:

- Static groundwater levels from bores surrounding the subject bore (or from all aquifers if the system is multi-layered).
- Review of lithology logs to determine sediment properties, in particular the presence of confining (or potentially confining) sediments, or lack thereof, in the profile. Also, knowledge of soils and vadose zone materials is useful.
- Review of any aquifer hydraulic properties (transmissivity, storativity, leakage and porosity) in the area. Aquifer testing of the subject bores is recommended to obtain robust estimates of aquifer properties.

Groundwater levels and associated bore locations obtained throughout the data collection process are used to inform groundwater contouring. The larger the data set, the better the accuracy of the contouring and therefore the smaller the uncertainty.

Using the available data, horizontal and vertical groundwater gradients are then developed:

- Horizontal groundwater gradients are estimated using the groundwater contouring mentioned above.
- Vertical groundwater gradients can be determined by obtaining the vertical difference between groundwater levels at the water table aquifer and in the pumped aquifer, and the interval between the base of the water table aquifer and the top of the pumped aquifer.

Horizontal and vertical transport velocities (in units of length/time) can be estimated based on groundwater gradients, the hydraulic conductivity of the aquifer system (from aquifer testing), and estimates of porosity. Darcy's law can be used to calculate the transport velocity in aquifer systems both horizontally and vertically, as follows:

$$Aquifer\ transport\ velocity = \frac{k}{\sigma}\frac{\Delta h}{\Delta L}$$

Where:	k	=	aquifer horizontal or vertical hydraulic conductivity (L/T)
	σ	=	aquifer transport porosity (dimensionless)
	Δh/ΔL	=	aquifer horizontal or vertical hydraulic gradient (dimensionless)

Using the above transport velocities, a broad-scale assessment of likely recharge zones for drinking water supplies can be obtained.

In order to determine the one-year travel time, the transport velocities calculated in this way can provide a conservative estimate of the up-gradient boundary. For across- and down-gradient boundaries, further refinement is needed to understand the "stagnation" points at which flow may be induced towards the bore. This is assessed through calculating the radius of influence of bores at the maximum likely consented daily pumping rates from within which pumping will induce altered hydraulic gradients towards to bore. For contamination to migrate 'up gradient', pumping induced drawdown would need to reverse the natural hydraulic gradient.

The above can be achieved with the use of a suitable analytical model. For example, in Canterbury, the aquifer system is typically a multi-layered system with an unconfined water table aquifer. Using the ‘11’ series equations of Hunt (2012) typically results in reasonable estimates of aquifer response. However, without a suitable conceptual model, an incorrect analytical model may be chosen for assessment purposes which may result in erroneous predictions of pumping-induced drawdown and associated groundwater flow changes. The likely capture zone, once natural groundwater gradients and altered pumping-induced gradients have been taken into consideration, can then be used to delineate flow boundaries.

B.2 AEM Modelling

As is the case with other tools, the first step with Analytical Element Modelling (AEM)is to develop the conceptual model of the area of interest. In order to do this, key features should be mapped together with topographic data such that elevation information can be applied for the features of interest.

Development of the conceptual model of the aquifer system, and parameterisation of this, will include consideration of:

- Base elevation (base of the aquifer system, e.g. a no flow boundary);
- Aquifer thickness (full aquifer material thickness above the base, regardless of saturation);
- Hydraulic conductivity;
- Porosity; and
- Recharge, including rainfall, irrigation, MAR (or similar) and any temporary recharge from ephemeral streams.

Surface water features are represented using line sinks, incorporating the start and end heads at either end of the line sink. Near field features (those closer to the sources being assessed) should be defined in more detail than far-field features. For far-field features, only major surface water features need to be defined, as their purpose is to control conditions outside of the area of interest. However, near-field features need to be defined with more link sinks, such that the geometry and groundwater inflows and/or outflows can be incorporated more accurately. Lake features can be defined as a constant head line sink, with equal starting and ending heads.

In addition to starting and ending elevations, it is also necessary to define:

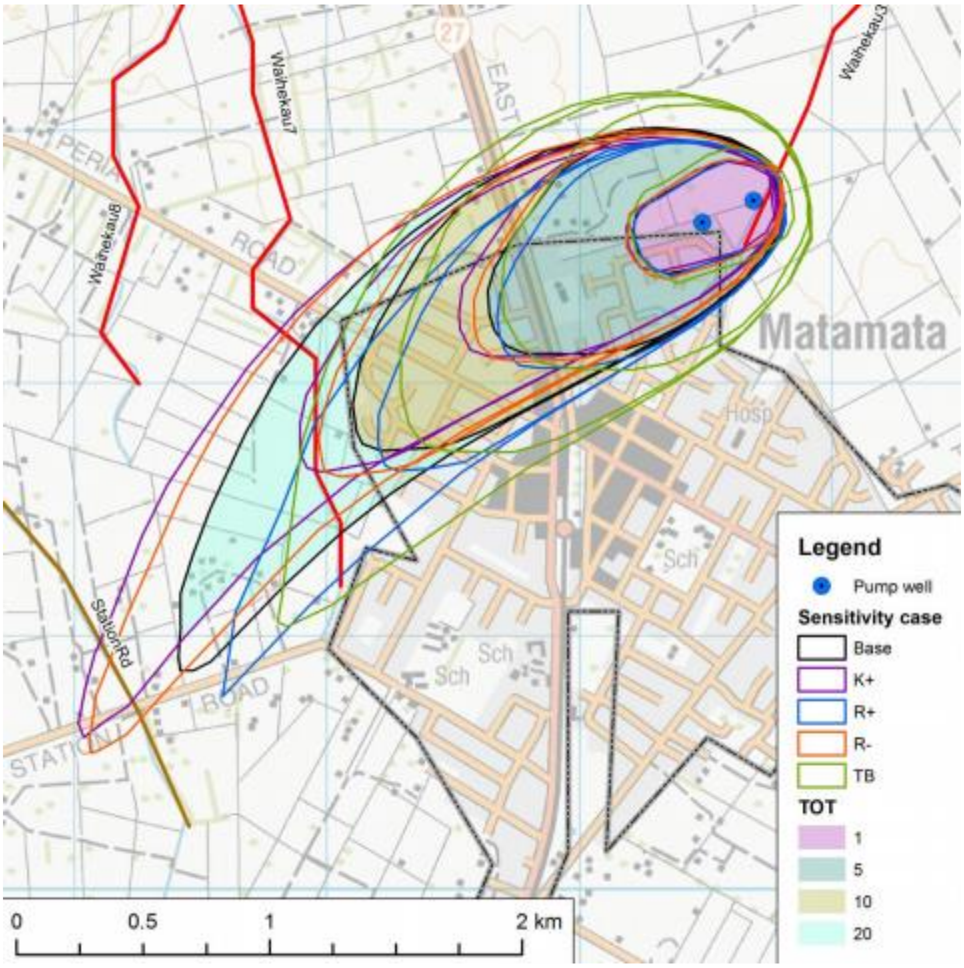
- Resistance to flow, calculated as bed thickness divided by vertical hydraulic conductivity of the bed; and
- Line sink effective width. Guidance as to how to set the effective width is provided in Badv and Deriszadeh (2005).

If there are differences across the model domain (for example, a change from unconfined to confined conditions, or a change in hydraulic conductivity between two areas), these can be built into the model through defining inhomogeneity and isotropy.

Having set up and run the model, the next step is the assessment of the results and calibration. This assesses whether the model adequately matches measured conditions. The results of this act as a guide to altering input parameters and obtain an improved fit.

The model can then be used to determine the source risk management area through backward particle tracking and scenario testing.

The results are dependent on several parameters, most of which are not well known. A sensitivity approach can also be used to determine which parameters the model is most sensitive to, and (if necessary) obtain further information to constrain the model. Extension of the sensitivity approach into stochastic methods allows for the distribution of input parameters to be applied to the model to obtain a distribution of model outputs. In this way, it is possible to determine a range of SWRMAs, and overlay these to develop an envelope of zones, an area that incorporates the uncertainties in the data. The approach might be (for example) to take the reasonable minimum and maximum values for porosity, hydraulic conductivity, and recharge.



Capture zone delineation for all sensitivity scenarios

B.3 Numerical Modelling

This approach assumes the use of an existing groundwater model. Producing a new numerical groundwater model for individual SWRMAs would be both time-consuming and costly, and may only be considered if there are numerous SWRMAs within a reasonably small spatial area, or if a greater degree of confidence is required with regards to the defined zones.

The following sections do not provide guidance for building a numeric groundwater model: this is a skill requiring considerable training and experience. However, the aim is to outline the important factors to consider when either building a numerical model or refining an existing model, for the purpose of delineating SWRMAs.

- Model setup and/or refinement:
  - Obtain background information and understand the conceptual model for each site using the same approach for other modelling techniques. This is essential for both the preparation of a new model and the refinement of existing models.
  - Ensure the model reflects the true vertical extent of the aquifer system and includes all likely formations (aquifers and aquitards) that are known to exist. Refine aquifer properties based on any information available, usually from aquifer testing.
  - Model boundary extent should be sufficient to ensure that the modelled effects do not extend beyond boundaries.

- Setup model boundary conditions, including constant head boundaries (e.g. coast), variable head boundaries (e.g. rivers), and recharge or no flow boundaries. River boundaries are particularly important if the source being modelled is in the water-table aquifer, or is otherwise heavily influenced by surface water features.
- Grid discretisation and/or refinement is likely to be required around wells to ensure that modelled groundwater level changes reflect reality. Changes in groundwater level are likely to be greatest within the cells in and near the production well, and the high local drawdown due to pumping needs to be modelled to ensure the vertical gradients are adequately represented.
- Calibration is important to assess how closely the models reflect reality. However, it is acknowledged that this process is often highly time-consuming and costly. For the purposes of SWRMA modelling, one option is to use conservative values for model inputs (e.g. aquifer parameters, constant head boundaries, etc.) that result in relatively large predicted travel distances of contaminants due to rapid migration from likely contamination sources.

- Model sensitivity and/or stress testing:

  Once a model has been set up, refined, and boundary conditions updated (if necessary), it is essential to test model uncertainty and sensitivity. Because of the imperfect knowledge of the data used to develop the model, as well as uncertainties in the model itself, predicting the location of the zones is inherently uncertain.

  Test, in a simplistic manner, the sensitivity of the results as follows:

  - Adjusting model stresses and parameters by ±25% as advised in Moreau *et al.* (2014b)
  - Reducing aquitard extent (both horizontal and vertically), if relevant.
  - Modelling local aquitard punctures (if relevant), as these will impact the preferential flow pathways between model layers should aquitards be non-continuous.
  - Testing the impact of “leaky bores” as some bores, if constructed badly, can provide a conduit through which contaminated water can be transmitted quickly from the uppermost layer (the water-table aquifer) to the abstraction aquifer.
  - Altering model recharge estimates (both land surface and river recharge) to assess the sensitivity of model results to these parameters.