Envirolink Tools Project – Capture Zone Delineation – Technical Report

M. Moreau
C. Daughney
C. Tschritter
S. Cameron
M. Gusyev

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M. Moreau GNS Science, Private Bag 2000, Taupo 3352

S. Cameron GNS Science, Private Bag 2000, Taupo 3352

C. Daughney GNS Science, PO Box 30 368, Lower Hutt 5040

M. Gusyev C/- GNS Science, PO Box 30 368, Lower Hutt 5040

C. Tschritter GNS Science, Private Bag 2000, Taupo 3352

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CONTENTS

TABLES

FIGURES

APPENDICES

ABSTRACT

For regional authorities to effectively manage land and water resources, they require information on how land use will affect the quality of water bodies. Key to this understanding is knowledge of the area of land from which a water body, or feature, receives its water – the capture zone (CZ) or time-dependent protection zone (PZ) – and potential contamination sources within these areas.

Two documents have been prepared to assist in the delineation of the CZ and PZ for a range of features that receive inflow from groundwater: wells, springs, and groundwater-fed lakes and wetlands, collectively referred to hereafter as hydrogeological features (streams, rivers and features that do not receive inflow from groundwater are not considered in this study). The guideline document leads the user through the process of deciding which method(s) are suitable for CZ and PZ delineation to meet their needs. It also provides equations and resources to undertake delineation. The technical document (this document) provides a literature review covering: CZ and PZ terminology; criteria, methods and thresholds for delineation; the treatment of associated uncertainty; and example New Zealand case studies.

The following zones (and associated criteria and thresholds) are recommended for wells, springs, and groundwater-fed lakes and wetlands in New Zealand:

- An immediate PZ, delineated by a minimum distance of 5 m around the hydrogeological feature.
- A PZ surrounding the immediate PZ, specifically to guard against microbial contamination. This PZ is to be either: a safeguarding distance; or a one-year travel time. The travel time refers to the time it takes groundwater to flow from a given point to the feature. This zone is designed to protect against bacterial and virus contamination in typical New Zealand settings.
- A CZ surrounding the PZ, for protection from other types of contaminants. This CZ is to be defined by either: a catchment or hydrogeological boundary; or a travel time of either 10 or 50 years. This CZ protects the hydrogeological feature from any contaminant that enters the groundwater system as a result of land use activity and then migrates in the aquifer towards the hydrogeological feature (the possibility of contaminant degradation or sequestration is not considered).

Delineation of such zones is to be undertaken by one of seven methods, which are listed in order of increasing complexity as follows: 1) the arbitrary fixed radius method, 2) hydrogeological mapping, 3) the calculated fixed radius method, 4) the simple analytical method, 5) the simplified variable shapes/hybrid method, 6) semi-analytic modelling; or 7) numerical modelling. A targeted approach is recommended whereby the appropriate delineation method is selected based on available data, resources, level of accuracy, budget and expertise requirements. However, when complex aquifer systems are expected and/or features supplying more than 500 people, the use of either modelling method is recommended.

The delineation methods were applied in five case studies selected to be representative of typical New Zealand hydrogeological settings, to investigate the practical aspects of delineation and to compare resulting zones. The case studies showed that all seven of the above-listed methods could be used for delineation at a well or spring. Only the hydrogeological mapping and numerical modelling methods were applicable for wetlands and lakes. Regardless of the method employed, the development of a good conceptual

hydrogeological understanding prior to delineation enables meaningful refinement of the obtained shapes. In some cases, this understanding was also used to validate the use of a simpler method against another (e.g. if surface water contribution is expected the hybrid method should be used instead of the uniform flow equation). The latter comment does not apply to modelling methods because they can integrate complexities. Large differences in the shape, size and orientation of the zones occurred where groundwater flow direction was not well constrained. The arbitrary fixed radius method is more conservative for confined than for unconfined aquifers, particularly for high yielding features. For all methods, it is recommended that uncertainty in zone boundaries should be accounted for by a consistent and easily applied sensitivity approach, in which model input parameters are varied by ±25%.

KEYWORDS

New Zealand guidelines, protection zone, capture zone, drinking-water supply protection, land use, groundwater wells, springs, groundwater protection, technical report.

1.0 INTRODUCTION

1.1 BACKGROUND

Many countries rely on groundwater as a source of public water supply. As such, the deterioration in groundwater quality is a major global concern. In most instances, the deterioration has anthropogenic origins and is caused by leaching of nutrients and/or contaminants derived from land use activities. For example, nitrate and pesticides can be introduced to groundwater as a result of agricultural land use activities, and organic compounds, such as chlorinated hydrocarbons, can be introduced to groundwater as a result of commercial and industrial practices. However, the slow groundwater movement in most aquifer materials, with the exception of karstic environments, means there can be a considerable time lag from when a contaminant enters the aquifer system to when it arrives at a groundwater discharge point such as a spring, lake, wetland or pumping well. It is recognized that this time lag can be used to take appropriate remediation to prevent or minimise the impact of the contaminant at the discharge point.

In the international context, various methods have been developed to estimate the area that contributes groundwater (and potentially a contaminant) to a discharge point, commonly referred to as the groundwater capture zone (CZ). Several countries and states have developed guidelines for CZ delineation, subject to the particular hydrogeological setting, availability of resources and the regulatory environment (e.g. US EPA, 1994; Carey *et al.,* 2009, Ministry of Environment of British Columbia, 2004; WHO, 2006).

In New Zealand, the requirement to consider the CZ of a drinking water supply is prescribed in the National Environmental Standard (NES) for drinking water supply sources (Moreau *et al.,* 2014a). Regional authorities also have responsibility to ensure sustainable management of hydrogeological resources under the Resource Management Act (Parliament of New Zealand, 1991). However, there is currently no clear guidance on how to identify a CZ for different hydrogeological features and settings in New Zealand. Developing a standardised approach for delineating CZs for New Zealand settings will assist in the sustainable management of groundwater resources and surface waters that receive inflow from groundwater. Defining the CZ for a hydrogeological feature is an important component of the management process.

To address the absence of national guidance, the Ministry of Business, Innovation and Employment (MBIE) contracted GNS Science and Environmental Science and Research (ESR) to undertake an Envirolink Tools Project to develop guidelines for the delineation of CZs for selected types of hydrogeological features, including wells, springs, and groundwater-fed lakes and wetlands in typical New Zealand settings. The project aim was to develop guidelines for delineating the CZ of a feature and the microbial protection zone (PZ) that occurs within the CZ. In addition, limitations and uncertainties associated with CZ and PZ delineation methods and extents were to be defined.

The project outputs consist of two documents:

1) Capture Zone Delineation – Guidelines document (Moreau *et al.,* 2014a)

   The purpose of this document is to provide background information and guidance in selecting an appropriate method for delineating the CZ for a given setting. A range of methods is discussed to address varying user needs and constraints, including precision requirements and restrictions on data and resource availability. The

Guidelines lead the user through the process of deciding which method or methods are suitable for meeting their needs. The regulatory context driving the need for the New Zealand CZ delineation guidelines is discussed in Section 1.2 of the Guidelines (Moreau *et al.,* 2014a).

2) Capture Zone Delineation – Technical Report (this document)

This report provides supporting information for the Guidelines, including the following:

- a comprehensive literature review of existing terminology and guidelines for CZ and PZ delineation, including a discussion of methods and criteria;
- a list of available software and tools for CZ and PZ delineation;
- a list of typical New Zealand aquifer materials and their hydraulic properties; and
- case studies of CZ and PZ delineation in New Zealand, based on different methods and for different types of hydrogeological features such as wells, springs and groundwater-fed lakes and wetlands.

Together these two documents are designed to provide clear, sound and defensible guidance on methods for CZ and PZ delineation in order to assist with water management and implementation of the NES. Both documents are directed towards end users such as regional and unitary councils, governmental authorities, consultants, research organisations, water suppliers and the informed public. They have been prepared by GNS Science and ESR with a users' advisory committee consisting of representatives from Waikato Regional Council, Environment Canterbury, Environment Southland, Greater Wellington Regional Council, Tasman District Council and Horizons Regional Council.

1.2 SCOPE OF THIS DOCUMENT

This project focuses on CZ and PZ delineation for only selected types of features, namely wells, springs and groundwater-fed lakes and wetlands. These are collectively referred to in this document as hydrogeological features, to reflect the fact that they receive all or some of their inflow from groundwater. This project does not consider CZ or PZ delineation for streams or rivers, although it is acknowledged that certain reaches may receive inflow from groundwater. Features that do not receive any inflow from groundwater at all are also excluded from consideration in this project.

The CZs and PZs produced using the methods evaluated in this project will represent, in theory, the entire land area from which a spring or well receives its water. In contrast, lakes and wetlands may receive only a fraction of their total water supply from groundwater, with the remaining inflows being sourced from rivers, direct rainfall and constructed channels, drains and so forth. The CZs and PZs produced using the methods evaluated in this project, will represent the land area from which groundwater is supplied to lakes and wetlands, but the land area from which surface water is supplied these features is not considered. In other words, a lake or wetland may receive water inflows (i.e. from surface water) from a larger and/or different area than is delineated based on the groundwater CZs and PZs that are delineated in this project. Where a lake or a wetland receives inflow from groundwater and surface water, both groundwater and surface water CZs must be considered in order to implement appropriate land and water management practices (Davies *et al.*, 2000).

This project does not specifically discuss contaminant attenuation or sequestration within the delineated CZs and PZs. It is also assumed that microbes enter the aquifer system during groundwater recharge and are advectively transported towards the groundwater discharge point. In fact, the nature of a contaminant will have impact on its attenuation or sequestration during transport, and therefore the time of travel that will define the PZ. These attenuation and sequestration processes can be addressed through specific contaminant transport modelling, however this subject is beyond the scope of this project.

The CZ and PZ delineation methods presented in this document are directed towards mapping the superficial projection of a 3-dimensional (3D) volume. This has implications for defining a CZ or PZ in a complex multi-layered aquifer where the surface projection may have a different size and shape for each layer (Frind *et al.,* 2002).

The CZ and PZ delineation methods introduced here are assessed for steady-state flow conditions (although a transient pumping scenario was included in the Pauanui case study as an example). The omission of transient conditions means that a situation such as the reversal of the natural hydraulic gradient due to pumping is not considered. The omission of transient flow conditions also has implications for CZ delineation for groundwater-fed lakes and wetlands, where seasonal variations in groundwater flow direction and velocity and the extent of both the feature and the corresponding CZ may be significant (Davies *et al.*, 2000). Evaluation of transient CZs or PZs requires/warrants transient numerical modelling, but this is outside the scope of this project.

In karstic systems, high groundwater velocities and preferential pathways further complicate the zone delineation process. In some cases, extensive site-specific data acquisition may be necessary before undertaking zone delineation. Although alternative methods suited for karst delineation are referenced in this document (see Section 2.2.2.1), it does not fully cover CZ and PZ delineation in karstic environments.

It is beyond the scope of this document to provide an implementation plan for the guidelines (for instance at what scale, national or regional, these should be implemented). An example of management within the zones is given in Section 2.3 of the Guidelines (Moreau *et al.,* 2014a).

2.0 LITERATURE REVIEW

2.1 DEFINITIONS

The term “Capture Zone” was introduced by Keely and Tsang (1983) to define the entire area of an aquifer that contributes groundwater to a pumping well. Subsequently, the focus of the international literature on CZ delineation has been for drinking water supply wells, in particular municipal water supply wells. A selection of published definitions is presented in Table 1. Generally, the definitions involve two land surface area types: the CZ and/or the PZ. A schematic example of the CZ and PZ for a pumping well in an idealised homogeneous aquifer is shown in Figure 1. The CZ encompasses the entire land area that contributes groundwater to a pumping well, bounded by the groundwater divide at which groundwater flow is diverted into the pumping well from the surrounding aquifer. The PZ is bound by a specific travel time from a point on the land surface to the pumping well. It is primarily used for protection of a water supply well from contamination, allowing for attenuation in the aquifer and/or providing a monitoring zone. Two PZs are depicted on Figure 1: the 1-year and 5-year time-of-travel (TOT) PZs. The choice of travel time depends on the desired level of protection, the contaminant type, and/or the hydrogeological conditions. For instance in the UK, a travel time of 50 days is used to protect for rapidly degrading toxic chemicals and water-borne disease (SPZ1), and a TOT of 400 days (SPZ2) is used to provide delay, dilution and attenuation of slowly degrading pollutants (Table 1). The PZ may also be arbitrarily set for a specific time, as is the 10-year PZ is used in Australia (SPZ2), or it may be defined strictly on distance (e.g. 50 m radius SPZ1, Australia) (Table 1). Different terminology may be used to define the area supplying groundwater to a feature. For example the US EPA (1987) defines the “zone of contribution” (ZOC), the “zone of influence” (ZOI), analogous to the cone of depression of a pumping well, and the “zone of transport” (ZOT), equivalent to the PZ (Figure 2). For comparison, Carey *et al.* (2009) defines concentric CZs and PZs referred to as SPZ1, SPZ2 and SPZ3 (Figure 3). The areal extent of the CZ/PZ can increase with time if hydrological conditions change. For example, the groundwater divide near the well can be shifted due to extensive groundwater abstraction, thus increasing the size of the CZ/PZ.

The following definitions were adopted in this document for clarity and to meet the specific objectives of this project:

- **CZ**: The total source area that contributes groundwater to the hydrogeological feature (well, spring, or groundwater-fed lake or wetland).
- **PZ**: The portion of the CZ that has a defined travel time for groundwater to arrive at the hydrogeological feature.
- **Zone**: Collective term to qualify items relevant to both CZs and PZs.

For the purpose of zone delineation, both pumping wells and springs can be regarded as point features with a specified groundwater discharge. Lakes and wetlands, however, cannot be regarded in the same manner as they do not necessarily have a point source for groundwater inflow.

Table 1: Commonly used terminology in protection of drinking water supply wells.

Source	Term	Definition
US EPA (1987)	Wellhead Protection Area	The surface and subsurface area surrounding a water well or well field, which supplies a public water system, through which contaminants are reasonably likely to move toward and reach such well or well field.
	Zone of Influence	The area within which the water table / piezometric surface is under the influence of the pumping of a well.
	Zone of Contribution	The entire area that recharges or contributes water to the well or well field
	Zones of Transport	The zones identified by contours of equal travel time (isochrones)
	Time-of-Travel	The time required for a contaminant to move in the saturated zone from a specific point to a well.
Carey *et al.* (2009)	SPZ1 – Inner Source Protection Zone	The zone is defined as the 50-day travel time from any point below the water table to the source. This zone has a minimum radius of 50 metres.
	SPZ2 – Outer Source Protection Zone	The zone is defined by a 400-day travel time from a point below the water table.
	SPZ3 – Source Catchment Protection Zone	The zone around a feature within which all groundwater recharge is presumed to be discharged at the source. In confined aquifers, the recharge area may be displaced some distance from the feature.
	Hydraulic Capture Zone	The zone is defined as the SPZ1, SPZ2 or SPZ3 derived through the modelling process.
ANWQMS (1995)	Wellhead Protection Zone	The part of the groundwater flow system which contributes to the discharge of the wells. This includes the cone of influence defined by drawdown to the water table, and the flow field up-gradient not affected by drawdown.
	SPZ1	The zone is defined as the 50 metres radius.
	SPZ2	The zone is defined by a 10-year groundwater residence time.
	SPZ3	The zone is defined where greater than 10-year residence time is available. This is usually the "catchment area of the contributing aquifer".
Fetter (1994)	CZ	A CZ consists of the up-gradient and down-gradient areas that will drain into a pumping well. If the water table is perfectly flat, the CZ will be circular and will correspond to the cone of depression. However, in most cases the water table is sloping, so the CZ and the cone of depression will not correspond. The CZ will be an elongated area that extends slightly down-gradient of the pumping well and extends in an up-gradient direction. CZs are controlled by the time that is takes for water to flow from an up-gradient area to the pumping well. If sufficient time elapses, the CZ will eventually extend up-gradient to the closest groundwater divide.
Keely and Tsang (1983)	CZ	The entire area of the aquifer that contributes groundwater to a pumping well.
USGS (1993)	Area Contributing Recharge	The area in which water enters the groundwater system at the water table, flows and is discharged from the feature.

2.2 CRITERIA AND METHODS FOR ZONE DELINEATION

Reviews of available techniques for zone delineation have been undertaken by several authors and/or organisations in New Zealand (Williams *et al.,* 2005; Hadfield and Nicole, 2000; Pattle Delamore Partners, 2012) and elsewhere (US EPA, 1994; WHO, 2006; Carey *et al.,* 2009). As a body of work, these reviews identify the main CZ delineation methods of varying complexity from simple arbitrary methods up to sophisticated numerical groundwater flow models. The criteria and methods for zone delineation were originally classified by US EPA (1987) for drinking water production wells. Subsequent publications introduced additional or variant methods and proposed criteria for selection of an appropriate method for given situation(s). The selection and application of a suitable criterion and method depends on a number of factors including credibility, ease of use, data availability, hydrogeological setting, and uncertainty.

2.2.1 Criteria for zone delineation

Zone delineation criteria refer to the technical and non-technical (e.g. administrative) considerations on which to base the actual delineation of a zone (US EPA, 1987). Technical considerations depend on the degree to which a criterion incorporates the processes affecting the likelihood of a water particle (or contaminant) reaching the hydrogeological feature of interest. The non-technical considerations are based on the desired level of protection and management for the hydrogeological feature of interest. The five following criteria are defined (US EPA, 1987; Carey *et al.,* 2009; Hadfield and Nicole, 2000; WHO, 2006):

- The **distance** criterion means the zone is delineated using a radius or dimension from a point feature. The disadvantage of the distance criterion is that it does not incorporate the process of groundwater flow. The distance criterion is commonly selected as a first step in zone delineation, and is used for generic delineation of microbial PZs (e.g. SPZ1 in Australia and the UK; (Table 1).
- The **drawdown** criterion refers to the extent to which a pumping well creates drawdown or a "cone of depression" (Figure 2), the limit of which defines the ZOI. In the common setting of a sloping water table, there is a difference between ZOI and the ZOC. In such cases, the use of the drawdown criterion will lead to a smaller zone extent down-gradient and larger zone extent up-gradient of the pumping well. The drawdown criterion is not relevant for hydrogeological features such as springs, lakes and wetlands.
- The **TOT** criterion refers to the maximum travel time for a water molecule or a contaminant to reach the hydrogeological feature of interest. Conceptually, TOT incorporates advective movement of groundwater and dispersion of contaminants dissolved in or carried by the groundwater.
- The **flow boundaries** criterion refers to the use of identified locations that control groundwater flow (e.g. groundwater divides, geological boundaries and/or hydraulic boundaries). Flow boundary criteria are useful for small aquifer systems where the CZ may be small and the "cone of depression" quickly intersects the physical limits of the aquifer. Use of flow boundary criteria is not recommended if the CZ is likely to be much smaller than the areal extent of the aquifer, e.g. in larger aquifers with areal extents of 10 – 100 km. An exception may be when the hydrogeological feature is located relatively close to the aquifer boundary or some other hydraulic boundary.

- The **assimilative capacity** criterion is based on the capacity of the aquifer to dilute or otherwise attenuate contaminant concentrations to acceptable levels before they reach the hydrogeological feature under investigation. Assimilative capacity depends on hydrogeological (dispersion and advection) and biological (biodegradation rates) factors that can be assessed using quantitative models (Chapelle and Bradley, 1999). For example, sand aquifers may provide a much better microbial attenuation compared to fractured rock aquifers.

2.2.2 Methods for zone delineation

2.2.2.1 Overview and relationship between methods and criteria for zone delineation

The US EPA (1987) described six methods for zone delineation for a pumping well or a flowing spring: the arbitrary fixed radius, the calculated fixed radius, simplified variable shapes, analytical methods, hydrogeological mapping, and numerical flow/transport modelling. The arbitrary fixed radius method defines the CZ or PZ as a circular zone with a radius that is selected arbitrarily and is centred on the hydrogeological feature of interest. The calculated fixed radius method is similar, except that the radius of the zone is determined using a simple equation that relates groundwater discharge rate to aquifer thickness, porosity and time. The simple analytical methods consist of solving analytical flow equations for defined hydrogeological conditions to obtain the surficial shape of the zone. Simplified variable shapes and the hybrid method (which were developed by Paradis and Martel in 2007) are a combination of shapes obtained through analytical equations. Hydrogeological mapping involves the use of multi-disciplinary information sources to delineate zones. Computer modelling methods involve the application of more complex numerical simulations of groundwater flow and transport. In 1994, the US EPA proposed a reclassification of these six methods into four categories: geometric methods, simple analytic methods, hydrogeological mapping, and computer modelling (Table 2).

It is beyond the scope of this document to fully cover the special case of karstic systems, however, alternative methods such as the use of vulnerability mapping based on epikarst, protective cover, infiltration conditions and karstic network (Doerfliger and Zwahlen, 1997) or the analysis of flow recession curve data (Civita, 2008) may be considered for zone delineation. The review from Kaçaroğlu (1999), listed in the references, provides some case examples and considerations around groundwater protection specific to these systems.

Relationships between the criteria and methods for zone delineation are summarized in Table 2. The TOT criterion can be used with various methods ranging from the calculated fixed radius to numerical modelling, whereas flow boundary criteria apply only to hydrogeological mapping. A CZ (as defined in this study) can only be delineated using the flow boundary criteria (Table 2). This is because CZ delineation encompasses the entire aquifer area that contributes groundwater to a feature and the other criteria do not lend themselves to such delineation. However, provided the TOT criterion is realistic and sufficient, a zone that is delineated on the basis of the TOT criterion can be used as a proxy for the CZ. Such an approach is proposed in this study.

Table 2: Methods and criteria for zone delineation.

Nomenclature			Criteria				
US EPA (1994)	**US EPA (1987)**	**This study**	**Distance**	**Drawdown**	**TOT**	**Flow boundary**	**Assimilative capacity**
Hydrogeological mapping	Hydrogeological mapping	Hydrogeological mapping	N/A	N/A	N/A	CZ	N/A
Geometric method	Arbitrary fixed radius	Arbitrary fixed radius	PZ	N/A	N/A	N/A	N/A
Geometric method	Calculated fixed radius	Calculated fixed radius	N/A	PZ	PZ, CZ	N/A	N/A
Geometric method	Simplified variable shapes	Simplified variable shapes	N/A	N/A	PZ, CZ	N/A	N/A
N/A	N/A	Hybrid (Paradis and Martel, 2007)	N/A	N/A	PZ, CZ	PZ, CZ	N/A
Simple analytical methods: • TOT using Darcy's Law and flow net, • Cone of depression/TOT, • TOT with sloping regional potentiometric surface, • Inter-aquifer flow and TOT, • Uniform flow equation, • Thiem equilibrium equation, • Non-equilibrium equations, • Vermont leakage and infiltration methods for bedrock wells receiving recharge from unconsolidated overburden, • Equations for special situations	Analytical methods	Simple analytical methods	N/A	PZ	PZ, CZ	N/A	PZ
Computer modelling method	N/A	Analytical Element Models	N/A	PZ	PZ, CZ	N/A	PZ
Computer modelling method	Numerical Models	Numerical Models	N/A	PZ	PZ, CZ	N/A	PZ

“N/A” stands for “Not applicable”.

Tracers (stable isotopes, age tracers, organisms, salts and dyes; Appendix 1, WHO, 2006) are neither a method nor a criterion that can be used to delineate a zone. However, tracers are useful tools for evaluation of groundwater flow pathways, mixing volumes and travel time, which can then be used to validate a zone that has been delineated using one of the above-listed methods, or to calibrate models that can be used to derive the zone. Tracer testing and interpretation requires skill and experience in order to obtain meaningful, unambiguous results.

2.2.2.2 Arbitrary fixed radius

Description: An arbitrary radial distance around the hydrological feature is set. The resulting zone is a circle that is centred on the hydrogeological feature. Although the zone radius may not be based on any scientific principle, the distance criterion can be applied based on generalised hydrogeological considerations and/or professional judgement (US EPA, 1987). For example, the zone radius can be set based on previous studies (IDEM, 1999) or on management plans, taking into account the size of the water supply, the hydrogeological context, land use activities surrounding the supply, and the amount of information available on the system (IDEM, 1999; WHO, 2006). Typical radial distances recommended or applied in previous studies range from 10 m to 300 m (Carey *et al.,* 2009).

Resource requirements: No site-specific data are required. Application of the method requires little expertise to implement, once the radial distance has been specified.

Advantages: It is the easiest delineation method to apply. It is inexpensive and quick to apply, particularly to a large number of features. It can be used as an initial estimate of a CZ or PZ until more sophisticated approaches are applied or until more hydrogeological data are available.

Limitations: This method does not include any consideration of groundwater flow direction or velocity. The approach can be over-protective if large radii are applied or under-protective if small radii are applied.

2.2.2.3 Hydrogeological mapping

Description: Hydrogeological mapping involves establishing groundwater flow boundaries that encompass the area of potential groundwater supply to a hydrogeological feature. The aim is to establish groundwater flow boundaries, locate recharge areas, and identify confining layers (as depicted by lithological or depositional changes) that inform the potential extent of the zone. Such mapping can integrate hydrogeological, geological, geomorphic, geophysical, geochemical and tracer datasets. It is applicable to both confined and unconfined conditions. In many cases, this method is used as a prelude to analytical or numerical modelling.

The approach used in hydrogeological mapping depends on the type of feature under consideration. For a well or a spring, hydrogeological mapping involves determination of the direction of groundwater flow, which is then combined with information on flow boundaries and recharge areas to delineate the zone. For lakes and wetlands with groundwater contribution, hydrogeological mapping consists of groundwater catchment delineation. Alternatively, the areal extent of the aquifer contributing to the lake or wetland can be used to delineate zones. Typically, for an isotropic aquifer that has a thickness equal to the length of the lake or wetland, it is expected that groundwater inflow would be derived from only the upper half of the aquifer (Davies *et al.*, 2000). If the length of the lake or wetland is five to ten times greater than the aquifer thickness, it is then expected that groundwater inflow will be drawn from the whole thickness of the aquifer. It has been proposed to use twice the length of the lake or wetland as the width of the zone (perpendicular to the groundwater flow direction) (Davies *et al.*, 2000).

***Resource requirements**:* Useful datasets include: geological, topographic and potentiometric surface maps (or discrete water level measurements around the feature), aquifer test data, well logs, geophysical surveys and interpretation (at the relevant scale), tracer tests results and hydrochemistry. Topographic contours can be used to define surface water drainage divides, which can be used as a proxy for groundwater catchment boundaries. Topographic data can also identify springs and fractures which constitute portions of the groundwater flow system. Groundwater chemistry can be used to identify specific rock types or areas supplying groundwater to the feature and flow paths. Comparison of groundwater and surface water levels and chemistry can be used to assess whether the systems are directly connected. Tracer techniques, crucial in carbonate/karst aquifers, identify preferential flow pathways and can be used to derive flow velocities under conduit or fracture flow conditions (IDEM, 1999; Carey *et al.,* 2009). In its simplest form this method requires a low to moderate level of expertise to implement; however, it may require a relatively high level of user expertise if multiple datasets need to be compiled and interpreted.

***Advantages**:* This method works well in environments with near-surface flow boundaries and highly anisotropic aquifers that are not easily modelled, especially where the assumption of porous flow implicit in other methods is invalid (e.g., karst or fractured rock aquifers). This method can be used alone or to support other methods. For lakes and wetlands with groundwater contribution, hydrogeological mapping is the only alternative to modelling.

Limitations: This method is not compatible with the TOT criterion, and will provide PZ delineation only if used in conjunction with tracer test results, where groundwater velocities can be factored into the delineation. For CZ delineation, this method may not work well in thick or large aquifers because it is likely to define large zones that may not be manageable. An exception may be when the hydrogeological feature is located relatively close to the aquifer or hydraulic boundary.

2.2.2.4 Calculated fixed radius

Description: This method consists of delineating a cylindrical zone around the feature. This cylindrical zone represents the volume of groundwater discharged from the feature over a given time period (Figure 4). It can be used for both PZ and CZ delineation, although the associated equations differ slightly.

For CZ and PZ delineation, this volume is translated into the radius of the cylindrical zone through the following two analytical equations:

$$r = \sqrt{\frac{Qt}{\pi n b}} \quad (1)$$

(from US EPA, 1994; Carey *et al.,* 2009)

Where Q [L^3/T] is the groundwater discharge rate (e.g. the pumping rate for a well), t [T] is the selected time, n [dimensionless] is the aquifer porosity and b [L] is the saturated thickness of the aquifer or the length of well screen. The underlying assumptions of this equation are: one-dimensional (radial) flow, aquifer homogeneity and isotropy, laminar Darcian flow, steady-state conditions, and absence of regional hydraulic gradient. In the case of partially penetrating wells, using the screened interval rather than the saturated thickness of the aquifer will result in an over-estimate of the zone volume, and as such will be more conservative. Because time is a variable in this equation, it only applies for PZ delineation. Although conceptualised in 3D, this equation should be only used to delineate 2-dimensional (2D) PZ.

The circular zone defined by the recharge equation represents the well's CZ, as follows:

$$r = \sqrt{\frac{Q}{\pi \times Recharge}} \quad (2)$$

where Q [L^3/T] is the pumping rate and the *Recharge* is the recharge rate [L/T] (Carey *et al.,* 2009).

For PZ delineation in an unconfined aquifer, Equation 1 should be applied in conjunction with the Recharge Equation 2. This is because the PZ obtained from Equation 1 may be larger than the CZ obtained from Equation 2, which poses a conceptual discontinuity[1]. In this situation the smaller recharge equation (2) zone should be adopted as the PZ.

For PZ and CZ delineation in a confined aquifer Equation 1 should be used, with an appropriate time proxy for CZ delineation (see sections 3.2.2 and 3.2.3). It is not appropriate to apply Equation 2 in a confined aquifer because recharge will not occur in the vicinity of well.

Resource requirements: Well/spring flow rate, aquifer porosity, saturated aquifer thickness (or open or screened interval of the well) and travel time to the well are needed to apply the method for PZ delineation. Groundwater discharge and recharge rates are needed for CZ delineation in an unconfined aquifer setting. An open-source, calculated fixed radius toolkit is available from the web either as a python code or a Geographical Information System (GIS) toolkit (GNS Science Groundwater capture zone GIS toolkit; Toews, 2013). A freely available Microsoft Excel (2010) spreadsheet was also developed to compare zones obtained using the arbitrarily fixed, the calculated fixed radius, the recharge and the uniform flow equations (the groundwater flow is assumed to be a straight line defined as the x-axis). Relevant input parameters must be infilled by the user (CZ_delineation_simple_methods spreadsheet, www.gns.cri.nz).

Advantages: This method is easy to apply, relatively inexpensive and requires limited technical knowledge. It provides an increase in accuracy over the arbitrary fixed radius method. This method is most appropriate for confined aquifers with no vertical leakage from overlying layers and less suitable for unconfined aquifers because the method assumes a fixed saturated thickness.

Limitations: This method may be reasonably informative and conservative provided the underlying assumptions are valid. The simple nature of the equation causes certain variables to exercise considerable control over the solution. This method does not cater for interference between closely located features, e.g. interference between multiple pumping wells. When delineating CZ for a well field, if the individual wells are closely located, it is

[1] This discontinuity occurs because Equation 2 incorporates recharge and Equation 1 does not. The incorporation of recharge causes a reduction in zone size proportional to the recharge value. The recharge equation calculates the radius around the well which is sufficient under natural recharge conditions, to sustain the volume of water extracted at the well.

expected that the delineated zones will overlap. Delineation using this method for a centralised synthetic well may then be more appropriate (see Section 4.6 case study).

2.2.2.5 Simple analytical methods

***Description**:* A number of analytical equations have been developed to describe groundwater flow in specific hydrogeological settings (confined/unconfined aquifers, single/multiple wells, fully/partially penetrating well). These equations were originally developed to solve for aquifer properties, but can be re-arranged to calculate specific groundwater travel time distances from a hydrogeological feature for the purpose of PZ or CZ delineation. Equations can also be combined to account for more complex situations, for instance: multiple fully-penetrating wells in a line perpendicular to uniform regional groundwater flow and pumping at equal rates (Javandel and Tsang, 1986; Erdmann, 2000), two arbitrarily located wells pumping at equal rates (Shan, 1999), or up to four arbitrarily located wells pumping at various rates (Christ and Goltz, 2002).

The list of simple analytical equations and their application is given in Appendix 2 and can be grouped by TOT and drawdown criterion as follows (US EPA, 1994):

- TOT criterion: Darcy's Law; Darcy's Law combined with flow net; cone of depression combined with sloping regional potentiometric surface; inter-aquifer flow; cone of depression; regional flow; and uniform flow equation.
- Drawdown criterion: Thiem equilibrium equation and its modified form for non-equilibrium situations; leakage and infiltration equations for bedrock wells receiving recharge from unconsolidated overburden; and equations for special situations. By itself, the drawdown criterion is not suitable for CZ delineation (Table 2).

One of the most useful and frequently applied analytical equations is the uniform flow equation (3):

$$x = \frac{-y}{\tan(2\pi kbiy/Q)} \qquad (3)$$

Where Q [L^3/T] is the groundwater discharge rate (e.g. the pumping rate for an abstraction well), k[L/T] is the hydraulic conductivity, b [L] is the aquifer thickness, i [-] is the hydraulic gradient in the aquifer, and x [L] and y [L] are the distances from the pumping well to the zone boundary in the x-direction and the y-direction, respectively. This equation incorporates Darcian flow and pumping effects, and both the flow boundary and TOT criteria. This equation describes groundwater flow to a well under steady-state discharge conditions, in a homogeneous isotropic confined aquifer with uniform hydraulic gradient, placing the hydrogeologic feature under consideration at the origin of the coordinate system (Bear and Jacobs, 1965; Todd, 1980; Grubb, 1993).

The distance in the x-direction from a pumping well to the down gradient tip of the CZ boundary, termed x_0, is called the stagnation point (Figure 5) and can be solved by Equation 4:

$$x_0 = \frac{-Q}{2\pi kbi} \qquad (4)$$

The distance in y-direction from the pumping well to the CZ boundary, termed y_0, is the half width of the CZ above and below the well (Figure 5) and can be solved by Equation 5:

$$y_0 = \frac{\pm Q}{4kbi} \qquad (5)$$

The delineated zone is an elongated parabolic area that begins slightly down-gradient of the pumping well and extends up-gradient along the regional flow path direction (Figure 5). The zone is bounded by:

- a stagnation point at its apex, down-gradient of the pumping well;
- flow lines with parabolic shape on the sides and up-gradient of the pumping well leading to the stagnation point, and;
- a groundwater divide at its extreme up-gradient end.

Although initially developed for a confined aquifer, equations 3 to 5 can be used in unconfined aquifers by replacing the aquifer thickness, *b,* by the uniform saturated aquifer thickness h_0, providing the drawdown induced by pumping is small in relation to the aquifer thickness.

Assuming the infinite distance up-gradient from the pumping well in x-direction leads to the maximum half width of the CZ boundary from Equation 3, the maximum width of the CZ along the y-direction ($y_{\max}$) will be:

$$y_{\max} = \frac{\pm Q}{2kbi} \qquad (6)$$

The travel time t_x from a point on the x-axis to the pumping well can be obtained from the following equation (US EPA, 1994):

$$t_x = \frac{n}{ki}[r_x + \frac{Q}{2\pi kbn}\ln(1 + r_x\frac{2\pi kbi}{Q})] \qquad (7)$$

where n [-] is the aquifer porosity and r_x [L] is the distance over which groundwater travels along the x-axis. t_x is positive in the up-gradient direction from the well. The travel time can also be obtained from net groundwater velocity in the aquifer, as determined from the hydraulic gradient and induced pumping velocities (US EPA, 1994).

Resource requirements: Discharge, site-specific estimates of transmissivity, porosity, hydraulic gradient, hydraulic conductivity and saturated aquifer thickness are required to apply the uniform flow equation. Other analytical equations may require additional information such as the aquifer properties of the confining layer/aquitard, head difference between two aquifers, or infiltration rate (Appendix 2).The hydraulic gradient can be obtained from groundwater contours; in unconfined conditions, where topographic gradient is not sub-horizontal, topographic contours may be used as a proxy. Delineating the shape of the parabola can be performed using either spreadsheets or dedicated software packages (e.g., WPHA2000 created by EPA; WINFLOW created by Scientific Software Group). Alternatively an open-source, calculated fixed radius toolkit is available from the GNS Science website either as a python code or an ArcGIS toolkit (GNS Science Groundwater capture zone GIS toolkit; Toews, 2013).). In most cases, once its dimensions are resolved, the parabola needs to be orientated to the regional groundwater flow direction manually. Simple analytical equations are relatively easy to apply, inexpensive and require moderate technical knowledge. A freely available Microsoft Excel (2010) spreadsheet was also developed to compare zones obtained using the arbitrary fixed radius, the calculated fixed radius, the recharge and the uniform flow equations (the groundwater flow is assumed to be a straight line defined as the x-axis). Relevant input parameters must be filled in by the user (CZ_delineation_simple_methods spreadsheet, www.gns.cri.nz).

Advantages*:* Simple analytical methods are suitable for cases where the underlying assumptions are appropriate (e.g. homogeneous, isotropic, horizontally infinite aquifer of uniform thickness; no leakage or recharge; steady-state conditions; horizontal flow). The method's accuracy is improved if site-specific data are available, and in the absence of hydrogeological complexities. This method can be applied for confined and unconfined aquifers, provided the drawdown is small in relation to the aquifer thickness in the latter case. When delineating a well field, if the individual wells are closely located, it is expected that the delineated zones will overlap. Delineation using this method for a synthetic well may then be more appropriate. Adjustments may be required to ensure individual well heads are also included in the delineated zone (see Section 4.6 case study).

Limitations*:* This method generally does not take into account hydrologic boundaries (streams, lakes, etc.) or aquifer heterogeneities, and it assumes no recharge. Some equations (based on the drawdown criterion) are not applicable to springs, lakes and wetlands with groundwater contributions. Other equations, such as the uniform flow equation, may be extended to springs but require aquifer thickness to be known or estimated. The relatively simple underlying assumptions may limit the use of these methods to zone delineation in two dimensions. These equations do not account for hydrodynamic dispersion or contaminant retardation processes.

2.2.2.6 Simplified variable shapes / hybrid method

Description: This method involves the use of "standardised forms" generated using analytical equations with both the flow boundary and TOT used as criteria (US EPA, 1994; Paradis and Martel, 2007) (Figure 6). The variable shapes are generated by using analytical equations, such as the uniform flow equation, to calculate the down-gradient extent of the zone. The TOT criterion is used to calculate the up-gradient extent of the zone for different sets of hydrogeological conditions (varying pumping rates, hydraulic gradients, storativities, and aquifer thicknesses). The calculated fixed radius equation can also be used to define simplified variable shapes (US EPA, 1994; Spayd and Johnson, 2003). When a CZ is to be delineated for a certain hydrogeological feature, the standardised form that most closely matches the groundwater discharge rate and site-specific hydraulic parameters is chosen.

Shape, size and orientation are strongly dependent on screen depth and the presence or absence of a confining layer. Groundwater flow direction determines the orientation of the zone: the standardised form is drawn over the hydrogeological feature with its long axis oriented in the direction of the groundwater flow. Zone shape and size are related to perceived contamination risk, in that unconfined aquifers and shallow screened wells have larger protection areas (up to 1 km long up-gradient and up to 200 m wide in other directions). Wells in confined aquifers that are screened at more than 70 m depth are often depicted as having circular protection areas of 100 m radius, taking no account of groundwater flow direction. The sizes of the zones can be based on the assessment of required setback distances from wastewater discharge points (Hasfurther *et al.*, 1992).

***Resource requirements**:* The aquifer properties and well data required for the zone delineations depend on which standardised form is chosen. Typically, required input data includes the pumping rate, porosity, hydraulic conductivity, hydraulic gradient, direction of groundwater flow and aquifer thickness. Initial development of standardised shapes is moderately expensive and requires significant data collection, technical knowledge and interpretation.

***Advantages**:* Once the standardised shapes for an area are determined, any well or spring within the surrounding area can have its CZ easily delineated within a short period of time.

***Limitations**:* The method cannot account for spatial variability of input variables and may not be accurate in areas where there are geologic heterogeneities and hydrologic boundaries, or where the groundwater flow direction is uncertain.

2.2.2.7 Analytical element models

***Description**:* Analytical element models (AEMs) are based on analytical functions that represent 2D groundwater flow and transport, accounting for spatially variable aquifer properties, recharge from rivers and rainfall, pumping wells and well fields. CZs are delineated in AEMs using backwards particle tracking, i.e. a number of particles are released at the feature and the model is used to track the particles in the up-gradient direction to delineate the recharge area for the feature of interest. The CZ is defined as the area within which all particles are tracked to the feature.

Resource requirements: Hydrogeological conceptual model, hydraulic conductivity, porosity, saturated aquifer thickness, flow gradients, pumping rates, aquifer storativity, areal distribution of recharge and river stream bed properties are required to build an AEM. The AEM community (2012) has made a short list of available software (http://www.analyticelements.org/index.html, Appendix 3). This method is moderately expensive and requires moderate modelling expertise. In the examples developed as part of this study, the software GFLOW© (Haitjema, 1995) was used. It is beyond the scope of this document to address the design and construction of a groundwater flow model, however it is recommended to refer to the Australian groundwater modelling guidelines to ensure that the selected model is fit for purpose (Barnett *et al.,* 2012).

***Advantages**:* An AEM can be developed rapidly and generally solved quickly with limited input parameters. The method handles well field problems and is very reliable for a single layer aquifer, such as unconfined gravel aquifers that are common in New Zealand. Simple spatial variations in hydraulic properties or recharge are supported. AEMs do not require the spatial discretisation (gridding) that is essential for many other numerical modelling approaches. This allows AEMs to provide a continuous solution across the domain, because only the boundary conditions are discretised. The absence of grids allows AEMs to cover large study areas whilst maintaining accuracy over small regions. This enables AEMs to provide realistic cones of depression due to pumping, and it ensures that results of backward particle tracking are realistic. The AEM approach is a cost effective alternative to a numerical modelling method.

***Limitations**:* Complexities such as spatial variations in aquifer properties need to be gradually implemented to maintain stability of the analytical functions upon which the AEMs are based. AEMs do not account for vertical flow and as a result are not suitable for shallow partially penetrating wells, heterogeneous or anisotropic aquifers, or multiple layer aquifer systems (Barlow, 1994).

2.2.2.8 Numerical models

***Description**:* This method uses computer models to approximate three-dimensional groundwater flow and to simulate contaminant flow paths. Numerical models can be classified into two categories: finite-difference flow models (e.g. MODFLOW, McDonald and Harbaugh, 1988); and finite-element flow models (e.g. FEFLOW, Diersch, 2002). In general, most numerical models provide a deterministic best estimate of the time-related CZ based on a calibrated groundwater flow model combined with a particle-tracking algorithm (e.g. MODPATH, Pollock, 1994) (e.g. Varljen and Shafer, 1991; Cole and Silliman, 1997; Vassolo *et al.,* 1998; Evers and Lerner, 1998; Guadagnini and Franzetti, 1999; van Leeuwen *et al.,* 2000).

***Resource requirements**:* Detailed knowledge of the hydrogeological setting including aquifer geometries, hydrogeological boundaries, vertical and spatial variations in hydraulic conductivity, porosity, aquifer saturated thickness, flow gradients, pumping rates, aquifer storativity, and areal distribution of recharge are required to build a numerical model. Numerical modelling is often very expensive and time-consuming because it requires substantial amounts of data and expertise. It is beyond the scope of this document to address the design and construction of a groundwater flow model, however it is recommended to refer to the Australian groundwater modelling guidelines to ensure that the selected model is fit for purpose (Barnett *et al.,* 2012).

***Advantages**:* Numerical models are appropriate for representation of complex three-dimensional aquifer systems that include spatially variable aquifer properties, non-uniform thickness, variable unconfined and confined conditions, transient flow, groundwater-surface water interaction and multiple wells with arbitrary locations, screen intervals and pumping rates. Because numerical models give an integrated solution over the model domain, groundwater flow paths and travel times can be determined with much greater precision than with other methods. This means that a well-calibrated numerical model provides the most accurate method for CZ and PZ delineation.

***Limitations**:* Numerical models require large amounts of data for proper construction, calibration, verification, and prediction. Numerical methods are usually incapable of calculating the stagnation point and so are not amenable to the direct calculation of the CZ boundary. This limitation can be overcome by numerically simulating a considerable number of stream lines to approximate the location of the CZ boundary (i.e. by particle tracking using a large number of particles).

2.2.3 Previous zone delineation studies in New Zealand

Relatively few CZ delineation projects have been previously undertaken in New Zealand. These previous CZ delineation projects were undertaken either for protection from specific contaminants (nitrate in Southland; pathogens in Bay of Plenty) or for general protection of groundwater supplies (Marlborough District, Waikato and Canterbury regions). The methods that were used in these studies are: the arbitrary fixed radius method, the calculated fixed radius method, the uniform flow equation, the hybrid method and numerical modelling. These previous projects are described briefly below in chronological order.

CZ delineation was undertaken in the Gore District to determine nitrate contamination potential at a groundwater supply well (Rekker, 1994). This project applied a single layer finite-difference groundwater model that incorporated the possible influence of the nearby Mataura River. The initially delineated CZ, called Recharge Zone, was subsequently refined following the drilling of 24 piezometers (producing detailed water level data), 36 geophysical soundings, land surface surveying and groundwater sampling (Rekker, 1995).

PZs were delineated for springs in the Rotorua district to define the risk of pathogen contamination of public water supplies (Pang *et al.,* 1996). The PZs were delineated using the calculated fixed radius method, split in three pathogen die-off zones: zone 1 (99% die-off, TOT=176 days); zone 2 (99.9% die-off, TOT=262 days) and zone 3 (99.99% die-off, TOT=350 days). Viruses can survive longer than bacteria in groundwater environments, therefore this project applied bacteriophage F-RNA as the indicator for pathogen transport.

In the Waikato region, a technical document was prepared to detail community groundwater resource supplies and discuss a strategy for their protection (Hadfield and Nicole, 2000). This document outlined existing methods and criteria from the US EPA (1987) and proposed three zones of protection: zone 1, defined by a fixed distance (30 m); zone 2, defined by a 100-day TOT; and zone 3, defined by either 2 or 5 year TOT. PZs and CZs were delineated at two community supplies (Waharoa and Pauanui) and three school supplies (Goodwood, Hautapu and Manawaru) as examples using the two-dimensional ASMWIN numerical model (Chiang *et al.,* 1998; Hadfield and Nicole, 2000).

In a review of community water supply protection rules for the Canterbury region, Moore (2001) suggested the use of vulnerability maps supported by risk assessment to define protection rules. This work identified the following factors as key to consider while defining well-head PZs for New Zealand: land use activity, risk level acceptability, the risk variations with aquifer vulnerability, and the use of modelling approaches for zone delineation. This project recommended the use of numerical modelling for CZ delineation.

In 2005 a methodology for delineating the drinking-water catchment for both surface water and groundwater sources was prepared for the Ministry of the Environment (Williams *et al.,* 2005). Three zones were defined for groundwater supplies: an intake zone (radius between 5 m and 30 m); a buffer zone (PZ defined by the lesser extent between a shape defined by the uniform flow equation and a 2 km up-gradient distance, and the shape defined as a 1-year TOT); and an entire catchment zone (CZ defined similarly to the buffer zone using a doubled pumping rate and a 5° rotation of the zone in relation to the ambient flow direction to the well, until the aquifer boundary is reached, or alternatively a 20-year to 30-year TOT). In the absence of information regarding the groundwater flow direction then the CZ must be delineated using the entire groundwater catchment boundaries. The 5° rotation of the zone is used to account for uncertainty. The document outlined the following methods: the arbitrary fixed radius, the calculated fixed radius, simplified variable shapes, analytical methods, hydrogeological mapping and flow and transport modelling. Two unnamed examples were given, both using analytical methods. It was noted in this report that “no examples were found of management zones for conjunctive situations involving combined use of surface and groundwater resources” (Williams *et al.,* 2005).

CZ delineation was undertaken in 2011 for seven Southland wells that are included in the National Groundwater Monitoring Programme (NGMP) (Gusyev *et al.,* 2011c). Each of the Southland NGMP wells draws groundwater from shallow unconfined aquifer systems across several groundwater management zones. PZs (1-year, 5-year TOT) and CZs were delineated using backward particle tracking based on AEM implemented with the GFLOW software (Haitjema, 1995). Each CZ had different size and shape due to site-specific conditions, generally elongated in the direction of the groundwater flow (0.2 km to 20 km up-gradient from a given well). In this study, previously measured concentrations of the age tracer tritium were used to validate the modelling. Modelled Mean Residence Times (MRT) obtained with forward particle tracking were compared with MRT values obtained from tritium samples at six of the wells. Consistency between the model and the measurement were observed at four of the wells. At one well the MRT based on tritium measurements was significantly older than the modelled value, possibly due to localised groundwater flow patterns that were not represented in the relatively simple analytical model developed for the zone delineation. Validation was not possible at the last well, because the tritium sample yielded an ambiguous MRT (Gusyev *et al.,* 2011c).

More recently, work has been done in the Canterbury Region and the Marlborough District to define and integrate PZs into regional plans and statements (Environment Canterbury, 2011 and 2012; Pattle Delamore Partners, 2012).

In Canterbury, PZs have an elongated shape (hybrid method) defined by a radius around the well (100 m to 400 m), an up-gradient distance along the groundwater flow direction (100 m to 1000 m) and a 25° angle variation along the flow direction (Figure 7, Environment Canterbury, 2012).

In Marlborough, three zones are considered: a circular Site Specific Well Head Zone (5 m radius PZ); a Site Specific Contamination Migration Zone (circular shape for wells screened in confined aquifers using the arbitrary fixed radius method; elongated shape for wells screened in unconfined aquifers, hybrid method), and a General Aquifer Recharge Zone (PZ or CZ circular shape for wells screened in confined aquifers and has an elongated for wells screened in unconfined aquifers). The schematic view of the elongated shapes and its dimensions are given in Figure 8. The General Aquifer Recharge Zone is not defined for wells screened in confined aquifer sited “sufficiently distant” from the unconfined recharge area of this aquifer. Worked examples indicate for Site Specific Contamination Migration Zone, radii ranging from 200 m to 400 m depending on the water supply size (confined aquifers) and elongated shapes extending 1 km up gradient distance, and a radius along the well varying from 50 m to 100 m (unconfined aquifers). Worked examples indicate, for the General Aquifer Recharge Zone, radii ranging from 200 m to 400 m depending on the water supply size (confined aquifers); and elongated shapes extending 2 km up-gradient, and a radii around the well varying from 50 m to 100 m (unconfined aquifers). For both zones, an angle variation of 5° is proposed along the groundwater flow path to account for uncertainty (Pattle Delamore Partners, 2012).

2.3 EXISTING GUIDELINES FOR ZONE DELINEATION

Since the 1990s, numerous guidelines have been developed worldwide for zone delineation, using an extensive list of alternative terminology pertaining to CZs and PZs (Table 3). The variable nomenclature is due to: the lack of international guidance; the selection of a specific delineation criterion for each individual study; and the different geographical locations and regulatory frameworks relevant to the studies (USA, Europe, Australia, and Canada).

The US EPA (1987, 1994) introduced the “well-head protection area”, which incorporates portions of the ZOI, or cone of depression, and the ZOC (Figure 2). The ZOC extends up-gradient to a flow boundary and contains only the portion of the ZOI from which groundwater flows to the well. It is the equivalent of the CZ defined in this document. The EPA also defined the ZOT (Figure 2). This is a TOT-delimited fraction of the ZOC that is equivalent to the PZ defined in this document. These three zones (ZOI, ZOC and ZOT) were defined because the EPA delineation methodology used one criterion or a combination of criteria that incorporated the drawdown, TOT and flow boundary criteria that are defined in this document. Equations presented in the EPA guidelines solve for distances relevant to these zones. The EPA guidelines recommended the implementation of three well-head protection areas but did not recommend thresholds for the associated criteria. The purpose of the three well-head protection area aim was to (US EPA, 1987):

- protect from unexpected contaminant release (remedial action zone, equivalent to a PZ);
- bring the concentrations of specific contaminants to desired levels by the time they reach the wellhead (attenuation zone, equivalent to a PZ); and
- manage all, or part, of a well or well field's existing or potential recharge area (well field management zone, equivalent to a CZ).

The US State-specific and British Columbia guidelines recommend delineation based on either the distance criterion or the TOT criterion for the smaller zone (remedial zone), using TOT thresholds between 1 and 5 years. The attenuation zone and the well-field management zone are generally defined using the 5-year and 10 to 12-year TOT thresholds (Table 3).

In European countries (Table 3), CZs are delineated using distance and TOT criteria. However, there is large variability between the thresholds for these criteria and how each zone is defined. The smallest zone varies from 10 m around the feature (France, Italy; García-García and Martínez-Navarrete, 2005; Martínez-Navarrete and García-García, 2003) up to 300 m (Ireland; DELG/EPA/GSI, 1999). The total number of zones varies between countries, usually from two to four zones, based on the level of protection from the following (WHO, 2006):

- rapid ingress of contaminants or damage at the well head (well head PZ);
- pathogen presence by setting a TOT threshold to allow pathogen reduction to an acceptable level (inner PZ);
- impact of slowly degrading substances by setting another TOT threshold to allow dilution and effective attenuation to an acceptable level (outer PZ); and optionally,
- long-term degradation of water quality by extending the PZ to the entire catchment area (equivalent to a CZ).

In Australia, three PZs are defined, somewhat arbitrarily, using the distance (50 m – inner zone 1) and TOT criteria (middle zone 2 – 10-year TOT, and outer zone 3 – greater than 10-year TOT) (Table 3, ANWQMS, 1995).

In some of the below-mentioned countries (e.g. UK, Australia and Ireland) PZs are further defined by overlaying groundwater vulnerability maps (Figure 9). The maps represent ranked vulnerability of groundwater to pollution from contaminants released at 1 to 2 m below the surface based on soil, water table depths, available information and experience (WHO, 2006).

Table 3: Terminology, criteria and thresholds applied in existing guidelines for zone delineation.

Country (reference)	PZ			CZ (flow boundary criterion)	Additionally defined zones / special cases
	Terminology	PZ criteria	Justification		
New Zealand – Canterbury Region (Environment Canterbury, 2012)	Protection Area	This zone is elongated and combines a circular shape around the well defined by a radius (B), and a 25° angle variation around a fixed distance (A) along the groundwater flow direction. • unconfined or semi-confined aquifers: A=1000 m and B=200 m for screen depth < 30 m, A=500 m and B=200 m for screen depth 30 to 70 m, A=100 m and B=100 m for screen depth > 70 m; • confined aquifers: A=100 m, B 100 m; • coastal confined aquifers : A=400 m, B 400 m.			
New Zealand – Marlborough District (Pattle Delamore Partners, 2012)	Site Specific Well Head Zone (Zone 1)	Distance	At least 5 m, where impractical within land practicalities. This zone is defined to protect against direct contamination		
	Site Specific Contamination Migration Zone (Zone 2)	This zone is elongated for unconfined aquifers (parabola shape) with set lateral and up-gradient attenuation distance, buffered by a 5° angle around the groundwater flow direction. Down-gradient and lateral distances were from 50 m and 100 m, respectively, with an up-gradient distance of 1 km. For confined aquifers a circular zone is defined (200 m radius), expect for large supplies (400 m).	Indirect contamination which could result in contaminant concentrations causing adverse effects. Distances are obtained by calculating contaminant-specific separation distances		
	General Aquifer Recharge Zone (Zone 3)	Zone 2 was extended to 2 km downstream for unconfined aquifers. In the confined aquifer cases, zones were not defined as the wells were considered to be located “sufficiently distant from any unconfined recharge area”.	Wider zone within which contamination could impact on the quality of the well water supply		
New Zealand – Waikato Region (Hadfield and Nicole, 2000)	Wellhead Protection Zone 1	Distance (30 m),	Immediate contamination		
	Wellhead Protection Zone 2	100-day TOT	Microbial die-off		
	Wellhead Protection Zone 3	2-year TOT (alternatively 5-year TOT could be used)	Enabling remedial action or supply replacement		
New Zealand (draft) (Williams *et al.*, 2005)	Intake Zone	Distance (5 m to 30 m).	Designed to exclude rainwater and floodwater to enter the casing.	Entire catchment zone	
	Buffer Zone	1-year TOT or a combination of distance (2 km up-gradient of the well) and drawdown (down-gradient and around the well) combination	The combination of distance and drawdown criteria is to be used in fast flowing dispersive systems		

Country (reference)	PZ			CZ (flow boundary criterion)	Additionally defined zones / special cases
	Terminology	PZ criteria	Justification		
	Entire catchment zone	20-year or 30-year TOT or a combination of distance (2 km up-gradient of the well) and drawdown (down-gradient and around the well, using doubled yield) combination. A 5°extension (flare) around the ZOC boundary is extended to the aquifer boundary.	The combination of distance and drawdown criteria is to be used in fast flowing dispersive systems		
Australia (ANWQMS, 1995)	Wellhead Protection Zone I	50 m distance,		Wellhead Protection Zone	
	Wellhead Protection Zone II	10-year TOT,			
	Wellhead Protection Zone III	>10-year TOT			
British Columbia (Ministry of Environment, BC, 2004)	TOT area 1	1-year TOT or Distance (300 m),			
	TOT area 2	5-year TOT,			
	TOT area 3	10-year TOT			
United States (US EPA, 1994)	Zone of travel, Wellhead Protection Area	TOT and Distance criteria		ZOC Wellhead Protection Area	ZOI, zone of attenuation
U.S. - Indiana State (IDEM, 1999)	Sanitary setback	Distance (30 m for confined, 61 m for unconfined aquifer)		Well protection area (special case)	In special cases hydrogeological boundary applies
	Well protection area	5-year TOT or Distance (914 m)	The 914 m threshold is based on model simulations.		
U.S. - Washington State (Washington State Department of Health, 2010)	Wellhead Protection Area zone 1	1-year TOT	TOT is defined considering response time to a contaminant release. The 1-year criterion is related to microbial contaminants respectively	Buffer zone (special case)	Buffer zone (area sloping up from the 10-yr wellhead PZ which can either focus on selected areas, such as outcropping areas, or the entire ZOC)
	Wellhead Protection Area zone 2	5-year TOT	TOT is defined considering response time to a contaminant release. The 5-year criterion is related to chemical contaminants respectively		
	Wellhead Protection Area zone 3	10-year TOT	The last zone is designed to encourage zone planners and decision makers to recognise the long-term source of the drinking water supply.		
U.S. - New Jersey State (Spayd and Johnson, 2003)	Wellhead Protection Area tiers (3)	2-year TOT			
		5-year TOT			
		12-year TOT			
Florida County (Palm Beach County, 2013)	Well field regulation zone 1	30-day TOT			
	Zone 2	The land area between the 30-day and 210-day travel time.			
	Zone 3	The land area between the 210-day and 500-day travel time.			
	Zone 4	The land area within the 1-foot drawdown			

Country (reference)	PZ			CZ (flow boundary criterion)	Additionally defined zones / special cases
	Terminology	PZ criteria	Justification		
Ireland (DEL/EPA/GSI, 1999; WHO, 2006)	Source protection area (inner)	100-day TOT or Distance (300 m)	The 100-day threshold for the inner zone is based on a conservative limit considering both the heterogeneous nature of Irish aquifers and attenuation and die-off of bacteria and viruses.	Source protection area (outer): the whole catchment	Karstic area: the whole aquifer is a PZ.
	Source protection area (outer)	Distance (1000 m) (when CZ cannot be defined)			
Austria (WHO, 2006)	Wellhead Protection Zone, inner zone	Distance (<10 m)		Recharge Area : the whole catchment (subdivided for large catchment areas based on radius of 2 km)	
	Outer zone	60-day TOT			
Denmark (WHO, 2006)	Wellhead Protection Zone	Distance (10 m)			
	Inner zone	60-day TOT or Distance (300 m)	The 60-day TOT / 300 m radius for the inner zone was selected for technical and hygienic protection.		
	Outer zone	10 or 20-year TOT	The 10-year to 20-year TOT for the outer zone was selected following pesticide contamination issues.		
France (Margane, 2003; García-García and Martínez-Navarrete, 2005)	Immediate perimeter	Distance (10 – 20 m)		Far away perimeter / Distant zone (usually between 0.2 and 15 km^2)	
	Nearest perimeter/Proximity zone	50-day TOT or Distance (up to 1 ha)			
Belgium (Margane, 2003)	I. Water supply zone	Distance 10 m		III. "Observation zone" : the whole catchment	
	II a. Confined aquifers	50-day TOT			
	II b. Unconfined aquifers	Sand: 50-day + 100 m Gravel: 50-day + 500 m Karst: 50-day + 1000 m			
The Netherlands (García-García and Martínez-Navarrete, 2005; Carey *et al.*, 2009)	Catchment area (extraction)	50 to 60-day TOT (replaced by risk assessment)			Fissured or karstic media only have a catchment area (extraction) and one protection area (2 km radius)
	Protection area I	10-year TOT for aquifers with intergranular porosity, this zone is not defined for aquifers with fissured porosity.			
	Protection area II	25-year TOT for aquifers with intergranular porosity, maximum radius of 2 km for aquifers with fissured porosity.			
	Recharge area	50 to 100-year TOT			
Slovakia (Margane, 2003)	Wellhead/spring Protection Zone	Distance 10 – 50 m		Outer Protection Zone: catchment area	
	Inner Protection Zone	50 days or > 50 m			
Germany (García-García and Martínez-Navarrete, 2005)	Zone I	For intergranular porosity: 20 m; In karstic media: >30 m		Wide Protection Zone (subdivided for large catchment areas based on radius of 2 km). Zone III b.: catchment area	
	Zone II	50-day TOT For intergranular porosity: >100 m; In karstic media: catchment area if the area calculated for 50-day TOT is larger than this one	Based on pathogenic bacteria and viruses travel time.		

Country (reference)	PZ			CZ (flow boundary criterion)	Additionally defined zones / special cases
	Terminology	PZ criteria	Justification		
	Zone III a	For intergranular porosity: 2 km distance; In karstic media: no division if there is no impervious cover; > 1 km with impervious cover			
	Zone III b	At least 1 km + 50-day TOT for intergranular porosity; No division in karstic media if there is no impervious cover; in case of impervious cover: zones protected by more than 8 m of clay and silt and less than 5 m and perched groundwater			
Hungary (Carey *et al.*, 2009)	Inner Zone	20-day TOT		Hydrogeological protective zone C	
	Outer Zone	6-month TOT			
	Hydrogeological Protective Zone A,	5-year TOT			
	Hydrogeological Protective Zone B	50-year TOT			
Italy (Carey *et al.*, 2009)	Absolute Guardianship Zone Respect Zone	Distance (10 m) 180 or 365-day TOT	180-day or 365-day zone depending on vulnerability and hazard.	PZ	
United Kingdom (Carey *et al.*, 2009)	Source Protection Zone 1	50-day TOT/Distance (50 m)	Set for rapidly degrading toxic chemicals and waterborne disease.	Source Protection Zone 3, Total capture zone: the whole catchment	Zone of special interest (surface water catchments located outside of aquifer outcrop area) In karst aquifers, the aquifer source protection area may also be mapped as the Inner Protection area.
	Source Protection Zone 2	400-day TOT/Distance (250 m if Q<2,000 m^3/d otherwise minimum radius is 500 m)	Based on delay, dilution and attenuation of slowly degrading pollutants.		
Switzerland (Garcia-Garcia and Martinez-Navarette, 2005)	S1 or Catchment Zone	Distance (20x20 m)			
	S2 or proximal PZ	Distance (100 m) or 10-d TOT			
	S3 or elongated PZ	Distance/size (double size of the inner zone)			
Portugal (García-García and Martínez-Navarrete, 2005; Carey *et al.*, 2009)	Immediate Zone	Distance (20 – 60 m) 20 m for porous confined aquifers, 40 m for porous unconfined aquifers, 30 m for porous semi-confined aquifers, 60 m for chalk aquifers, 60 m for fissured igneous and metamorphic aquifers, 40 m for scarcely fissured or altered igneous and metamorphic aquifers.			Special zone

Country (reference)	PZ			CZ (flow boundary criterion)	Additionally defined zones / special cases
	Terminology	PZ criteria	Justification		
	Intermediate Protection Zone	50-day TOT or Distance (40 – 280 m) 40 m for porous confined aquifers, 60 m for porous unconfined aquifers, 50 m for porous semi-confined aquifers, 280 m for chalk aquifers, 140 m for fissured igneous and metamorphic aquifers, 60 m for scarcely fissured or altered igneous and metamorphic aquifers.			
	Elongate Protection Zone	3500-day TOT or Distance (350 – 2400 m) 350 m for porous confined aquifers, 500 m for porous unconfined aquifers, 400 m for porous semi-confined aquifers, 2400 m for chalk aquifers, 1200 m for fissured igneous and metamorphic aquifers, 50 m for scarcely fissured or altered igneous and metamorphic aquifers.			
Indonesia (WHO, 2006)	Zone category I	Distance (10 – 15 m)		Zone category II	
	Zone category II	50-day TOT			
Oman (WHO, 2006)	Inner source Protection Zone	1-year TOT		Outer Source Protection Zone: the whole catchment	Oman is an area where water is short in supply, and therefore zone definitions are more conservative.
	Middle Protection Zone	10-year TOT			
Ghana (WHO, 2006)	Wellhead Protection Zone	Distance (10 – 20 m)	TOT chosen as a compromise, as most aquifers are weathered crystalline basins where high water velocities will create large PZs.	Whole catchment	
	Inner zone	50-day TOT			
Turkey (Margane, 2003)	Zone I	50 m (porous); 100 m (karst)		Catchment area	
	Zone II	50 – 250 m (porous); 100 – 500 m (karst)			
	Zone III (recharge area)				

In summary, up to four zones are defined worldwide, however, justification for setting thresholds of both the distance and TOT criteria are often not provided in the various guideline documents. The distance threshold used for immediate protection of a wellhead varies, from 10 m (Switzerland, Denmark, Austria) to 300 m (Ireland) (Table 4). For larger zones, the threshold value varies according to the aquifer confinement status, flow processes, aquifer lithology or other site-specific considerations. For instance, the distance threshold used for intermediate (mostly microbial) PZ varies from 40 m (Portugal, based on aquifer type) to 914 m (Indiana State, based on model simulations). The equivalent corresponding TOT threshold ranges from 50 days to 365 days (Table 3). The additional intermediate zone (in most cases defined to provide protection from slowly degrading chemicals) has TOT thresholds from 400 days to 10 years. The CZ is often approximated by selecting a travel time varying between 10 years and 100 years. In most cases, the 10-year TOT is selected based on zone management timeframes. Where specific studies have been undertaken, the TOT is longer (e.g. Denmark, 10 to 30 year TOT), but justification for larger thresholds (e.g., The Netherlands, 100-year TOT) could not be found in the literature.

Not all guidelines include a detailed methodology for zone delineation, however, when such information is included, there is consistency in method selection between countries. The calculated fixed radius method, analytical method, numerical modelling and hydrogeological mapping are common to most guidelines (Table 4). The arbitrary fixed radius method is not used in Washington State, as only the TOT criteria was selected for delineation. There are several cases where the distance and TOT criteria are both applied, with the larger of the two zones adopted as a conservative approach (e.g. Ireland, Table 3). The use of the simplified variable shapes method requires the shapes to be developed, and this initial work may involve hundreds of calculations (US EPA, 1994). For this reason, where shapes have not been previously defined, guidelines do not specifically favour this method. The AEMs were absent from both the Irish and the Washington State guidelines (Table 4). In the Irish case, the complex nature of the aquifers generally required the numerical modelling approach.

Several countries have defined karst aquifers as a special case, where PZs cannot be delineated robustly and hence the whole catchment becomes the CZ. Hydrogeological mapping is the accepted best suited method for karst aquifers (IDEM, 1999; DELG/EPA/GSI, 1999; Carey *et al.,* 2009). Some countries require permission to use hydrogeological mapping, as the sole means for delineating the CZ, from the regulatory authorities (IDEM, 1999).

All guidelines specify that choosing an appropriate delineation method requires consideration of the hydrogeological setting, water resource management plans and resources, with the choice often a balance between the need for accuracy and available resources (IDEM, 1999; Hadfield and Nicole, 2000; García-García and Martínez-Navarrete, 2005; Carey *et al.,* 2009). Resources that need to be considered in selection of an appropriate method include: equipment, technical expertise and funding. To best match a model to site hydrogeological features, the site hydrogeology must first be characterised. Characterisation includes: type of aquifer material, hydraulic properties of the aquifer, aquifer confinement, flow boundaries and local flow gradients and directions. Water resource management plans need to be considered so that the zone delineation method is defensible, consistent with management strategies, appropriate for well field geometry/pumping rate and nearby groundwater pumping activity. As some zone delineation methods are better suited to certain hydrogeological situations than others, it is important to choose an approach that is capable of simulating the groundwater flow regime at the site of interest.

Table 4: Zone delineation methods recommended in existing guidelines.

	Method						
Existing guidelines	**Arbitrary fixed radius**	**Calculated fixed radius**	**Simplified variable shapes**	**Simple analytical**	**Hydro-geological mapping**	**Analytical element model**	**Numerical model**
Ireland (DELG/EPA/GSI, 1999)	yes	yes		yes	yes		yes
England (Carey *et al.,* 2009)	yes	yes	yes	yes	yes	yes	yes
British Columbia (Ministry of Environment, BC, 2004)	yes	yes	yes	yes	yes	yes	yes
United States (US EPA, 1994)	yes	yes	yes	yes	yes	yes	yes
Indiana State (IDEM, 1999)	yes	yes	yes	yes	yes	yes	yes
Washington State (Washington State Dep. Of Health, 2010)		yes		yes	yes		yes
New Jersey (Spayd and Johnson, 2003)		yes		yes		yes	yes
Australia (ANWQMS 1995)	yes	unspecified					
New Zealand – Waikato technical document (Hadfield and Nicole, 2000)	yes	yes	yes	yes	yes	yes	yes
New Zealand (Williams *et al.,* 2005)	yes	yes	yes	yes	yes	yes	yes

Existing guidelines recommend different strategies for implementing zones into management plans. The scale of the zoning may or may not be defined nationally (García-García and Martínez-Navarrete, 2005). An example of an implementation strategy is the Wellhead Protection Program for public water supply systems (Indiana State; IDEM, 1999). The program consists of two phases. Phase I involves 1) the delineation of Wellhead Protection Areas (WHPAs); 2) the identification of potential sources of contamination; and 3) the creation of management and contingency plans for the WHPA. Phase II involves the implementation of the plan created in Phase I. Communities are required to report to IDEM how they have protected groundwater resources.

2.4 UNCERTAINTY IN ZONE DELINEATION

Uncertainty is inherent in the delineation of a PZ or CZ due to a number of factors that can be broadly grouped into two categories: measurement uncertainty and model uncertainty. Measurement uncertainty arises because no measurement is exact. When a quantity is measured, the outcome depends on the measuring system, procedure, operator skill, and environment. Even when a quantity is measured several times by the same procedure, a different measured value is often obtained. Model uncertainty is caused by simplistic or incomplete description of the modelled system. For example, the hydraulic conductivity (K) of an aquifer can vary by several orders of magnitude but simplistic CZ delineation models (e.g. uniform flow equation) only allow for a single value of K to be used as input. More complex delineation methods, such as numerical models, can account for lateral and vertical variation in parameters values. However, information on spatial variation of such parameters is almost always lacking and assumptions are required. Typically, the K value of an aquifer used in a model is based on one or several aquifer tests. In situations where no aquifer tests have been undertaken the value is obtained from the literature for a similar geology.

Uncertainty analysis determines the bounds of confidence for model outcomes associated with different values of input parameters (Hill and Tiedeman, 2007). A number of different approaches have been used to quantify uncertainty, including “best judgement”, sensitivity testing (Esling *et al.,* 2008), probability distribution and envelope of predictive uncertainty (Varljen and Shafer, 1991; Vassolo *et al.,* 1998; Feyen *et al.,* 2001; Theodossiou and Latinopoulos, 2008).

Often only a “best estimate” CZ is presented, without taking into account the uncertainty associated with likely variation in model input parameters. The UK Environmental Agency (Carey *et al.,* 2009) suggested a more pragmatic approach to determining CZs that reflected the uncertainty in the conceptual understanding of the flow regime around a feature and the uncertainty in parameter values. They proposed a two-step approach incorporating sensitivity analysis and hydrogeological judgement to address both these aspects (Carey *et al.,* 2009):

- A limited sensitivity analysis on the “best estimate” CZ based on realistic variations in the main parameters of the model, i.e.:

  “Best estimate” model runs with the following recommended variation:

  - 15% decrease in recharge
  - 30% increase in K
  - 30% decrease in K

  Particle tracking using “best estimate” model:

  - 30% decrease in porosity

- A hydrogeological judgement to modify the "best estimate" CZ, with mandatory reporting of any modifications and supply of supporting information.

This approach can be used for zones delineated by sophisticated AEMs or numerical models and by more simplistic delineation methods with variation of fewer parameters. The range of parameter values needs to be justified before the start of modelling. It was suggested that if the numerical model provides an acceptable representation of the groundwater system, the evaluation of uncertainty could be limited to accounting for a decrease in porosity (Carey *et al.,* 2009).

Another option for quantifying uncertainty around a modelled parameter or system is the stochastic approach, such as Monte Carlo techniques. These techniques allow a distribution of values for each parameter, rather than a single value, to be used as the inputs to calculations. The technique works by extracting a randomly-selected value from the distribution of each input parameter and carrying out the calculation to provide a single output value. This process is repeated as many times as the modeller wishes, each time selecting another set of parameter values as input for the calculation. The result is an output that is a distribution of results, not a single value. The distribution of results provides more information about the statistics of the uncertainty, allowing percentile values to be determined if desired. For example, specify an interval such that there is (say) a 95% chance that what happens is contained in the interval. Commercial software "add ins" for spreadsheet software, such as Excel®, are available for this. Such an approach was used to estimate the uncertainty associated with modelling separation distances between drinking water wells and septic systems in New Zealand (Moore *et al.,* 2010).

Other similar approaches for uncertainty analysis are: Markov Chain Monte Carlo; least squares; and the Bayesian approach. The Markov Chain Monte Carlo methods are algorithms for sampling from probability distributions (Theodossiou and Latinopoulos, 2008). The least squares approach involves fitting a linear or non-linear polynomial to the data set to minimize the sum of the squares of the errors. The Bayesian approach dictates how a subjective degree of belief should rationally change to account for evidence (Feyen *et al.,* 2001; Dudley Ward and Kaipio, 2013). A list of references, selected by the Stochastic Analysis of Well-Head protection and Risk Assessment (W-SAHaRA) European consortium is given in Appendix 4.4.

2.4.1 Factors constraining zone geometry

Factors that influence the geometry (size and/or shape) of a delineated CZ or PZ contribute to its uncertainty. It is worth being aware of these factors because it may be appropriate to include one or more in an uncertainty analysis. The factors can be classified into four categories (Carey *et al.,* 2009): hydrogeological factors; field data factors; assumptions and limitations of calculations and models; and model specific issues.

2.4.1.1 Hydrogeological factors

- Abstraction rate or volume: an increase in abstraction rate will widen the CZ or PZ, and vice-versa.
- Recharge: increasing recharge will reduce the size of the CZ or PZ, and vice-versa.
- Hydraulic boundaries (edge of aquifer, surface water body, etc.): presence of a hydraulic boundary will terminate the length of the CZ or PZ and may cause a

corresponding increase in width depending on the delineation method employed and the connectivity of the aquifer and surface water bodies.

- Hydraulic conductivity (K) and its vertical and horizontal spatial variation: variation in K cannot be accounted for in simple methods – an average or most appropriate value needs to be selected and used. Numerical models can incorporate spatial variation in K. Incorporating variation would likely cause CZ width to decrease in areas of higher K and increase in areas of lower K. The vertical hydraulic conductivity is rarely considered due to lack of data.
- Aquifer thickness: increasing aquifer thickness will reduce the width and length of the PZ and decrease the width only of the CZ, and vice-versa. A 50% increase in aquifer thickness causes and approximate halving of the PZ area. Aquifer thickness and hydraulic conductivity determine the transmissivity of an aquifer and volume of water in the aquifer.
- Effective porosity (n): increasing n will decrease the size of the CZ or PZ, and vice-versa. A 50% increase in porosity causes a 2-4 fold decrease in zone area.
- Hydraulic gradient (i): increasing i will decrease the length and width of the PZ and decrease width only of the CZ, due to greater through-flow, and vice-versa.
- Direction of groundwater flow: a change in the direction of groundwater flow due to pumping or artificial recharge could potentially have a major effect on the shape of the CZ or PZ. Failing to account for such factors may lead to incorrect zone delineation.

2.4.1.2 Field data factors

The accuracy and hence uncertainty associated with field data measurements influence the geometry of PZ and CZ for several reasons.

- Field data are sparse but parameter values are required for the whole of the aquifer unit. For example, groundwater level contours are drawn based on interpolation of limited water level data and do not account for lateral and vertical variation.
- The data may be based on estimates of average or regional conditions which may not be representative of local conditions in the vicinity of the feature.
- Aquifer parameters may be derived from tests carried out on features that may not be typical of the aquifer. For example, K values may only be available for aquifer tests undertaken on larger groundwater abstractions which are located in areas of higher transmissivity.
- Estimates of parameters derived from aquifer tests may be dependent on the method of analysis used and/or duration of the test.
- Field values may be functions of scale or of local conditions (e.g. estimates of rainfall may be based on data from one site but rainfall may vary significantly over the catchment).

2.4.2 Assumptions and limitations of calculations and models

The geometry of CZs and PZs can also be influenced by the methods used to delineate them. For example, manual or analytical methods generally produce a zone with simple shape. Numerical models can enable more accurate zone delineation because they allow a more detailed representation of the hydrogeological environment. Regardless of the method chosen for zone delineation, assumptions are made to simplify complex real world hydrogeological systems. Typical assumptions and limitations associated with zone delineation are listed below.

- The assumption of steady-state flow conditions (in reality, groundwater flow varies with time).
- Horizontal groundwater flow to the feature. Typically, partially penetrating wells can induce significant vertical flow (Barlow, 1994), which may lead to a mismatch between the delineated zone and the actual zone. However, practically, insufficient data/information on the vertical hydraulic conductivity and its spatial variation often limit justification to undertake modelling in three dimensions.
- Intergranular or diffuse fracture-flow in the aquifer. Where conduit-flow occurs through discrete open fracture zones and cave systems (i.e. karstic aquifers) the groundwater flow is non-Darcian, invalidating the use of related flow equations. In such aquifers, flow velocities are high (up to several km/day). Groundwater travel times can be of such short duration that the PZ may coincide with the CZ.
- Adequacy between the model resolution and the delineated zone extent.
- Relative accuracy of the model when simulating observed conditions such as groundwater levels.
- Representativeness of data used to build the model (included field data).
- Underlying interpretations necessary to construct and calibrate the model and/or during zone delineation.

2.4.2.1 Model specific issues

A number of issues may influence the accuracy of zones delineated with numerical models, particularly those methods that rely on discretisation of the flow domain. These issues include:

- Model mesh spacing (Figure 10). Insufficient resolution around pumped wells results in a poor approximation of the cone of depression. When applying a particle tracking algorithm, this leads to inadequate divergence of particles and narrow CZs.
- Weak sinks. These occur where an abstraction does not account for all the flow into a model cell element. In this instance, particle tracking algorithms can struggle to determine the pathway for individual particles (to the abstraction point or out of the cell).
- Partial penetration (Figure 11). Single layer models cannot adequately represent boundary conditions (e.g. a river or a well) that only partially penetrate the thickness of the aquifer.

The above-listed issues apply to the finite-difference model MODFLOW. Other models, particularly finite element models, permit larger changes in mesh scale. Weak sinks and mesh spacing problems are less of an issue with these finite-element models.

3.0 PROPOSED ZONE DELINEATION FRAMEWORK FOR NEW ZEALAND

3.1 DELINEATION CRITERIA

Based on previous work, the distance and TOT criteria are considered most relevant for zone delineation in New Zealand. Out of the five existing criteria, most countries use a combination of the distance and TOT criteria for protection against microbial contamination. The use of the drawdown criterion is limiting because it is not suited for springs, lakes or wetlands with groundwater contribution. The assimilative capacity criterion was not retained due to its contaminant specificity regarding physical and chemical aquifer properties (US EPA, 1994). Only the TOT and the flow boundary criteria are directly applicable to CZ delineation (Table 2); however, some of the other methods can be adapted to CZ delineation by specifying a time or groundwater discharge that approximates steady-state conditions. To delineate a microbial PZ, an appropriate travel time needs to be used that ensures die-off of microbes. Alternatively, appropriate distance criteria for the arbitrarily fixed radius method can be used as a proxy for these zones. The following sections present distance and TOT thresholds that have been used in previous CZ and PZ studies or guidelines, and identifies which distance and TOT thresholds may be appropriate for New Zealand.

3.2 ZONES

3.2.1 Immediate PZ

An immediate zone should be considered to protect for contamination directly around hydrogeological features (e.g. spills). The threshold distance recommended for New Zealand is at least 5 m for wells and springs. This minimal distance is consistent with the minimum proposed for New Zealand by Williams *et al.* (2005; Table 3). In the case of karstic springs, the surface catchment of all contributing sinkholes should also be delineated for this zone (Kaçaroğlu, 1999).

The distance threshold used for immediate protection of hydrogeological features varies between countries, but generally a minimum of 10 m is adopted (Demiroğlu and Dowd, 2014; Table 3). Where the threshold distance is based on aquifer confinement status, larger distances are used for unconfined aquifers (61 m in Indiana State, 40 m in Portugal; Table 3) or for particular aquifer types that may not be relevant to New Zealand (e.g. 60 m for chalk aquifer, Portugal; Table 3).

3.2.2 Microbial PZ

In this study, a conservative approach for the delineation of microbial PZs is proposed and either a set distance (i.e. arbitrary fixed radius), or 1-year TOT is used at a hydrogeological feature. The 1-year TOT threshold is consistent with previous New Zealand studies (Williams *et al.,* 2005) and recent international guidelines (Ministry of Environment, British Columbia, 2004; Washington State Department of Health, 2010). Where site-specific information is available, a different TOT threshold may be used to delineate the microbial PZ. This threshold can be calculated provided estimates of groundwater velocity, spatial removal rates, and the required log reduction for a particular pathogen are known (Appendix 4).

TOT thresholds used for microbial protection in other countries vary according to country-specific hydrogeological settings. For instance, in Ireland a 100-day TOT is used in conjunction with a 300 m distance zone (DEL/EPA/GSI, 1999). TOT thresholds range from 50 to 60 days in most of Europe, to 5 years in the US (IDEM, 1999; Williams *et al.,* 2005). In The Netherlands, where the current microbial threshold is 50 days, recent studies advocate a revision of this threshold to a 1 to 2 year travel time because bacteria and virus survival time can exceed 50 days in groundwater (Schijven *et al.,* 2006). Larger TOT threshold values are required for protection against viruses than bacteria due to virus persistency and easy transport owing to their small size and limited tendency to attach to aquifer materials (Schijven *et al.,* 2006).

Arbitrarily fixed radii used for microbial protection in other countries range from 40 m (Portugal) to 914 m (Indiana State) (Table 4). Similar to the immediate zone thresholds, microbial protection radii are often linked to aquifer material and confinement status, with greater radii for unconfined aquifers. For example, the largest radius of 914 m in Indiana is equivalent to a TOT threshold of 5 years, and the State's guidelines suggest that the radius is reduced as appropriate based on hydrogeological setting (IDEM, 1999).

3.2.3 CZ

The CZ extent should be defined by a catchment or hydrogeological boundary. However, to implement methods that delineate a TOT CZ, the 50-year TOT threshold should be used. Where impractical, a 10-year threshold could be used, however, selecting a 10-year TOT may significantly underestimate the size of the CZ and, as discussed below, is considered too short for New Zealand. The 10-year TOT threshold is used in most countries, with its limited extent often justified by managerial constraints (Table 3).

There are large discrepancies amongst countries as to the appropriate threshold for a TOT CZ. In most countries, the threshold varies from 10 years to 100 years (Table 4), with the exception of karstic aquifers that are generally considered as a "special case". The 50-year TOT threshold for CZ delineation in New Zealand is based on the median Mean Residence Time (MRT) of groundwater at NGMP sites, which varies from to less than a year to 300 years (Table 5). The average MRT of groundwater at NGMP sites exceeds 10 years in all regions, and the national average and median MRT of groundwater across all NGMP sites are 74 and 49 years, respectively. The MRTs at NGMP sites are known to be representative of other hydrogeological features in New Zealand. For instance, groundwater from the Putaruru township well field and nearby Blue Spring have a MRT of 55 to 125 years respectively (based on tritium age tracer) (Gusyev *et al.,* 2011a).

Table 5: Summary of mean residence time (MRT) measured at all locations within the NGMP.

Region	Min MRT (years)	Max MRT (years)	Average	Median	Number of sites	Number of sites where MRT was ambiguous
Auckland	43	300	203	215	6	0
Bay of Plenty	8	165	87.8	74.5	6	1
Canterbury	1	160	66.3	40	6	0
Southland	1	190	57.5	4	5	2
Gisborne	39	180	145.2	180	5	1
Greater Wellington	0.5	107	31.5	35	11	3
Hawke's Bay	4	140	71.1	59	7	1
Marlbourough	1	>250	41.2	6.2	6	1
Manawatu-Wanganui	42	150	88.5	81	4	0
Northland	26	142	65	58	8	1
Otago	49	51	49.7	49	3	7
Tasman	1.5	225	64.2	13	8	2
Taranaki	8	165	100.7	144	5	0
West Coast	1	50	17.2	4.2	6	3
Waikato	0.5	122	28	4.7	8	2
New Zealand	min 0.5 year	max 300 years	average 74 years	median 49 years	94 total sites	24 sites where dating was ambiguous

3.3 DELINEATION METHODS AND APPROACH

A range of CZ and PZ delineation methods are required to cover the variety of New Zealand settings and water management frameworks. This range needs to include: simple delineation methods that can be applied quickly and at low cost to provide a reasonably conservative assessment of the area in which the actual CZ or PZ is likely to occur; and robust approaches that provide a high degree of certainty that the delineated zone is correct.

There are around 200 major aquifers in New Zealand (Rosen and White, 2001). These aquifers have a large range of lithologies, thickness, confinement, and hydraulic properties (Table 6; Appendix 4.1). These aquifers occur in a wide range of geomorphic and hydrological settings, including alluvial gravel plains, incised fractured volcanic terrain, valleys infilled with sedimentary deposits and hill country composed of indurated sediments. These settings range from low to very high intensity farming areas, towns, cities and coastal communities. Demand on water resources is variable throughout these aquifer systems, ranging from extremely high in intensive farming areas of the Canterbury Plains and cities dependent on groundwater as their water supply, to very minimal in low intensity land use areas where adequate water supply can be obtained from rainfall collection. Water resource management within a catchment is the responsibility of the regional authorities. Regional plans, district plans and resource consents under the Resource Management Act (Parliament of New Zealand, 1991) are designed to assist the management of source water quality (Williams *et al.,* 2005).

Table 6: Summary of aquifer properties measured at wells included in the NGMP (a detailed compilation is given in Appendix 4.1).

Aquifer type	Storativity range	Transmissivity range (m^2/d)
Confined	0.00005 – 0.2	0.1 – 25000
Semi confined	0.0005 – 0.1	0.5 – 260
Unconfined	0.0001 – 0.14	0.5 – 25000

To provide good protection of a water source, while at the same time not being overly restrictive, a targeted approach for selection of the delineation method is proposed for New Zealand. This approach can be split into four steps:

1. Data uptake: available site-specific information is compiled to develop a conceptual model given available resources. This includes the identification of the required level of accuracy in zone delineation.
2. Method selection based on the conceptual model and delineation requirement identified in the previous step. The simple approaches (arbitrarily fixed radius, hydrogeological mapping) can be used in the absence of site-specific data (although the use of site-specific data is preferred as it reduces uncertainty), whereas the more complex approaches require site-specific data to achieve accurate and defensible representation of the system (Table 7; additional details and comparative tables for method selection are given in Section 2 of the Guidelines). In the absence of site-specific data, typical values for similar hydrogeological settings can be used; however, an increase in conveyed uncertainty should be used to acknowledge this. A range of input parameter values for typical New Zealand hydrogeological settings is provided in Appendix 4. For large groundwater supplies (> 500 people) or complex aquifer systems

(e.g. multi-layered aquifers, interconnected surface water – groundwater system) the direct use of more robust modelling methods is recommended.

3. Delineation of relevant zones is undertaken (where applicable, including uncertainty).

4. Optional site-specific zone refinement may be required depending on the feature type and the selected method. Examples of zone refinements are: for CZ delineation at a spring, exclusion of the area located below the spring elevation; for closely sited wells, the use of a synthetic well may be tested; in the case of delineation using modelling method particle tails may require truncation; when clipping a zone based on hydrogeological boundaries, consideration should be given to increase the zone area accordingly (see Section 4.4 case study)

Table 7: Recommended methods for zone delineation and their applicability to hydrogeological features in New Zealand.

Method	Features	Applicability
Arbitrary fixed radius (safe guarding distance)	Wells and springs	Simplest method to be applied where little information is available. Applied if the need for great accuracy is not justified or if no potential contaminant sources are identified in the vicinity of the feature. It is over-protective if large radii are selected. It is not suitable for groundwater-fed lakes or wetlands. This method should not be applied if there is a known to be a significant ambient regional groundwater flow.
Hydrogeological mapping	Wells, springs, wetlands and lakes with groundwater contribution, karstic systems	Applicable to near-surface flow boundaries and highly anisotropic aquifers. Unsuitable for wells in deep or large aquifers (results in overly large zones), except if the hydrological feature is located relatively close to the aquifer boundary or some other hydraulic boundary.
Calculated fixed radius	Wells and springs	Where the following assumptions apply: one-dimensional (radial) flow, aquifer homogeneity and isotropy, laminar Darcian flow, steady-state conditions, absence of regional hydraulic gradient.
Uniform flow equation method	Wells and springs	Where the following assumptions apply: homogeneous, isotropic, horizontally infinite aquifer of uniform thickness; no leakage or recharge; steady-state conditions, horizontal flow. This method can be applied for confined and unconfined aquifers, provided the drawdown is small in relation to the aquifer thickness in the latter case.
Simplified variable shapes	Wells and springs	Once the standardised shapes for an area are determined, any well or spring within the surrounding area can have its CZ easily delineated within a short period of time.
Semi-analytic numerical models	Wells, springs, wetlands and lakes with groundwater contribution, karstic systems.	This method integrates surface water and hydrogeological boundaries, with low to moderate heterogeneities. It is not suitable for very complex spatial changes in parameters (e.g., hydraulic conductivity, recharge) or multiple layers aquifer systems.
Numerical models	Wells, springs, wetlands and lakes with groundwater contribution, karstic systems	This method will cater for complex systems, but requires a large amount of data for construction, calibration and validation.

3.4 UNCERTAINTY ANALYSIS

Estimating the uncertainty associated with PZs and CZs delineated by the range of methods proposed in this document requires an easily applied, robust and consistent approach that does not demand specialist skills or understanding. The approach for uncertainty analysis must be applicable to the manual, semi-analytical and numerical modelling methods listed in Table 7. The approach must reflect the uncertainty in the conceptual understanding of the flow regime around a feature and the uncertainty in parameter values.

A sensitivity type approach, similar to that proposed by Carey *et al.* (2009), is therefore recommended for uncertainty analysis. Average or median values for input parameters should be used for the "best-estimate" calculation, whereas PZs and CZs should be delimited by the outer edges of the zones obtained through input parameter variations. Uncertainty should be estimated by systematically varying input parameter values over a plausible range to define the likely variation in size of the zone. In circumstances in which no information about the plausible range of input values to the calculation is available, the input values for establishing the uncertainty should be set to ±25% of the value used for the "best-estimate" calculation. Where site specific data are available, the minimum and maximum values of input parameters should be used to evaluate uncertainty in the zone boundary.

Implementation of this approach for uncertainty analysis requires running a series of calculations with combinations of parameter values to define the outer limits of the uncertainty for the zone. The manual methods for zone delineation involve relatively few input parameters, so running a series of calculations using different parameter values is not too time consuming. The semi-analytic numerical and numerical modelling methods involve more input parameters than manual methods. The method of manually varying the input parameters over a plausible range and re-running the calculations for each input dataset can be used with these methods to estimate the limits of uncertainty. However, more sophisticated, stochastic methods can provide an automated, more refined means of assessing uncertainty for the more complex modelling approaches.

Hydrological mapping methods, which map surface water catchments, or geological contexts, or groundwater catchments defined from potentiometric maps, and the arbitrary radius method, have a low level of certainty. The basis of these methods does not readily allow the calculation of uncertainty. However, the scale of the mapping, or data from site-specific surveys, can give some idea of the uncertainty when hydrological mapping is used. Where no estimate of the uncertainty is possible, the user needs to be aware that the CZ obtained from these methods may bear little resemblance to the actual CZ, either in terms of shape or location.

4.0 CASE STUDIES

4.1 SITE AND METHOD SELECTION

All of the methods discussed above were applied at five case study areas to explore the practical aspects of zone delineation and to allow comparison of results. Where possible, the case studies included more than one hydrogeological feature. The sites were selected to encompass typical New Zealand hydrogeological settings: an unconfined gravel aquifer (Gore); a confined gravel aquifer (Ruataniwha Plains); an unconfined coastal sand aquifer (Pauanui); an unconfined (leaky) fractured volcanic aquifer (Putaruru); and a groundwater system with connections to surface water (Poukawa). Multi-layered aquifers such as the Wairau Plains (Davidson and Wilson, 2011) and karst systems, such as the Arthur Marble Aquifer in Tasman (Stewart and Thomas, 2008) also occur in New Zealand but were not considered as case studies in this project.

The following five zone delineation methods, in increasing order of complexity, were used in each case study:

A. Hydrogeological mapping (surface water catchment).

B. Calculated fixed radius (incorporating hydrogeological mapping, Equations 1 and 2).

C. Simple analytical method (uniform flow equations; Equations 3 to 7).

D. Hybrid method (combining PZ, CZ and CZ uncertainty areas from B and C).

E. AEM/Numerical model (backward particle tracking).

Hydraulic parameters that were used for the simpler delineation methods and details of the associated models are listed in Table 8. For the simpler methods, zones were delineated using the open-source GNS Science Groundwater capture zone GIS toolkit (Toews, 2013). Zone uncertainty was evaluated using the sensitivity approach by varying the value of the following input parameters: groundwater recharge, riverbed conductance, porosity, hydraulic conductivity, hydraulic gradient and aquifer thickness.

Table 8: Summary of hydrogeologic features considered and methods applied in the five case studies.

	Hydrogeological feature information				Hydraulic parameters used for the simpler methods						
Case study	**Bore name**	**Diameter (mm)**	**Depth (m)**	**Screen interval (m)**	**Q (m^3/d)**	**Recharge (mm/a)**	**Hydraulic conductivity (m/d)**	**Aquifer thickness (m)**	**Effective porosity (unitless)**	**Hydraulic gradient (unitless)**	**Analytical element or numerical model summary**
Gore	Coopers Well#1	N/A	NA	N/A	4056	223	45	15	0.2	0.005	The semi-analytic groundwater model GFLOW (Haitjema, 1995) was used for zone delineation. The model includes the relevant major surface water features (Mataura River and Gold Creek) as strings of line-sinks. The model was calibrated to groundwater levels (Gusyev *et al.,* 2011b).
	Coopers Well#2	1200	7.65	3.0 – 6.8							
	Jacobstown Well#1	N/A	N/A	N/A	636					0.007	
	Jacobstown Well#3	N/A	N/A	N/A							
Ruataniwha Plains	Well#1762	150	48.9	31.08 – 45.60	1129	1	9	25	0.15	0.012	Hawke's Bay Regional Council developed a three layer, steady-state groundwater flow model using Visual MODFLOW (Schlumberger Water Services, 2011). The original model was calibrated to overall water balance and groundwater elevations from 47 observation wells. The model was updated in order to perform zone delineation. Updates included implementation of additional wells, refinement of the model grid, and changes to the screen depth of abstraction wells. Zones were delineated using backward particle tracking in MODFLOW (Gusyev and Toews, 2012).
Putaruru	Blue Spring	N/A	0	N/A	45000	390	5	280	0.16	0.02	The semi-analytic groundwater model GFLOW (Haitjema, 1995) was used for zone delineation. It was calibrated to groundwater heads, stream flow and the MRT (derived from tritium measurements) (Gusyev *et al.,* 2011a).
	GS#2	150	70	N/A	3000		5	10	0.135	0.017	
	GS#3	200	180	N/A	800		5	86	0.135	0.017	
	Synthetic well				3800		5	10	0.135	0.017	
Poukawa	Well#3134	300	50	N/A	2420	60	5.6	50	0.14	0.02	A steady-state and pseudo transient finite element model was developed using FEFLOW (Diersch, 2002) to simulate the effect of groundwater pumping on surface and groundwater flow in the south-eastern area of the Poukawa basin. The steady-state model was calibrated to stream flow hydraulic head. The pseudo-transient model was initially calibrated on the steady-state model, and further calibrated to groundwater level drawdown and stream depletion (Cameron *et al.,* 2011). The pseudo-transient model was used for zone delineation.
Pauanui	N1	150	15.6	10.3 – 15.3	267	266	46	15	0.15	0.01	A transient MODFLOW (McDonald and Harbaugh, 1988) groundwater flow model of the Pauanui Peninsula was developed to investigate potential impact of treated waste water application in a designated area for a consent application (URS, 2010). The original steady-state MODFLOW model was calibrated to groundwater heads. It was subsequently used in transient mode for scenario modelling. The transient model was updated for selected parameters (to allow for maximum travel time) and used as per the original calibration to delineate CZs through backward particle tracking in MODFLOW (Moreau *et al.,* 2014b).
	N2	150	18	13.0 – 18.0	267		46	15	0.15	0.01	
	N3	200	17.7	12.3 – 17.71	267		46	15	0.15	0.01	
	Synthethic well				800		46	15	0.15	0.01	

4.2 GORE – UNCONFINED GRAVEL AQUIFER

In this case study, CZs and 1-year PZs were delineated for two municipal water supply well fields. The Cooper's and Jacobstown well fields provide a drinking water supply for Gore Township. They draw groundwater from the shallow unconfined Knapdale aquifer, which consists of Quaternary glacial outwash and alluvial terraces associated with the Mataura River. The Knapdale Aquifer is recharged through rainfall infiltration and surface water flow loss from the Mataura River and its tributaries (Gusyev *et al.,* 2011b). Zone delineation was undertaken for both well fields. For the simpler zone delineation methods, each well field was represented by a single synthetic well using the combined maximum abstraction rate, due to the close proximity of the wells (Table 8).

Delineation of the CZ using the hydrogeological mapping - surface water catchment method at the Cooper's and Jacobstown well fields yielded large zones (40.2 km^2 and 8.28 km^2 respectively), which included the Triassic conglomerate hills surrounding the valley (Figure 12, inset A). The zones defined using the calculated fixed radius method were truncated by hydraulic boundaries of the Mataura River and Gold Creek. Both rivers are in hydraulic connection with the Knapdale Aquifer (Gusyev *et al.,* 2011b). The portion of the circular zones located on the opposite side of the river from the well fields were discarded (Figure 12, inset B). The resulting CZ and 1-year PZ areas are: 3.88 km^2 and 0.88 km^2 at Cooper's, and 1.08 km^2 and 0.14 km^2 at Jacobstown well fields, respectively. The difference in radii at the Cooper's (1-year PZ, 530 m) and Jacobstown (1-year PZ, 210 m) well fields is due to the difference in abstraction rates.

The groundwater flow path to the well fields and associated hydraulic gradients were inferred from topographic contours. The flow path at both well fields is away from the river and towards the surrounding hills. The location and direction of the inferred groundwater flow path is controlled by the accuracy of the topographic data and the contour interval. The flow path was derived using 20 m contours with an elevation change of 30 m. Although the flow path line was traced to the water divide, the last part of the flow path was not used to calculate the hydraulic gradient because the topography becomes steeper in the conglomerate hills and is not expected to be representative of the slope of the water table.

The uniform flow equation was applied at each synthetic well, allowing zones with elongated parabola-shapes to be delineated (Figure 12, inset C). The parabola's width is a function of the hydraulic gradient and is narrowest where the hydraulic gradient is greatest. Dredge tailings in the vicinity of the Cooper's well field likely cause non-homogeneity and anisotropy of aquifer hydraulic properties, which cannot be accounted for using the uniform flow equation or in the uncertainty analysis associated with the method. The CZ and 1-year PZ areas derived from the uniform flow equation are: 9.23 km^2 and 0.83 km^2 at Cooper's, and 1.45 km^2 and 0.09 km^2 at Jacobstown well fields, respectively.

The hybrid zones were obtained by combining the zones derived from the calculated fixed radius method and the uniform flow equation, for a more conservative approach compared to either of the individual methods (Figure 12, inset D). The delineated CZ and 1-year PZ areas are 10.97 km^2 and 2.35 km^2 at Cooper's, and 1.17 km^2 and 0.19 km^2 at Jacobstown well fields, respectively. This more conservative hybrid method is better suited to this case study because the CZ produced by the uniform flow equation does not intercept the river (groundwater flow direction was derived from topographic contours, not groundwater contours). The hybrid method indicates that the wells may derive a component of water from the river.

Zones were also delineated using an AEM (Table 8), which incorporated simulation of the aquifer and river systems and their hydraulic continuity (Figure 12, inset E). In this instance, the AEM simulated pumping from individual wells (Well#1 and Well#2 at Cooper's well field and Well#1 and Well#3 at Jacobstown well field) and associated pumping interference. Each well was assigned its maximum pumping rate (Gusyev *et al.,* 2011b). The AEM 1-year PZs were larger in size than those delineated by other methods at both well fields (1.68 km^2 at Cooper's and 0.55 km^2 at Jacobstown). In this case study, the 10-year PZ was used as a proxy for CZ delineation. The corresponding AEM CZ at Cooper's well field was the smallest in extent (5.82 km^2) compared to those delineated using other methods. At the Jacobstown well field the model delineated 10-year PZ is the second largest (1.95 km^2), the largest being delineated using the hybrid method (2.35 km^2). A previously defined best-estimate CZ delineated at Cooper's well field (1.62 km^2) by Rekker (1995), produced using a numerical model, is displayed in Figure 12, inset E. This best-estimate CZ is contained within the uncertainty of the output from the AEM. However, there is a difference in orientation (about 15° angle difference) between the CZs produced by the numerical model and the AEM, which is attributed to the difference in areal extent of the two models, with the AEM covering a larger area. The AEM CZ is considered to be the more comprehensive as it was constructed with inclusion of the model information of Rekker (1995).

The uncertainty in the CZs produced using the simpler methods (calculated fixed radius, uniform flow equation and hybrid) is uniform around the perimeter of the "best estimate" zones (Figure 12). However, the uncertainty around the "best estimate" zone for the AEM modelling method is non-uniform, with uncertainty increasing with distance away from the pumping well. The AEM modelling method was the only applied method that could incorporate uncertainty associated with the change in aquifer hydraulic parameters caused by the dredge tailings.

4.3 RUATANIWHA PLAINS – CONFINED GRAVEL AQUIFER

In this case study, CZs and 1-year PZs were delineated for one municipal water supply well. Well#1762 supplies up to 7900 m^3/week (daily pumping rate of 1129 m^3/d, Table 8) to the Takapau Township on the Ruataniwha Plains. The Ruataniwha Plains aquifer system consists of a shallow unconfined gravel aquifer, underlain by a confining clay layer, in turn underlain by a deeper confined gravel aquifer. Well#1762 draws groundwater from the deeper confined aquifer (Gusyev and Toews, 2012).

A CZ was defined around Well#1762 using the hydrogeological mapping - surface water catchment method. The surface water catchment contributing to Well#1762 is bounded by water divides to the north, south and west. The eastern boundary of the catchment is the well elevation contour line. The catchment is about 1.74 km^2, and includes the basement hills surrounding the valley; however, given the confined nature of the aquifer, this zone is unlikely to be a valid protection area (Figure 13, inset A).

The 10-year and 1-year PZs delineated using the calculated fixed radius method yielded areas of 1.96 km^2 and 0.20 km^2, respectively. This is because the confined status of the aquifer invalidates the use of the recharge equation. Therefore, the calculated fixed radius method for a 10-year PZ was used as a proxy for the CZ. Both zones could not be refined using geological map information (Figure 13, inset B). A potentiometric map was constructed from forty-seven groundwater level measurements (Gusyev and Toews, 2012). The groundwater flow path to the well and the associated hydraulic gradient were inferred from this map. A CZ and 1-year PZ were delineated using the uniform flow equation; these zones were orientated using the potentiometric surface (Figure 13, inset C). However, the spatial extent of groundwater level data did not allow the potentiometric map to extend to the hydraulic boundary. Consequently, only a PZ could be delineated. The equivalent TOT along the flow path from the well to the potentiometric map boundary was 33 years, calculated using equation (7). The 33-year PZ is a generally E-W elongated parabola bending slightly south towards the western boundary. The respective areas for the CZ and 1-year PZ are 9.07 km^2 and 0.36 km^2, respectively.

For a more conservative approach, CZ and 1-year PZ were delineated using the hybrid method, obtained by combining the zones produced by the calculated fixed radius method and the uniform flow equation (Figure 13, inset D). In this instance, the radius around the well was adjusted to be the 33-year PZ delineated using the calculated fixed radius for consistency (865 m radius), and used to generate the hybrid shapes. The corresponding areas of the 33-year and the 1-year PZs are 11.2 km^2 and 0.40 km^2, respectively.

A basin wide, 803 km^2, steady-state, groundwater flow model developed by Hawke's Bay Regional Council (HBRC) (Baalousha, 2009, Table 8) was used to delineate zones using the numerical modelling approach combined with backward particle tracking. Modifications to the HBRC model were required for CZ delineation, such as grid resizing and addition of more observation wells in the vicinity of the Well#1762 (Gusyev and Toews, 2012). The modelled CZ and 1-year PZ are elongated zones, oriented WSW-ENE, with areas of 6.27 km^2 and 0.17 km^2, respectively. Although the zones delineated using the uniform flow equation, the hybrid method and numerical model methods, are all of similar size, their orientations are significantly different. Both the similarity in size and different orientation are because of the limited spatial extent of groundwater level information used to constrain the zones delineated with the uniform flow equation and the hybrid method compared to basin-wide coverage of the numerical modelling method.

4.4 PUTARURU – FRACTURED LEAKY VOLCANIC AQUIFER

In this case study, CZs and 1-year PZs were delineated for a spring and a municipal water supply well field. The Putaruru well field and the Blue Spring serve as main source of drinking water for the town of Putaruru, South Waikato. The Putaruru well field contains two supply wells that provide up to 3,800 m^3/d (Table 8). Wells GS#2 and GS#3 are 70 m deep (10 m screen length) and 180 m deep (86 m open hole), respectively. The Blue Spring is a "fracture spring" located approximately 4 km east of Putaruru, with an outflow of ca. 45,000 m^3/d (Table 8). The source water for both water supplies is the Whakamaru Ignimbrite aquifer (Gusyev *et al.,* 2011a).

Zone delineation by the hydrogeological mapping - surface catchment method was undertaken using 100 m contour interval from the 1:250,000 topographic map series. The deeply incised and complex valley system around both sites prohibited the use of the 20 m contour data from the 1:50,000 topographic map series. The Blue Spring surface water catchment is large (about 41 km^2) and extends east to the ridgeline of the Kaimai Range (Figure 14, inset A). The surface water catchment of the well field is of much smaller extent (2.49 km^2), bounded by a low ridgeline to the north and a natural drainage feature creating a hydrological boundary to the south.

The CZ (37.0 km^2) and 1-year PZ (0.65 km^2) for the Blue Spring were delineated using the calculated fixed radius method and refined using topographic contours. The area below the elevation of the spring was removed from the zone because it is unlikely to contribute to spring flow. This modification reduces the original CZ area of 42.1 km^2 by 34%, causing the area required to support spring flow to be underestimated (Figure 14, inset B). This underestimation can be compensated by enlarging the radius of the refined CZ so its area is equivalent to the original calculation. Assuming a similar reduction factor, the adjusted radius would be about 5,215 m. The original CZ radius calculated by the recharge equation was 4,230 m. At the well-field, there is a large difference in calculated radii for wells GS#2 (675 m) and GS#3 (120 m), caused by the difference in pumping rate, well depth and screen interval between the two wells (Table 8). The zones delineated at well GS#2 encompass the zones at well GS#3, which causes the zones at each well to be underestimated because pumping interference is not accounted for. To address this, the combined abstraction rate was applied to a synthetic well, sited between wells GS#2 and GS#3 (Table 8). The resulting CZ and 1-year PZ for the synthetic well, produced using the calculated fixed radius method, have areas of 4.75 km^2 and 1.84 km^2, respectively (Figure 14, inset B).

Groundwater flow paths were estimated using the 100 m interval topographic contours as a proxy for the potentiometric surface. The zones delineated using the uniform flow equation were oriented WNW-ESE and were similar for both of the wells and the spring (Figure 14, inset C). The zones for GS#3 were again entirely included within the zones for GS#2, and therefore a synthetic well was used. The zones based on the uniform flow equation were larger for the synthetic well (CZ 76.2 km^2 and 1-year PZ: 0.94 km^2) than for the spring (CZ 153 km^2 and 1-year PZ: 4.76 km^2). The hybrid shapes were obtained by combining the zones produced using by the calculated fixed radius method (after refinement as described above) and the uniform flow equation, for a more conservative zone delineation (Figure 14, inset D). The CZ and 1-year PZ delineated by this approach had areas of 91.6 km^2 and 0.94 km^2, respectively at the Blue Spring; and 153 km^2 and 4.76 km^2, respectively, at the Putaruru synthetic well.

A 1,417 km^2 steady-state AEM (Table 8) was constructed to delineate zones using backward particle tracking. The AEM included surface water features such as the Waihou River (in which the Blue Spring is located) and the nearby Oraka, Waimakariri, Pokaiwhenua, Waipapa and Purere streams. The modelled CZ and 1-year PZ at the Blue Spring are elongated, curved shapes oriented WNW-ESE, with respective areas of 91.6 km^2 and 2.49 km^2 (Figure 14, inset E). The modelled CZ and 1-year PZ at the Putaruru wells (both wells were implemented individually) are also elongated, curved shapes oriented WNW-ESE, with areas of 71.3 km^2 and 0.21 km^2, respectively (Figure 14, inset E). The CZs for the wells delineated using the AEM differ significantly in width and orientation compared to the CZs delineated using the uniform flow equation. The difference is attributed to the incorporation of surface water features and variation in lateral hydraulic conductivity in the AEM, as well as the use of topographic contours as a proxy for potentiometric surface during application of the uniform flow equation.

4.5 POUKAWA – UNCONFINED LAKE SEDIMENTS / CONFINED LIMESTONE AQUIFER

In this case study, CZs and 1-year PZs were delineated for three hydrogeological features in the Poukawa Basin: Lake Poukawa, the Pekapeka Wetland and Well#3134. The Poukawa Basin is an NW-SE trending asymmetrical syncline, with Pliocene-Pleistocene age limestone, siltstone and sandstone forming the adjacent hills and Quaternary alluvial and lake sediments at its centre. Lake Poukawa and Pekapeka Wetland rest on the Quaternary sediments, which contain a shallow unconfined aquifer that is hydraulically connected to the lake and the wetland. At depth, the sediments contain alternating aquitards and confined aquifer units (Cameron *et al.,* 2011). The Quaternary sediments also act as a confining layer for the underlying Pliocene-Pleistocene sandstones and limestone. Well#3134 is 36 m deep and draws groundwater from the confined limestone aquifer (Table 8).

The water level in Lake Poukawa is maintained by a combination of groundwater-fed stream flow and direct groundwater inflow from the unconfined aquifer. Baseflow to the contributing streams is from springs flowing from the limestone aquifer (Cameron *et al.,* 2011).

The CZ for the lake, delineated using the hydrogeological mapping - surface water catchment method, is extensive at ca. 56 km^2 (Figure 15, inset A). This area can be refined using the geological boundary of the Quaternary alluvial and lake sediments (Figure 15, inset B). The area of the refined CZ is ca. 11.4 km^2. The calculated fixed radius method, the uniform flow equation and the hybrid method are not applicable for delineation of capture or protection zones for lakes, as these methods are for point features and require input of a groundwater discharge value, which is generally unknown for a lake. A CZ for Lake Poukawa was delineated using a numerical model of Poukawa Basin (110 km^2), which yielded a 11.8 km^2 CZ (Figure 15, inset C). This delineated zone indicated that there is considerable groundwater contribution to the lake from the limestone aquifer. The CZ derived from the numerical model extended further north than the CZ delineated from the surface water catchment.

The Pekapeka Wetland is located at the northern end of the Poukawa Basin (Figure 16, inset A). It is fed by streams down-gradient from Lake Poukawa and from the Poukawa Stream that flows from the lake. Its surface water catchment is essentially the entire basin of about 111 km^2 (Figure 16, inset A). Applying the wetland CZ delineation method proposed by Davies *et al.* (2000), whereby the CZ width is twice the width of the wetland when measured perpendicular to the direction of groundwater flow, a CZ of 13.0 km^2 is produced (Figure 16, inset B). The CZ derived from the numerical model is quite similarly sized at 15.7 km^2, although it is wider at the up-gradient western end (Figure 16, inset C). In comparison, the surface water catchment zone is clearly over-protective.

The CZ delineated for Well#3134 by the hydrogeological mapping - surface water catchment method was derived from 20 m interval topographic contours (1:50,000 map series). The CZ is relatively small (0.26 km^2), it does not extend to the boundary of the basin, and is likely to be under-protective (Figure 17, inset A). This is because the topography up-gradient of the well is relatively steep and the 20 m contours were too detailed for meaningful CZ delineation by this method in this setting. A larger topographic contour interval (say 100 m) would be more appropriate.

The 10-year and 1-year PZs for Well#3134 produced using the calculated fixed radius method were refined by consideration of the basin boundary (Figure 17, inset B) and have areas of 1.77 km^2 and 0.23 km^2, respectively. This is because the confined status of the aquifer invalidates the use of the recharge equation. Instead the calculated fixed radius method was used to delineate a 10-year PZ as a proxy for the CZ delineation. The groundwater flow path to Well#3134 was inferred from groundwater contours, allowing the flow line to extend to the basin boundary. The equivalent TOT along the flowpath from the well to the potentiometric map boundary was calculated using equation (7) to be 4.8 years (1745 days). The 5-year and 1-year PZs delineated using the uniform flow equation had areas of 0.89 km^2 and 0.18 km^2, respectively (Figure 17, inset C). The hybrid shapes were obtained by combining the zones produced by the calculated fixed radius method (after refinement to account for truncation by the basin boundary) and the uniform flow equation. The maximum TOT defined by the uniform flow equation is less than the 10-year proxy obtained from the calculated fixed radius. It is therefore regarded as conservative to develop hybrid zones by combining the 10-year circular PZs from the calculated fixed radius and the uniform flow PZs. The resulting 10-year and 1-year PZs had areas of 2.23 km^2 and 0.29 km^2, respectively (Figure 17, inset D). In contrast, the best-estimate CZ and 1-year PZ delineated by the numerical modelling method were of smaller extent (0.14 km^2 and 0.07 km^2, respectively) and does not extend to the basin boundary (Figure 17, inset E). In this case, uncertainty was not incorporated in model simulations so a CZ was not delineated by modelling for this well (Cameron *et al.,* 2011).

4.6 PAUANUI – COASTAL SAND AQUIFER

In this case study, CZs and 1-year PZs were delineated for a municipal water supply well field. The Pauanui groundwater supply consists of three wells (N1, N2 and N3) installed in an unconfined coastal sand aquifer on the Pauanui Peninsula (Table 8). The aquifer is about 15 m thick and overlies a rhyolite dome that outcrops at the southern end of the peninsula (Moreau *et al.,* 2014b).

The CZ delineated for the three wells using the hydrogeological mapping - surface water catchment method encompasses the entire peninsula (2.49 km^2; Figure 18, inset A). CZs were also delineated for each well using the calculated fixed radius method. The pumping rate for each well was estimated by dividing the combined consented abstraction rate (800 m^3/d) equally between the three wells. Hydraulic property values were obtained from the literature (Table 8) for similar aquifer materials. The resulting CZs overlap due to the close proximity of the wells. This causes the size of the zones to be underestimated because pumping interference is not accounted for (Figure 18, inset B). To address this issue, the recharge equation was applied to a synthetic well sited at the geometric centre of the three wells, pumping at 800 m^3/d. The resulting CZ produced using the calculated fixed radius method covered most of the southern half of the peninsula (1.28 km^2). The 1-year PZs (cumulative zone area of 0.24 km^2) derived for each well using the calculated fixed radius method overlap considerably. (Figure 18, inset B), Therefore a delineation was undertaken using the previously defined synthetic well. The corresponding 1-year PZ also covered an area of 0.24 km^2.

The groundwater flow path and hydraulic gradient for each well were inferred from a groundwater contour map. The SW-NE oriented flow paths were terminated at the aquifer edge, where the rhyolite dome outcrops at the southern end of the peninsula. Zones derived from the uniform flow equation were generated for both the individual wells and the synthetic well (Figure 18, inset C). The 1-year PZs delineated for individual wells overlap and, therefore, the size of each zone is underestimated, because pumping interference is not considered. The 1-year PZ for the synthetic well is larger than those of the individual wells but it does not encompass all of the well sites. Therefore, the four zones produced using the uniform flow equation were combined, providing a single zone that incorporated a component of pumping interference and included all of the well sites (CZ 0.09 km^2; 1-year PZ 0.09 km^2). The TOT calculated along the flow path to the edge of the aquifer outcrop, is 175 days (Figure 18, inset C). The hybrid zones are slightly more conservative than the individual approaches, with areas of 1.28 km^2 for the CZ and 0.28 km^2 for the 1-year PZ (Figure 18, inset D).

Zones were delineated using the backward particle tracking function on a modified transient, 2.5 km^2 numerical model (Table 8). The wells were treated individually, and resulting zones were aggregated, because the modelling could account for well pumping interferences. The 1-year PZs are almost circular for each well, with a total area of 0.01 km^2 (Figure 18, inset E). The 10-year PZ is an elongated zone of NNW-SSE orientation, with an area of 0.14 km^2 (Figure 18, inset E). The radically different orientation of the zones arises because the numerical model accounts for the application of municipal wastewater, which is not accounted for by any of the previously used simpler methods. The numerical model CZ represents a 10-year TOT and covers the extent of the area in which the municipal wastewater is applied. If the modelled wastewater application is an accurate reflection of reality it is likely to impact the local groundwater flow direction because the application rate greatly exceeds the natural rate of rainfall recharge. However, the wastewater application area falls outside the zones delineated by the simpler methods. Therefore, in this instance, numerical modelling is the most appropriate method for zone delineation because it is able to incorporate the greater complexity introduced by the wastewater application.

4.7 COMPARISON OF MICROBIAL PZS

The 1-year PZs defined in the case studies are intended to provide protection from microbial pathogens. The arbitrary fixed radius method can also be applied to determine safeguarding distances for microbial pathogens (Section 3.2.2). For each of the case studies, the 1-year PZs, delineated using the five different methods described in the previous sections, were compared to the PZs delineated using two arbitrary fixed radii based on international guidelines: 50 m (Australia, ANWQMS, 1995; United Kingdom, Carey *et al.,* 2009, Table 3) and the conservative 300 m (Ireland guidelines, to account for natural heterogeneity amongst Irish aquifers, DELG/EPA/GSI, 1999, Table 3).

There is only one case were the smaller arbitrarily fixed radius PZs are found larger than PZs delineated using more complex method (Figure 19): the unconfined sand aquifer of Pauanui. There were no instances where PZs produced using the larger arbitrary fixed radius encompassed all of the 1-year PZs produced by the other methods. In three cases the arbitrarily fixed radius PZ was larger than PZs delineated using the calculated fixed radius method (confined aquifers of Ruataniwha Plains and Poukawa, unconfined aquifer of Pauanui). Given the similar aquifer properties used for delineation between Gore and Pauanui (Table 8), this might reflect the low abstraction rate at Pauanui.

As a general statement, counter-intuitively, the numerical model derived PZs were not the smallest PZs in all cases, only in four cases out of seven microbial delineation comparisons (Ruataniwha Plains, Putaruru well field, Pauanui and Poukawa well). The two well fields in Gore are thought to have a surface water contribution to the flow and, therefore, it is expected that the model 1-year PZ will be larger than zones delineated with simpler method (not accounting for surface water inflows).

5.0 SUMMARY AND CONCLUSIONS

The purpose of this document is to provide technical information to support the companion document: "Capture zone guidelines for New Zealand" (Moreau *et al.,* 2014a). Hydrological features considered in this project include wells, springs and groundwater-fed small lakes and wetlands. Because of the large variety in CZ related terminology, definitions and classifications in the international literature, we propose the following definitions to provide clarity and to meet the specific objectives of this study:

- CZ: the total source area that contributes groundwater to the hydrogeological feature (well, spring, lake or wetland with groundwater contribution).
- PZ: the portion of the CZ that has a defined travel time for groundwater to arrive at the hydrogeological feature.

In the New Zealand context, three of the five existing criteria are useful for delineation of a CZ or PZ: TOT (the maximum travel time for a water molecule or a contaminant to reach a hydrogeological feature); distance (a radius or dimension from a hydrogeological feature); and flow boundary (locations that control groundwater flow). Criteria not retained for consideration are the drawdown and the assimilative capacity.

Numerous guidelines for zone delineation have been developed worldwide since the 1990s, using an extensive list of alternative terminology. The proliferation of guidelines has arisen due to: the lack of international guidance; the selection of a specific delineation criterion for each individual study; and the different geographical location and regulatory frameworks of the studies (USA, Europe, Australia, and Canada). PZs most frequently defined in the literature are defined using either the distance or the TOT. However thresholds for these criteria and the number of zones (up to four) vary widely between countries. Three zones are proposed for New Zealand (use one or a combination of the above three criteria):

- Immediate Zone using a distance criterion of at minimum 5 m. The literature review indicated that immediate PZ around the world are defined with distances varying from 5 to 60 m. Some countries varied the distance as a function of aquifer matrix from 20 m in porous aquifers up to 60 m for lower permeability chalk (Portugal).
- Microbial PZ using whichever is the greater of a 1-year TOT criterion or a safeguarding distance criterion. TOT thresholds for microbial PZ in international guidelines vary from 100 days (Ireland), to 1 – 2 years (The Netherlands), up to 5 years (Indiana State); and distance thresholds range from 40 m (Portugal – porous aquifers) up to 914 m (Indiana State).
- CZ using steady-state conditions that delineate the entire recharge area of a feature, truncated as appropriate by flow boundary criteria. Alternatively, the CZ can be delineated using a TOT criterion of 10 years for management purposes or 50 years or flow boundary criteria. The 50-year threshold is based on groundwater age tracer information suggesting that a TOT of between 50 – 100 years is appropriate for New Zealand. The area of the CZ will likely be overestimated if it is defined solely by flow boundary criteria.

After a comprehensive review of existing delineation methods in New Zealand and existing guidelines, the following seven CZ or PZ delineation methods have been selected as appropriate for application in the New Zealand context (in order of increasing complexity): arbitrary fixed radius, calculated fixed radius, simplified variable shapes or hybrid method, analytical method, hydrogeological mapping, AEMs and numerical flow/transport models.

These methods cover the range from simple approaches that can be applied quickly and cheaply to provide a reasonably conservative assessment of the area in which the actual CZ or PZ is likely to occur, to robust approaches that provide a high degree of certainty that the delineated zone is correct.

A targeted approach is proposed for zone delineation, where available data are used to develop a conceptual model of the aquifer system at the feature. Information pertaining to the required level of accuracy for delineation and availability of resources (e.g. available data and expertise) are also needed. These elements will lead the user through the method selection. Zones should then be delineated by applying the selected method and, if required, refined to suit site-specific conditions. Work undertaken in this project identified that it is not practical or valid to delineate CZs or PZs for lakes or wetlands by using the simpler delineation methods originally developed for pumping wells. This is primarily because 1) lakes and wetlands cannot be represented as point locations and 2) it is difficult to accurately determine the rate of groundwater discharge to lakes and wetlands. It is also recommended that for supplies serving more than 500 people; to use either of the modelling methods.

A simple approach to uncertainty analysis, easily and consistently applied and which does not require specialist skills or understanding, is required at the national scale. A sensitivity type approach is recommended for uncertainty analysis, which reflects the uncertainty in the conceptual understanding of the flow regime around a feature and the uncertainty in parameter values. With this approach, the general principle for estimating the uncertainty associated with zones delineated using manual, semi-analytical or numerical model methods is similar. For each method, uncertainty is estimated by systematically varying input parameter values over a plausible range to define the likely variation in size of the zone. Average or median values for input parameters should be used for the “best estimate” calculation. This requires running a series of calculations with combinations of parameter values to define the outer limits of the uncertainty. In circumstances in which no information about the plausible range of input values is available, the input values for establishing the uncertainty should be set to ± 25% of the average or median values that were used for the “best estimate” calculation. Both the zone including uncertainty and the “best estimate” zone should be displayed when reporting delineation.

All proposed zone delineation methods were applied at five case study areas to explore the practical aspects of zone delineation and to compare the results. Where possible, the case study areas included more than one hydrogeological feature. The sites were selected to encompass typical New Zealand hydrogeological settings: unconfined gravel aquifer (Gore); confined gravel aquifer (Ruataniwha Plains); unconfined coastal sand aquifer (Pauanui); unconfined (leaky) fractured, volcanic aquifer system (Putaruru), and an aquifer system with strong groundwater-surface water interaction (Poukawa). Uncertainty associated with the delineated zones was accounted for by a consistent and easily applied sensitivity approach in which the model input parameters were varied by ± 25% relative to their “best estimate” values.

The case studies showed:

- At wetlands and lakes, only two of the proposed zone delineation methods (hydrogeological mapping and numerical modelling) can be applied.
- All six proposed zone delineation methods can be applied at a well or spring.

- For the arbitrary fixed radius method to be conservative and encompassing for microbial protection purposes, it needs to be based on a relatively low porosity value, cautiously applied in areas of steep hydraulic gradient, and is more conservative for confined than for high yielding features drawing groundwater from unconfined aquifers.
- For unconfined aquifers, the surface water catchment delineation method produces the largest CZs (2.5 km^2 to 111 km^2 for the case studies considered in this project). For leaky or confined aquifers, the largest CZs (2.2 km^2 to 153 km^2 for case studies considered in this project) were obtained by the simplified variable shapes method and the modelling methods, which account for groundwater flow.
- Regardless of the method employed, the development of a good conceptual hydrogeological understanding prior to delineation enabled meaningful refinement the obtained shapes. In some cases, this understanding was also used to validate the use of a simpler method against another (e.g. if surface water contribution is expected the hybrid method should be used instead of the uniform flow equation in the Gore case study). The latter comment does not apply to sophisticated modelling methods because they can integrate complexities.
- Large differences in the shape, size and orientation of zones occurred where groundwater flow direction was not well constrained, and these discrepancies increased with distance from the hydrogeological feature.

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FIGURES

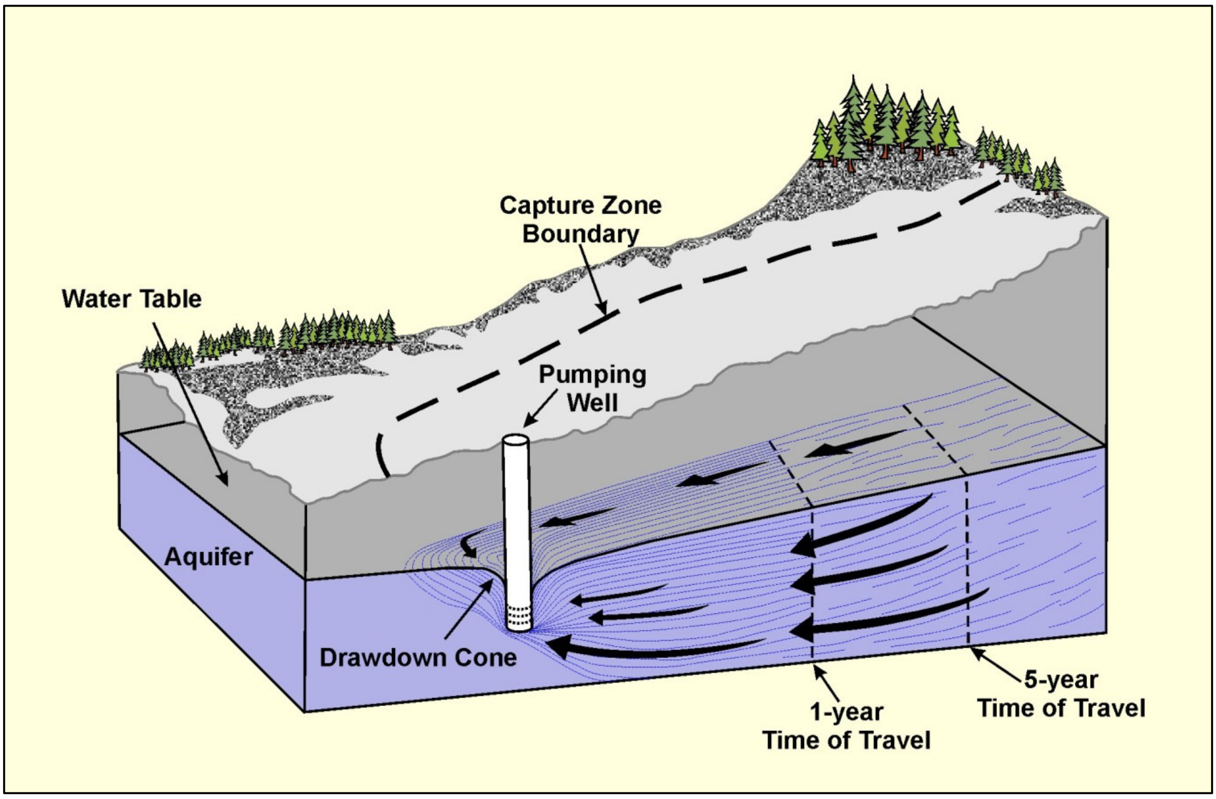

Figure 1: Idealised shape of the CZ for a well in a homogeneous isotropic unconfined aquifer. The regional groundwater flow direction is from right to left (modified from Ministry of Environment, British Columbia, 2004).

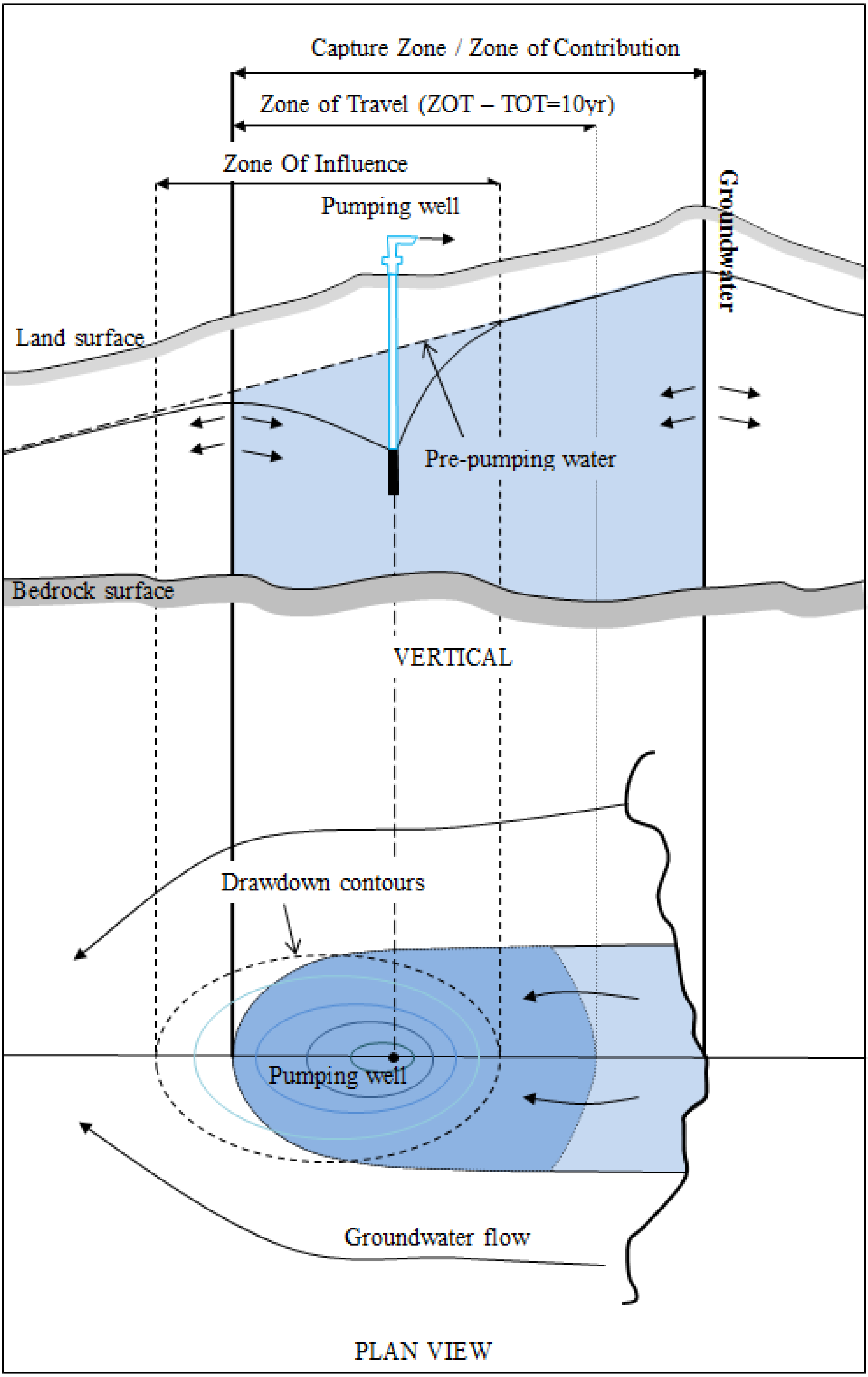

Figure 2: Schematic representation of CZ, ZOT, ZOC and ZOI around a pumped well (Adapted from US EPA, 1987; *Carey et al.*, 2009).

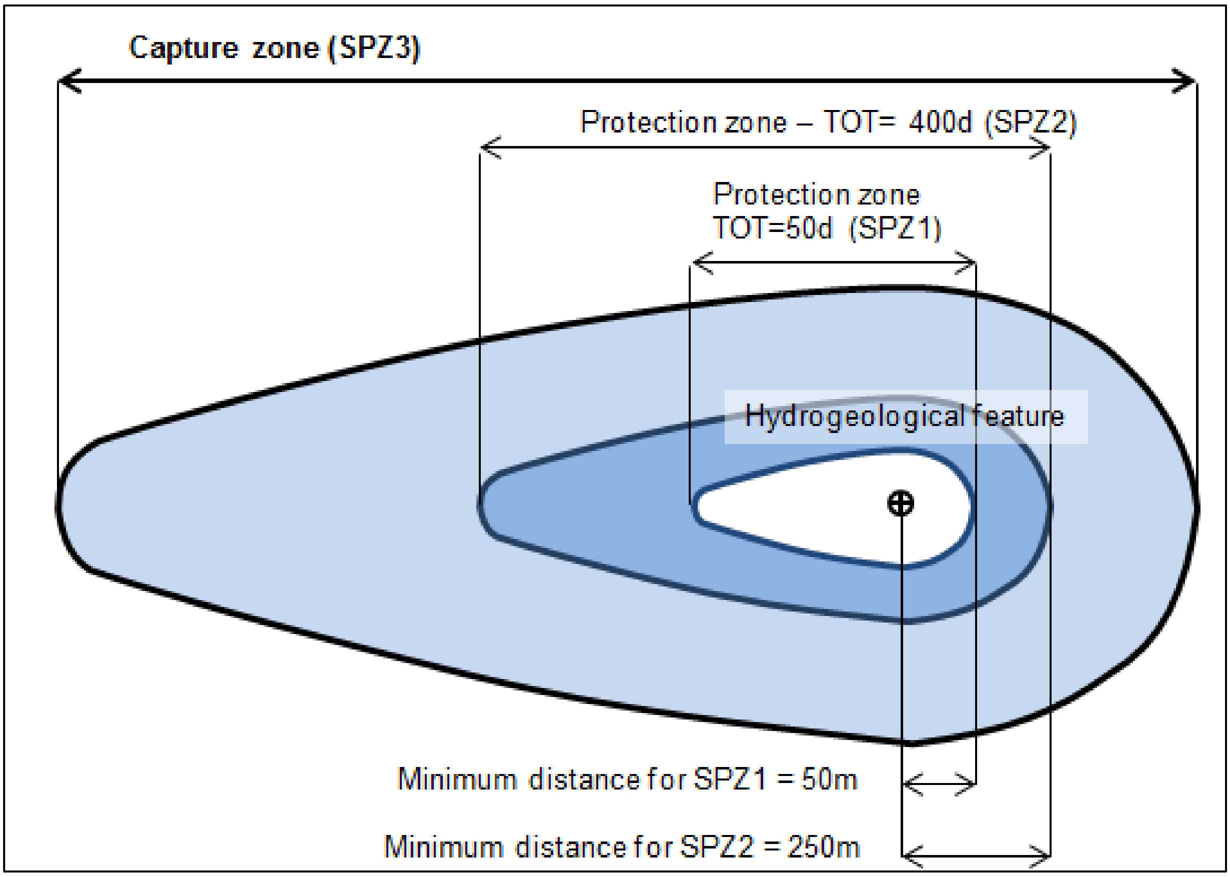

Figure 3: Schematic representation of CZ and PZ for a pumping well in a homogeneous anisotropic aquifer (modified from Carey *et al.,* 2009). The regional groundwater flow direction is from left to right. Drawdown contours are not shown.

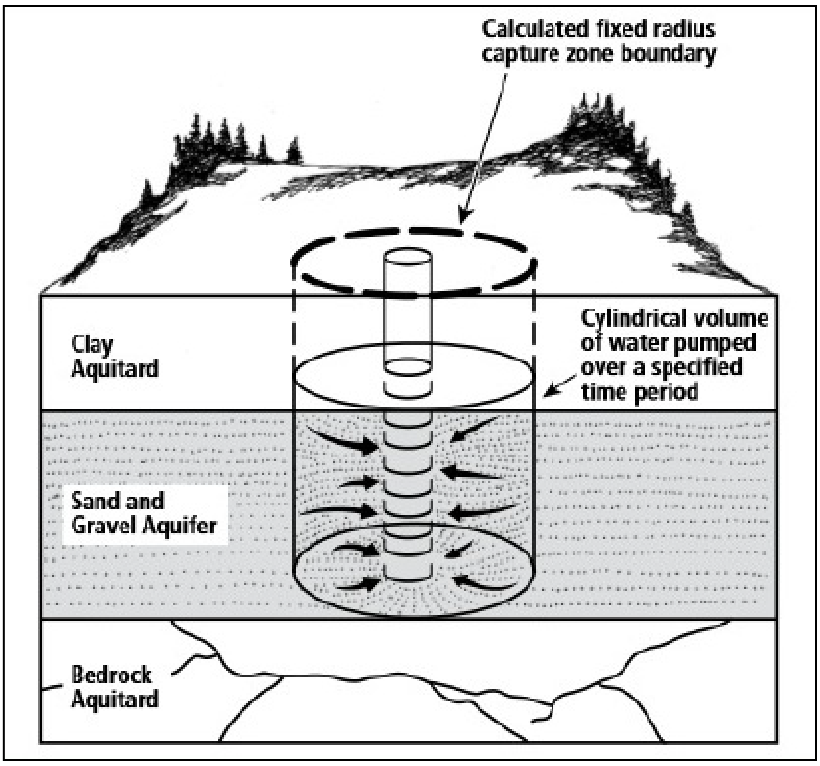

Figure 4: CZ based on the calculated fixed radius method (Ministry of the Environment, British Columbia, 2004).

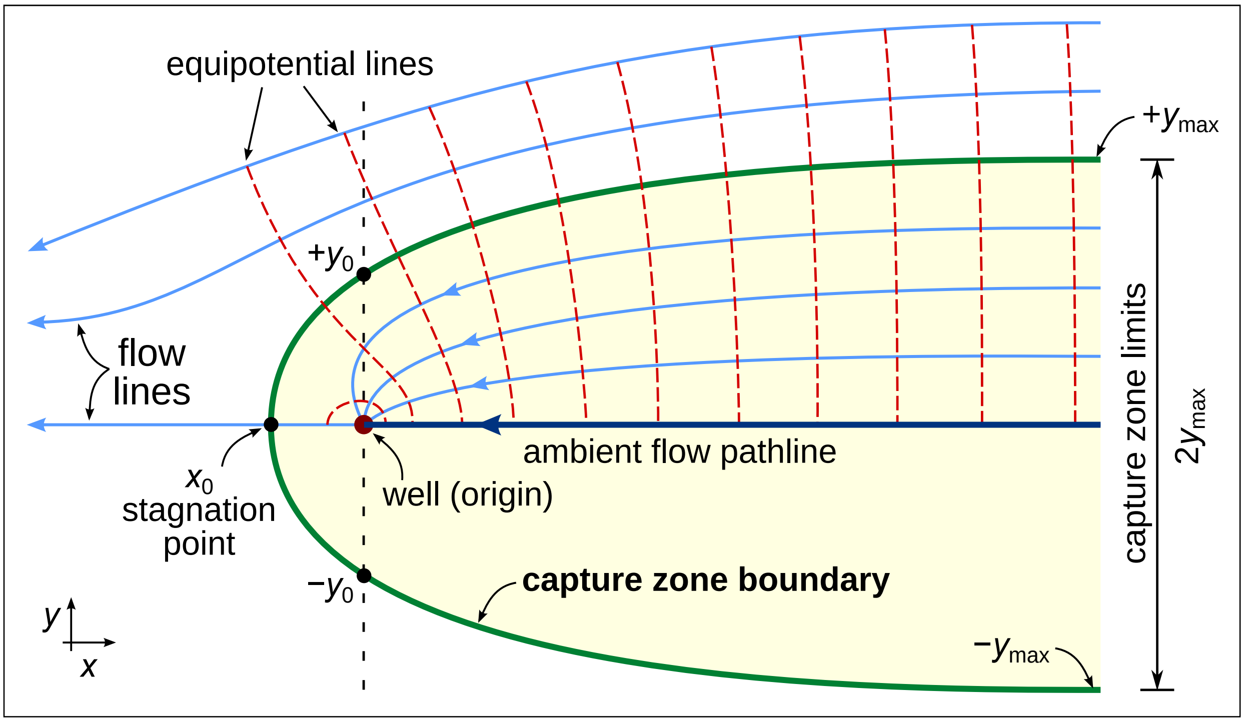

Figure 5: CZ for a pumping well, determined using a simple analytical method (from US EPA, 1987).

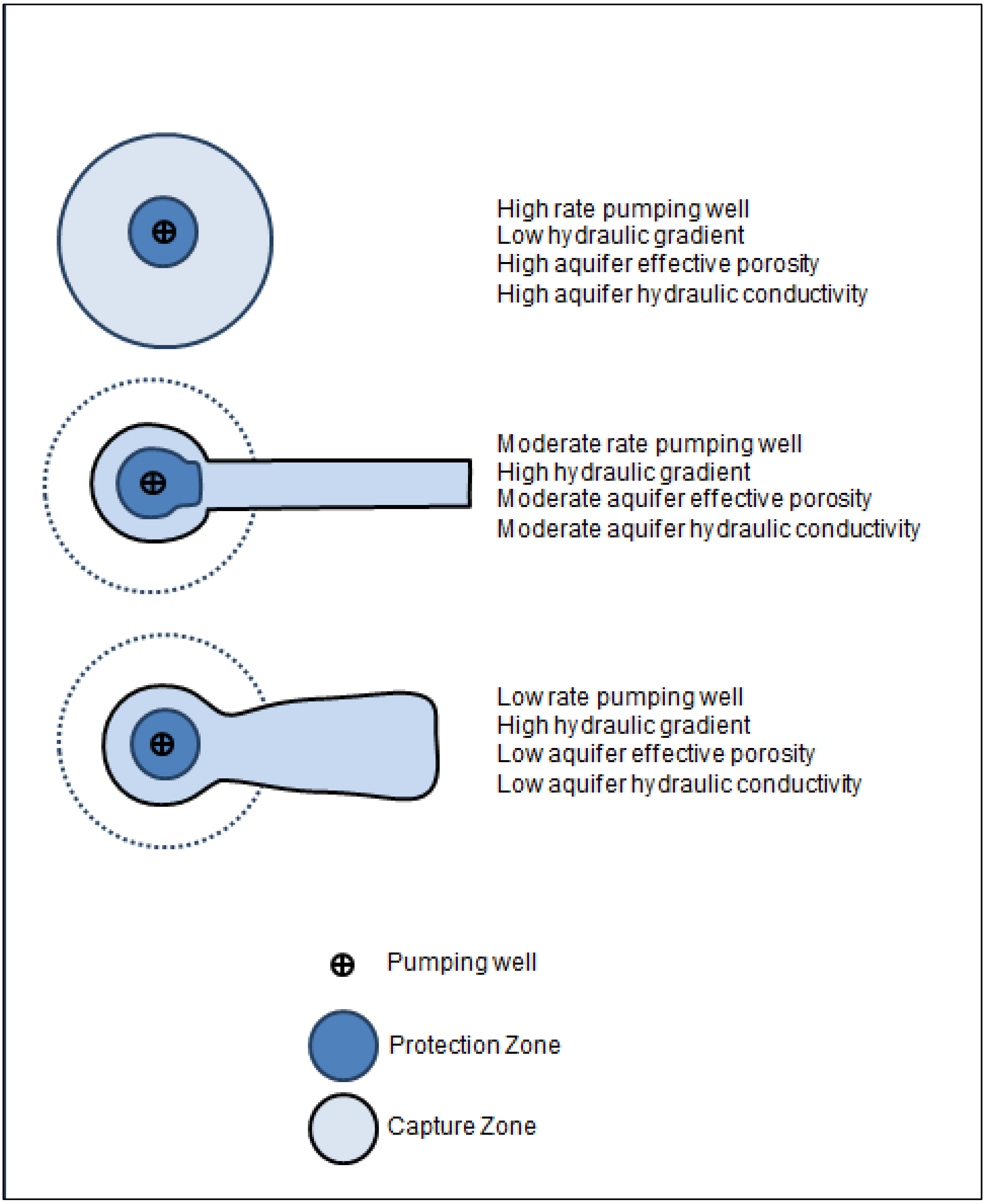

Figure 6: CZs delineated using simplified variables shapes adapted to selected aquifer conditions (modified from US EPA, 1994).

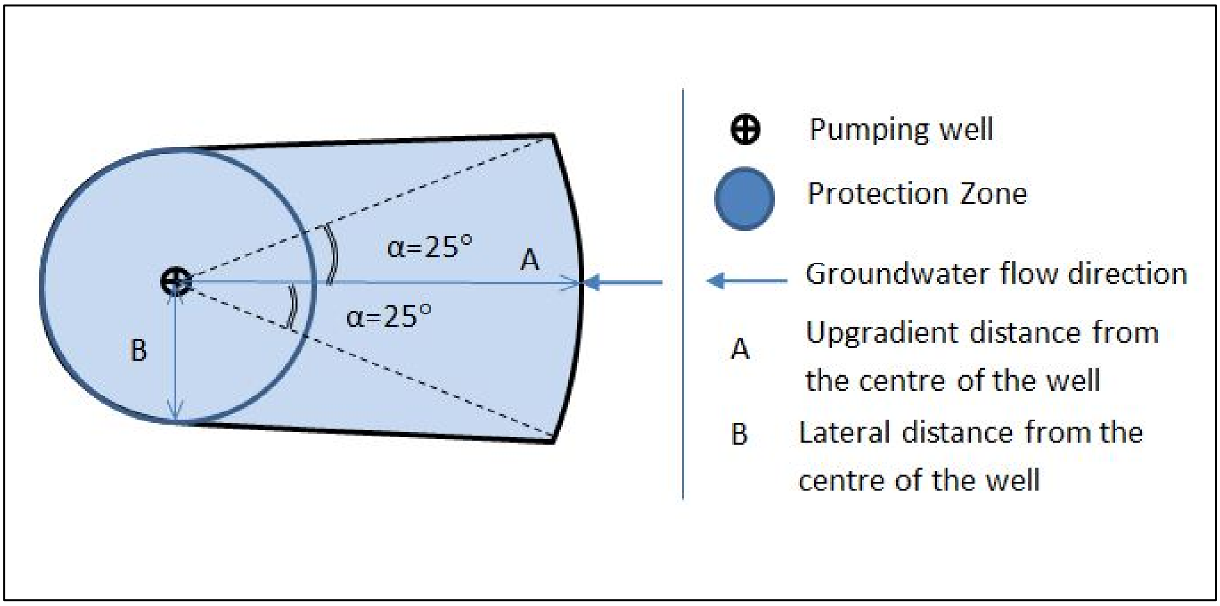

Figure 7: Shape used to delineate provisional Community Drinking Water Supply PZ (adapted from Environment Canterbury, 2011).

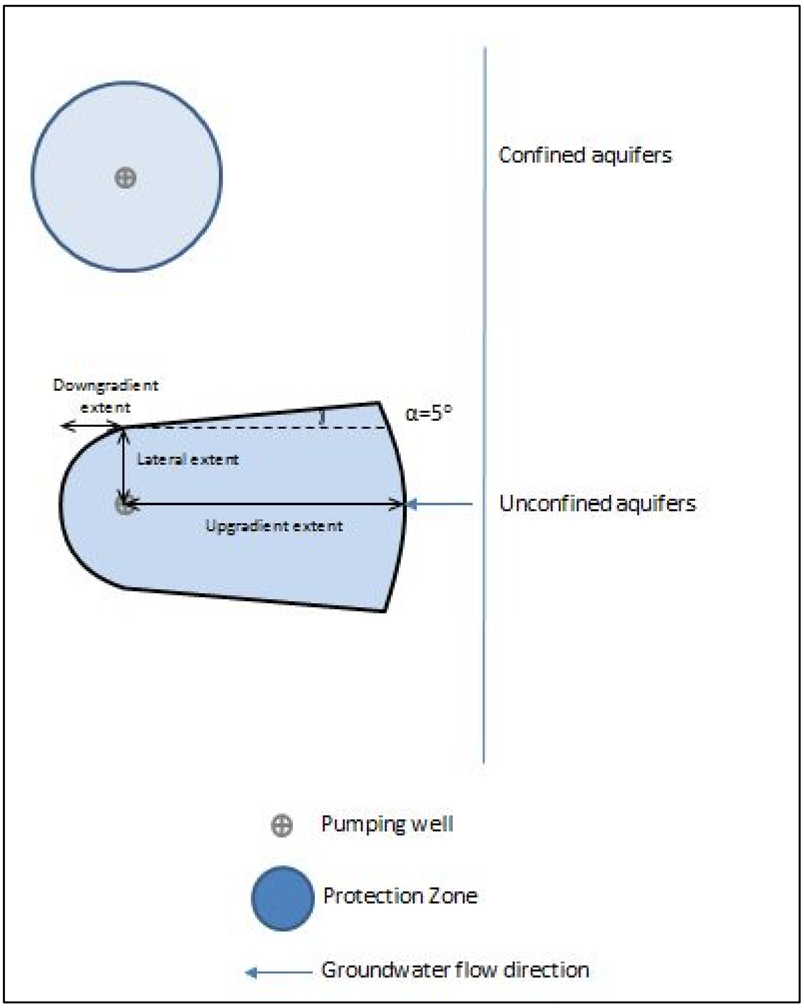

Figure 8: Shape used to delineate PZ in the Marlborough District, for the unconfined case (adapted from Pattle Delamore Partners, 2012).

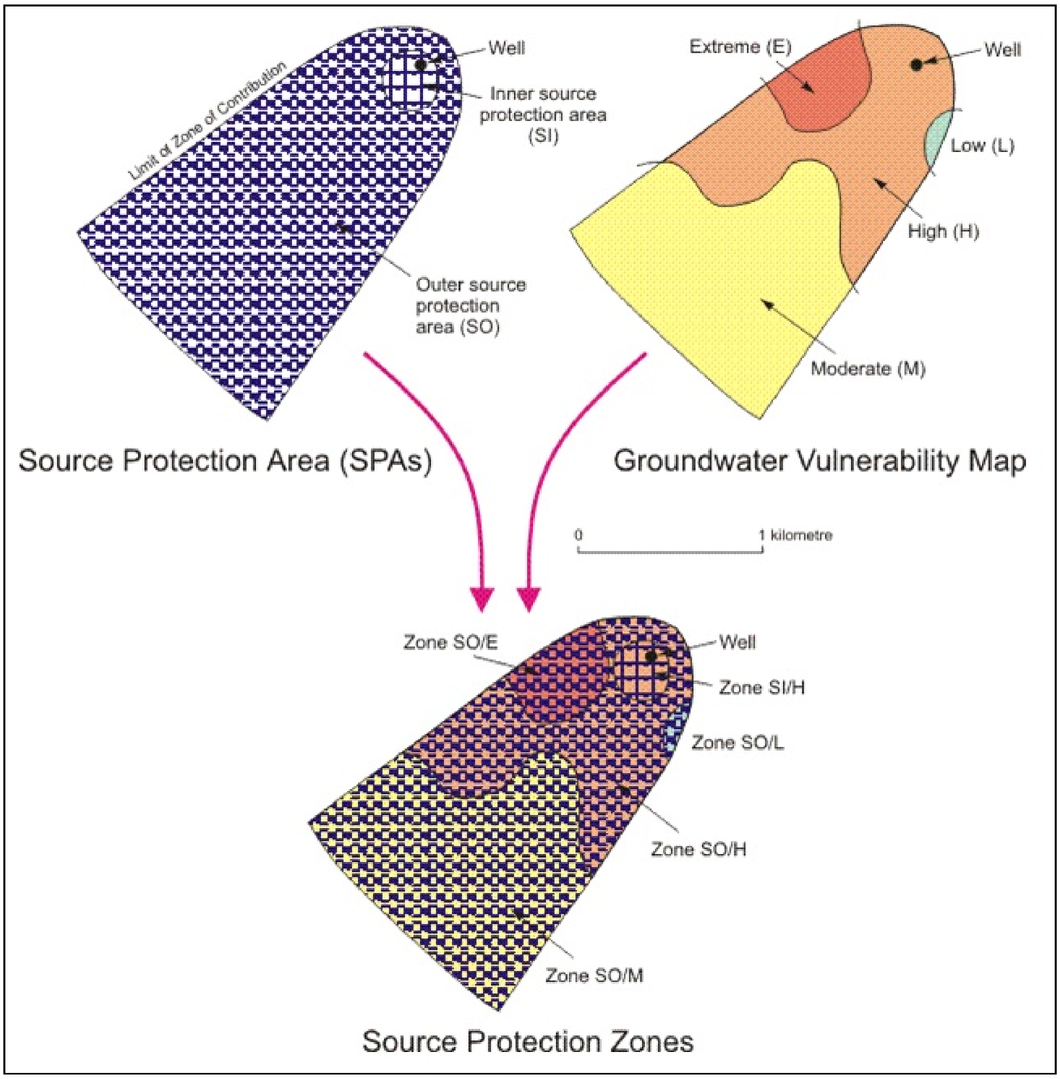

Figure 9: Delineation of source PZs around a public supply well from the integration of the source protection area map and the vulnerability map (DELG/EPA/GSI, 1999).

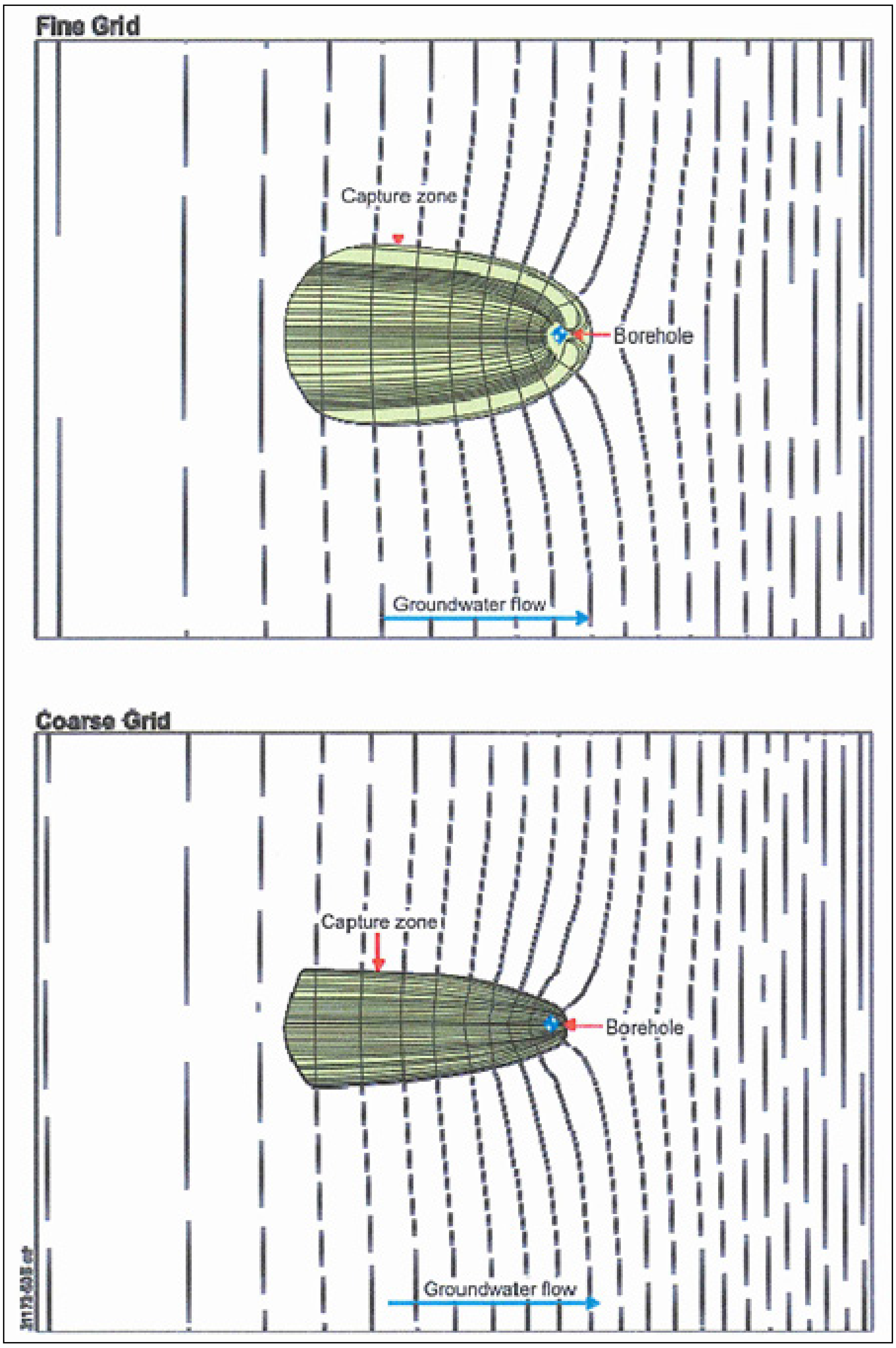

Figure 10: Effect of grid size on CZ (Carey *et al.,* 2009).

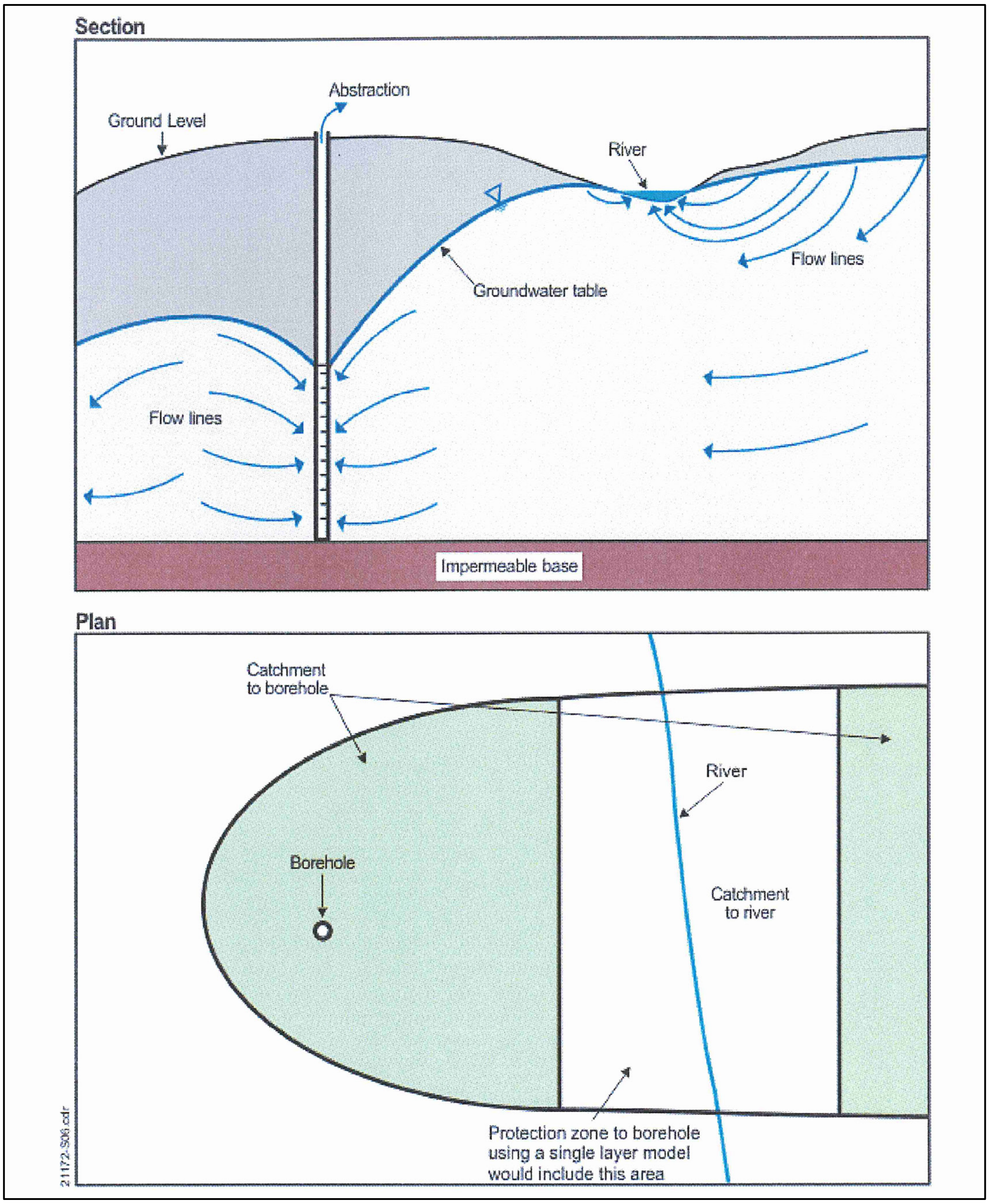

Figure 11: Effect of partial penetration on CZ (Carey *et al.,* 2009).

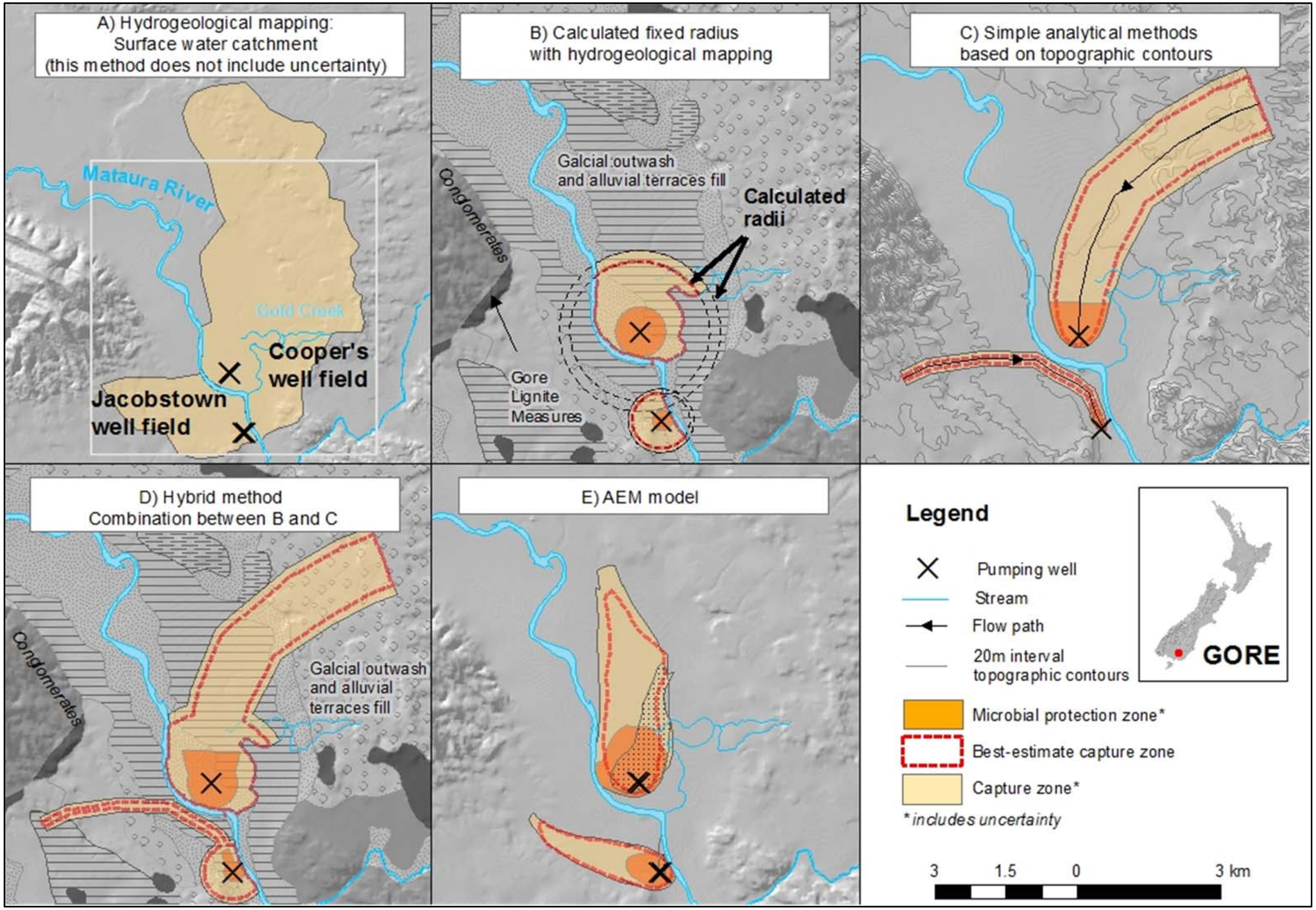

Figure 12: Comparison of CZs and 1-year PZs produced by different delineation methods, Gore case study.

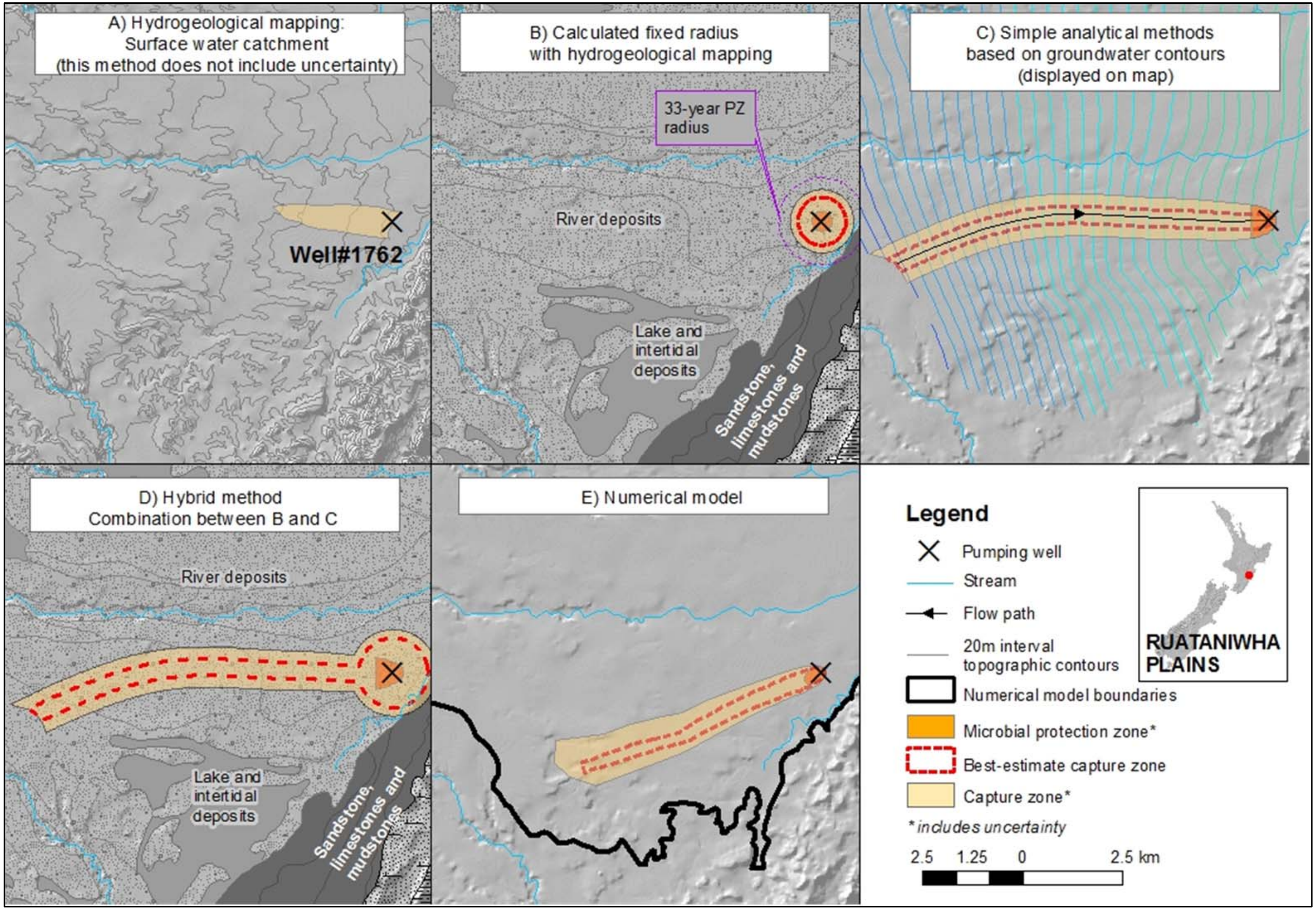

Figure 13: Comparison of CZs and 1-year PZs produced by different delineation methods, Ruataniwha Plains case study.

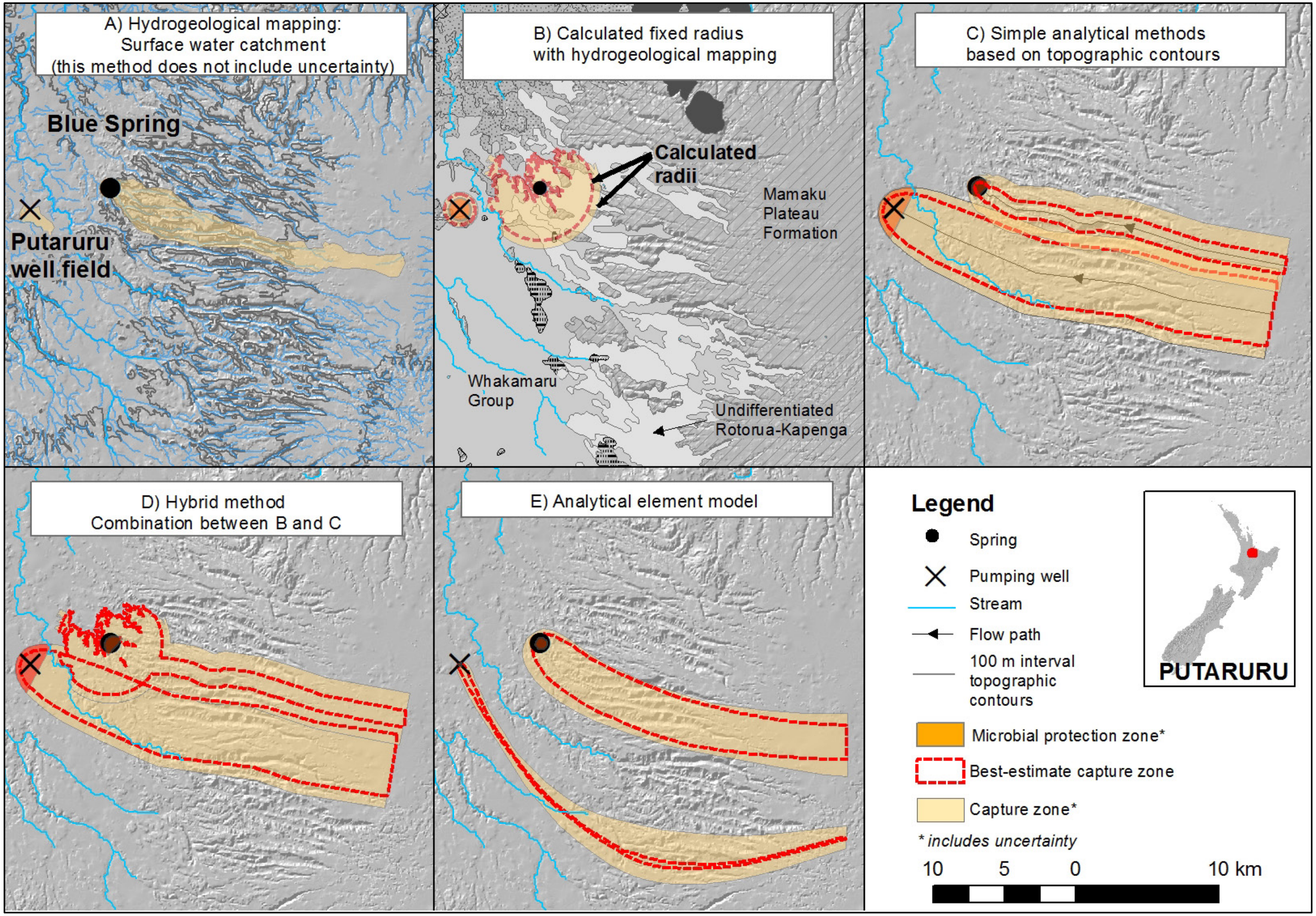

Figure 14: Comparison of CZs and 1-year PZs produced by different delineation methods, Putaruru case study.

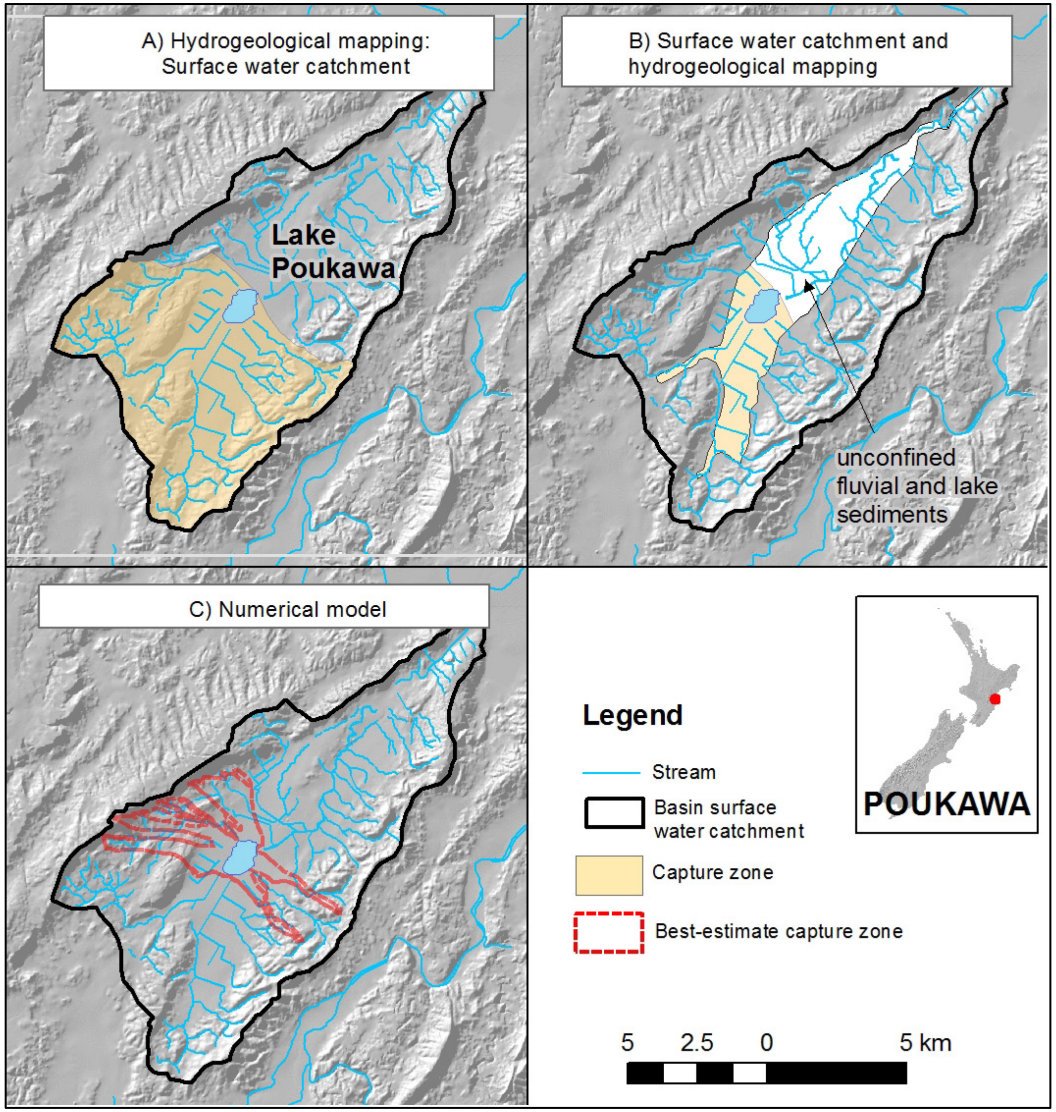

Figure 15: Comparison of CZs and 1-year PZs produced by different delineation methods, Lake Poukawa, Poukawa case study. Uncertainty was not taken in consideration in the modelling method (inset C).

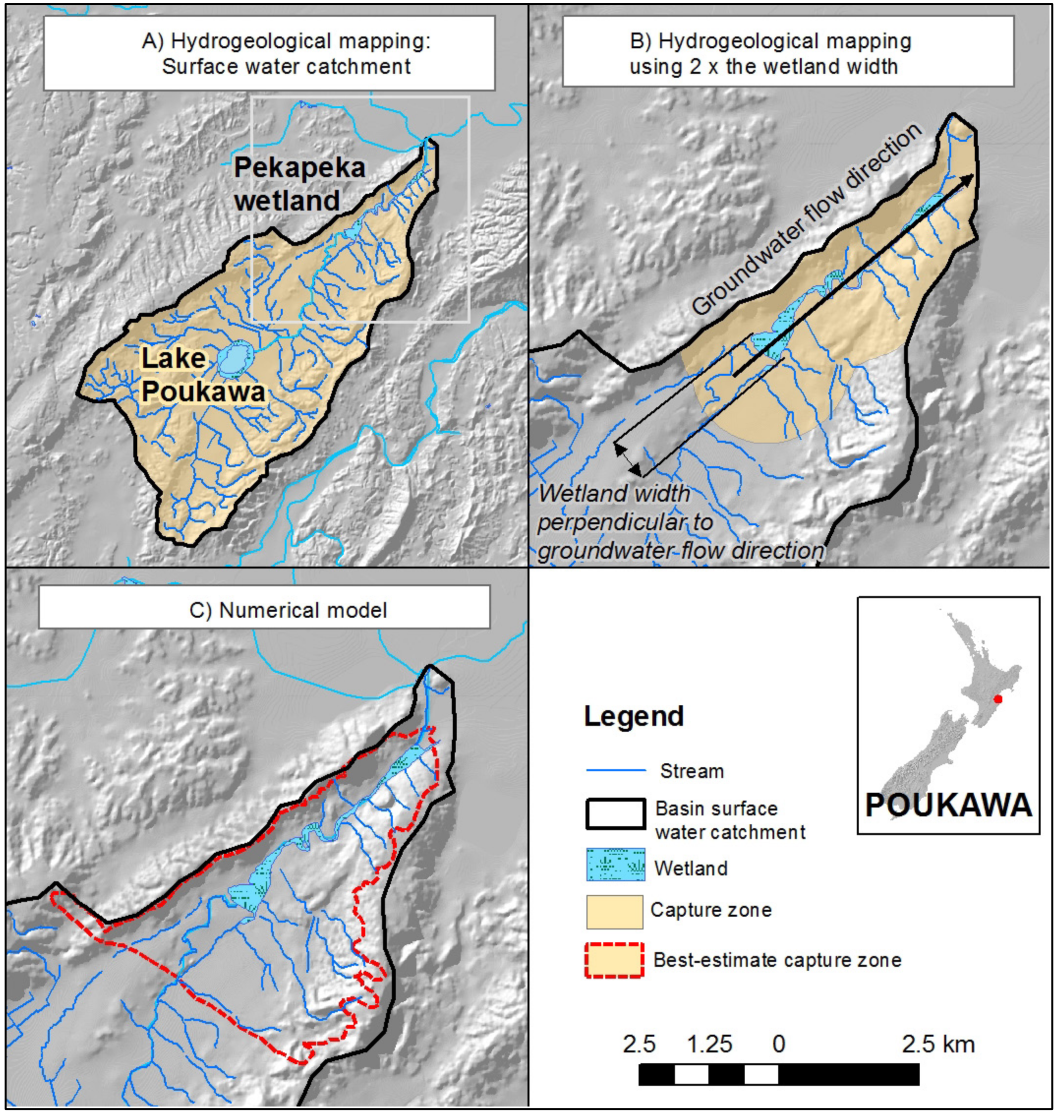

Figure 16: Comparison of CZs and 1-year PZs produced by different delineation methods, Pekapeka Wetland, Poukawa case study. Uncertainty was not taken in consideration in the modelling method (inset C).

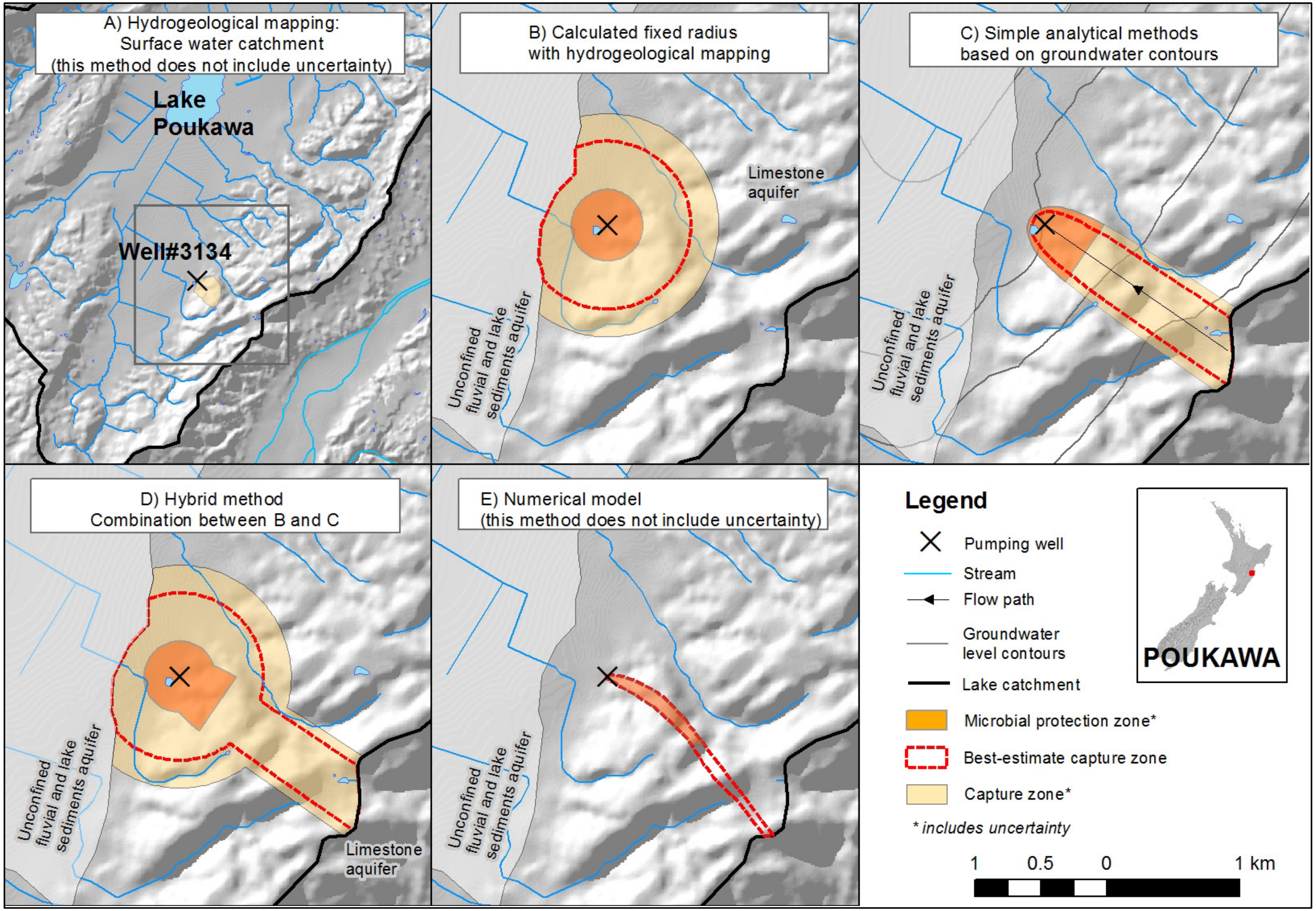

Figure 17: Comparison of CZs and 1-year PZs produced by different delineation methods, Well#3134, Poukawa case study. Uncertainty was not taken in consideration in the modelling method (inset C).

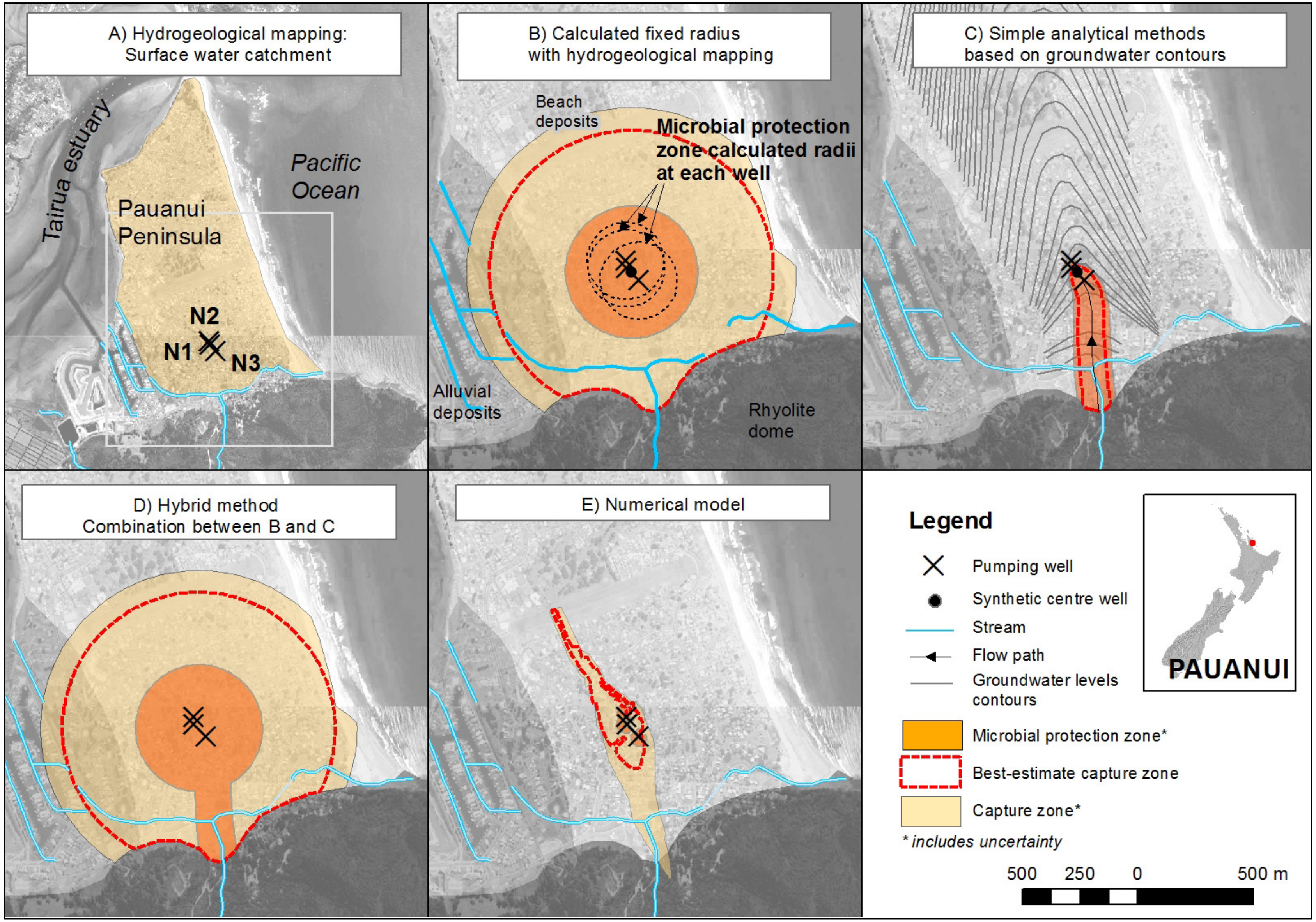

Figure 18: Comparison of CZs and 1-year PZs produced by different delineation methods, Pauanui case study.

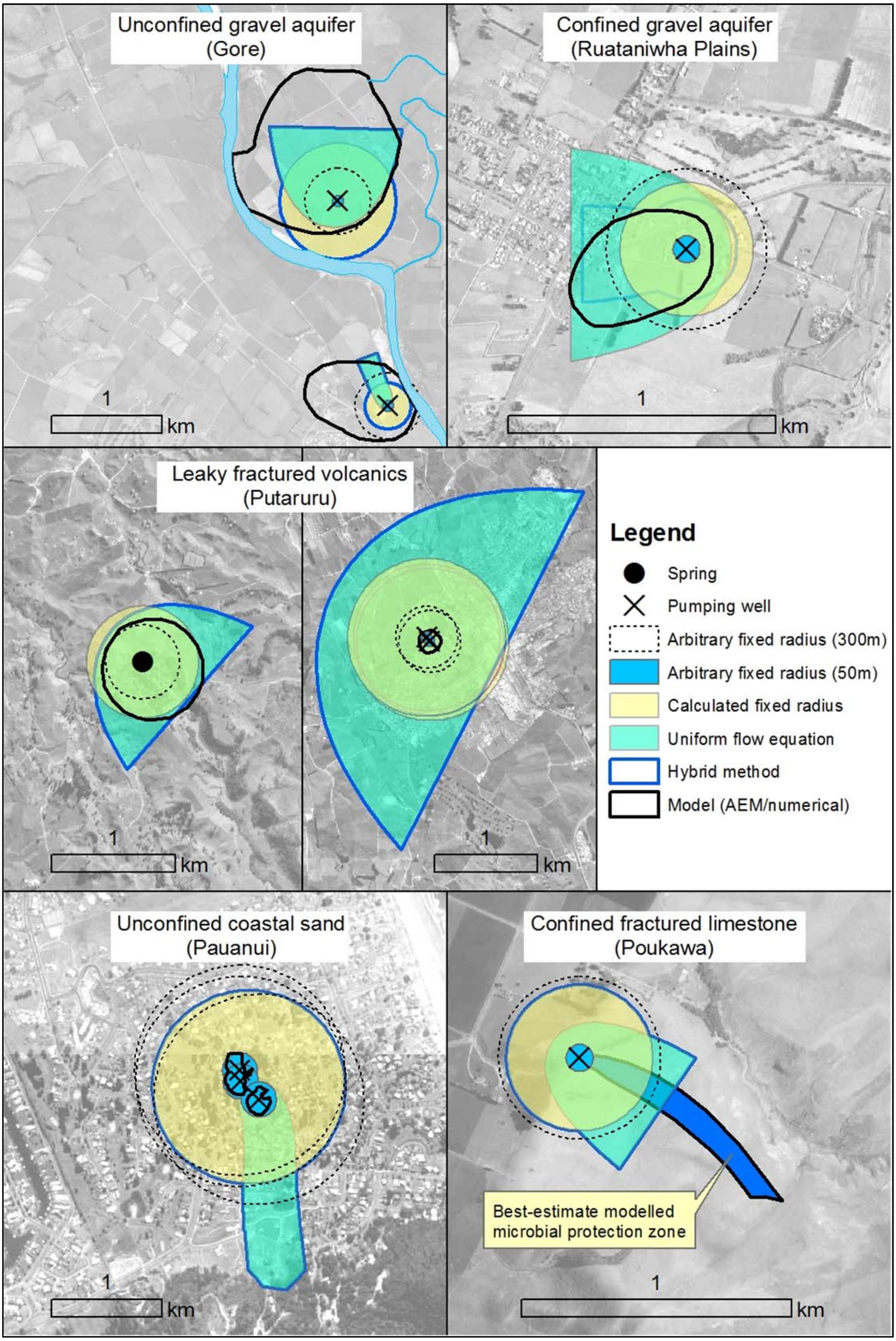

Figure 19: Comparison of 1-year PZs delineated using various methods in five different hydrogeological situations.

APPENDICES

APPENDIX 1: TRACERS COMMONLY USED IN GROUNDWATER (WHO, 2006)

Tracer	Examples	Advantage	Disadvantage	Comment
Natural environmental isotopes (stable/unstable)	^{2}H, ^{18}O, ^{3}H, ^{4}He, ^{39}Ar, ^{85}Kr, ^{36}Cl, ^{13}C, ^{14}C, ^{34}S, ^{15}N, ^{234}U	No artificial input needed. Huge spatial and temporal interpretation possible	Expensive measuring techniques due to low concentrations Complicated interpretation	Omnipresent substances (no artificial input required) Useful for calculation of mixing proportions, ages and travel times
Fluorescent dyes	Uranine	Economic Non-toxic Very low sorptivity High solubility in water	Sensitivity to light and oxidising substances Strong pH-dependence Difficult evaluation if Uranine is already in the hydrologic system	Very good tracer analysing groundwater flow and flow velocities Uranine should be restricted to groundwater in reasonable concentrations
	Rhodamine B	Low sensitivity to light and pH High solubility in water	Carcinogenic High sorptivity	Good tracer for short term tests and surface water with low contents of suspended organic and mineral particles
	Amidrhodamin G	Low sensitivity to light and pH Low sorptivity High solubility in water Easy to measure parallel to Uranine		Good tracer for groundwater and surface water
Salt	NaCl	Cheapest Cl tracer Easily available Highly soluble	Toxic concentrations for warm blooded animals are > 3000 mg/kg and for fish >10000 mg/kg	First and most widely used tracer To avoid density driven flow maximum concentration of 3 g/L or warm water should be used

Tracer	Examples	Advantage	Disadvantage	Comment
Salt	Lithium salts	Li has a small ionic radius, therefore least subjected to ion exchange	More expensive Toxic concentration for warm blooded animals are >526 mg/kg and for fish>10000 mg/kg Detection disturbed by Calcium, which as to be extracted	Can be used in porous aquifers up to flow ca 200 m Good results have been observed in karstic aquifers Cheapest salt is LiCl Use of non-plastic should be avoided because of exothermic reaction during solution
Radioactive tracers	^{3}H, ^{51}Cr, ^{60}Co, ^{82}Br, ^{131}J, ^{24}Na	Low chemical impact on the environment Disappearance due to radioactive decay Easy and economic detection	Possible radiation during artificial input of the tracer More complicated evaluation	Have been applied as artificial tracers both in surface and groundwater with satisfying results; especially useful for sewage water with high amounts of suspended particles
Bacteria	E. coli, faecal streptococci, sorbitol-fermenting bifido-bacteria	Transport behaviours models pathogenic bacteria movements	Limited persistence of sensitive indicator bacteria May have environmental rather than faecal source	Would not usually be injected directly as a tracer but monitored in relation to known hazard sites to determine impact
Bacteriophages	F-specific RNA bacteriophage, coliphages	Transport behaviour similar to viruses can be used as either index organism or process indicator	Isoelectric point and sorption dependent upon pH and need to ensure	Appropriate especially for investigating transport behaviour of viruses in order to define groundwater detection zones
Spores	Clostridium perfringens	Long survival times which can mimic more robust pathogens	Potential for interference by natural populations	Spores are often dyed or prepared to facilitate its behaviour and detection

APPENDIX 2: LIST OF ANALYTICAL EQUATIONS (US EPA, 1994)

A2.1 INTERAQUIFER FLOW AND TOT

The equation (modified from Darcy's law) to determine the flow from one aquifer to another is

$$Q_{l=(K_v/m)AH}$$

Where Q_l is the quantity of leakage, K_v is the vertical hydraulic conductivity of the confining unit, m is the thickness of the confining unit, A is the cross-sectional area and H is the difference in head between the two wells.

The TOT across a confining layer is defined as

$$t_v = nmx/K_vH$$

Where t_v is the vertical TOT across the confining layer, n is the porosity and x the travel distance across the confining strata.

A2.2 THIEM EQUILIBRIUM EQUATION

This equation calculates the distance to a specified drawdown criterion for a pumping well that has reached equilibrium:

$$s = [Q/2\pi Kb]\log\frac{r_e}{r}$$

Where s is the drawdown from original potentiometric surface (threshold criterion), Q is the discharge, K the hydraulic conductivity, b the aquifer thickness, r the radial distance at the point of drawdown observation and r_e is the radial distance of zero drawdown of cone of depression.

The underlying assumptions are: homogeneous and isotropic aquifer, infinite areal extent of the aquifer, full penetration of the well, the regional water table is flat.

A2.3 NON EQUILIBRIUM EQUATIONS

These have been derived to calculate the radius of a PZ:

$$r = \sqrt{\frac{u4Tt}{S}}$$

Where T is the aquifer transmissivity, t is the time to reach steady state and S is the storativity or specific yield of the aquifer and u is a dimensionless parameter related to the well function:

$$W(u) = \frac{4\pi Ts}{Q}$$

Where s is the drawdown at the maximum radius of influence and Q is the pumping rate. Well function and u values can be found in references tables from hydrogeology textbooks.

The underlying assumptions are: the aquifer is homogeneous, isotropic and of infinite extent, the well penetrates the entire aquifer, the well diameter is infinitesimal, the water removed from storage is discharged instantaneously with decline of head and the regional water table is nearly flat.

A2.4 EQUATIONS FOR BEDROCK WELLS RECEIVING RECHARGE FROM UNCONSOLIDATED OVERBURDEN

These equations were developed to calculate the radius of a PZ where the well receives additional recharge from the unconsolidated overburden through fracture. This means that there is an additional source of water to the well that that directly from the aquifer and as a result the PZ in the aquifer will be an over estimate. The leakage is calculated using the following equation:

$$r = \sqrt{\pi \left({}^{Q}/_{K} \right)}$$

Where r is the radius, Q the pumping rate and K the hydraulic conductivity. This equation was derived from Darcy's law assuming a hydraulic gradient of 1. The infiltration equation:

$$r = \sqrt{\pi \left({}^{Q}/_{I} \right)}$$

where Q is the pumping rate, r the radius and I the infiltration rate; is then used when the overburden is not saturated throughout the year and assumes that all infiltrating precipitation is available to the pumping well.

A2.5 EQUATIONS FOR SPECIAL SITUATIONS

Isotropic non leaky artesian aquifer with fully penetrating wells and constant-discharge conditions:

$$s = \frac{1146Q}{T} W(u) \qquad u = \frac{187r^2S}{Tt}$$

Isotropic non leaky artesian aquifer with partially penetrating wells and constant-discharge conditions:

$$s = \frac{1146Q}{T} W\left(u, \frac{r}{m}, \gamma\right) \quad u = \frac{187r^2S}{Tt}$$

$$\gamma = \frac{m - m_d}{m}$$

Isotropic leaky artesian aquifer with fully penetrating wells and constant-discharge conditions without water released from storage in aquitard:

$$s = \frac{1146Q}{T} W\left(u, \frac{r}{B}\right) \qquad u = \frac{187r^2S}{Tt}$$

$$\frac{r}{B} = \frac{r}{\sqrt{T/(P\prime/m\prime)}} \quad s = \frac{229Q}{T} K_0\left(\frac{r}{B}\right)$$

Isotropic water-table aquifer with fully penetrating wells and constant discharge conditions:

$$s = \frac{1146Q}{T} W\left(u_{xy}, \frac{r}{D_t}\right) \quad u_x = \frac{187r^2S}{Tt}$$

$$u_y = \frac{187r^2S_y}{Tt} \qquad \frac{r}{D_t} = \frac{273r}{\sqrt{T/D_tS_y}}$$

$$D_t = \frac{\left({}^{r}/_{D_t}\right)^2 \left({}^{1}/_{u_y}\right)}{4t}$$

Where:

- s is the drawdown,
- Q is the discharge,
- T is the transmissivity of the aquifer,
- S the coefficient of storage of the aquifer,
- r the distance from the production well to the observation point,
- t the time after pumping started,
- m the saturated aquifer thickness,
- m_d the distance from the top of the aquifer to the top of the screen,
- P' the permeability of the aquitard,
- m' the saturated thickness of the aquitard, and
- S_y the specific yield of the aquifer.

The following functions are well functions and can be found in hydrogeological references textbooks:

$$W(u), W\left(u, \frac{r}{m}, \gamma\right), W\left(u, \frac{r}{B}\right), K_o\left(\frac{r}{B}\right), W\left(u_s, \frac{r}{D_t}\right)$$

APPENDIX 3: MODELLING SOFTWARE RELEVANT TO CZ DELINEATION

A3.1 SELECTED AEMS

Computational Engine	User Interface
SLWL (comes with book Groundwater Mechanics)	WINFLOW/AquiferWin32
SLAEM	SLAEM
MLAEM	MLAEM/2,MLAEM
CZAEM	[command line]
ModAEM	GMS
GFLOW1	GFLOW, WhAEM2000
Split	ArcAEM, Visual AEM
3DFlow	[command line]
PhreFlow	[command line]
AnAqSim	AnAqSim
TimML	Visual AEM
TTim	[command line]
Bluebird	Visual AEM
AEM-Based Transport Simulators	
Cardinal(bluebird)	Visual AEM
Robin(split)	Visual AEM

Source: http://www.analyticelements.org/mw/index.php/AEM_Software (last May 2013).

A3.2 FREEWARE RESOURCES FROM THE INTEGRATED GROUNDWATER MODELLING CENTER

3DADE	A Fortran computer program for evaluating a series of analytical solutions of the 3-Dimensional Advection-Dispersion Equation.
AGU-10	A collection of screening level analytical flow and transport programs for homogeneous, isotropic flow fields, based on the American Geophysical Union's Water Resources Monograph 10.
Argus ONE	The Argus Open Numerical Environments (Argus ONE) enable you to easily and intuitively prepare your data for any modelling package, finite element as well as finite difference based. By automatically linking the physical data you enter in GIS layers to grid blocks or mesh nodes and elements, Argus ONE keeps your data reusable. Changing your mesh or grid doesn't require you to re-enter your data. Argus ONE integrates a variety of tessellation modules including the Argus MeshMaker®Finite difference grids module and the Argus MeshMaker Triangular and Quadrilateral finite element modules.
AT123D	AT123D is based on an analytical solution for transient one-, two-, or three-dimensional transport of a dissolved chemical or radionuclide or heat in a homogeneous aquifer with uniform, stationary regional flow. The program assumes a stationary flow field parallel to the X-axis and allows for retardation (based on reversible instantaneous linear equilibrium sorption isotherm) and first-order decay.

AT123D-AT	This updated version of AT123D corrects for errors in the original AT123D for pulse sources, and also includes new numerical integration schemes that allow one to accurately simulate rapidly changing transient sources. New series solution approximations for finite-depth aquifers and checks for steady state nodes are included to improve solution accuracy and efficiency. The new program is rewritten using FORTRAN 90 standards, and still runs all legacy input files for the original AT123D. In addition, AT123D-AT has additional input options for new numerical integration methods, and includes new output options for creating areal plume plots and time series plots at selected monitoring points.
BIOCHLOR	Remediation by natural attenuation (RNA) of dissolved solvents at chlorinated solvent release sites.
BIOPLUME III	EPA version of popular 2D flow/transport/aerobic biodegradation model
BIOSCREEN	Remediation through natural attenuation of dissolved hydrocarbons at petroleum fuel release sites.
CANVAS	A composite analytical-numerical code for simulation of transport and fate of viruses in ground-water.
CAPZONE	An analytical flow model that can be used to construct ground-water flow models of two-dimensional flow systems characterized by isotropic and homogeneous confined, leaky-confined, or unconfined flow conditions.
CASE	Dealing with salinization of coastal fresh water aquifers.
CHEMFLO	Screening model for flow and transport in soils.
COVAR	A program for generating two-dimensional fields of auto-correlated parameters which are normally or log-normally distributed (e.g., hydraulic conductivity).
CXTFIT	Successful predictions of the fate and transport of solutes in the subsurface hinges on the availability of accurate transport parameters.
CZAEM (Capture Zone Analytic Element Model)	A single-layer model for simulating steady flow in homogeneous aquifers using the Analytic Element Method.
EPA-VHS	A screening level model to predict maximum concentration of a pollutant at a prescribed distance downstream from a continuous source (at the compliance point).
EnvironInsite	A groundwater data visualization application developed for practicing hydrogeologists. It is a workspace for exploring and communicating complex geologic and environmental conceptual models. EnviroInsite's ease of use and low cost make it the only choice for groundwater visualization on every desktop! Environmental Insite is a desktop tool for analysis and communication of environmental groundwater data.
GEOEAS	Geostatistical environmental assessment software: Kriging Software.
GEOPACK	User-friendly geostatistical software system: Kriging Software .
GFLOW	A highly efficient stepwise groundwater flow modelling system developed by Haitjema Software. A Windows program based on the analytic element method. It models steady state flow in a single heterogeneous aquifer using the Dupuit-Forchheimer assumption.
GMS	A comprehensive package which provides tools for every phase of a groundwater simulation including site characterization, model development, post-processing, calibration, and visualization.
GWFLOW	The program 'GWFLOW' brings together seven frequently used analytical solutions for ground-water flow problems.

HELP	A quasi-two-dimensional, deterministic, water-routing model for determining water balances.
HOTWTR	A block-centred finite difference model for simulating three-dimensional steady-state groundwater flow and heat transport in an isotropic, heterogeneous confined aquifer system with uniform thermal properties.
HPS	A analytical model for simulating three-dimensional contaminant transport from a Horizontal Plane Source in a uniform regional ground water flow field.
HSSM	The Hydrocarbon Spill Screening Model (HSSM) is intended for simulation of subsurface releases of light non-aqueous phase liquids (LNAPLs) in homogeneous soils.
HST3D	Simulates ground-water flow and associated heat and solute transport in three dimensions.
HYDRUS-1D	A MS Windows Program for Simulating Water Flow, Heat and Solute Movement in One-Dimensional Variably Saturated Media with full-color, high-resolution Graphics User Interface.
HYDRUS-2D/3D	A MS Windows Program for Simulating Water Flow and Solute Transport in Two and /Three-Dimensional Variably Saturated Media with full-color, high-resolution Graphics User Interface.
ICE-1	A research model for the analysis of coupled flow of water, heat and solute in unsaturated, partially frozen soils, may include heave effects.
INFIL	A numerical simulation model for solving the problem of ponded transient infiltration into a deep, homogeneous soil .
INFIL3.0	A grid-based, distributed-parameter watershed model to estimate net infiltration below the root zone.
INVFD	A two-dimensional, steady-state ground-water flow model, which may be used to estimate parameters by nonlinear regression.
JDB2D/3D	Simple Two- and Quasi-Three-Dimensional Numerical Flow Model .
JUPITER-API and Applications	Joint Universal Parameter IdenTification and Evaluation of Reliability - Application Programming Interface.
MINTEQA2	An equilibrium speciation model that can be used to calculate the equilibrium composition of dilute aqueous solutions in the laboratory or in natural aqueous systems.
MINTEQAK	An extensive modification of the MINTEQA2 code to model the change in composition of aqueous flow as it traverses a wetland/reactor system.
MMA	A computer code for multi-model analysis, constructed using the JUPITER API.
MOC	A two-dimensional model for the simulation of non-conservative solute transport in saturated ground-water systems.
MOC3D	A 3D flow and transport model. The method of characteristics transport model is integrated with modflow and considers advection, dispersion, mixing from other fluid sources, linear sorption, and radioactive decay. Includes manual, source, executable and example files.
MOCDENSE	A two-dimensional, cross-sectional model for the analysis of saltwater intrusion. It simulates conservative solute transport and dispersion of one or two constituents in a ground-water system with density-dependent flow.
MODALL	MODular ALLocation Tool for Designing and Optimizing Capture Systems. MODALL uses the MODFLOW-calculated cell-by-cell flow terms to evaluate internodal flow balances to determine the percentage of flow in each cell which has either originated from a given source(s) or flows to a specified sink(s).

MODFE	A modular 2D finite element model for simulation of steady-state or transient areal, cross-sectional, and axi-symmetric ground-water flow.
MODFLOW2000	A block-centred finite difference code for steady-state and transient simulation of two-dimensional, quasi-three-dimensional, and fully three-dimensional saturated, constant density flow problems in combinations of confined and unconfined aquifer-aquitard systems above an impermeable base.
MODFLOW-GUI PIE	Preprocessor and postprocessor graphical-user interfaces for preparing MODFLOW-96, MODFLOW-2000, MODFLOW-2005, MOC3D, MODPATH, and ZONEBDGT input data and viewing model output for use within Argus Open Numerical Environments (Argus ONE).
MODFLOWP	A parameter estimation package that can be used in conjunction with MODFLOW to improve model construction and calibration.
MODMAN	MODMAN - (MODflow MANagement) adds optimization capability to the U.S.G.S. finite-difference model for groundwater flow simulation in three dimensions.
MPNE1D	General analytical solution for one-dimensional solute transport.
MT3DMS	Modular 3-D multi-species transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems.
NAPL Simulator	Conducts a simulation of the contamination of soils and aquifers which results from the release of organic liquids commonly referred to as Non-Aqueous Phase Liquids (NAPLS).
NETFLO	A model to simulate steady-state three-dimensional ground-water flow in a heterogeneous medium using an equivalent network of series and parallel flow members.
NETPATH	An interactive program for calculating NET geochemical reactions and radiocarbon dating along a flow PATH.
ONE-D	A package of five analytical models of the one-dimensional convective-dispersive transport equation with linear adsorption, zero-order production, and first-order decay.
ONESTEP	A program for estimation of up to five unknown parameters in the van Genuchten soil hydraulic property model.
OPTP	A simple, user-interactive DOS program for computing the optimal discharge of a well in terms of benefit (of water produced) versus pumping cost, using a single-variable (i.e., discharge) constrained nonlinear programming algorithm.
PARFLOW	is an integrated, parallel watershed model that makes use of high-performance computing to simulate surface and subsurface fluid flow. The goal of the ParFlow project is to enable detailed simulations for use in the assessment and management of groundwater and surface water, to investigate system physics and feedbacks and to understand interactions at a range of scales.
PAT	An analytical model for the computation and graphical representation of pathlines and travel times of ground-water in an infinite or semi-infinite homogeneous and isotropic confined aquifer.
PATH3D	A powerful and widely used particle-tracking program for MODFLOW. PATH3D is a valuable extension to a groundwater flow model, and is frequently a practical alternative to a contaminant transport model.
PEST	The industry standard software package for parameter estimation and uncertainty analysis of complex environmental and other computer models.

PESTAN	The program PESTAN represents model for evaluating the one-dimensional vertical transport of organic pollutants through homogeneous soil to ground-water.
PHREEQC	A computer program for speciation, reaction-path, advective transport, and inverse geochemical calculations.
PHREEQE	A geochemical reaction model which is based on an ion pairing aqueous model.
Phreflow	A program that models three dimensional unconfined transient groundwater flow and transport using the superposition of analytic functions
PHRQPITZ	A computer program capable of making geochemical calculations in brines and other electrolyte solutions of high concentrations using the Pitzer virial-coefficient approach for activity-coefficient corrections.
PMWIN (Processing Modflow for Windows)	A totally integrated simulation system for modelling groundwater flow and transport processes with MODFLOW-88, MODFLOW-96, PMPATH, MT3D, MT3DMS, MOC3D, PEST and UCODE (version 5.3.1 is freeware).
RETC	A computer program which may be used to analyse the soil water retention and hydraulic conductivity functions of unsaturated soils.
RITZ	A screening level model for simulation of unsaturated zone flow and transport of oily wastes during land treatment.
ROBIN	3-D reactive transport modelling using the deterministic streamline method.
SEAWAT	A Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow and Transport.
SIM_ADJUST	A Computer Code that Adjusts Simulated Equivalents for Observations.
SLUGC	A graphic program for determining hydraulic conductivity values based on the analysis of slug tests using the Cooper, Bredehoeft and Papadopulos et al. method.
SLUGT2	An updated version of program 'SLUGT' and computes hydraulic conductivity values based on the analysis of slug-test data.
SOHYP	An analytical model for calculation of the unsaturated hydraulic conductivity function.
STANMOD2	Computer Software for Evaluating Solute Transport in Porous Media Using Analytical Solutions of the Convection-Dispersion Equation.
SUMATRA1	A one-dimensional Hermitian finite element (HFE) model for simulation of simultaneous movement of water and a solute in a heterogeneous soil profile.
SUMMERS	A screening level interactive computer program for estimating soil cleanup levels.
SURGE	A computer program which enables to generate a surface as an interpolation (approximation) function of two independent variables.
SutraSuite	SutraSuite contains the SUTRA ground-water simulation code and a number of utilities for both pre- and post-processing for simulations in both two spatial dimensions (2D) and three spatial dimensions (3D).
SWACROP (Soil WAter and CROP production model)	A transient one-dimensional finite difference model for simulation of the unsaturated zone. It incorporates the process of water uptake by roots.
SWANFLOW	A three-dimensional finite-difference code for simulating the flow of water and an immiscible non-aqueous phase under saturated and unsaturated near-surface conditions.
SWICHA	A three-dimensional finite element code for analysing seawater intrusion in coastal aquifers.

SWI	The Sea Water Intrusion (SWI) package for MODFLOW - is intended for the modeling of regional seawater intrusion with MODFLOW. The SWI package simulates the evolution of the three-dimensional density distribution through time; effects of the density distribution on the flow are taken into account explicitly.
SWMS-2D	http://igwmc.mines.edu/zipfiles/swms2.htm- A computer program for simulating water and solute movement in two-dimensional variably saturated media.
TGUESS	A computer program for estimating transmissivity from specific capacity data.
TimML	A computer program for the modelling of steady-state multi-aquifer flow with analytic elements and consists of a library of Python scripts and FORTRAN extensions.
UCODE_2005	A DOS/UNIX universal inverse modelling program.
WIDE	Responses of four major types of aquifers to well placement, rate of extraction, and well number.
Visual AEM	A graphical user interface for single and multi-layer analytic element modelling of (mostly) steady-state groundwater flow and numerical/analytical modelling of vertically-averaged contaminant transport.
WATEQ4F	A program for the calculation of chemical equilibrium in natural waters.
WhAEM2000	A public domain, ground-water flow model designed to facilitate capture zone delineation and protection area mapping in support of the State's Wellhead Protection Programs (WHPP) and Source Water Assessment Planning (SWAP) for public water supplies in the United States.
WHPA	A semi-analytical ground water flow simulation program used for delineating capture zones in a wellhead protection area.
Zonebudget (ZONBUD)-	A computer program that computes sub-regional water budgets using results from the MODFLOW ground- water flow model.

Source: http://igwmc.mines.edu/software/freeware_list.html, last accessed May 2013.

APPENDIX 4: EQUATION TO CALCULATE TOT THRESHOLD BASED ON REMOVAL RATES

The TOT required to reach a desired log reduction in a microbial population can be expressed as:

$$Time\ of\ travel = \frac{required \log reduction}{groundwater\ velocity \times spatial\ removal\ rate}$$

For example, if the required log reduction in virus concentration is 15 $\log_{10}$, the groundwater velocity is 3 m/d, and the spatial removal rate of viruses in the particular aquifer material is 2 $\log_{10}$/m, the corresponding TOT threshold will be:

$$Time\ of\ travel = \frac{15}{3 \times 2} = 2.5\ days$$

The required log reduction depends on the pathogen concentration in the water at the point of contamination and the concentration considered acceptable at the hydrologic feature. Moore and co-workers in the *Guidelines for separation distances based on virus transport between on-site domestic wastewater systems and wells* (Moore *et al.,* 2010), conservatively calculated that a 16 $\log_{10}$ reduction in rotavirus is needed between an on-site wastewater disposal field and a well directly down-gradient. This was based on an estimation of the rotavirus concentration in the effluent and the maximum acceptable rotavirus concentration at the well. The maximum acceptable rotavirus concentration was determined from an annual probability of infection of 1 in 10,000, which is considered to be a tolerable infection probability by jurisdictions overseas. The details of these calculations are given in the Technical Appendix of the separation distance guidelines (Moore *et al.,* 2010).

APPENDIX 5: REFERENCE VALUES FOR HYDRAULIC PARAMETERS

A5.1 HYDRAULIC PARAMETERS INFERRED FROM AQUIFER TESTS IN THE NGMP WELLS

Region	Feature ID	Hydraulic type	Aquifer title	Depth (m)	Screen length (m)	Storativity	Hydraulic conductivity (m/d)	Transmissivity (m^2/d)
Auckland	76	Confined	Unnamed Aquifer	84.5		0.00645		0.1
Canterbury	37	Semi-confined to confined	Not Defined	27.5	1	0.1	54	350
Canterbury	40		Riccarton Gravel	30.5	6.1	0.001	250	1500
Bay of Plenty	56	Confined	Matahina Ignimbrite	319.5	24.5	0.0001		200
Bay of Plenty	58	Unconfined	Mamaku Ignimbrite	103.6	23.8			
Waikato	348	Unconfined	Hinuera Formation	6	3.2		28	113
Waikato	347	Confined	Hinuera Formation	22.2	16.2	0.15	534	20000
Waikato	17	Unconfined	Franklin Basalt	35	10.2			150
Hawke’s Bay	27	Unconfined	Ruataniwha Plains Aquifer	25.19	5.14	0.001	50	1000
Hawke’s Bay	23	Unconfined	Heretaunga Plains	47.77		0.0003	890	25000
Hawke’s Bay	359	Unconfined	Fluvial Postglacial Gravel	254	1	0.0003	890	25000
Hawke’s Bay	25	Unconfined	Heretaunga Plains Aquifer	66.45	6.71	0.0001	2860	20000
Marlborough	437	Semi-confined	Omaka	60	45.1	0.0001		0.5
Marlborough	352	Unconfined	Omaka	82.5	67.5	0.0001		0.5
Marlborough	353	Confined	Brancott	91.5	61.5	0.0001		5
Marlborough	351	Confined	Rarangi Shallow Aquifer	3		0.2		200
Marlborough	2015	Semi-confined to confined	Wairau confined	25.5	3.25	0.00005		300
Marlborough	354	Confined	Wairau-Recharge Zone	10	3.35	0.2		2500

Region	Feature ID	Hydraulic type	Aquifer title	Depth (m)	Screen length (m)	Storativity	Hydraulic conductivity (m/d)	Transmissivity (m^2/d)
Marlborough	2016		Wairau unconfined	6	0.8	0.1		4000
Marlborough	355	Confined	Wairau	25.3	5.8	0.001		6500
Marlborough	356	Unconfined	Wairau-Coastal Confined Zone	26.21	5	0.00015		6500
Marlborough	456		Wairau Aquifer, Unconfined Zone	83.5		0.004		10000
Marlborough	552	Semi-confined	Not Defined	29.4	5.13			
Marlborough	512	Confined	Not Defined					
Manawatu-Wanganui	14	Unconfined	Not Defined	33.5	3			
Northland	140	Confined	Tara Basalt	49				18
Northland	139	Semi-confined	Waipapa Greywacke	12				24
Northland	403	Confined	Not Defined					
Northland	2013	Semi-confined	Waipapa Greywacke	67.5	49			
Northland	360	Confined	Ahipara Sand	31.5	12.5			
Otago	66	Unconfined	Clutha Recent Outwash	40	8.6			
Otago	72	Unconfined	Hawea Outwash	26.4	0.9			
Otago	70	Confined	Hawea Outwash	16	0.9			
Otago	68	Confined	Clutha Recent Outwash	21.3	0.9			
Otago	71	Confined	Clutha Outwash Alluvium	29.4	2.4			
Tasman	73	Unconfined	Appleby Gravel Unconfined	8	2.8			
Tasman	3	Unconfined	Motueka Gravel Aquifer	10.74	3.1			
Tasman	10	Unconfined	Lower Confined Aquifer	38.1	6.1			
Tasman	8	Confined	Shallow & Middle Moutere Aquifer	236	194			

Region	Feature ID	Hydraulic type	Aquifer title	Depth (m)	Screen length (m)	Storativity	Hydraulic conductivity (m/d)	Transmissivity (m^2/d)
Tasman	74	Unconfined	Motueka Gravel Aquifer	14.5	2.75			
Taranaki	29	Unconfined	Matemateaonga Formation	300				
Wellington	54	Semi-confined	Wainuiomata	6.5				150
Wellington	468	Confined	Pouawha Groundwater Zone, Aquifer 2	38	3			250
Wellington	465	Semi-confined to confined	Carterton Groundwater Zone, Aquifer 2	27.4	4.6			260
Wellington	45	Unconfined	Waitohu Groundwater Zone	27	11.5	0.003		350
Wellington	52	Confined	Waikanae	10.4	2.7	0.002		500
Wellington	466	Unconfined	Te Ore Ore Groundwater Zone, Aquifer 2	54				1400
Wellington	464	Confined	Lake Domain Groundwater Zone, Aquifer 2	17.4	8.7			2036
Wellington	467		Tawaha West Groundwater Zone, Aquifer 2	16	8.5	0.001		2740
Wellington	42	Unconfined	Raumati/Paekakariki Groundwater Zone	15.5	0.5	0.007		6500

Source: GNS Science (2013).

A5.2 HYDRAULIC CONDUCTIVITY IN NEW ZEALAND (MOORE *ET AL.*, 2010)

Region	Sub-region	Hydraulic conductivity (m/d)		
		Mean	Min	Max
Auckland	Kaawa	148	13	2026
	Basalt	136	20	1416
	Waitemata	1.2	0.12	33
Waikato	Waikato River	67	0.2	2237
	Hamilton	57	0.091	1400
	Pauanui	4.3		
	Matamata	155	1.3	1622
	Wairakei	121	1.12	1685
	Whitianga	5.5	0.195	94
Hawke's Bay	Ruataniwha Plains	2847	34	3129
	Heretaunga Plains	379	4.7	42200
Taranaki	Patea	1.5		
	Waverley	4.8		
	Deer Park	0.031		
Wellington	Wairaprapa	898	5	17270
	Paraparaumu	119	24	2400
Marlborough	Wairau Aquifer	2215	16.7	21450
	Rarangi	402	282	648
Tasman	Motueka	5369	132	92928
	Takaka-Pupu Springs			
	Well6535	58212		
	Appleby	11965	3217	22000
Canterbury	Burwood	10		
	Canterbury Plains	1300	10	7200
Otago	Alexandra	139	1.03	2172
	Clinton	79	2.14	2384
	Cromwell-Tarras	2043	13.3	45723
	Pomohaka Basin	37	3.7	3204
	Lake Hawea-Luggate	1010	0.7	43440
	Wakatipu Basin	281	5.2	18938
	Roxborough	1156	461	4992
Southland	Riversdale-Gore	1505		
	Edendale	1596		
	Mossburn	1174		

A5.3 HYDRAULIC CONDUCTIVITY AND EFFECTIVE POROSITY IN NEW ZEALAND (MOORE *ET AL.*, 2010)

Aquifer type	Effective porosity (unitless)	Hydraulic conductivity (m/d)
Alluvial gravel	0.0032	1300
Alluvial (coarse) sand	0.2	80
Pumice sand	0.3	80
Coastal sand	0.2	10
Sandstone and non-karrstic limestone	0.1	0.01
Karstic and fractured rock (e.g. basalt and schist)	0.1 and 1 for matrix and fractures respectively	1000

A5.4 SELECTED REFERENCES ON STOCHASTIC ANALYSIS OF WELL-HEAD PROTECTION AND RISK ASSESSMENT

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Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657

www.gns.cri.nz