Capture zone guidelines for New Zealand

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ABSTRACT

For regional councils and unitary authorities to manage effectively the land and water resources for which they have responsibility, they require information about how decisions regarding land use may affect the quality of water bodies. Key to understanding how land use decisions may influence water quality is knowledge of the area of land from which a water body, or feature, receives its water – the capture zone – and potential contamination sources within this area.

This Guideline document, and the associated technical document (Moreau *et al.,* 2014a) assist in the delineation of protection and capture zones for wells, springs and lakes or wetlands with groundwater contribution. Apart from regional councils and unitary authorities, potential users of the Guidelines include: territorial authorities, water suppliers (many of who will be territorial authorities), consultants and research organisations.

The associated technical report provides more in-depth discussion of the use of delineation methods and the justification for zone thresholds. It also includes five New Zealand case studies for a range of hydrogeological settings.

The Guideline's purpose is to provide information and guidance in selecting an appropriate method for delineating the protection and/or capture zones for a given setting and purpose. A set of methods, ranging from unsophisticated desktop methods through to numerical modelling, is discussed to address varying user needs and constraints. These include precision requirements and restrictions on data and resource availability. Uncertainty in delineating zones is also discussed and, where applicable, guidance on either qualifying or quantifying the uncertainty is given. The Guidelines lead the user through the process of deciding which method or methods are suitable for meeting their needs. It also provides equations and resources to undertake delineation.

A worked example and reporting template, is provided to show the practical application of manual methods in zone delineation.

KEYWORDS

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

1.0 INTRODUCTION

Regional councils and unitary authorities have responsibility for the sustainable development of water resources in their region or district. To fulfil this responsibility they need to understand the implications for water quality of decisions made in respect of land and water use. Key to this understanding is knowledge of the area of land from which a water body or feature receives its water – the capture zone – and potential contamination sources within this area. This information allows informed decisions to be made that will ensure adequate protection of the water feature, and avoid unreasonably restrictive decisions affecting land and water use.

Two documents have been prepared to assist in delineating capture zones:

a) Capture Zone Delineation – Guidelines (this document)

   The purpose of this document is to provide background information and guidance in selecting an appropriate method for delineating the capture zone 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.

b) Capture Zone Delineation – Technical Report (Moreau *et al.,* 2014a)

   The technical report provides the user with a detailed literature review of capture zone delineation methods and New Zealand case study examples. While the user may wish to refer to it, use of the Guidelines should be sufficient for identifying the appropriate method for delineating the capture zone for a specific situation.

The Guidelines have been prepared by a consortium of scientists from the Institute for Geological and Nuclear Sciences Ltd (GNS Science) and Environmental Science and Research Ltd (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. Feedback on draft versions of the Guidelines was also sought and received from the Regional Groundwater Forum, The Water Supply Management Group and the Ministry of Health, and incorporated in this final version.

1.1 CAPTURE ZONES AND MICROBIAL PROTECTION ZONES

For the purposes of this document the following definitions are used:

Capture zone: The total source area that contributes groundwater to the hydrological feature (well, spring, wetland or lake that have a groundwater contribution). For management purposes, the *capture zone* may be defined as the area delineated by the time it takes for groundwater to flow from a given point to the feature. For features located away from natural flow boundaries, a 50-year threshold may be used as a proxy. Where impractical, a 10-year threshold could be used, although it should be kept in mind that the *zone* obtained will be an underestimate of the actual *capture zone*.

Protection zone: The portion of the capture zone that has a defined travel time for groundwater to arrive at the hydrological feature. In the case of karstic springs, contributing sinkholes should be considered when delineating protection zones (Kaçaroğlu, 1999). An *immediate protection zone* of at least 5 m radius around wells and springs, is defined to provide protection from direct contamination (e.g. spills). This safeguarding distance is based on a review of international guidelines. A *microbial protection zone* is determined by either the 1-year travel time zone or a safeguarding distance (see Section 2.4.1.1). The 1-year travel time threshold takes account of bacteria and virus survival. Where site-specific information is available, a different time of travel threshold may be justified to delineate the *microbial protection zone*. 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 1).

Zone: Collective term to qualify items relevant to both capture and protection zone delineation.

Further information regarding zone time of travel and safeguarding distance thresholds can be found in Section 3.2 of the Technical Report.

1.2 WHY ARE THE GUIDELINES NEEDED?

1.2.1 What is the problem?

At present, the approach to delineating capture zones in New Zealand is *ad hoc*. Some councils may be reluctant to delineate capture zones because the process is perceived to be too difficult. Others may question the value of delineating a capture zone if they are unable to calculate the uncertainties associated with the estimated area.

Without adequately establishing a hydrological feature's capture zone, sufficient data for sustainable management of the resource may not be gathered, data that are gathered may be incorrectly interpreted, or time and resources may be wasted in acquiring information from outside the capture zone.

1.2.2 How do the Guidelines address the problem?

The Guidelines provide a transparent, standardised approach to selecting and implementing methods for delineating capture zones and estimating the uncertainty of the defined zones. Adoption of a standardised approach to method selection and uncertainty estimation, as given in this document, ensures that there is an understanding of the area from which a hydrological feature obtains its water. This:

a) supports decisions in granting resource consents because it clarifies whether a proposed activity lies within a capture zone;

b) helps in determining consent conditions;

c) allows appropriate positioning of monitoring sites for assessing the effects of a proposed land use with respect to a hydrological feature;

d) can inform the development of land use management policies and rules aiming to protect water quality;

e) supports the implementation of the *National Environmental Standard* (NES) for Sources of Human Drinking Water by clarifying whether a proposed activity lies within the capture zone of a hydrological feature used as a water supply source (Ministry for the Environment, 2007);

f) reduces the likelihood of challenges to methodology during consent hearings; and

g) assists in interpreting the effects of land use on water quality by determining whether a hydrological feature is likely to receive water that could be affected by a specific land use.

1.2.3 The NES for sources of human drinking water in a nutshell

The NES contains regulations designed to help water suppliers protect the quality of their source water (Ministry for the Environment, 2007). A fundamental principle in managing the risk of waterborne diseases is the use of multiple barriers to contaminants reaching the consumer. The most important of these barriers are those preventing the entry of contaminants into a water supply's source. In general, water suppliers are not empowered to manage their supply's catchment; this is the responsibility of the regional council or unitary authority. Consequently, the NES is an important component in the set of tools used to protect the safety of water supplies.

The NES provides councils with a framework to help in making resource consent decisions and in developing regional plans. It prohibits consents being granted for activities, or regional plan rules permitting activities, if the activity is likely to have adverse effects on the water beyond certain limits. The extent of the adverse effect depends on the existing quality of the treated water or the raw water, and, under some conditions, on the capability of existing treatment to remove contaminants. The NES currently applies only to supplies serving more than 500 people for 60 or more days a year. As such, it has no relevance to protection of the quality of groundwater entering a small lake or wetland.

To implement the NES, councils need to know whether a proposed activity will lie within the capture zone of a drinking-water supply source. From supply information provided from the Ministry of Health's water supply data management system (Water Information New Zealand) and consent information regional councils will be able to determine which hydrological features in their region need to be considered with respect to the NES. Once these have been identified, delineation of the capture zones will allow the council to assess which activities, or proposed activities, may have an influence on the quality of the water used by a drinking-water supply.

1.3 Scope of the Guidelines

The Guidelines provide three areas of guidance in:

1. Selecting and applying appropriate capture zone delineation methods.

   Users of the document are likely to have different needs when defining capture zones with respect to the robustness of the determination, and the resources and expertise available. Consequently, methods of varying degrees of sophistication and reliability are presented in this document.

   Delineation of a capture zone allows land uses or activities that may affect the quality of a water feature to be identified. Rules for managing activities within the zone can then be developed or imposed.

2. Delineating immediate and microbial protection zones.

   A range of possible contaminants may exist within a capture zone. Microorganisms are the contaminant type of paramount importance with respect to human health in drinking-water supplies (Ministry of Health, 2008). By establishing a microbial protection zone, the user/authority will know the separation distance from the water feature that will ensure a satisfactory microbiological water quality at the feature. The microbial protection zone will be contained within the capture zone as it constitutes a portion of a capture zone.

3. Establishing uncertainty associated with defined capture zones and microbial protection zones.

   The various methods delineate capture zones or microbial protection zones with differing accuracies. The purpose for undertaking a delineation and the possible implications of the estimated capture zone being larger or smaller than it is in reality need to be considered when selecting the delineation method. Consequently, the user is provided with methods for estimating the uncertainty in the delineated zones.

1.4 WHO MIGHT USE THE GUIDELINES

1.4.1 Regional councils and unitary authorities

Under the Resource Management Act 1991 (RMA) regional and unitary authorities have responsibilities for the management of water bodies in their region or district (Section 30 (1)(c) of the RMA, Parliament of New Zealand, 1991). The Guidelines, by delineating the zone within which activities might affect the quality of a water body, can help regional councils and unitary authorities in carrying out several of their responsibilities. They may assit in:

a) developing regional policies and rules that protect environmental water quality;

b) managing land use and discharges through consideration and granting of resource consents;

c) implementing the NES;

d) meeting the objectives of the National Policy Statement for Freshwater Management.

1.4.2 Territorial authorities

The RMA requires territorial authorities (city/district councils) to prepare a district plan. The district plan is the main document for managing land use and development within a district, primarily through the policies and rules it contains. The resource consent process is the means by which the district plan is implemented. Proposed activities, ranging from the construction of individual dwellings to land subdivision are controlled by this process.

Knowledge of the capture zones of hydrological features in a district allows informed decisions to be made about the possible effects proposed activities, such as subdivision development, may have on near-by features. The Guidelines provide local authorities with a guide to selecting an appropriate methodology for delineating capture zones to assist in their decision-making.

1.4.3 Drinking-water suppliers

Of fundamental importance to every water supply is its source. This is recognised in the Health Act 1956 by clause 69(u)(i) which sets out the water supplier’s responsibilities with respect to their raw water source (Ministry of Health, 1956).

Every drinking water supplier[1] must take reasonable steps to (a) contribute to protection from contamination of each source of raw water from which that drinking water supplier takes raw water (b) protect from contamination all raw water used by that drinking water supplier.

Few water suppliers have direct control over the management of their water source's catchment or recharge zone. Regional and unitary councils are responsible for water resources in their jurisdiction. By ensuring that concerns about the potential impact of proposed activities on the quality and quantity of the water they abstract for supply are heard through the consenting process water suppliers can have a hand in influencing the management of their catchment/recharge zone.

Water suppliers may rely on their regional or unitary council, or consultants, to delineate the capture zones of hydrological features they use as the source of their supplies. However, water suppliers should be aware of these guidelines to provide them with an understanding of the tools regional council's have available to delineate capture zones.

1.4.4 Consultants

Applicants for resource consents for proposed activities frequently employ consultants in the preparation of the application. The Guidelines, in conjunction with regional or district rules, will ensure that consultants are aware of acceptable methodologies for establishing whether a proposed activity may affect the quality of neighbouring water bodies. Having a clearly defined approach to establishing capture zones should improve the efficiency of the consenting process, as disputes over methodology will be minimised. The guidelines also provide a robust methodology for the calculation of uncertainties associated with delineated capture zones.

1.4.5 Research organisations

Research organisations may undertake work to understand the factors influencing the quality of surface- and groundwaters. Guidance in methodologies for delineating capture zones will be helpful to these organisations in linking water quality data with activities in the vicinity that may impact on the water quality.

1.5 OVERVIEW OF CAPTURE ZONE DELINEATION METHODS USED IN THE GUIDELINES

The Guidelines present several possible methods that can be used to delineate a capture zone, depending on the requirements of the user, and the limitations of their hydrological data and their resources. The process for selecting which method to use and the use of the method are discussed fully in Section 2. This section provides a brief outline of the four method categories, which are distinguished on the basis of their sophistication. The level of expertise required to use the method, the amount of information required by the method, the time involved implementing the method and therefore the cost, are factors influencing which methods for capture zone delineation a user may select. A detailed description of each method and their relationships to zone delineation criteria are given in Section 2.2.2 of the Technical Report. The justification for selecting these delineation methods is given in Section 3.3 of the Technical Report.

[1] For legal purposes, not everybody who operates a water supply is a water supplier. The Health Act 1956 clause 69G defines a drinking-water supplier, and in clauses 69S to 69ZJ sets out their responsibilities.

In brief, the methods categories considered, in order of increasing sophistication, are:

a) Desktop review

Arbitrary fixed radius: This method draws a circle of fixed radius around the hydrologic feature of interest. The radius is not based on any hydrological parameter specific to the site of interest.

Hydrogeological mapping: These methods delineate the capture zone on the basis of the potential recharge area of a feature. The recharge area is inferred from information about groundwater flow direction, and geologic, geophysical and geomorphic characteristics of aquifers and aquifer materials.

b) Manual methods

In general, these methods have two to four input parameters.

Calculated fixed radius: Again, a circle is drawn around the feature of interest, but the radius is calculated on the basis of a defined time (time of travel) calculated for a water molecule to travel to the feature through the aquifer material. In this instance the radius can be based upon three site specific hydraulic parameters. For capture zone delineation, the recharge rate of the aquifer is required instead of the time of travel.

Uniform flow equation: the method delineates a capture zone around a spring or a well discharging at a fixed rate. The capture zone is an elongated parabola, with the feature at the focus of the parabola. The zone extends from a stagnation point slightly down-gradient of the feature to a boundary up-gradient beyond which water will not contribute.

Simplified variable shapes: Shapes are drawn around the feature based on time of travel and drawdown equations. The shapes will depend on the aquifer characteristics and rate of pumping. The initial generation of such a shape may be labour intensive. However, once the shape, or a combination, has been established for given conditions, it can be easily applied by selecting the shape (size of the supply, hydrogeological setting and the feature type dependent) orientating it correctly with respect to local groundwater flow direction and drawing it on a base map; further mathematical calculations are not required.

c) Analytical element models

These models require implementation on computers. They use numerical techniques to approximate complex analytical solutions, and provide a two-dimensional (2D) discrete solution in either time or space. The capture zones can be based upon site specific hydraulic parameters. In general, analytical element models (AEMs) have fewer than 10 input parameters.

d) Numerical models

These models require the use of dedicated software packages. They use the same equations as analytical models, but obtain approximate solutions using numerical techniques. Numerical models are able to address complex situations as they are less constrained by the simplifying assumptions required to obtain discrete solutions to the analytical equations. The capture zones can be based upon site specific hydraulic parameters. Numerical models typically have more than 15 input parameters.

Tracers (age dating, organisms, salts and dyes) can be used to acquire helpful information on groundwater preferential pathways, mixing volumes and travel time. This can assist to calibrate models used to derive the *zone*. Tracer testing can be difficult and and interpretation requires skill and experience. It may be expensive to acquire unambiguous results in some hydrogeological settings. A comprehensive list of tracers and their uses is given in Appendix 1 of the Technical Report).

1.6 INCORPORATING UNCERTAINTY INTO CAPTURE ZONE DELINEATION

1.6.1 Why does zone boundary uncertainty need to be known?

Capture and protection zones are delineated to inform decisions about land and water management. The zones produced by all delineation methods have a degree of uncertainty. Uncertainty will generally decrease with increasing sophistication of the delineation method.

By considering this uncertainty, the distance beyond and within the delineated boundary where the actual boundary might lie can be taken into account. From this information a more reliable understanding of the likelihood that a particular land use might influence the water quality of a hydrological feature can be gained.

1.6.2 Sources of uncertainty

The uncertainty in a capture zone's boundaries can arise from a number of sources:

a) Experimental uncertainty in the measurement of input parameters for the capture zone calculation. Field parameters may also be estimated from other data because direct determination of the parameter has not been, or cannot be, made.

b) The natural range of values an input parameter may have. For example, in a heterogeneous aquifer, the porosity will not be the same throughout a given region, but will have a range of values.

c) Uncertainties associated with the mathematical approximation of the physical situation. These uncertainties arise from the level of sophistication of the mathematics used in the calculation or model, and limitations arising from simplifying assumptions used to make the problem tractable. More sophisticated models try to improve the accuracy of their calculation by reducing the assumptions that may be used in simpler models. For example, the use of an arbitrary radius assumes, amongst other things, that groundwater flows in all directions towards a feature. The use of a standard shape tries to address this assumption by taking account of the groundwater flow direction.

1.6.3 Incorporating uncertainty in capture zone delineation

Uncertainties can be incorporated into all the methods for capture zone delineation, although the approaches for doing this vary with the method:

a) Desktop reviews

There are no parameters used in the arbitrary fixed radius method. The uncertainty is established by the radius selected by the user.

Hydrological mapping methods, which map surface water catchments, geological contexts, or groundwater catchments defined from potentiometric maps, may have a variable level of certainty. The scale of the mapping, or data from site-specific surveys, can give some idea of the uncertainty when hydrological mapping is used, however it may not be quantifiable.

Where no estimate of the uncertainty is possible, the user needs to be aware that the capture zone delineated from these methods may not well represent the actual capture zone, both in terms of shape and location.

b) Manual methods, AEMs and numerical models

The general principle for estimating the uncertainty associated with capture zones delineated using manual, AEM or numerical model methods is similar. Two approaches are probably the most helpful.

Sensitivity analysis

For each delineation method, uncertainty can be estimated by systematically varying input parameter values over a plausible range. Depending on the delineation method, changes in the input parameters will define the likely variation in size, shape or orientation of the zone.

To obtain a “best estimate” capture/protection zone, input parameters should be set at a central value of the data, such as the average or median value. The uncertainties in the calculations can be estimated by selecting for the input values the boundaries of the plausible range of parameter values. A series of calculations needs to be run, each using a different combination of the possible boundary values. The outer limits of the uncertainty in the zone will be apparent from the set of input values delineating the largest area. This will define the capture or the protection 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 base calculation (the rationale for using 25% is given in the Technical Report, Section 3.4).

Stochastic determination of uncertainty

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 the less sophisticated models. However, analytical element and numerical models require progressively more input parameters due to their greater complexity and their ability to more accurately represent a hydrological system than manual methods. As a result, more sophisticated, stochastic methods, such as a Monte Carlo simulation, can provide a more refined means of assessing uncertainty for these delineation methods.

A Monte Carlo simulation uses a distribution of values as the inputs to calculations rather than a single value. The simulation works by extracting a randomly-selected value from each input distribution 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 input values. The result is an output that is a distribution of results, not a single value. The distribution of results provides information about the statistics of the uncertainty, allowing percentile values to be determined if desired. Commercial software “add ins” for spreadsheet software, such as Excel®, are available for this.

1.7 LIMITATIONS OF THE GUIDELINES

The guidelines are envisaged as a live document that should be revised or updated as knowledge on delineation criteria, method and thresholds grows, and limitations of the proposed procedures are realised with implementation.

The following aspects are beyond the scope of these guidelines and are not addressed:

- Transient flow simulations. Capture and protection zones are delineated under steady-state conditions, where it is assumed that wells and bores are continuously pumped, although it may be for a fixed duration. It is also recognised that water divides and wetland extent may shift seasonally and/or as a result of groundwater pumping. The guidelines do not consider these transient conditions. Pseudo transient conditions, in which there may be intermittent pumping of a bore, can be modelled using numerical methods. This is done in one of the case studies contained in Section 4 of the Technical Report.
- Pumping interference. Pumping interference is not taken into account by the simpler methods. Cases where capture zones overlap (e.g., a well field) will result in underestimation of the zone. The case of delineating the capture zone for multiple pumping wells using the simpler methods is discussed in the case example, with some consideration to address this issue. AEM and numerical models can account for pumping interference.
- Pumping effects. Reversal of vertical hydraulic gradient in a multi-layered aquifer system due to pumping from a well.
- Capture zone dimensionality: Capture zones are three-dimensional. The methods discussed in the guidelines enable the delineation of the 2D surface expression of the capture zone.

2.0 USING THE GUIDELINE DOCUMENT

2.1 OVERVIEW

Section 1.5 of this document identifies several methods that can be used to delineate a capture zone. The reason for carrying out the delineation, the available hydrological data, and the resources available will determine which of these methods best suits the user's needs.

Section 2 provides a process for establishing which method should be used. It leads the user through:

- a stocktake of the available information, resources and required accuracy;
- selecting a suitable method given the available information; and
- applying the selected method.

2.2 STEP 1 – IDENTIFY WHAT IS KNOWN

There are four categories of information needed for selecting a suitable method for capture zone delineation:

1. Nature of the hydrological feature

   Four types of hydrological feature are considered for the Guidelines: well, spring, lake, and wetland with groundwater contribution. In some instances, the nature of the feature will determine the delineation method that can be used. Capture zones for lakes and wetlands cannot be delineated using manual methods, nor features sited in karstic aquifers. Hydrogeological mapping, analytical element or numerical methods are required, or the whole surface water catchment must be defined as the capture zone.

2. Level of accuracy required

   To assess the accuracy of the delineation required, the user should consider the reason for making the delineation and the consequences of the delineated zone not mathing well the actual capture zone. Considerations may include: the number of people affected; the way they may be affected; the monetary implications; ecological consequences; potential for a contaminant source to occur within the delineated capture zone; and feasibility of the management plan within the zone.

   The greater the risk (determined by likelihood and consequence) associated with a possible error in estimating the capture boundary, the more sophisticated the selected delineation method should be to minimise the uncertainty in the capture zone boundary. More sophisticated methods are recommended for the delineation of capture zones for water supplies serving more than 500 people for at least 60 days per calendar year. The public health consequences of contamination of the water supplies of communities of this size are considered sufficiently serious that their source waters warrant protection through the NES (Ministry for the Environment, 2007).

   When dealing with a well field, the capture zone may be delineated by treating the wells individually or representing the whole field by a single synthetic well. This decision can be taken on a case by case basis, but needs to take account of the possible underestimation of the actual capture zone when capture zones overlap.

3. Available resources

Resources fall into two sub-categories:

i. Available budget

This includes the staff time available, funding for software purchases and employing consultants if these are necessary. Should the other selection factors indicate the need for a sophisticated method, the most sophisticated method that can be afforded should be used. Indicative costs, at the time of publication, are provided in Table 2.1 as a guide to the resources required for the different methods. The calculations for the table assume that a search has been undertaken for site specific data, and that the value ranges suggested in this document are used only if site specific information is unavailable.

Table 2.1: Resources, expressed in terms of time and dollars, required for the use of the methods described here*.

Method	Time (days)	Rate ($/day)	Cost (no reporting)	Reporting time (days)	Cost (with reporting)	Assumptions
Desktop review	1	1,000	1,000	2	3,000	
Manual	2	1,000	2,000	2	4,000	
Analytical element model	3	1,500	4,500	3	9,000	Generic site specific model with limited data and calibration
	5	1,500	7,500	5	15,000	Aquifer scale model with adequate data and calibration
Numerical model	5	1,500	7,500	10	22,500	Generic site specific model with limited data and calibration
	30	1,500	45,000	15	67,500	Aquifer scale model with adequate data and calibration

* The table assumes that time will need to be spent in identifying data sources.

ii. Staff skill and expertise

Without funds for employing external help, the level of in-house skill and expertise available may limit the sophistication of the method that can be used for the delineation. The skills and capabilities of staff need to be considered.

4. Data/models available

Increasing model sophistication usually comes with an increasing need for data. If very few hydrological data are available, this will likely limit the complexity of the delineation method. In some instances, a measured value for a model input parameter may not be available. However, its derivation from another parameter, or an estimation using published values for a similar hydrological setting or material may provide a satisfactory estimate of the required input parameter.

The method that should be used will determine which of these four factors is the limiting factor, and there may be more than one limiting the selection, for example, lack of funds and a poor dataset on which to base the delineation.

2.3 STEP 2 – METHOD SELECTION

Having assessed what information and resources are available, and identified the accuracy requirements of the delineation, the method of delineation is selected. This section discusses what should be considered in making this selection.

Four types of delineation method are presented in this document, which, in order of increasing complexity, are:

- desktop reviews;
- manual methods;
- AEM modelling;
- numerical modelling.

Generally, the simplest method produces the largest capture zone. It can be used to quickly delineate a conservative capture zone that encompasses a considerable proportion of the "actual" zone. However in some hydrogeological situations (e.g. thick unconfined aquifer, high recharge unconfined aquifer, high hydraulic conductivity or steep hydraulic gradient, low yield) the simplest method may not be conservative and produce a narrow or small zone; see Technical Document Section 4.7.

Figure 2.1 provides an overview of the data requirements of the four delineation method types and an indication of their relative resource needs and accuracy. The figure shows that hydrogeological mapping is a delineation method that does not require the hydrogeological data used in either manual methods or modelling. However, the nature of the data required for hydrogeological mapping means that this method can be used to improve the delineation of the other methods.

To select which method will meet their needs, the user should consider:

a) the accuracy provided by the method;

b) the level of expertise required to use the method;

c) the difficulty in using the method;

d) the relative cost of using the method;

e) the nature of the zone (capture or protection) required;

f) the advantages and limitations of the method.

Table 2.2 summarises these characteristics of the delineation methods to help the user in selecting a method. Table 2.3 summarises the advantages and limitations of each method.

Karstic systems are a special case. It is beyond the scope if this document to fully cover delineation of capture zones in these systems. However, other approaches such as vulnerability mapping (Doerfliger and Zwahlen, 1997) or recession curve analysis (Civita, 2008) may be helpful. The review by Kaçaroğlu (1999), provides some case examples and considerations around groundwater protection specific to these karstic systems.

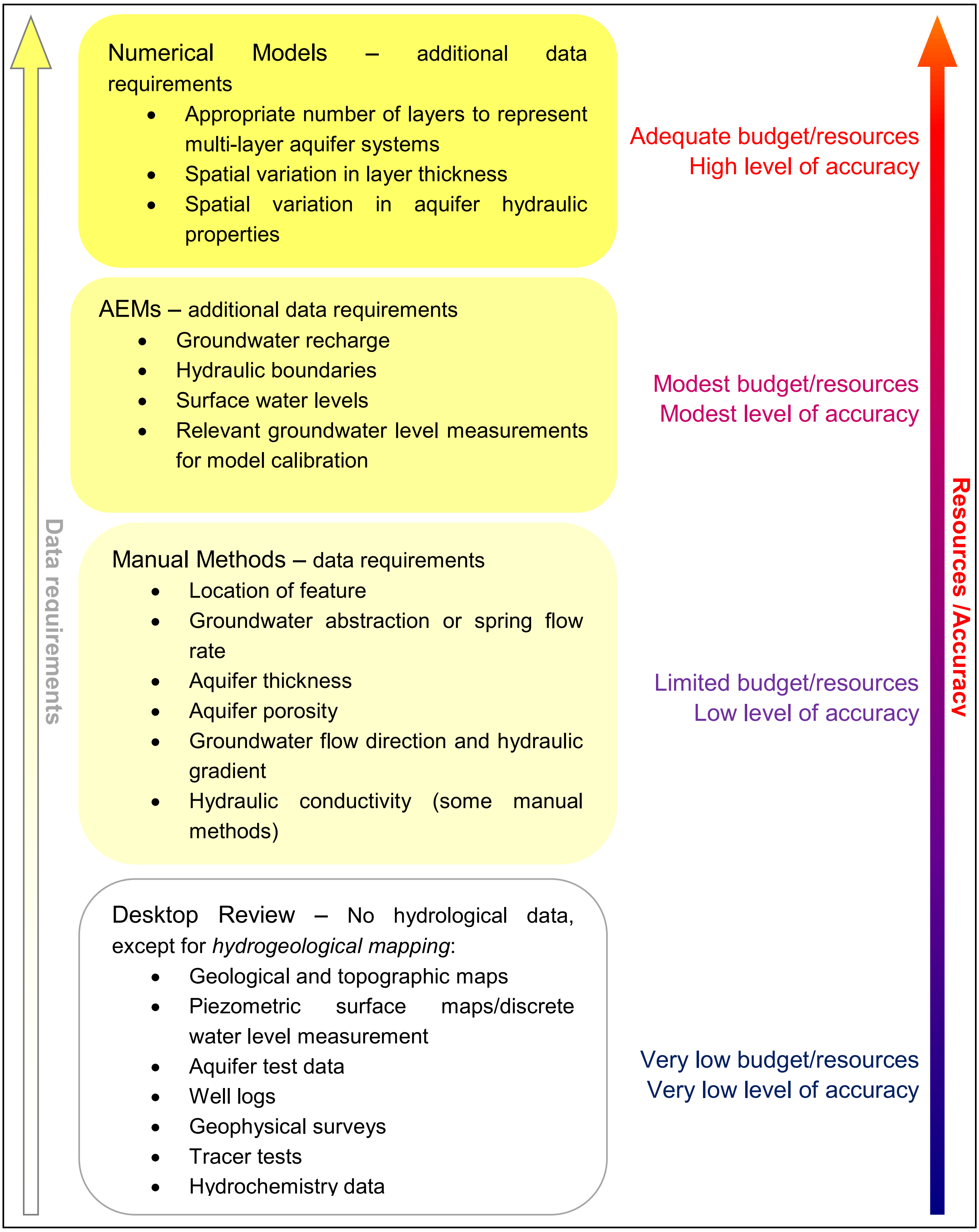

Figure 2.1: Listing of the four types of methods for capture zone delineation with indications of their data and resource needs, and the level of accuracy they will provide.

Table 2.2: Summary of the characteristics of delineation methods.

Tier	Method	Accuracy	Skill/expertise level required to implement	Cost	Difficulty of implementation	Zone type that can be delineated
Desktop review	Arbitrary fixed radius	Low	Low	Low	Low	Protection
	Hydrogeological mapping	Low - moderate	Low - moderate	Low	Low - moderate	Capture
Manual methods	Calculated fixed radius	Low - moderate	Low - moderate	Low	Low	Protection Capture
	Simplified variable shapes	Low - moderate	Low - moderate	Low	Low (once standardised forms developed)	Protection Capture
	Uniform flow equation method	Low - moderate	Low - moderate	Low	Low - moderate	Protection Capture
AEMs		Moderate	Moderate - high	Moderate - high	High	Protection Capture
Numerical models		Moderate - high	High	High	High	Protection Capture

Table 2.3: Summary of the advantages and limitations of delineation methods.

Category	Method	Features	Advantages	Limitations
Desktop reviews	Arbitrary fixed radius	• Wells • Springs	• Easiest delineation method • Inexpensive and quick • Little expertise required	• Highly susceptible to legal challenge • Likely to over-protect except in the case of vulnerable aquifers where it may under-protect • No groundwater flow consideration • Unsuitable for karstic systems
	Hydrogeological mapping	• Wells • Springs • Wetlands/lakes	• Works well where there are near-surface flow boundaries and highly anisotropic aquifers where modelling is difficult • Suitable for karstic systems	• Not compatible with the time-of-travel criterion • Relatively high level of expertise required • May not work well with deep and large aquifers
Manual	Calculated fixed radius	• Wells • Springs	• Easily applied • Relatively inexpensive • Does not require extensive technical knowledge • Increased accuracy over arbitrary fixed radius method • Reasonably accurate for confined aquifers	• Over-protects down-gradient, under-protects up-gradient • Relatively inaccurate for unconfined aquifers • Heterogeneous and anisotropic conditions can cause inaccuracies • Does not cover well pumping interference • Unsuitable for karstic systems
	Uniform flow equation	• Wells • Springs	• Applies to both confined and unconfined aquifers • Suitable when the following assumptions about the aquifer are valid: ○ Homogenous ○ Isotropic ○ horizontally infinite ○ of uniform thickness • Suitable when there is no leakage from, or recharge into, the aquifer and flow is horizontal • Accurate when input data are available and there are no hydrogeological complexities	• Over-protects down-gradient if applied to springs • Does not take account of hydrologic boundaries (e,g., streams, lakes) • Limited general use • Limited to 2D analysis of flow systems and delineation • Does not cover well pumping interference • Unsuitable for karstic systems

Category	Method	Features	Advantages	Limitations
Manual	Simplified variable shapes	• Wells • Springs	• Once shape is defined for an area, delineation for features in the area is easy and rapid	• Initial shape development may be relatively complex • Requires significant data collection and interpretation • Cannot account for parameter variability • Possibly inaccurate where there is: o geologic heterogeneity o hydrologic boundaries o flow direction uncertainty • Does not cover well pumping interference • Unsuitable for karstic systems
AEMs		• Wells • Springs • Wetlands/lakes	• Simple input • Rapid model development • Provides rapid solutions • Suitable for well-field delineations • Very reliable for single layer aquifers • Supports simple variations in hydraulic aquifer properties and recharge • Cost effective alternative to numerical modelling • Once developed, the model may cover a large enough area to allow multiple capture zone delineations, and can take account of pumping interference between wells • Suitable for karstic systems	• Level of complexity that can be represented is limited • Can only be used for representation of a single layer aquifer in 2D. • Unsuitable for partially penetrating wells, multi-layered aquifers and heterogeneous anisotropic aquifers (vertical flow is not covered)

Category	Method	Features	Advantages	Limitations
Numerical models		• Wells • Springs • Wetlands/lakes	• Most accurate delineation method • Allows three-dimensional simulation of aquifers • Takes account of aquifer variation • Relatively precise determination of flow paths and travel times • Once developed, the model may cover a large enough area to allow multiple capture zone delineations, and can take account of pumping interference between wells • Suitable for karstic systems	• Substantial data required • Expensive • Time-consuming • Requires high level of expertise • Provides particle track information, stagnation points may not be accurately determined

One of the factors to consider regarding the level of accuracy required for a method is the feasibility of implementing a meaningful management plan within the zone. The method selected needs to be defensible and consistent with the plan's strategies for zone management. The example below, from work by Pattle Delamore Partners Ltd (PDP; Pattle Delamore Partners, 2012), shows how the zones may be managed and how management influences the selection of the delineation method.

PDP prepared a report proposing definition and management within Groundwater Protection Zones (GPZs) and General Aquifer Recharge Zones (GARZs) for Marlborough District Council's largest community supply wells. This document was drafted to support the inclusion of these zones in the Regional Policy Statement.

GPZs are similar to protection zones, whereas GARZs are similar, but not strictly equivalent, to the capture zones defined in this document. PDP (2012) proposed three zones:

a) The site-specific well head zone (GPZ1)

   This zone protects against direct contamination of the well. It is ideally defined as 5 m circle around the well, although in some cases this is limited by the practicalities of each well. In the GPZ1, the installation of concrete pads, and if necessary ground contouring, are recommended to secure the well and to prevent surface runoff ponding around the well head.

b) The site-specific contamination migration zone (GPZ2)

   This zone protects the well from indirect contamination which would result in contaminant concentrations high enough to have an adverse effect at the hydrogeological feature. The GPZ2 is contaminant specific. In this zone activities such as on-site wastewater disposal systems, wastewater discharges and chemical storage facilities should be controlled and some monitoring should be undertaken in the migration zone. Careful control of non-point contamination sources is also recommended within this zone.

c) The GARZ

   Management strategies within the GARZ include conditions on discharge permits and consents, as well as limitations on some general land use activities such as irrigation.

GPZ1 is delineated by the arbitrary fixed radius method. A more accurate delineation method is required for GPZ2, as it is important that this zone correctly identifies which contaminant sources may affect the hydrologic feature and consequently require control and monitoring.

2.4 STEP 3 – APPLICATION OF SELECTED METHOD

The purpose of this section is to provide the user with information about the various methods that might be used for capture zone delineation. This section gives a brief description of each method, a description of assumptions that might be made in its use, an indication of the data required, the formula(e) needed for the calculation (except where delineation requires software, such as for numerical methods), and the suggested approach to estimating the uncertainty in the capture zone area delineated.

Before using any of these methods, the user should aim to have sufficient understanding of:

a) aquifer confinement;

b) direction of groundwater flow.

(Knowledge of flow direction is unnecessary if the arbitrary fixed radius or calculated fixed radius methods are used.)

Geological maps, potentiometric maps, and, where appropriate, bore logs, screen and bore depths can help to provide this understanding. In the absence of any other data to help in assessing flow direction, topographic contours can be used.

2.4.1 Desktop Review

2.4.1.1 Arbitrary fixed radius

Description: The method is based on the selection of an arbitrary distance from a hydrologic feature. The distance may not be based on any scientific principle, but can be based on generalised hydrogeological considerations and/or professional judgement. The resulting zone is circular (Figure 2.2). This method can be used for protection zone delineation but is not recommended for capture zone delineation. To estimate the radius, one may use the calculated fixed radius equation using generic input values relevant to the hydrogeological setting of the feature.

Assumptions: Assumed values are somewhat representative of conditions

Required data: No site-specific data are required, but research experience or expert judgement is required for selecting the radius of the zone.

Formula: Arbitrary fixed radii for protection zones vary between countries. In Australia and the UK a 50 m distance is proposed as an alternative for time-of-travel criteria for protection from pathogens (ANWQMS, 1995; Carey *et al.,* 2009). In some cases, radii are defined based on aquifer types and confinement status (e.g. 40 m for porous confined aquifers, 280 m in chalk in Portugal; Garcia-Garcia and Martinez-Navarrete, 2005). Where large heterogeneities are expected between aquifers nationwide, larger distances were considered for microbial protection (e.g. 300 m in Ireland; DELG/EPA/GSI, 1999). A more comprehensive, referenced table summarising zones and their thresholds is available in Section 2.3 of the Technical Document. .

Uncertainty: Not applicable.

Resources: For further details on this method, see Section 2.2.2.2. of the Technical Report.

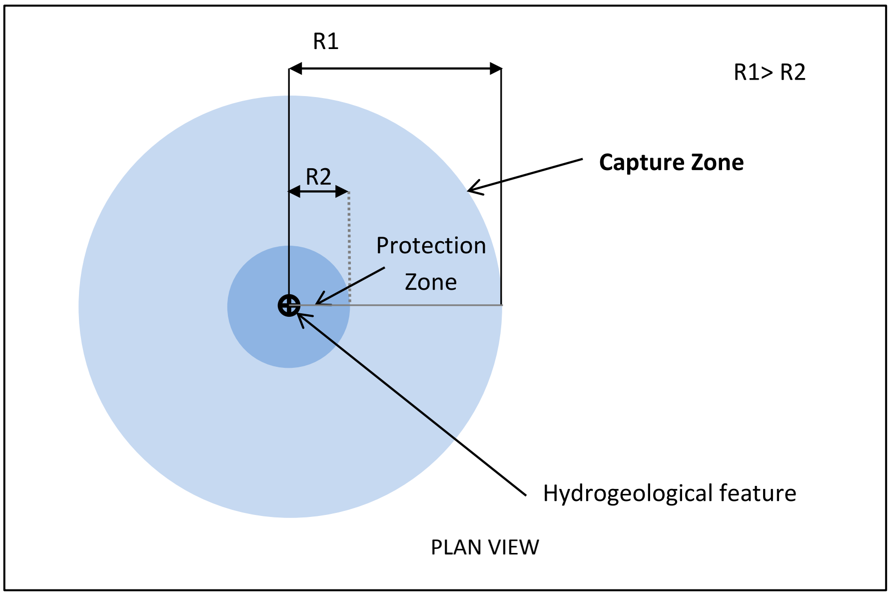

Figure 2.2: Diagram showing a capture zone delineated using the arbitrary fixed radius method.

2.4.1.2 Hydrogeological mapping

Description: Hydrogeological mapping refers to the use of the groundwater divide and/or other physical and hydrologic features to develop a conceptual model of groundwater flow to a given feature. Such mapping integrates hydrogeological, geomorphic, geophysical, geochemical and dye tracing datasets. In many cases, hydrogeological mapping is used as a prelude to analytical or numerical solutions. The shape of the obtained zone will be a combination of hydraulic/geologic/topographic boundaries (Figure 2.3 and Figure 2.4).

Assumptions: -

Required data: Geological and topographic maps, piezometric surface maps or discrete water level measurements around the feature, pump test data, well logs, geophysical surveys (interpretated at a relevant scale), tracer tests results and hydrochemistry results.

Formula: Not applicable to mapping techniques.

For karstic systems, the location of sinkholes, springs and caves should be shown on the same map as the capture/protection zone. Protection zones should include both springs and sinkholes (Kaçaroğlu, 1999).

For wetlands and lakes with groundwater contribution, the areal extent of the aquifer contributing to the feature could be used to infer zones. Typically for an isotropic aquifer that has an aquifer thickness equal to the lake or wetland length, only the upper half of the aquifer is expected to contribute (Davies *et al.,* 2000). If the lake or wetland is five to ten times longer than the thickness, it is then expected that it draws groundwater from the whole thickness of the aquifer. As a first approximation, use twice the width of the lake or wetland open-water surface as the width of the capture zone (perpendicular to the groundwater flow direction, Davies *et al.*, 2000).

Uncertainty: Not applicable.

Resources: Geological Maps: http://www.gns.cri.nz/Home/Products/Maps

Topographical data: http://www.linz.govt.nz/about-linz/linz-data-service

Coordinate conversion: http://www.linz.govt.nz/geodetic/conversion-coordinates/ online-conversion-service

Other geodata (land cover, satellite images etc.): http://koordinates.com/

For further details on this method, see Section 2.2.2.3 of the Technical Report.

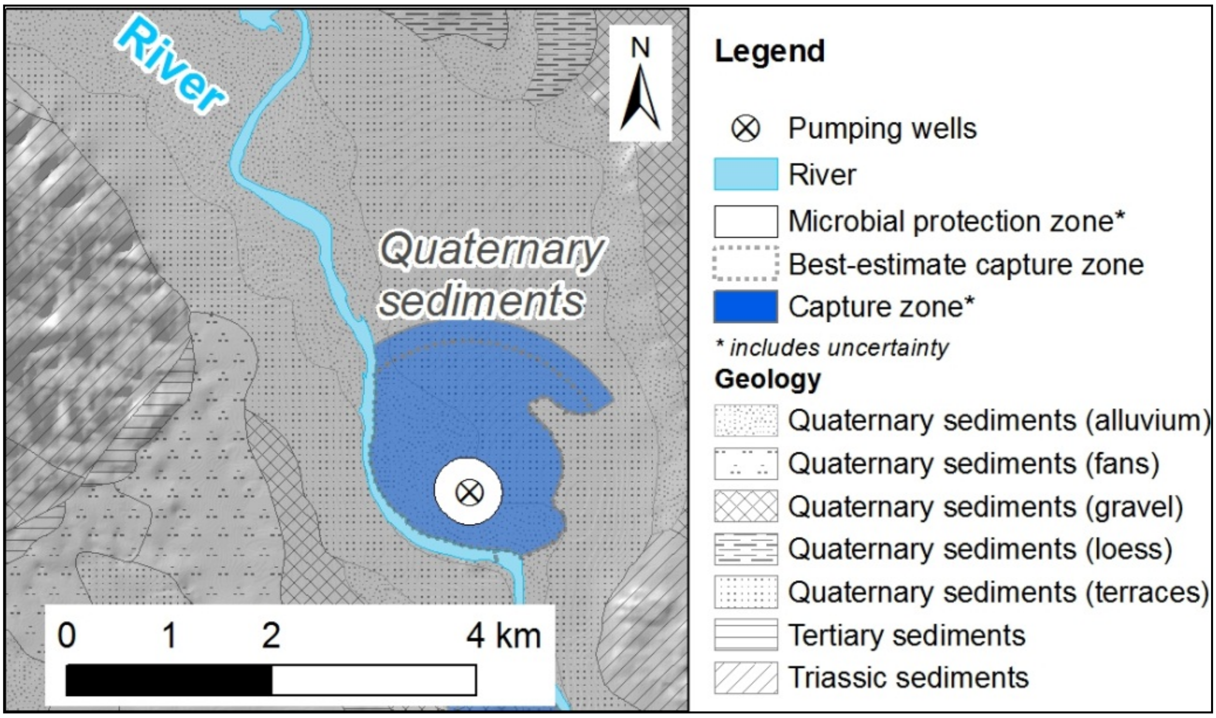

Figure 2.3: Diagram showing zones delineated using the hydrogeological mapping method at an unconfined aquifer well. In this case, the hydrogeological mapping method has been applied to refine zones initially delineated using the calculated fixed radius method. The uncertainty pertains to the calculated fixed radius initial shape.

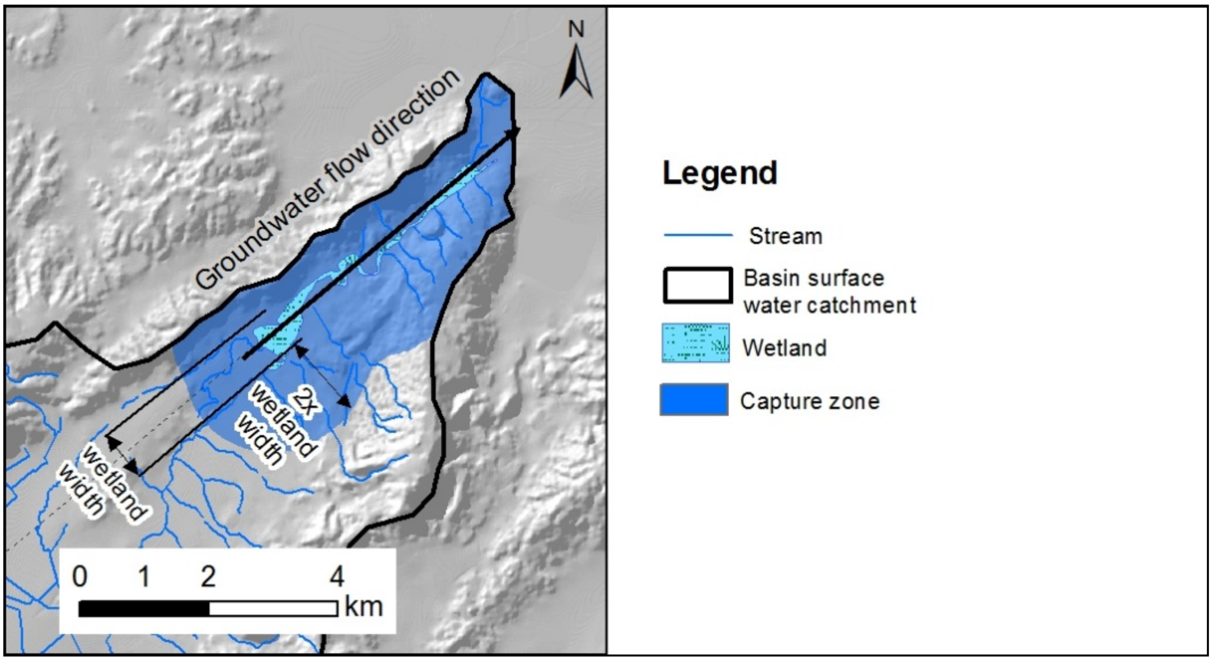

Figure 2.4: Diagram showing a capture zone delineated using the hydrological mapping method at a wetland.

2.4.2 Manual Methods

2.4.2.1 Calculated fixed radius (with or without hydrogeological mapping)

Description: The method delineates a cylinder around the hydrological feature having a radius determined by the required time-of-travel to the feature. The resulting zone is circular (Figure 2.5).

Consideration of the effect of hydrogeological features on groundwater flow, for example, surface waters or ecological boundaries, can be used to modify the capture zone delineated by the fixed radius calculation.

Assumptions:

- One dimensional flow.
- Homogeneous and isotropic aquifer.
- Steady-state conditions.
- No pumping interference.

Required data:

- Well pumping rate or spring flow rate.
- Aquifer porosity.
- Screen length or aquifer thickness.
- Time-of-travel to the well (microbiological protection zone: one year; capture zone: 10 or 50 years).

Typical values of porosity for a range of aquifer media are given in Table A 2.1 in the appendix.

Formula: For protection zone delineation:

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

where r = the radius (L), Q = pumping or flow rate (L^3/T), t = time-of-travel ((T), n = porosity (dimensionless), and b = the screen length or aquifer thickness (L).

For capture zone delineation in an unconfined aquifer:

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

where *Recharge* = recharge rate (L/T).

For protection zone delineation in an unconfined aquifer, equation (1) should be applied in conjunction with equation (2). This is because the protection zone derived from equation (1) may be larger than the capture zone obtained from equation (2), which is conceptually incorrect. In this situation the smaller zone obtained from equation (2) should be presented as the protection zone.

For protection zone and capture zone delineation in a confined aquifer, equation (1) should be used, with an appropriate time proxy for capture zone delineation (see Section 1.1 and Technical Report Section 2.2.2.4). It is not appropriate to apply equation (2) in a confined aquifer because recharge will not occur in the vicinity of well.

Uncertainty: Systematically vary the input values to obtain the greatest results for *r*. Where the range of possible values for a parameter is known, substitute the lower and upper bounds of the range in the calculation, as reducing the value of some input parameters increases *r*. Where this information is unavailable, reduce or increase the values used in the calculation by ± 25% to obtain an estimate of the lower and upper bounds of the range.

The "best-estimate" capture or protection zone is delineated using the median input values, whereas the capture or protection zone is delineated by the outer edges of the shapes obtained through input parameter variations.

Resources: Freely available GIS tool: www.gns.cri.nz/gw-tools/gis
For further details on this method, see Section 2.2.2.4 of the Technical Report.

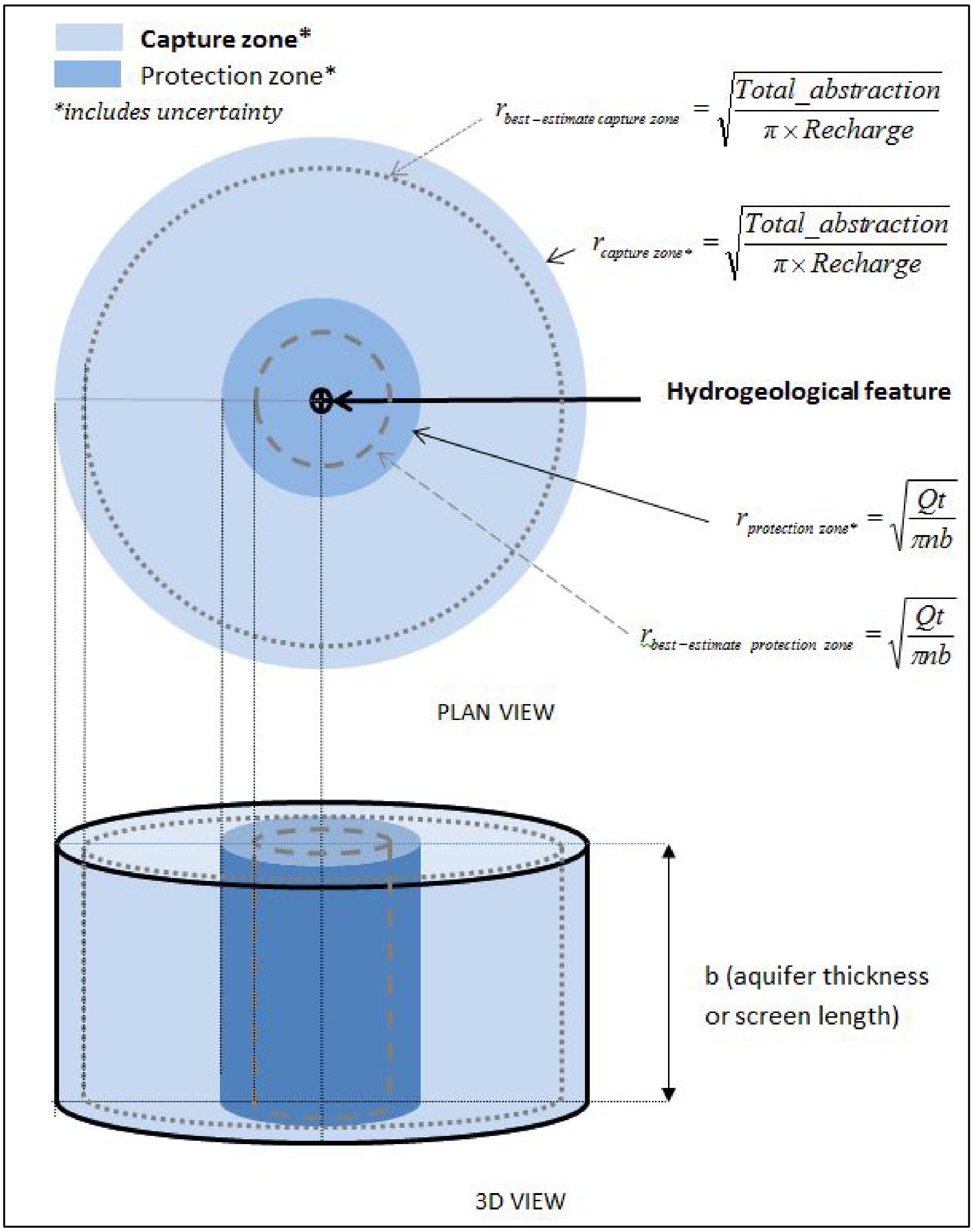

Figure 2.5: Diagram showing zones delineated using the calculated fixed radius method.

2.4.2.2 Uniform flow equation method

Description: The method delineates a capture zone around a well being pumped at a fixed rate. The capture zone has an elongated parabola shape, with the pumped well at the focus of the parabola (Figure 2.6, Figure 2.7). The zone extends from a stagnation point slightly down-gradient of the well to a boundary up-gradient beyond which water will not be drawn into the well.

Water outside the boundaries of the zone will pass by the well.

Assumptions:

- One-dimensional flow.
- Homogeneous and isotropic aquifer.
- Steady-state pumping conditions.

Required data:

- Well pumping rate.
- Aquifer porosity.
- Hydraulic conductivity.
- Screen length or aquifer thickness.
- Time-of-travel to the well (microbiological protection zone: one-year; capture zone: 10-year or 50-year).

Typical values of porosity and hydraulic conductivity for a range of aquifer media are given in Table A 2.1 in the appendix. Mean, minimum and maximum hydraulic conductivity values for regions and subregions in New Zealand are provided in Table A 2.2.

Formula:

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

where Q = pumping rate (L^3/T), k = hydraulic conductivity (L/T), b = the aquifer thickness (L), i = the hydraulic gradient in the aquifer (L/L), and x and y are the distances from the pumping well at the origin to the boundary line in the x and y directions respectively.

The distance along the x-axis to the stagnation point is given by:

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

The distance along the y-axis from the pumping well to the capture zone boundary is given by:

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

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.

The maximum width of the zone in the y up-gradient direction is approximated by:

$$y_{\max} = \frac{\pm Q}{2kbi} \tag{6}$$

The time of travel, t_x (T), along the x-axis is given by

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

where n is the aquifer porosity (dimensionless) and r_x is the distance over which groundwater travels along the x-axis and is positive if up gradient from the well, and negative if down gradient from the well.

Uncertainty: Systematically vary the input values to obtain the greatest results for x_0, y_0 *and* y_{max}. Where the range of possible values for a parameter is known, substitute the lower and upper bounds of the range in the calculation, as reducing the value of some input parameters increases x_0, y_0 *and* y_{max}. Where this information is unavailable, reduce or increase the values used in the calculation by ± 25% to obtain an estimate of the lower and upper bounds of the range.

The “best-estimate” capture or protection zone is delineated using the median input values, whereas the capture or protection zone is delineated by the outer edges of the shapes obtained through input parameter variations.

Resources: Freely available GIS tool: www.gns.cri.nz/gw-tools/gis

For further details on this method, see Section 2.2.2.5 of the Technical Report.

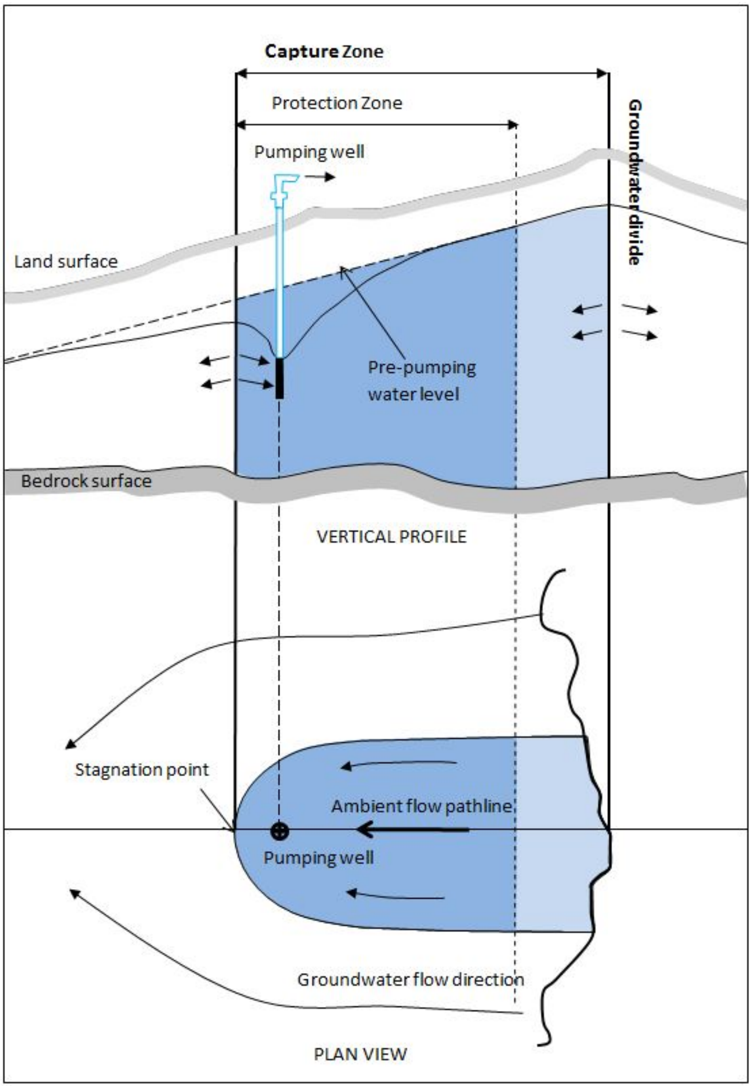

Figure 2.6: Schematic representation of protection and capture zones around a pumped well using the uniform flow equation method.

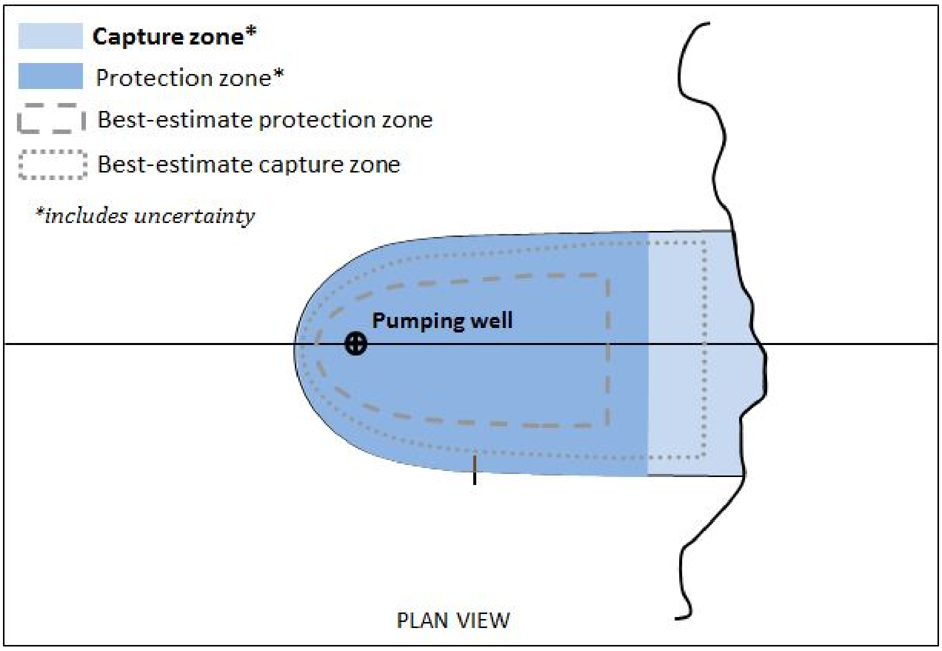

Figure 2.7: Diagram showing zones delineated using the uniform flow equation method.

2.4.2.3 Simplified variable shapes

Description: This method uses analytical models and boundary flow and time-of-travel criteria to calculate “standardised forms” to delineate the capture zone.

To delineate a capture zone, the standardised form that was generated using the pumping rate and hydraulic parameters most closely matching those at the well of interest, is chosen. This standardised form is then drawn over the well in the direction of the groundwater flow. The resulting zone will have a geometric shape, possibly elongated along the ambient groundwater flow direction (Figure 2.8). In the absence of specifically developed shapes, the combination of the calculated fixed radius and the uniform flow equation shapes may be used.

Assumptions: Assumptions specific to the analytical equation used.

Required data: Typically,

- pumping rate
- porosity
- hydraulic conductivity
- hydraulic gradient
- direction of groundwater flow
- aquifer thickness

however, the aquifer properties and well data required depend on which standardised form is chosen.

Formula: Calculated fixed radius, uniform flow equation, see Technical Report Section 2.2.2.5 and Appendix 2 for more analytical equations.

Uncertainty: Systematically vary the input values to obtain the greatest size shapes. Where the range of possible values for a parameter is known, substitute the lower and upper bounds of the range in the calculation, as reducing the value of some input parameters increases the shape size. Where this information is unavailable, reduce or increase the values used in the calculation by ± 25% to obtain an estimate of the lower and upper bounds of the range.

The “best-estimate” capture or protection zone is delineated using the median input values, whereas the capture or protection zone is delineated by the outer edges of the shapes obtained through input parameter variations.

Resources: For further details on this method, see Section 2.2.2.6. of the Technical Report.

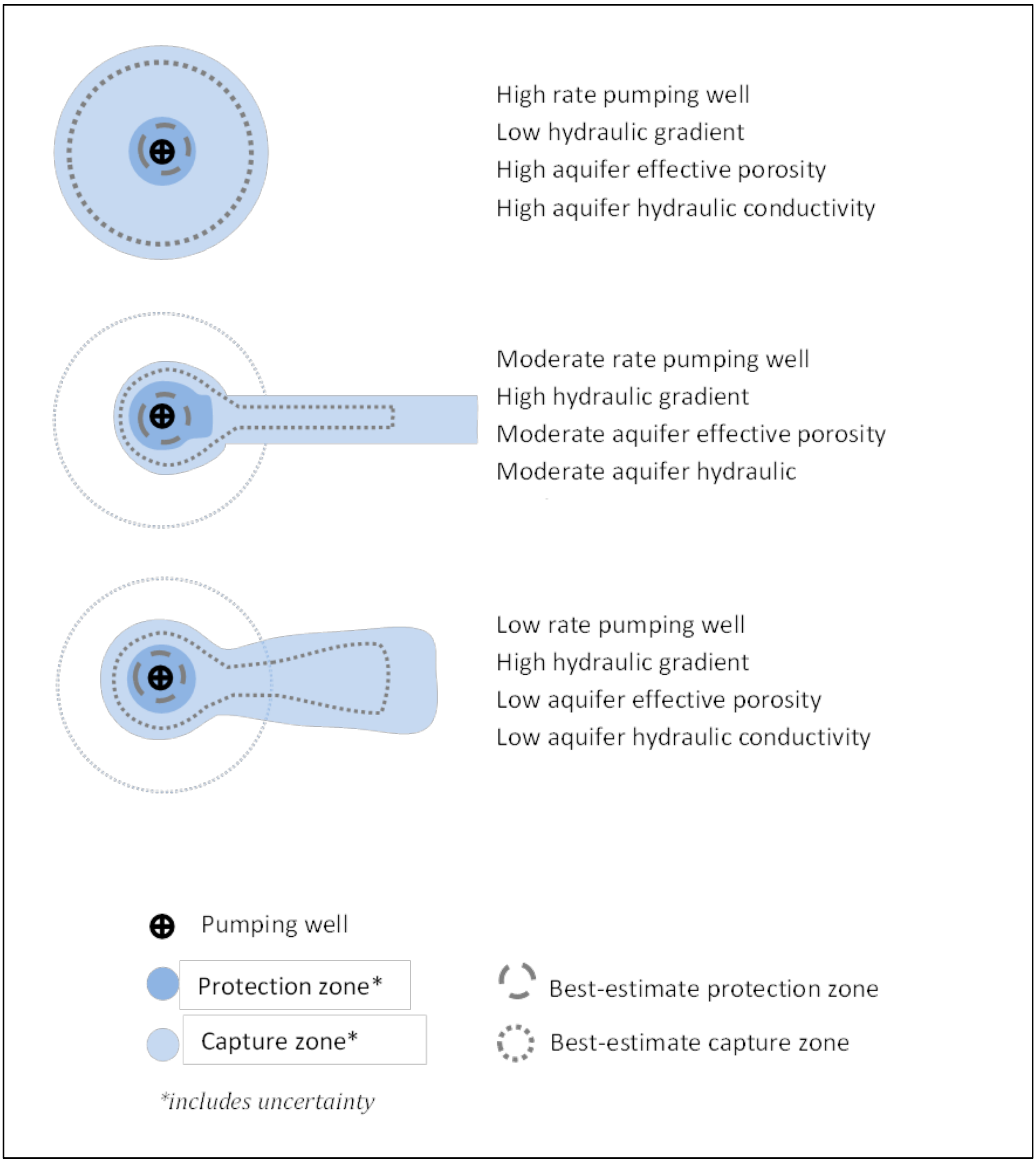

Figure 2.8: Diagram showing zones delineated using the simplified variable shapes method

2.4.3 Analytical element models

Description: Analytical element modelling (AEM) is a groundwater flow modelling technique based on analytical functions and does not require model space discretisation. AEMs simulate 2D groundwater flow although with limitations on the variability of input variables (e.g., rivers, aquifer properties, recharge, pumping wells and well fields) and discretised boundary conditions. They provide a continuous solution across the domain as only the boundary conditions are discretised. AEM can cover large study areas whilst maintaining accuracy over small regions providing for realistic cones of depression due to pumping and backward particle tracking paths. Complexities need to be gradually implemented to maintain analytical stability. Capture zones are delineated in AEMs using backwards particle tracking, i.e., a number of particles are released at the feature and tracked backwards in time to delineate the recharge area. The capture zone is defined as the area within which all particles are tracked to the feature (Figure 2.9).

AEMs are generally built over larger areas than the simpler methods, and consequently, may be able to delineate more than one capture zone within the area. They also have the ability to take account of pumping interference between wells.

This method is moderately expensive and requires moderate modelling expertise.

Assumptions: The assumptions made in this method depend on the nature of the model used.

Required data: 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.

Time-of-travel for particle tracking (microbiological protection zone: one-year; capture zone: 10-year or 50-year).

Formula: Contained within model software. It is beyond the scope of this document to provide detailed documentation on how to build, calibrate and assess an AEM, however the Australian groundwater modelling guidelines may be used for that purpose (Barnett *et al.,* 2012).

Uncertainty: Stochastic methods can be used to assess the uncertainties in the results derived from these models. Distributions of values for the input parameters for the models are used to obtain a distribution of model outputs. This allows capture zones boundaries to be delineated with a specified level of uncertainty.

Alternatively, a more simplistic approach is to systematically vary input values (e.g. recharge, hydraulic conductivity) to obtain the greatest size shapes. Where the range of possible values for a parameter is known, substitute the lower and upper bounds of the range in the calculation, as reducing the value of some input parameters increases the shape size.

Where this information is unavailable, reduce or increase the values used in the calculation by ± 25% to obtain an estimate of the lower and upper bounds of the range.

The appropriate way of implementing these methods will depend on the nature of the model being used.

The "best-estimate" capture or protection zone is delineated using the median input values, whereas the capture or protection zone is delineated by the outer edges of the shapes obtained through uncertainty analysis.

Resources: The AEM modelling package used in the Technical Report is GFLOW© (Moreau *et al.,* 2014a). W*h*AEM2000 is open-source software designed for capture zone delineation by the US Environment Protection Agency. W*h*AEM2000 runs on Windows versions 98, 2000, NT and XP. GFLOW was developed subsequently and independently by the same programmer.

Other AEM modelling software (and user interfaces) are listed in the Technical Report (Appendix 3.1), and at the following url: www.analyticelements.org.

Further information on the AEM method can be found in Section 2.2.2.7 of the Technical Report.

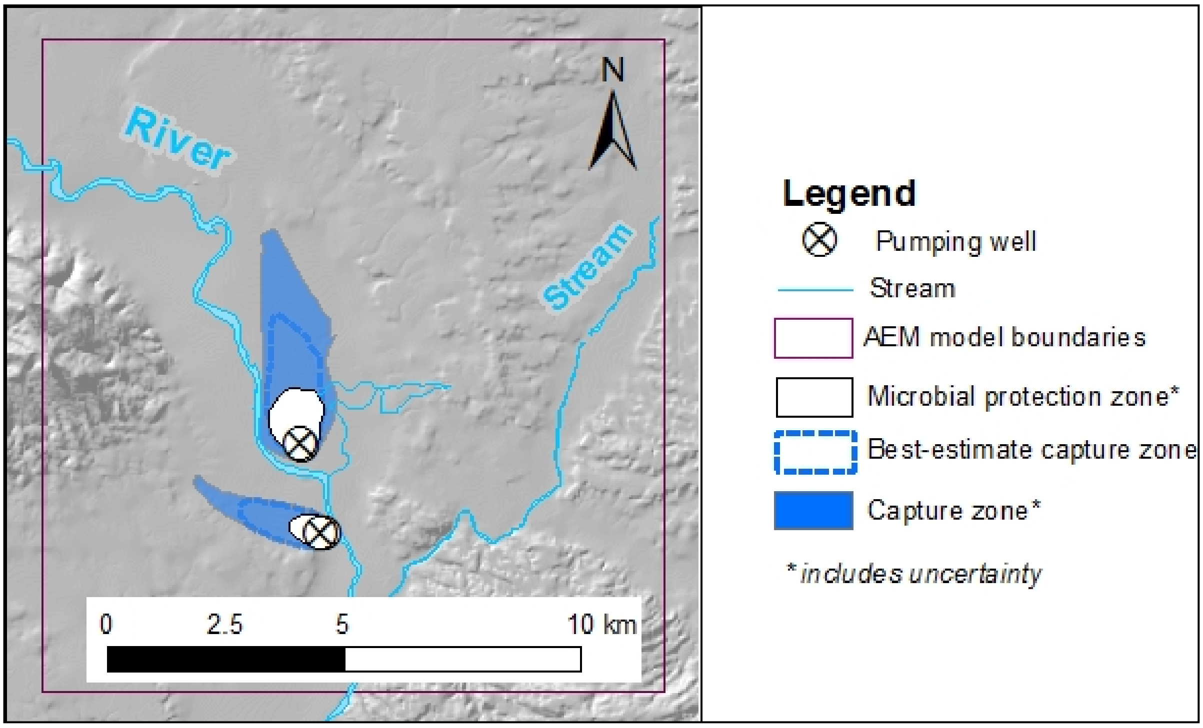

Figure 2.9: Diagram showing zones delineated using an AEM.

2.4.4 Numerical models

Description: These models are designed for analysing complex systems and simulate three-dimensional contaminant flow paths. Unlike the simpler methods, numerical methods are able to take account of parameters such as aquifer heterogeneities, non-uniform aquifer thickness, unconfined flow, transient flow, and multiple wells with arbitrary locations, screened intervals and pumping rates.

The types of models include:

- Finite-difference flow models.
- Finite-element flow models.
- Analytical element flow models.

Numerical methods do not provide a direct calculation of the capture zone curve. The capture zone is determined from the calculation of multiple particle tracks, and it is from these that the capture zone is estimated (Figure 2.10).

Numerical models are generally built over larger areas than the simpler methods, and consequently may be able to delineate more than one capture zone within the area. They also have the ability to take account of pumping interference between wells.

Use of numerical models requires training in this skill.

Assumptions: The assumptions made in this method depend on the nature of the model used.

Required data: Detailed knowledge of:

- aquifer geometries;
- hydrogeologic boundaries;
- vertical and spatial variations in hydraulic conductivity;
- porosities;
- aquifer saturated thickness;
- flow gradients;
- pumping rates;
- aquifer storativity;
- areal distribution of recharge.

Note that these are the minimum data requirements.

Time-of-travel for particle tracking (microbiological protection zone: one-year; capture zone: 10-year or 50-year).

Formula: Contained within model software. It is beyond the scope of this document to provide detailed documentation on how to build, calibrate and assess a model, however the Australian groundwater modelling guidelines may be used for that purpose (Barnett *et al.,* 2012).

Uncertainty: Stochastic methods can be used to assess the uncertainties in the results derived from these models. Distributions of values for the input parameters for the models are used to obtain a distribution of model outputs. This allows capture zone boundaries to be delineated with a specified level of uncertainty.

Alternatively, a more simplistic approach is to systematically vary input values (e.g. recharge, hydraulic conductivity) to obtain the greatest size shapes. Where the range of possible values for a parameter is known, substitute the lower and upper bounds of the range in the calculation, as reducing the value of some input parameters increases the shape size. Where this information is unavailable, reduce or increase the values used in the calculation by ± 25% to obtain an estimate of the lower and upper bounds of the range. The appropriate way of implementing these methods will depend on the nature of the model being used.

The "best-estimate" capture or protection zone is delineated using the median input values, whereas the capture or protection zone is delineated by the outer edges of the shapes obtained through uncertainty analysis.

Resources: Example of numerical models are: MODFLOW (open-source US Environment Protection Agency) and FEFLOW (DHI™).

More details on this method are given in Section 2.2.2.8 of the Technical Report.

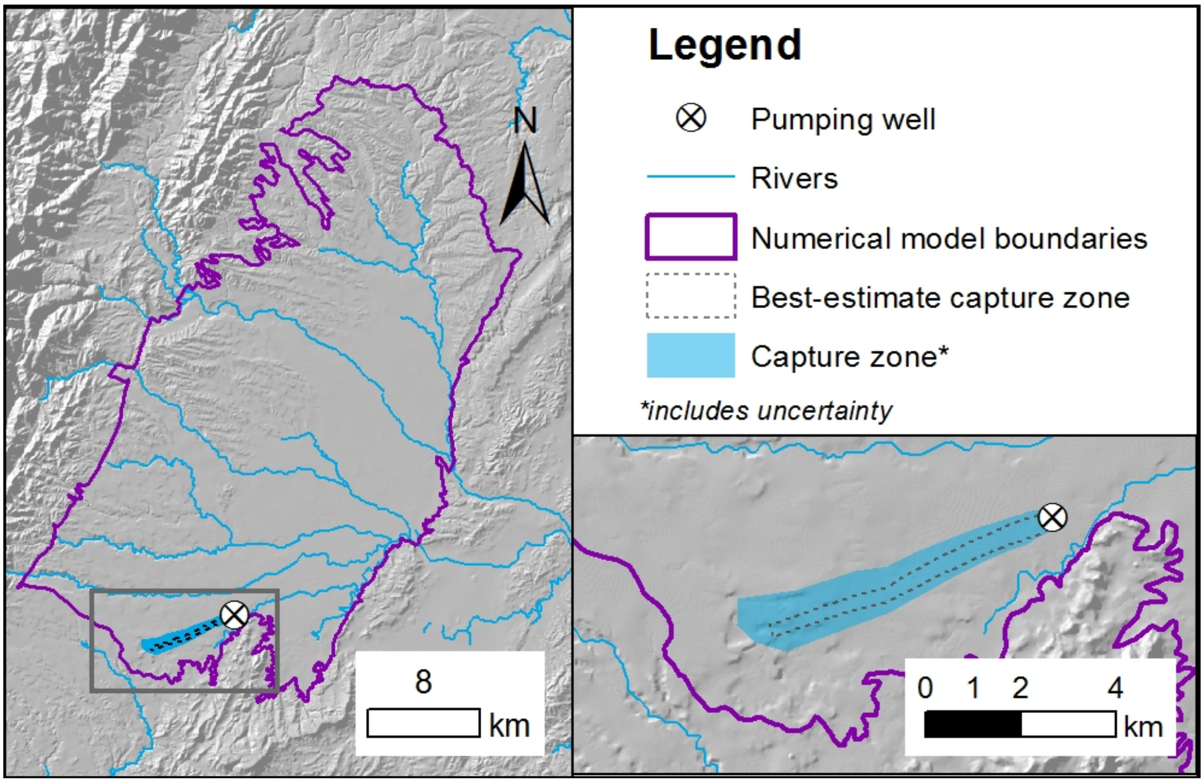

Figure 2.10: Diagram showing a capture zone delineated using a numerical model.

2.5 STEP 4 – REPORTING

Once a capture zone has been delineated, the last step is to present the data in a way that allows those who have to use the information to understand it and its implications.

The information listed below is non-exhaustive; however, it aims to represent the minimum data required for zone delineation reporting:

1. Capture zone delineation purpose and method selection

   Include in this section:

   - The purpose of the capture zone delineation.
   - The delineation criteria. In the case of protection zone delineation, if the option to take the largest of either a safe distance or a time-of-travel criteria is adopted, this should be specified here.
   - The delineation method, with justification for selection. If a capture zone or protection zone was delineated previously, this should be recorded here.

2. Hydrogeological feature information

   Include in this section:

   - A feature description (type, water use).
   - Location information (grid reference and coordinate system).
   - Identification code (if one exists).
   - Construction details (if appropriate).
   - Any existing aquifer test data (if appropriate) and/or historical information about the feature.

3. Hydrogeological setting of the feature

   Include in this section:

   - Information on local topography and ground drainage around the feature, and if applicable a list of the closest surface water features.
   - A description of the geological formation on which the feature is resting.
   - A description of the formation sourcing groundwater to the feature.
   - Any relevant hydrogeological information such as local aquifer name, confinement status if known, lithological description, water chemistry, lateral variations.
   - Any water levels or groundwater quality data from samples obtained from this feature (including age dating information).

4. Capture zone delineation

   Include in this section:

   - Delineation method (or reference to the guidelines).
   - Calculation input parameter values and the source of each value (e.g. measured value, estimated or calculated value, generic value).

- Assumptions made in the calculation or modelling (e.g. truncation of the zone because of known geological or hydrogeological features).

5. Handling of uncertainties

   Include in this section:

   - The resolution/interval of the dataset used for delineation, e.g. topographic contour interval (qualitative uncertainty).
   - The range of input parameter values used, with a justification for their use (quantitative uncertainty).
   - The scale and extent of the model used, if relevant.

6. 2D representation of zones

   How the capture zone is presented will depend on the sophistication of the approach used and the tools the user has available. Capture zones delineated with the less sophisticated methods lend themselves to being drawn manually on a suitable map. Although manual presentation of the capture zone may be possible with the least sophisticated methods, use of GIS is preferable in all cases, as it readily allows other information to be displayed with the capture zone shape. Possible options for presenting the zone are suggested in Table 2.4.

   The estimated uncertainty in the zone shape should be included with the graphical representation of the zone, to produce the protection or capture zone. The shape directly obtained, without uncertainty should be shown as a “best-estimate” zone (see Figure 2.7). Relevant information such as a nearby geological boundary or fault should also be displayed on the graphical representation, with reasonable legibility.

Table 2.4: Possible ways of presenting the capture zone for each delineation method.

Delineation method		Comment	
		Manual presentation	**Geographical Information System (GIS) presentation**
Desktop	Arbitrary fixed radius	• Use a compass with the appropriate radius	• Display feature and any nearby relevant features (same aquifer), AND • Superimpose a land use layer (if available), AND • Delineate the zone (using the “buffer” geoprocessing function)
	Hydrogeological mapping	• Sketch the zone shape manually on the map	• Display feature and any nearby relevant features (same aquifer), AND • Superimpose a land use layer (if available), AND • Display surface water feature of relevance, AND • Display topographic/groundwater contours or discrete water levels measurement location and values, AND • Display flow path to the feature, AND • Use editing tools within GIS to delineate the zone, OR • Sketch the zone shape manually and digitise it
Manual methods	Calculated fixed radius	• Use a compass with the appropriate radius	• Display feature and any nearby relevant features (same aquifer), AND • Display surface water feature of relevance, AND • Superimpose a land use layer (if available), AND • Either calculate the radius through the calculated fixed radius equation and delineate in GIS (buffer function) OR • Delineate the zone using GNS Science capture zone toolkit (Toews, 2013)

<table>
<tr><th colspan="2">Delineation method</th><th colspan="2">Comment</th></tr>
<tr><th colspan="2"></th><th>Manual presentation</th><th>Geographical Information System (GIS) presentation</th></tr>
<tr><td rowspan="2">Manual methods</td><td>Uniform flow equation method</td><td>• Set up equations within a spreadsheet to generate the zone shape
• Scale to a size appropriate for the map, and print out the shape so that it can be transferred to the map</td><td>• Display feature and any nearby relevant features (same aquifer), AND
• Display surface water feature of relevance, AND
• Superimpose a land use layer (if available), AND
• Display topographic/groundwater contours or discrete water levels measurement location and values, AND
• Display flow path to the feature, AND
• Set up equations within a spreadsheet to generate the zone shape and digitise in GIS OR
• Delineate the zone (using GNS Science capture zone toolkit)</td></tr>
<tr><td>Simplified variable shapes method</td><td>• Set up calculated fixed radius or uniform flow equations in a spreadsheet to generate the zone shape
• Sketch the shape onto the map</td><td>• Display feature and any nearby relevant features (same aquifer), AND
• Display surface water feature of relevance, AND
• Superimpose a land use layer (if available), AND
• Set up calculated fixed radius or uniform flow equations in a spreadsheet to generate the zone shape and digitise in GIS OR,
• Delineate both the uniform flow equation and calculated fixed radius zones (using GNS Science capture zone toolkit) and combine the shapes in GIS (using the “dissolve” geoprocessing function)</td></tr>
</table>

Delineation method	Comment	
	Manual presentation	**Geographical Information System (GIS) presentation**
AEMs		• Display feature and any nearby relevant features (same aquifer), AND • Display surface water feature of relevance, AND • Display model extent, AND • Superimpose a land use layer(if available), AND • Export path lines for a given time from the modelling software and digitise the corresponding protection zone (outer envelope polygon) in GIS, OR • Export all path lines from the modelling software and digitise the corresponding capture zone (outer envelope polygon) in GIS, OR • Extract capture zone/protection zone polygons from the modelling software in GIS format
Numerical models		• Display feature and any nearby relevant features (same aquifer), AND • Display surface water feature of relevance, AND • Display model extent, AND • Superimpose a land use layer(if available), AND • Export path lines for a given time from the modelling software and digitise the corresponding protection zone (outer envelope polygon) in GIS, OR • Export all path lines from the modelling software and digitise the corresponding capture zone (outer envelope polygon) in GIS, OR • Extract capture zone/protection zone polygons from the modelling software in GIS format

3.0 WORKED EXAMPLE: APPLICATION OF SIMPLE METHODS TO THE PAUANUI GROUNDWATER WELLS

3.1 INTRODUCTION

The worked example discussed in this section shows how simple methods can be applied to delineating protection and capture zones. It also identifies the reasons why a method may prove unsatisfactory and why a more sophisticated method may be needed to obtain a delineated zone that is more likely to be representative of the actual zone. This section summarises a capture zone delineation comparative method study at the Pauanui groundwater wells (Moreau *et al.,* 2014b).

3.2 THE SETTING

The Pauanui groundwater supply consists of three wells (N1, N2 and N3) installed in an unconfined coastal sand aquifer on the Pauanui Peninsula (Figure 3.1). The aquifer is about 15 m thick and overlays a rhyolite dome that outcrops at the southern end of the Peninsula.

The resource consent allows a combined 800 m^3/d to be abstracted from the three wells for 365 days a year. However, the wells are only operated during peak demand periods so in reality groundwater is only abstracted over a limited time period (December to February).

3.3 USE OF THE CALCULATED FIXED RADIUS METHOD

Splitting the abstraction rate (800 m^3/d) equally between the three wells and using hydraulic properties found in the literature (Table 3.1), the calculated fixed radius of each well for a one-year protection zone is 120 m. These protection zones slightly overlap, due to the proximity of the wells (Figure 3.1).

Recharge over the Pauanui Peninsula was estimated using the mean annual rainfall value (1774 mm per annum) from the last ten years of complete records at the Tairua climate station (National Climate Database, 2014) and an estimate of the rainfall-recharge of 15% (the percentage of rain reaching the saturated zone; URS, 2010).

Using the abstraction over recharge equation (see Section 2.5.2.1), the radius of the capture zone for each well is calculated to be 350 m. Mapping the corresponding circular area around the three wells results in considerable overlap of individual capture zones and a consequent underestimation of each zone. To address this issue, the recharge equation was applied to a synthetic well sited at the geometric centre of the three wells, to which the combined abstraction rate of the three wells was assigned. The resulting capture zone radius is 600 m, covering most of the southern half of the peninsula (Figure 3.1).

The water table contours indicate a general northward groundwater flow direction along the peninsula, with a hydraulic gradient of 0.01. In this situation, the calculated fixed radius method is overly protective as it is unlikely that groundwater will flow from the northern end of the peninsula to the wells.

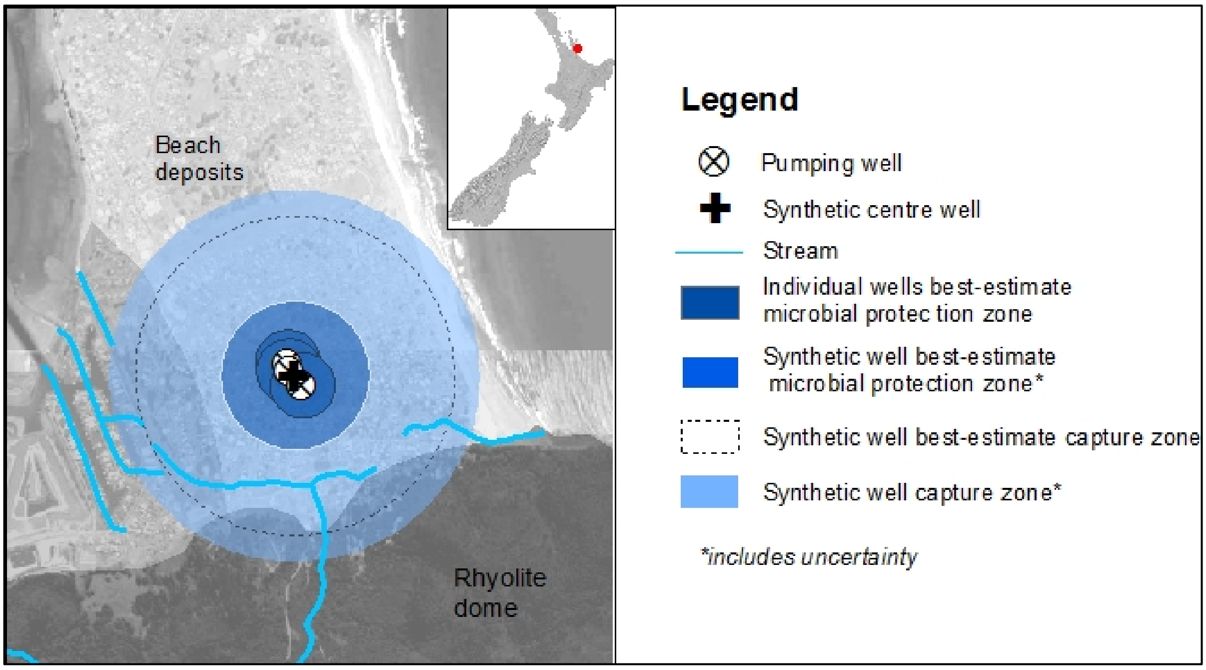

Figure 3.1: Microbial protection zone and capture zone delineated using the calculated fixed radius method at the Pauanui wells.

Table 3.1: Summary of zone delineation parameters and characteristics.

		Bore no			Synthethic well
		N1	**N2**	**N3**	
Hydrogeological feature information	Diameter (mm)	150	150	200	
	Depth (m)	15.6	18	17.7	
	Screen interval (m)	10.3 – 15.3	13.0 – 18.0	12.3 – 17.71	
	Q (m^3/d)	267	267	267	800
Hydraulic parameters used for delineation	Recharge (mm/a)	10			
	Hydraulic conductivity (m/d)	45			
	Aquifer thickness (m)	15			
	Effective porosity (unitless)	0.15			
	Hydraulic gradient (unitless)	0.01			

3.4 USE OF THE UNIFORM FLOW EQUATION METHOD

Using the existing water table contours to derive flow path and hydraulic gradient, the uniform flow equation was subsequently applied to each well. Flow paths were terminated at the geological boundary, where the rhyolite dome outcrops at the southern end of the peninsula. It is likely that the capture zone extends to the rhyolite as it is described as a fractured aquifer. However, it is expected that the hydraulic properties of the Pauanui Sands are not the same as those of the rhyolite dome. Capture zones were delineated using the freely available GIS tool (Toews, 2013) and the hydraulic parameters listed in Table 3.1. Estimated travel times for each capture zone (individual and synthetic wells) were less than 365 days therefore; in this case, microbial protection zones coincide with capture zones.

The delineated one-year individual well capture zones have considerable overlap because the flow paths are similar (Figure 3.2). As a result the delineated zone is an underestimate of the actual zone. To address this problem, the previously defined synthetic well was used for delineation. The resulting zone is larger than the individually delineated zones, however, it does not include the individual wells (Figure 3.2). To meaningfully delineate the capture zones (best-estimate and including uncertainty), individual zones were retained until they coalesced and from this point forward (in the up-gradient direction) the synthetic zone shape was used, and truncated at the aquifer boundary (Figure 3.2).

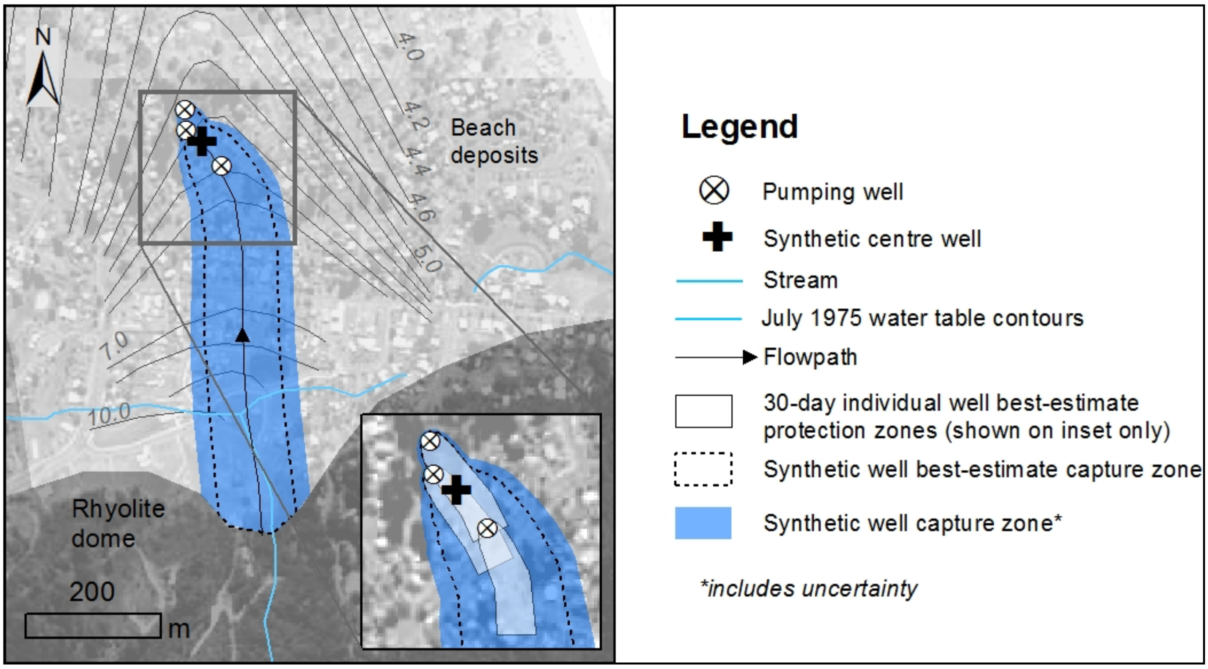

Figure 3.2 Capture zone for the Pauanui wells delineated using the uniform flow equation method. In this case the microbial protection zone coincides with the capture zone.

4.0 ACKNOWLEDGEMENTS

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APPENDICES

APPENDIX 1: EQUATION TO CALCULATE TIME-OF-TRAVEL THRESHOLD BASED ON REMOVAL RATES

The time-of-travel 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 time of travel 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.

APPENDIX 2: TYPICAL EFFECTIVE POROSITY AND HYDRAULIC CONDUCTIVITY VALUES

Table A 2.1 Effective porosity and hydraulic values for generic aquifer types (Moore *et al*., 2010).

Aquifer type	**Effective porosity, n (unitless)**	**Hydraulic conductivity, K (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-karstic limestone	0.1	0.01
Karstic and fractured rock (e.g., basalt and schist)	0.1 and 1 for matrix and fractures respectively	1000

Table A 2.2 Hydraulic conductivity values determined in sub-regions within 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	Wairarapa	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			
	Well 6535	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		

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