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Technical Guidelines for Drinking Water Source Protection Zones

Ministry for the Environment

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Technical Guidelines for Drinking Water Source Protection Zones

Prepared for

Ministry for the Environment

June 2018

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Quality Control Sheet

TITLE	Technical Guidelines for Drinking Water Source Protection Zones
CLIENT	Ministry for the Environment
VERSION	Final
ISSUE DATE	27 June 2018
JOB REFERENCE	C01671502
SOURCE FILE(S)	C01671502R001_Final_DWSPZ_Guidelines

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Limitations:

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Acknowledgments

These guidelines refine and update an earlier report *Methodology for Delineating Drinking Water Catchments* prepared for the Ministry for the Environment (MfE) in 2005. That report was prepared by Pattle Delamore Partners Ltd (PDP) and the Institute of Environmental Science and Research Limited (ESR), with input from a peer review committee comprising experts in groundwater and surface water resources and planning, primarily from Regional Councils and MfE.

Executive Summary

In 2005, Pattle Delamore Partners Ltd and the Institute of Environmental Science and Research Limited prepared the report *Methodology for Delineating Drinking Water Catchments* for the Ministry for the Environment. The report was prepared to inform the development of the regulations that later became the *Resource Management (National Environmental Standards for Sources of Human Drinking Water) Regulations 2007,* commonly known as the Drinking Water NES.

The Ministry for the Environment is currently undertaking a review of the Drinking Water NES and has engaged Pattle Delamore Partners to review and update the 2005 report in order to inform the potential use of source protection zones as a spatial criterion within the Drinking Water NES.

These Technical Guidelines for Drinking Water Source Protection Zones ('Technical Guidelines') are based on current national and international best practices for delineating and implementing source protection zones for drinking water sources. The Technical Guidelines recommend default source protection zones to which the regulations within the NES could apply. Methods for refining the zones to take into account site-specific circumstances are also outlined.

The Technical Guidelines provide national guidelines for establishing drinking water source protection zones that can be applied consistently across the country for drinking water supplies derived from surface water and groundwater. The primary intention is to support the implementation of the Drinking Water NES and to inform improvements to related policies and practices.

The Technical Guidelines are based on the well accepted method for evaluating contamination risks to drinking water sources, which involves assessing:

- the **source** of contamination
- the **receptor** that may be adversely affected by the contamination
- the **pathway** that allows the contaminant to reach the receptor.

In this report, the relevant receptor is a drinking water supply intake. For a risk to be identified, all three aspects (i.e. source, pathway and receptor) must be present. A common method for managing risks to drinking water is to eliminate one of these three components – or to make the pathway between the source of contamination and receptor contain sufficient barriers (e.g. sufficient attenuation of contaminant concentrations), so that the risk of an adverse effect on the drinking water supply is acceptably low.

Defining a drinking water source protection zone involves delineating an area within which risks to a drinking water supply intake from contaminant sources are identified and appropriately managed. The size and shape of the source protection zone takes into account the characteristics of migration pathways that

occur over land and through surface water and the subsurface environment. Longer migration pathways induce greater attenuation of the concentration of a contaminant due to naturally occurring processes of:

- dispersion and dilution
- filtration, adsorption and sedimentation
- bio-degradation and chemical transformation
- evaporation
- die-off.

These Technical Guidelines propose three generic drinking water source protection zones, each recognising different degrees of contaminant attenuation that occur along migration pathways. For all zones, it is important to consider the potential for preferential pathways, which could affect contaminant transport time and attenuation.

Source Protection Zone 1: This is an immediate zone around the drinking water supply intake, where contaminants could directly impact on the intake structure. Land-use activities in this zone should be strictly controlled. For groundwater supplies this zone is defined on the basis that the well is properly constructed and sited to avoid rainwater and floodwaters from directly entering the well casing.

Source Protection Zone 2: This intermediate zone is focused on specific land-use activities or discharges that might directly contaminate the water source. For **surface water** sources, the extent of the zone is based on providing an early warning of a potential contamination event and to limit the concentrations of microbial pathogens in surface water prior to abstraction and treatment. For **groundwater** sources, the zone's primary purpose is to limit the potential for microbial contaminants to reach the water supply in an infective state. While this zone is primarily intended to provide for sufficient microbial attenuation, where possible, it is also considered sufficiently large to provide protection against many other contaminant discharges, including accidental spills. Zone 1 is contained within Zone 2.

Source Protection Zone 3: This zone encompasses the entire upper catchment for **surface water** sources and/or the entire capture zone or catchment for **groundwater** sources. Within this zone non-point sources arising from general land use, cumulative effects from small point sources and large scale discharges may need to be managed. This zone is also intended to address persistent contaminants that may not attenuate significantly before reaching a water supply intake, such as nitrate, pesticides and some emerging contaminants.

Default Source Protection Zones

Practical default source protection zones have been defined in these Technical Guidelines as indicated in the table below. These default source protection zones are based on the updated literature review, practical experience and a theoretical assessment of contaminant migration. The term 'conjunctive' in the table relates to situations where both groundwater and hydraulically-connected surface water are drawn into an intake.

Theoretical example delineations based on the recommendations in the table below are provided in Appendix D.

Site Specific Source Protection Zones

In many cases, it may be appropriate to replace the default zones with site specific zones based on the particular water supply intake configurations and the environment in which they are situated.

Methods to develop site specific zones need to involve an assessment of contamination risk and contaminant attenuation along migration pathways towards the particular water supply intake. These Technical Guidelines provide information and practical advice on methods for delineating site specific source protection zones.

Specifications for Default Drinking Water Source Protection Zones

Zone	*Surface Water Source*	*Groundwater Source*	*Conjunctive Source*
Zone 1: **Intake/Wellhead Protection Zone** to control direct effects on the intake structure	• Minimum of 5 m landward of the water's edge (flood plain edge), or a larger zone of at least 30 m landward (where this can be achieved in a practical manner) on both sides for the 1000 m upstream reach of the intake and 100 m downstream, including all tributaries within that distance. • For lakes a 500 m radius from the intake should apply, and 5 m landward of the water's edge, or a larger zone of at least 30 m (where this can be achieved in a practical manner).	• 5 m radius around well head, or a larger zone of at least 30 m (where this can be achieved in a practical manner).	• For galleries and wells within a river bed, the same intake zone as for a surface water take would apply. • For springs, the same intake zone as for a groundwater source would apply.
Zone 2: **Intermediate Zone** for protection from microbial contamination and chemical discharges or spills	• 8 hours travel time to intake (assuming a river water velocity of 1m/s if no site specific information is available), 100 m downstream and 100 m landward of the water's edge for the reach of surface water described in the preceding point, including all tributaries within that distance. • For lakes, the whole lake and 8 hours travel time within tributaries with a 100 m buffer strip.	• 1 year time of travel to the well intake (based on microbial attenuation via the migration pathway), out to a maximum distance of 2.5 km, with a conservative allowance for parameter variability and uncertainty. • If no information is available on the groundwater flow direction then the zone shall be defined by an area of 2.5 km radius around the well. • For aquifers where long travel distances with little attenuation are known to occur (such as karst aquifers), the Zone 2 definition could be replaced with Zone 3.	• For wells where Zone 2 intersects a surface waterway, both the surface water and groundwater protection zones should apply. • For springs and small groundwater fed lakes, the same zones as for wells should be applied.
Zone 3: **Entire Catchment/ Capture Zone**	The entire surface water catchment upstream of a point 100 m downstream of the intake.	• The total capture zone for the well or catchment that could contribute water to the well, with a conservative allowance for parameter variability and uncertainty. • In the unlikely event that no information is available on the groundwater flow direction then the zone shall be defined as the entire groundwater catchment. • In addition, where a number of wells draw from the same groundwater system, it may be more pragmatic to make Zone 3 the entire groundwater catchment.	The total extent of the groundwater and surface water catchments contributing to the well or surface waterway.

Table of Contents

Table of Figures

Table of Tables

Appendices

1.0 Introduction

1.1 Background

Pattle Delamore Partners (PDP) and the Institute of Environmental Science and Research (ESR) prepared the report *Methodology for Delineating Drinking Water Catchments* for the Ministry for the Environment (MfE) in 2005. The report was prepared with input from a peer review committee comprising experts in groundwater and surface water resources and planning, primarily from Regional Councils and MfE.

The purpose of the guidance within that report was to help inform the development of the regulations that later became the *Resource Management (National Environmental Standards for Sources of Human Drinking Water) Regulations 2007,* commonly known as the Drinking Water NES.

MfE is currently undertaking a review of the Drinking Water NES to determine whether the regulations have achieved their intended purpose and remain fit for purpose. The review is also considering the findings and recommendations of the Government Inquiry into Havelock North Drinking Water, including the potential use of source protection zones as a spatial criterion within the Drinking Water NES. MfE has engaged PDP to prepare these *Technical Guidelines for Drinking Water Source Protection Zones* ('Technical Guidelines'). These Technical Guidelines build on the 2005 work, and have the primary purpose of identifying specifications for establishing source protection zones for drinking water sources, based on the unique characteristics of freshwater resources in New Zealand.

These Technical Guidelines consider current national and international best practices for delineating and implementing source protection zones for drinking water sources, particularly regarding Priority 1 and Priority 2 determinands as defined in the *Drinking-water Standards for New Zealand 2005 (Revised 2008)* (DWSNZ) and discussed further in Section 1.3 of this report.

Source protection is a fundamental component of the multiple barrier approach to drinking water safety recommended by the World Health Organisation and the Ministry of Health in New Zealand. The DWSNZ emphasises that risks to public health from contaminated drinking water are best managed through the establishment of multiple barriers to reduce the likelihood of contamination. The *Report of the Havelock North Drinking Water Inquiry: Stage 2* prepared by the Government Inquiry into Havelock North Drinking Water also stressed the importance of the multiple barrier approach to drinking water safety. The Stage 2 report identified that the first of these barriers involves *"minimising the extent of contaminants in the source water that must be dealt with by the treatment process"*. The subsequent barriers identified relate to treatment processes and protection of the treated water from subsequent contamination in the distribution network.

The *Report of the Havelock North Drinking Water Inquiry: Stage 2* identifies six fundamental principles of drinking water safety for New Zealand. Principle 1 is *"A high standard of care must be embraced"*. This outlines that all those involved in supplying drinking water (from operators to politically elected representatives) must embrace a high standard of care, given the consequences of a failure are illness, injury or death on a large-scale.

Principle 2 is *"Protection of source water is of paramount importance"* which identifies that protection of the source of drinking water provides the first, and in some cases the most significant, barrier against drinking water contamination and illness. The report emphasises that risks to sources of drinking water must be understood, managed and addressed appropriately.

To ensure the protection of drinking water sources, the effective control of potential contaminant sources and a high standard of care from all those involved in supplying and managing risks to drinking water is essential.

The benefit of good raw water quality prior to treatment, to minimise the consequences if a treatment failure occurs, is highlighted by a number of contamination events in New Zealand. These include the 2012 campylobacter outbreak in Darfield[1], when chlorine treatment was inadvertently not occurring during use of a back-up supply from a shallow irrigation gallery near the Waimakariri River *(29 confirmed cases, 109 probable)*. The *Report of the Havelock North Drinking Water Inquiry: Stage 1* records a similar campylobacter outbreak in Ashburton in 1996, when there was a chlorination failure at another infiltration gallery *(19 confirmed cases, 33 probable)*. That report also refers to a campylobacter outbreak at Te Aute College in the Hawke's Bay in 2001, due to a malfunctioning UV treatment system *(137 confirmed cases)*.

Conversely, where treatment is not occurring because a supply has been deemed to have a sufficiently low risk of contamination, contamination of the raw water has severe consequences, as illustrated in the campylobacter outbreak event at Havelock North in August 2016, where 5,500 people were estimated to have become ill.

The Government Inquiry into Havelock North Drinking Water following that event found that the water supplier made key omissions, including in its assessment of risks to the drinking water supply, and it breached the DWSNZ. It found that the aquifer from which the wells drew water was vulnerable to contamination and was not protected by a low permeability confining layer (as was assumed prior to

[1] Community & Public Health Report to the Darfield Community: An Outbreak of Waterborne Gastroenteritis in Darfield, Canterbury, July- August 2012 (18 February 2013)

the Inquiry's process). It was stated that, at best, it might have been characterised as semi-confined, with a thin and variable confining layer.

The Inquiry also found the aquifer had been penetrated by a significant number of disused or uncapped wells and that, in at least one area, the confining layer had been affected by earthworks. These activities were identified as leaving it vulnerable to entry from contaminated water. This event highlights the importance of a sound understanding of risks to a supply and effective management of the risks. A source protection zone is an important tool to help achieve this.

1.2 The role of protection zones

Establishing a suitably defined source protection zone around a groundwater supply is an important barrier for preventing contamination for a sufficiently deep well and can be very effective for helping ensure good raw water quality with respect to both Priority 1 and 2 determinands. This is achieved by limiting the potential for contamination (via controls on activities within the zone) and as a result of the natural treatment processes that occur within soil and groundwater systems (uptake by vegetation, dilution, filtration, microbial decay and biodegradation).

Achieving good raw drinking water quality for surface water supplies (lakes and rivers) is more difficult, because most surface waterways experience microbial contamination with respect to the DWSNZ due to natural processes (e.g. pathogens from birds) or existing land-use activities in the catchment. However, a source protection zones with appropriate controls on activities can limit pathogen concentrations to reduce the risk of ineffective treatment of pathogens and reduce the potential consequences if a failure in treatment occurs. An appropriate source protection zone for surface water supplies is also important for minimising the risk of contamination from chemical determinands.

This report focuses on the basis of the methods to define source protection zones. A protection zone with good controls on activities within it still cannot guarantee an uncontaminated supply. It is the responsibility of the water supplier to ensure they have designed the supply to reduce the risk of contamination at the source, and provided the necessary treatment to further reduce risks to public health.

The purpose of the source protection zones defined in these Technical Guidelines is primarily to assist MfE to consider the potential inclusion of a spatial criterion in the Drinking Water NES, which will require Regional Councils and Unitary Authorities to manage activities in a manner that:

- enables a timely response to a specific pollution event such as an accidental discharge

- controls activities that may pose a risk to drinking water safety in a way that appropriately recognises the risk of unacceptable contaminant concentrations reaching the water abstraction point.

These Technical Guidelines may also be of assistance to water suppliers[2] in the preparation of a Water Safety Plan under the Health (Drinking Water) Amendment Act 2007[3], which requires that all community drinking water supplies with a population of greater than 500 people develop such a plan for their drinking water supply.

These Technical Guidelines may also assist other organisations who supply potable water but are not currently classed as water suppliers (for example ski-fields and industrial plant supplies), public health bodies such as District Health Boards, whose tasks relate to approving Water Safety Plans, and the Ministry of Health, who is responsible for potable water supplies from a health perspective.

1.3 Priority 1 and Priority 2 determinands

MfE require these Technical Guidelines to specifically consider source protection zones in relation to Priority 1 and Priority 2 determinands as defined in DWSNZ. Priority 1 and Priority 2 determinands are described in this section.

Priority 1 determinands are those whose presence can lead to rapid and major outbreaks of illness and the DWSNZ identifies bacteria, protozoa and viruses as belonging to this category, stating that this could change as new evidence becomes available. The Priority 1 determinands specified in the DWSNZ are Escherichia coli (*E. coli)* and protozoa (Cryptosporidium and Giardia).

- *E. coli*, which is a common gut bacterium living in warm-blooded animals, is included as the reference bacteria, because it is an internationally accepted indicator of the contamination of water by faecal matter material, indicating the potential presence of pathogenic bacteria. Only some strains of *E. coli* are pathogenic.
- For protozoa, cryptosporidium is the reference protozoan, because it is more difficult to treat than Giardia, meaning that any measures taken to manage risks from Cryptosporidium will also manage risks from Giardia.
  - The DWSNZ do not include viral criteria, due to lack of reliable evidence, but it is intended they will be included in a future standard

[2] The Health (Drinking Water) Amendment Act 2007 defines a "drinking water supplier" as a person who supplies drinking water to people in New Zealand or overseas from a drinking water supply, and specifically identifies who that includes.
[3] The Health (Drinking Water) Amendment Act 2007 defines a "public health risk management plan" (now known as a Water Safety Plan) as a plan prepared and operated by a drinking water supplier or other person under section 69Z or 69ZA. Under these sections, a Water Safety Plan must identify the public health risks (if any) associated with that drinking water supply; and identify critical points in that drinking water supply; and identify mechanisms for— (A) preventing public health risks arising in that drinking water supply; and (B) reducing and eliminating those risks if they do arise.

when the effectiveness of viral removal or inactivation by water treatment processes is better understood. The DWSNZ also consider that, if no human effluent is in a drinking water supply catchment, viruses will not pose a risk to public health. Animal faecal matter presents a risk for bacteria and protozoa.

Priority 2 determinands in the DWSNZ are those determinands of public health significance in a specific supply or distribution zone that are present at concentrations that exceed 50 percent of the Maximum Acceptable Values (MAV) and, for microorganisms, are present at concentrations that represent an unacceptable risk to health. The Priority 2 determinands for individual drinking-water supplies are listed in the Register of Community Drinking-water Supplies and Suppliers in New Zealand. Priority 2 determinands encompass the following four categories.

- *Priority 2a* determinands are chemical and radiological determinands that could be introduced into the drinking-water supply by the treatment chemicals at levels potentially significant to public health.
- *Priority 2b* determinands are chemical and radiological determinands of health significance that have been demonstrated to be in the drinking-water supply at levels potentially significant to public health. These include includes chemicals present in the raw water that may not be removed by the treatment process, as well as any disinfection by-products and determinands introduced into drinking-water from the distribution system. Cyanotoxins in surface water supplies are also included.
- *Priority 2c* determinands are chemical determinands of health significance that may appear in consumers' drinking-water, having arisen from their plumbing or fittings.
- *Priority 2d* determinands are micro-organisms of health significance that have been demonstrated to be present in the drinking-water supply. This may occur, for example, when high numbers of micro- organisms are present in the raw water and *E. coli* is present in water leaving the treatment plant. The monitoring protocols that apply will usually include a catchment assessment to try to identify the source of the contamination.

Priority 2b and 2d determinands are relevant to source protection zones because the definition includes the determinands being present in the raw water. Priority 2a and 2c determinands are relevant only to the treatment or distribution system.

1.4 Structure of the guidelines

These Technical Guidelines build on the earlier report (PDP and ESR, 2005) to include the following.

- A short commentary of the findings and recommendations of the *Report of the Havelock North Drinking Water Inquiry: Stage 2*, prepared by the Government Inquiry into Havelock North Drinking Water, regarding 'first-barrier protection' and the use of source protection zones.
- An updated literature review to include national and international literature published since the 2005 guidelines relating both to the delineation of capture zones and contaminant transport behaviour (including transport of different microbes).
- The principles behind the definition of protection zones.
- An outline of a spatial criterion for default drinking water protection zones that could be considered for inclusion within the Drinking Water NES.
- An outline of the methods that could be used to create site-specific drinking water source protection zones.

2.0 Havelock North Drinking Water Inquiry

A multiple barrier approach is essential for the protection of human drinking water sources. The environment, or the water source, is the first and most significant barrier of protection. The Drinking Water NES regulations were enacted to address 'first barrier protection' by setting out requirements for local authorities to follow in order to help reduce the risk of sources of human drinking water from becoming contaminated. The Government Inquiry into Havelock North Drinking Water ('the Inquiry') stated that first barrier protection under the Resource Management Act (RMA) was inadequate and recommended MfE consider amendments to the RMA and the Drinking Water NES to give greater prominence to the protection of drinking water sources in RMA decision-making processes.

In its findings regarding the Drinking Water NES, the Inquiry stated the use of a spatial criterion, i.e. source protection zones, could help improve the implementation and effectiveness of these regulations. The Inquiry also stated that consideration should be given to extending the scope of the Drinking Water NES to include all land-use activities, including existing activities, in addition to water and discharge permits.

The Inquiry also stated that using a spatial criterion, as described in these Technical Guidelines, better aligns with the Drinking Water NES objective to "ensure a catchment component to managing human drinking water".

3.0 Literature review results

A review of New Zealand and international literature on the definition of zones for drinking water source protection is presented in Appendix B. The results from this review show that, in general, methods used for the delineation of the zones range from decisions not clearly related to any technical details, through those involving simple calculations based on well-established parameters, to more complex numerical modelling based on site specific data for groundwater supplies.

A ‘three zone’ approach is the most common approach for delineating drinking water protection zones internationally, however, a range of one to five zones are applied across various jurisdictions. Fixed distances around the intake point combined with time of travel (TOT) generally define these zones.

While the literature review revealed extensive implementation of drinking water protection zones internationally, water source protection guidelines or legislation generally do not specify the methods from which time of travel and fixed distances are derived. This may be due to the site-specific nature of water source risk assessments used to inform drinking water source protection zones.

A growing consensus in the academic literature considers time of travel to be limited as the sole measure of the delineating protection zones. Vulnerability assessment of the whole catchment is expressly recommended and often applied for site-specific cases. Vulnerability of drinking water sources in discussed further in the subsequent section of these Technical Guidelines.

A time of travel restriction can provide a useful default zone, provided it is sufficiently long in duration to provide attenuation along the contaminant pathways present. It is important to recognise that the purpose of the protection zone is to provide for contaminant attenuation, rather than simply transport times. A site specific assessment needs to consider the vulnerability of the supply to contamination risks and water resource managers need to ensure more distant sources are appropriately controlled.

3.1 Groundwater protection zones

Delineation methods for groundwater range from fixed distances, simple analytical equations, up to sophisticated numerical groundwater flow models, depending on the level of knowledge of the aquifer system and the significance of the water supply (population served). The time of travel approach is often used to allow a sufficient travel distance for contaminants so that they are attenuated to acceptably low concentrations by the time they reach the water supply intake. Some countries divide source protection areas based upon natural characteristics. For example, several Adriatic countries class their source protection zones based on aquifer type and this method is also used by Environment Canterbury for default zones.

There is a wide diversity of methods used and groundwater protection zone sizes chosen, with varying degrees of accuracy and resource requirements. The range of methods commonly used is summarised in Figure 1 and Table 1, as per PDP and ESR (2005). Further details of application of these methods are provided in Appendix B. There is also a comprehensive review of these methods provided in Moreau et al (2014). However, most recent methods involve the modelling of zones of contribution (ZOC) with TOT distances of up to 25 years, or by undertaking a vulnerability assessment for the whole catchment. The most common analytical approach for defining the zone of contribution and time of travel is included in Appendix A. The differing rates of attenuation of contaminants in different groundwater settings is a likely to in part be the reason for the differently sized protection zones that are used in different countries. Selected examples are presented in Table 2.

The Environment Agency (England) provides an example of an interactive website where the viewer may view various groundwater protection zones for any part of the jurisdiction[4].

[4] The Environment Agency - Groundwater source protection zones interactive map: http://apps.environment-agency.gov.uk/wiyby/37833.aspx

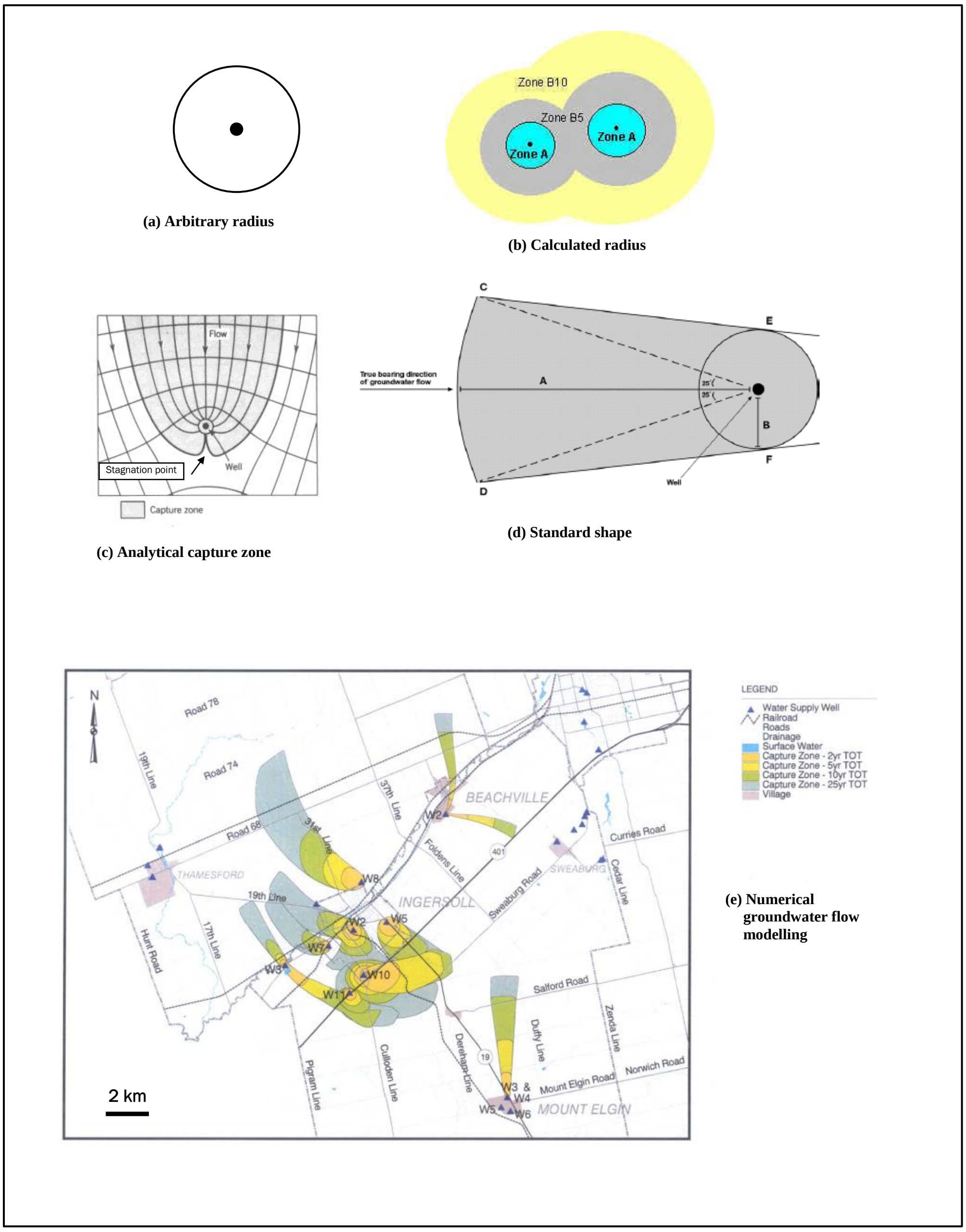


Figure 1: Groundwater protection zone example methods

Table 1: Uncertainty, resource costs and methods of delineating groundwater source protection zones

Assessment uncertainty	Method	Description of method	Advantages	Disadvantages	Relative costs	Estimated time (hours)	Complexity of approach
high	**Arbitrary fixed radius**	Fixed radius circle drawn around abstraction wells – most uncertain.	Easy, inexpensive, quick, requires little expertise.	Heterogeneous and anisotropic conditions make selection of radius problematic. Accuracy uncertain.	Low: large number of wells can be completed in short period.	1	low
	Calculated fixed radius	Drawn circle of specified TOT using analytical method based on abstraction rate. Requires data but completed quickly.	Easy, inexpensive, relatively quick, provides increased accuracy over arbitrary method.	Groundwater flow, heterogeneous and anisotropic conditions can cause inaccuracies in radius calculation.	Low: data requirements make this more expensive than arbitrary fixed radius method.	3 to 5	
	Simplified variable shapes	Derived from hydrogeological and abstraction rate data, orientates shape according to flow direction.	Implementation of shape designation is quick and inexpensive after standard shapes have been developed.	Initial development of standardised shapes is moderately expensive and requires significant data collection, cannot account for parameter variability.	Low: Initial development costs high.	2 to 5 (initial development 200 hours)	
	Analytical methods	Equations used to define flow and contaminant transport, requires hydrogeological data and expertise, most widely used method.	Very accurate if data are available and region lacks hydrogeological complexities.	Results not as accurate as numerical modelling of flow and transport, if there is sufficient information to enable a more complex model.	Medium: Depends on availability of data.	2 to 20	
	Hydrogeological investigations	Requires specialised expertise (geophysics, mapping) and other techniques such as dye tracing, good for small aquifers.	Works well in environments with near-surface flow boundaries, highly anisotropic aquifers that do not respond well to modelling.	Requires high level of expertise and significant data collection over a protracted period. May not work well in deep or large aquifers. Additional calculating of capture zone required following testing.	Medium to high: Depends on availability of data.	> 20	
low	**Flow and transport modelling**	Much input data required, complex modelling expertise required, careful verification, estimation of log reductions.	High potential for accurate boundary designation, incorporates hydrologic boundaries such as streams and parameter variability.	Requires high level of expertise and significant data collection.	High: Depends on complexity of region modelled.	10 to > 100	high

Table 2: Selected examples of groundwater source protection zones (Modified from Table B-1, Appendix B, with NZ examples).

Country	Wellhead protection (inner zone)	Middle zone	Outer zone
	Travel time (days or years) or radius of zone (metres). WC = whole catchment.		
New Zealand (Waikato Regional Council)	30 m	100 day TOT	2 to 5 year TOT
New Zealand (Horizons Region)		Wells < 50 m deep - 500 m radius and 2 km up-gradient (allowance for variation groundwater flow direction) Wells > 50 m deep - 500 m radius	
New Zealand (Greater Wellington)	5 m	1 year TOT	2 year +
New Zealand (Marlborough District)	5 m around the wellhead	Calculated based on TOT/ microbial removal. Up to 200 m radius for confined aquifers, 1 km up-gradient for unconfined aquifers	2 km up-gradient of the wellhead
New Zealand (Environment Canterbury)		Up to 2 km up-gradient, up to 400 m in other direction (ECan)	-
New Zealand (Environment Southland)		250 m up-gradient, to be replaced with site specific zones (one site completed)	-
Australia	50 m	10 years	10 years/WC
Austria	< 10 m	60 days	WC
Canada	Varies (50 days, 100 m)	Varies (2 to 10 year, 5 to 50 years, 0 to 2 years, 2 to 10 years)	Varies (5 years to WC, 10 to 25 years)
Denmark	10 m	60 days or 300 m	10 to 20 years
Germany	10 to 30 m	50 day TOT	WC
Hungary	20 days	6 months	WC including 5 year and 50 year subzones
Netherlands		60 days[5]	
Switzerland	10 m	Individually defined	Double size of middle zone
UK	50 days and 50 m minimum	400 day TOT	WC
United States			
Maine	91 m	200 day TOT	2500 day
Wyoming		200 day/1000 day TOT	WC
Iowa		61 m or 2 years	762 m or 5 years
Oregon		2 to 5 years	10 - 15 years

[5] Schijven and Hassanizadeh (2002) indicate, in the Netherlands, for a 5 to 5.9 log protection against virus contamination by attachment and inactivation, residence times of about three to seven times longer than the current guideline of 60 days are needed, depending on abstraction rates, aquifer thickness and grain size of the aquifer medium.

3.2 Surface water protection zones

There is a wide diversity of methods used and surface water protection zone sizes chosen (Table 3 and Table 4). For surface water protection zones, the whole catchment is often considered, with additional specifically defined zones around the intake or immediately adjacent to the surface water body.

Many jurisdictions use a response time, to allow resource managers to respond to catastrophic spills within an inner protection zone. There are methods whereby the length of this upstream zone is determined on the basis of the mean stream velocity, based on an appropriate response time for the water supply operator. This concept is illustrated in Figure 2. Most jurisdictions, however, use an apparently arbitrary distance that may not allow for attenuation of potential contaminants.

As with groundwater protection zones, several countries use a three zone approach to surface water protection. The Water Framework Directive (2000/60/EC) underpins this three zone approach in Europe. Several countries including Italy, Bosnia and Herzegovina, Croatia and Slovenia distinguish between standing and flowing surface water bodies, defining water protection zones accordingly.

Some schemes employ a middle zone where management of the contributing zone is less stringent than the protection for the intake zone. However, it appears that all schemes employ a whole catchment approach to the outer zone.

Table 3: Selected examples of flowing surface waterway protection zones (Modified from Table B-2, Appendix B, with NZ examples).

Country	Intake protection	Middle zone	Outer zone
	Travel time (hours, days or years) or zone radius (metres), WC = whole catchment		
New Zealand (Horizons Region)		100 m either side of the waterbody, extending 1,000 m upstream and 100 m downstream of the intake point	
New Zealand (Greater Wellington)		100 m wide buffer strip extending for a distance of 8 hours travel time at median flow velocity	
New Zealand (Environment Canterbury)		1000 m upstream, 100 m downstream. 50 m from bed	
New Zealand (Environment Southland)		250 m upstream	
Australia	2 km (No degradation)	(No increased risk)	WC (risk managed)
United States			
California	122 m and 61 m	762 m	WC
Massachusetts	122 m and 61 m	-	WC
South Dakota	16 km upstream and 800 m buffer	40 km radius of intake	WC
Wyoming	30 m radius of intake	24 km upstream or 8 hour flow time	WC
Canada			
British Columbia	Complex	100 m buffer to water body	WC
New Brunswick	Defined watercourse	75 m setback to water body	WC
Albania	10 m radius of intake	200 m upstream and downstream	-

Table 4: Selected examples of lake/standing surface water protection zones (Modified from Table B-2, Appendix B, with NZ examples).[6]

Country	Intake protection	Middle zone	Outer zone
	Travel time (hours, days or years) or zone radius (metres), WC = whole catchment		
New Zealand (Environment Canterbury)		500 m radius from point of take	
Bosnia & Herzegovina	Undefined	50 m setback to water body	Minimum 100 m setback from water body. Additional protection of feed source.
Croatia	10 m radius from water body	100 m radius from water body	WC
Italy	Two zones up to 200 m from water body		Expert judgement
Slovenia	100 m radius from intake	20 day TOT to intake	WC

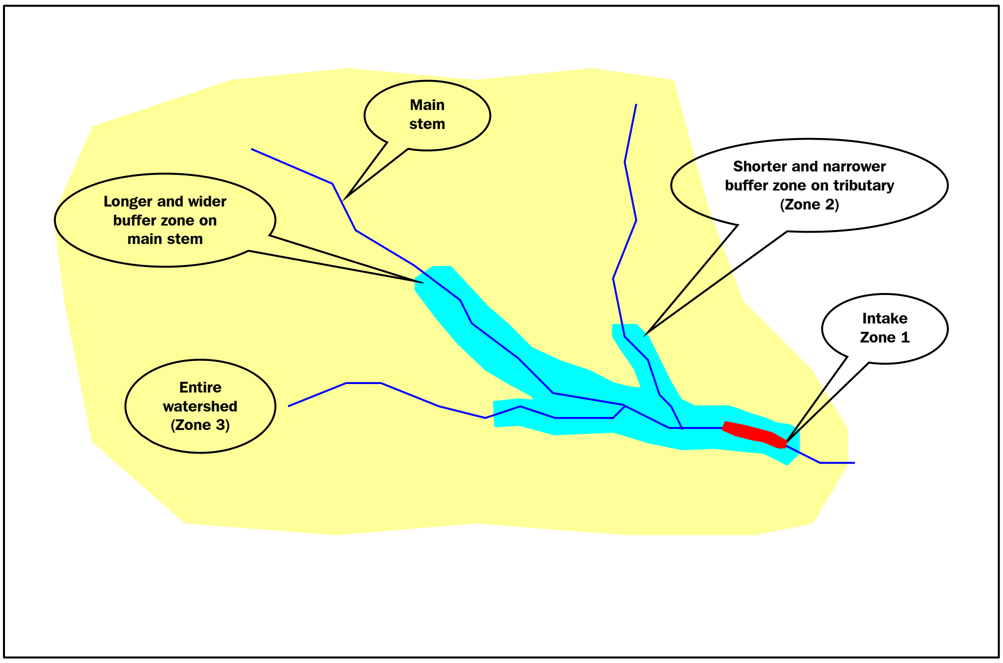


Figure 2: Surface water zone example method (tributary zones shorter due to lower flow velocity)

[6] Specific controls are also applied in catchments of dammed drinking water supply reservoirs by many water suppliers, e.g. Nelson City Council.

3.3 Conjunctive protection zones

While literature advocating the need for conjunctive management involving combined use of surface and groundwater resources was found, there were limited examples encountered of applied protection zones for conjunctive situations.

3.4 Conclusions from literature review

The following conclusions have been reached as a result of the literature review.

- The delineation of groundwater protection zones has become more rigorous with time, with the result that the preferred delineation method currently appears to be an analytical approach, or by numerical modelling for groundwater sources.
- Methods of delineation for groundwater protection zones vary from arbitrary fixed radius and distance systems to numerical modelling (Table 2). Different methods involve very different data and resource requirements. The 'time of travel' method is the most commonly applied approach within existing regulatory tools.
- For groundwater protection, few jurisdictions specifically justify their choice of time of groundwater travel distances in terms of contaminant attenuation, the type of groundwater protection that they desire, or the risks they wish to reduce. This may explain why there appears to be a general lack of examples of jurisdictions that have formally undertaken or published a risk analysis of the contaminant hazards.
- For surface water protection, there is a strong tendency for the delineation of surface water protection zones where part or all of the catchment is anticipated or controlled, but with special attention to zones around the intake or immediately adjacent to the surface water body (Table 3, Table 4).
- Delineation of conjunctive source protection zones appears to be not commonly addressed in a rigorous, quantitative manner. A procedure for delineation of conjunctive source protection zones will need to rely on the corresponding surface water and groundwater methods.

Overall, the factors used to delineate drinking water source protection zones include geology, topography, climate, water budget, time of travel, contaminant attenuation and overland flow (summarised in Table 5).

Table 5: Common factors considered in source protection zone delineation

Resource type	Approach	Knowledge required
Groundwater	Time of travel	Hydraulic conductivity Hydraulic gradient Average pumping rate Aquifer porosity Contributing flow area to a well and flow direction
	Contaminant attenuation	Contaminant transport and attenuation parameters
Surface water	Time of travel	Velocity and dispersion characteristics
	Dilution	Flow contributions and waterway morphology within a catchment
	Buffer zones	Overland flow pathways and relative contributions
	Contaminant attenuation	Contaminant transport and attenuation parameters

These factors can be applied to consider risks to water supplies posed by different contaminant types, which in turn can form the basis of defining appropriate drinking water source protection zones for New Zealand.

Water supply management (and drinking water supply source protection zone definition) should follow a risk-based assessment approach. These matters are discussed further in Section 4.

4.0 Principles of drinking water source protection zones

This section introduces the concept of source protection zones as a means of protecting the water source from contamination. The size and shape of source protection zones should be related to their ability to achieve attenuation of contaminants prior to abstraction of water at an intake.

4.1 Contaminant types and supply vulnerability

Prior to describing the delineation of source protection zones around drinking water supply intakes, it is first necessary to consider the contaminants likely to be present in a water supply catchment area and the land uses that produce them. The risk and nature of contamination differs under different land uses. Table 6 outlines the types of contaminants that should be considered in the assessment of potential contaminant migration towards water supply intakes. These are categorised into three groups:

- pathogenic micro-organisms (Priority 1 and 2d determinands in the DWSNZ) and associated compounds (Priority 2b determinands)
- point source generated compounds (Priority 2b determinands)
- non - point source compounds (Priority 2b determinands).

The vulnerability of a public drinking water supply intake is a measure of the risk that contaminated water might enter it. The process of source protection zone delineation outlines areas in which activities are best regulated in order to reduce the risk of direct contamination, or to allow attenuation to reduce the risk of contaminated water reaching an intake. Examples of contaminant sources, pathways and levels of intake vulnerability are provided in Table 7.

Within the delineated source protection zones, planning tools can also enable warning of an actual or a proposed event, and keep the public and stakeholders informed (e.g. water supply managers, regional councils).

The size of a delineated source protection zone should be dependent upon the vulnerability of a water intake or intakes. Greater distances, expressed also as travel times, provide for greater attenuation by natural processes that are the primary means of defence available to intakes.

Table 6: Contaminant types and typical contaminants

Contaminant class	Example contaminants	Persistence	Toxicity – effects	Ease of entry & typical medium
Pathogenic micro-organisms and associated compounds	Micro-organisms	Variable, but generally less than 1 year	Very high: Immediate human health effects	High: entrained in water but die-off occurs
	Cyanotoxins	Persistent during blooms in surface water bodies	Very high: Immediate human health effects	Released during growth of cyanobacteria
	Suspended sediment	-	Low, but reduces effectiveness of disinfection	High: entrained in flowing water
Point source generated compounds	Solvents	DNAPL, miscible, decays	Carcinogenic: Human health and odour effects	High: highly mobile DNAPL, some with low solubility
	Petroleum hydrocarbons	Miscible and poorly soluble petroleum product, LNAPL	Carcinogenic: Human health and odour effects	High: highly mobile LNAPL
	Pesticide and related compounds	Slightly soluble, high persistence	High: Insidious or long term effects	Slow transport but many sources
	Dissolved metals	Dissolved metals, acids, alkalies, highly mobile except in carbonaceous or clay-rich materials	Low, Medium & High: Insidious or long term effects	Variable: highly soluble liquids and solids to poorly soluble powders
	Emerging contaminants	Some emerging contaminants such as PFAS are highly persistent.	Low, Medium & High: Insidious or long term effects	Variable
Non-point source compounds	Nitrate nitrogen (may include dispersed sources of point source generated compounds)	Highly soluble - agricultural leachate, silage leachate, animal waste, fertiliser, effluent.	Low when <11 mg/L Medium at higher concentrations	High: highly mobile dissolved ions

Table 7: Vulnerability analysis of common contaminant pathways to intakes

Intake / resource type	Hazards	Potential pathways	Vulnerability	Comments
Groundwater	Land use activities/ discharges to land	Through soil into aquifer	Medium	Multi-process attenuation of contaminant through unsaturated zone and then during sub-surface flow within aquifer
	Accidental spills	Through soil into aquifer	Low	
		Directly into aquifer	Medium to high	Where soil absent or removed; attenuation of contaminant through unsaturated zone and then during sub-surface flow within aquifer. Also applies to direct discharges.
Surface water	Land use activities/ discharges	Through soil into waterway	Medium	Multi-process attenuation of contaminant through plant uptake, soil and unsaturated zone adsorption, sub-surface flow towards waterway
		Along surface into waterway	Medium to high	Attenuation by dilution, dispersion and degradation, affected by topography, vegetative cover, drainage density, soil type and rainfall intensity
		Direct deposition into surface water	High	Attenuation by dispersion, dilution and degradation
	Accidental spills	Through soil into waterway	Low	Multi-process attenuation of contaminant through plant-uptake, soil and unsaturated zone adsorption, and sub-surface flow towards waterway
		Along surface into waterway, or direct deposition into surface water	Low to medium	Attenuation by dilution and degradation, affected by topography, soil type and rainfall intensity and surface flow conditions

4.2 Source – pathway – receptor

The concept of source-pathway-receptor is a method for evaluating contamination risks. It is based on identifying:

- the source of contamination
- the receptor that may be adversely affected by the contamination
- the pathway that allows the contaminant to reach the receptor.

For the purposes of this report, the relevant receptor is a water supply intake. For a risk to be present, all three components (i.e. source, pathway and receptor) must be present. A method for managing contamination risks is to eliminate one of these three components – or to make the pathway between source and receptor contain sufficient barriers that the risk of an adverse effect is acceptably low.

Defining a drinking water source protection zone involves setting an area within which risks to a water supply receptor from contaminant sources are identified and appropriately managed. The size and shape of the zone recognises the characteristics of migration pathways that occur over the land, through surface water and through the subsurface environment.

In zones where the pathway to the receptor is direct, with very little opportunity for attenuation there must be rigorous controls on potential sources of contamination. However, in more distant zones sources of contamination may require less rigorous controlled because the pathway between source and receptor is not so direct and there is significant attenuation that occurs along the travel path. Therefore, the definition of drinking water source protection zones for land management purposes requires an understanding of the attenuation that occurs as contaminants move through both surface and subsurface pathways.

4.3 Contaminant attenuation

Contaminants become attenuated during transport as a result of a range of processes, particularly:

- dispersion and dilution
- filtration, adsorption and sedimentation
- bio-degradation and chemical transformation
- evaporation
- die-off.

These attenuation processes act in concert, producing a range of concentration reductions. For microbes in particular, these are often expressed in terms of the logarithm of the reduction (e.g. 1 log reduction is a ten-fold concentration reduction).

Appendix C presents examples of natural attenuation to indicate the effect of various processes that operate to reduce contaminant concentrations to acceptable levels prior to a water supply intake point.

Based on the review of micro-organisms in Appendix C, it is clear that there are large differences in the attenuation that can be achieved in different hydrogeological settings, and that the log reduction required varies with different sources and pathogens. In terms of time of travel (TOT), the setback distances equate to travel times of around 1 – 2 years. Literature on specific inactivation rates, leaving aside other attenuation processes, indicates most microbes are unlikely to survive in groundwater for more than 1 year, or 2 years at most. Many microbes die-off to non-infective concentrations/states within a matter of days to weeks.

When factored in with filtration, dispersion and other attenuation processes, it is considered that a 1 year travel time is long enough to allow for sufficient microbial attenuation in most settings. However, it is important that the 1 year travel time allows for preferential pathways, such as occur in settings such as alluvial systems, karst or fractured rock.

4.4 Recommended source protection zones

Based on the literature review (Section 2 and Appendix B) and the consideration of attenuation mechanisms it is suggested that three types of source protection zones should be delineated for every water supply intake. Different management controls would apply for each zone. The exact controls for activities will be determined by regional councils and water suppliers, in consultation with affected land users and the wider community. However, the following notes provide an example of the type of land use control that could be applied:

- **Intake/Wellhead Protection Zone (Zone 1)**
  This zone would define the area where contaminants could directly enter the intake. It is a zone that could be fenced off to prevent access by animals (stock) and unauthorised personnel. Direct sources of contamination such as fuel or chemical storage that could pose a risk to the supply and discharges of other contaminants should be prohibited in this area.

- **Intermediate Zone/Microbial Source Protection Zone (Zone 2)**
  This zone would define the area where contaminants could reach the water intake, indirectly, at concentrations high enough to cause adverse effects, from land use activities, specific point discharges, such as wastewater and stormwater discharges, and spillages from chemical storage facilities. These activities would therefore require strict control

and monitoring within the intermediate zone. These controls would be imposed through the consideration of resource consents and permitted activity rules.

The size of Zone 2, for groundwater supplies especially, is designed primarily for the attenuation of point source pathogenic micro-organisms (Priority 1 and 2d determinands in the DWSNZ) but also offers ancillary protection through attenuation of other contaminants such as petroleum hydrocarbons (Priority 2 b determinands). While it would be unrealistic to achieve no pathogenic micro-organisms in most surface water sources, due to natural sources such as birds, the aim of management within this zone should be to limit activities which could increase the concentration of microbial organisms, to reduce the risk to public health if a failure of the treatment system were to occur.

Careful control of land use activities that contribute non-point contamination sources is required within this intermediate zone. For example, irrigated agricultural activity and stock numbers may need to be controlled.

For groundwater supplies, the management of other wells within Zone 2, and potentially over a wider area, is of great importance. If these are not properly constructed, operated and maintained, there is a risk they could create a rapid pathway for contaminants to reach a drinking water source that by-passes the attenuating characteristics provided by soil and strata. The one year time of travel calculations for Zone 2 will not usually consider pathways via wells, so it is very important that well construction, operation and maintenance is controlled both within and beyond Zone 2. This could be achieved via a rewording of the Drinking Water NES, regional council controls and changes to the NZS 4411[7] and other regulations. The Government Inquiry into Havelock North Drinking Water suggested changes to such documents to achieve this[8]. It is noted that some jurisdictions include additional zones to address wells that provide a direct pathway through confining layers, such as the Environment Agency (England).

In surface waterways, activities that could lead to an increase in turbidity, such as logging, weed removal and earthworks should also be carefully controlled, to avoid adverse effects on the treatment process.

The presence of preferential pathways is a very important consideration for Zone 2.

[7] New Zealand Standard 4411:2001 Environmental Standard for Drilling of Soil and Rock

- **Whole Catchment Zone (Zone 3)**
  A third, wider zone would define where general land use activities, large point source discharges or cumulative effects from smaller point sources could impact on the quality of the water supply at the intake.

  Large discharges, such as those from sewage treatment works or large industrial activities will be controlled by conditions on discharge permits. It is important that the consenting process for such activities takes into consideration the presence of the water supply intake.

  More general land use activities would relate to nitrate concentrations arising from irrigated and non-irrigated agriculture. Limitations on such activities may be required within the wider catchment of a drinking water intake.

  It is acknowledged that most regional councils are already managing for cumulative effects within surface water catchments and groundwater catchments and recharge zones to avoid general declines in water quality. Specific contaminants that could impact on drinking water supplies will require careful consideration in this outer zone, for example chemicals that may be highly persistent or toxic at very small concentrations (such as PFAS) as well as cumulative effects from more common contaminants such as nitrate.

5.0 Default source protection zone delineation

The review of source protection zone delineation literature in Section 3.0 and the technical basis for using attenuation as the mechanism for controlling contaminant concentrations at an intake, outlined in Section 4.0, is used to show how source protection zones may be delineated for surface water, groundwater, and conjunctive catchments.

Default source protection zones are described here with a view for possible inclusion as a spatial criterion in the Drinking Water NES. Site specific approaches should ultimately be used to modify source protection zone size where resources allow (Section 6.0).

Other relevant organisations may also opt to use the default zones, or alternatively, choose to use one of a variety of site-specific options, to better suit their local situation. Site-specific methods of delineation may be costly in terms of the data requirements and human resources, but will result in a more accurate zone that does not unnecessarily restrict activities in the wider area. However, where site-specific data regarding attenuation are absent or are not clearly understood, then it is recommended that the default source protection zones be used.

The three zone approach is proposed, based on international practice and on the need for different degrees of management within the area up-gradient or upstream of an intake. This is similar to the approach currently used by Greater Wellington, and the recommended zones are similar.

5.1 Surface water protection zones

5.1.1 Intake zone (Zone 1)

Zone 1 is proposed to reduce the risk of direct discharge of contaminants into the surface water body by allowing a mixing zone up-stream of the intake, and allowing a small response time buffer, but this is dependent upon immediate reporting of incidents by those involved.

It is proposed that the intake is protected by a strip expanding 5 m landward from the water’s edge, or a larger zone of at least 30 m where this can be achieved in a practical manner, for a distance of 1000 m upstream and 100 m downstream. The justification for the 1000 m mixing zone setback is that calculations of mixing zone distances are in this order of magnitude.

Although formulae can be used to determine the minimum length of surface flow over which full mixing of a contaminant might be expected to occur (e.g. Chin 2000), these require precise, site-specific data. Examples using site-specific data indicate that a generic 1000 m mixing zone length is probably sufficient except in slow-moving rivers that lack turbulence. The 5 to 30 m (or more where practical) width of Zone 1 is analogous to the exclusion zone proposed for groundwater intakes in that it aims to prevent discharges directly into the surface waterway.

For a lake, it is recommended that a 500 m radius around an intake point apply together with a 5 m landward strip from the water's edge, or a larger zone of at least 30 m where this can be achieved in a practical manner.

5.1.2 Surface water intermediate zone delineation (Zone 2)

It is proposed that a long buffer zone, representing an intermediate zone, be used to allow for considerable attenuation by dilution and dispersion within the flowing water body, and some attenuation across and within the unsaturated and saturated zone underlying the buffer strip of land either side of the waterway.

This intermediate source protection zone consists of a buffer strip along the water course for a distance equivalent to 8 hours median water travel time upstream of the intake (approximately 25 km for a river flowing at slightly less than one metre per second) and 100 m downstream of the intake. The recommended width of the buffer strip is 100 m and is based on a consideration of two factors: typical surface slope towards the river and the general ability of land within a buffer to absorb and transmit contaminants to an adjacent waterway.

It is considered that an 8 hour travel time should allow sufficient time for water suppliers and other organisations to be notified in the event of a spill that could pose a risk to the supply, with appropriate procedures in place.

For lakes, it is suggested that the whole lake is included in Zone 2, with an 8 hour travel time applied to tributaries and a 100 m strip around the lake and tributaries.

5.1.3 Whole catchment zone (Zone 3)

It is considered appropriate to delineate entire catchments upstream of a point 100 m downstream of the water supply intake to recognise that there is a water supply intake downstream of any activity. There may not be specific management rules related to activities in this zone but it would be important that permitted activities are authorised on the basis of being of low risk to a drinking water supply and that the effects of all consented activities on the water supply or supplies are appropriately considered.

5.2 Groundwater source protection zones

5.2.1 Well head protection required at groundwater intakes (Zone 1)

The purpose of a well head protection zone is to reduce the risk of contamination via the well casing, and within a zone of disturbed strata adjacent to the casing.

It does this by facilitating attenuation of any contaminants discharged within this zone.

For groundwater intakes, a minimum well head protection area with a 5 m radius is proposed. Where practical, the zone could be extended out to 30 m. Ideally, this intake zone should be owned and managed by the water supplier. In this zone, desirable activities should only be those related to water supply, and storage of chemicals that would pose a risk to the supply should be prohibited (storage of chemicals related to treatment may be required within this zone).

This zone is defined on the basis that the groundwater supply is drawn from a properly constructed and sited well to avoid rainwater and floodwaters from directly entering the well casing.

The reasons for the delineation of this zone are to ensure that the well head integrity and the sanitary seal around the well casing are not the only barriers in place.

5.2.2 Groundwater microbial source protection zone delineation (Zone 2)

As a general guideline, the purpose of this zone would be to provide sufficient pathogenic micro-organism contaminant attenuation within the aquifer and also offer ancillary protection through attenuation of other compounds. Within this zone, other contaminants discharged at surface may reach the intake, but at acceptable concentrations providing that discharges are maintained to a high standard and land uses well controlled. The Drinking Water Standards for New Zealand 2005 require at least 5 log cycle reduction in the concentration of protozoa for water that is considered ‘high’ risk’ (Table 5.1: DWSNZ 2005). As described in Appendix C, viruses are expected to require a much greater log reduction.

It is recommended that the extent of Zone 2 should be defined by a one year time of travel (TOT) to achieve the microbial attenuation set out above and in Appendix C, with a maximum default up-gradient distance of 2.5 km based on the maximum distance for virus attenuation in Blaschke (2016). At a minimum, the method used for that outlined in Appendix A should be used, with a consideration of variations in flow velocity, particulate in relation to preferential flow pathways. Where no flow direction or velocity information is available, a circle with a radius of 2.5 km should be applied.

The influence of a confining layer on the size and shape of Zones 2 and 3 is a site-specific issue. In general, the presence of a confining layer needs to be confirmed with drillers’ logs and/or appropriately designed pumping tests, in order that the degree of confinement may be assessed, together with the extent and integrity of that confining layer. In some particular circumstances, such as deep confined aquifers with low permeability overlying strata, it may take more than 1 year for contaminants to travel both horizontally from the recharge zone and vertically from the land surface (which may not even be possible with strong upwards piezometric gradient unless this is reversed).

The 1 year travel calculations for confined aquifers might result in a situation where there is a smaller zone around the well itself and a larger microbial protection zone in a separate recharge zone, if a well is located beneath a confining layer with limited up-gradient extent.

However, consideration should also be given to the potential short circuiting through the confining layer or layers created by other wells, excavations and building foundations. In any sized zone, consideration of controls on penetrations of a confining layer over an appropriate area is very important.

5.2.3 Total up-gradient catchment (Zone 3)

For most groundwater intakes, Zone 3 should extend out as far as the ultimate boundary of the capture zone, or catchment. In groundwater catchments with slow-moving flows, consideration may be given to limiting the extent of a site-specific Zone 3 to a 10 year to 50 year isochrone. However, it is considered best that no limits are defined to provide on-going, long term protection to sources of drinking water.

Within an entire groundwater catchment, outside the delineated Zone 2, permitted and consented activities that could affect the water supply should be controlled by regional plans, taking into account the groundwater characteristics for each area.

5.3 Conjunctive sources

The term ‘conjunctive’ relates to situations where both hydraulically-connected groundwater and surface water are drawn into an intake.

Where public drinking water supplies abstract water that is a combination of groundwater and surface water such as a gallery or a well receiving water from an adjacent surface water source, then source protection zones will be required for each component as if each were a single source. The same would apply for a surface water take from a waterway that receives significant groundwater inflows, for example a spring.

Conjunctive source protection zones should include the recommended zones around the respective surface water and groundwater components to provide sufficient protection and allow for a timely response in the event of contaminating event. It is proposed that calculation of the zones of protection for each portion of the resource is done irrespective of how much water comes from each source. The respective default methods for source protection delineation recommended should be applied to both resources.

5.4 Source Protection zones and existing uses

The proposed source protection zones are likely to include existing activities that pose a risk to groundwater which may not comply with the management measures that are determined for that zone. Consideration will be required on which management measures will be used and whether they will be applied retrospectively to all land uses or other activities.

However, it is noted that the current definition in the Drinking Water NES of ‘upstream’ of a drinking water source implicitly defines a large zone representing the entire catchment or capture zone, which is equivalent to Zone 3 that is being proposed in these Technical Guidelines.

6.0 Site-specific source protection zone delineation

In Section 5.0, default methods for delineating source protection zones are proposed for use where available data or resources do not permit site-specific analyses to be undertaken.

This section considers factors that can be used to modify the size of generic source protection zones. These include a risk analysis and site-specific measurements of attenuation characteristics such as those provided by tracer tests, hydrological parameters such as those defined from aquifer testing, groundwater age determinations and the monitoring of groundwater quality and its variability.

The details of how these site-specific delineations should be carried out are specific to each zone and require input from people with a sound knowledge of groundwater and surface water environments to make an expert judgement on the work required.

There will always be a trade-off between the size of the source protection zone and the control of land use activities within the zone. The zone needs to be sufficiently sized to appropriately minimise the risks to the supply, without being too large to unnecessarily restrict activities or impose undue time and costs to persons undertaking those activities.

For groundwater, within Zones 2 and 3 there may need to be special zones in which a higher or lower level of management could be required as a result of variability in aquifer confinement, recharge sources, upward hydraulic gradients (artesian), land use and other factors.

Definition of the default source protection zone criteria for each individual water intake based on standard definitions will ideally be carried out via cooperation of the water supply controlling authority and/or the regional council for the area. However, initiatives to define more site-specific zones may also come from other parties, including users of land who wish to carry out specific activities that may be inconsistent with the defined source protection zone controls.

6.1 Risk analysis

An analytical approach to risk analysis may be used to determine the probability and consequences of the occurrence of specific hazards that could impact on water quality. Such hazards might include the risk of chemical spillage, the failure of on-site wastewater treatment systems, volcanic debris contaminating surface waters, floods and earthquakes changing contaminant pathways as identified in the Government Inquiry into Havelock North Drinking Water, traffic or rail incidents (Lacey & Cole 2003), or turbidity associated with deforestation or flooding (Hicks et al. 2004). Risk analysis may be used to suggest appropriate modification of a generic delineation scheme for a specific site.

6.2 Site specific groundwater protection zones

The geology of a catchment has a direct and strong relationship with the attenuating characteristics of the materials through which groundwater flows towards an intake. Groundwater flow in consolidated rock is commonly by way of fractures within which attenuation may occur by various mechanisms, but if the fractures are wide, as in karstic carbonate rocks, then the protection afforded by attenuation may be lost.

The specific methods that can be used for groundwater protection zones are outlined in Table 1 in Section 3.1 and described in more detail in Appendix B. These are also covered in Moreau et al. (2014).

Factors to be used for modifying a default source protection zone delineation to a site-specific one would include aspects of: soil and underlying strata grain size and mineralogy; aquifer anisotropy, and heterogeneity (including the potential for preferential flow paths); rock fracture width and spacing; rock and soil chemistry; depth to water table; groundwater flow direction and magnitude (including vertical flow direction); hydraulic conductivity and storage properties; the presence, or not, and extent of confining layers and their ability to transmit water and characteristic land use within the catchment.

Confining layers may significantly reduce the need for source protection zones 2, or require a smaller zone, dependent on their thickness, conductivity and lateral continuity. A site specific assessment for a confined aquifer should consider whether the pumping may reverse an upwards gradient, and allow for this in attenuation calculations. Aquifer testing that provides information on both vertical and horizontal flow within the system can be very useful in supporting these calculations.

Where the rate of pumping varies throughout the year, the calculated capture zone should be based ideally on the peak demand periods, or alternatively be allowed for in numerical modelling, or suitable alternative.

Pumping interference effects need to be accounted for, particularly where there is more than one supply well, or nearby wells with significant pumping.

Potential pathways from both the land surface surrounding the intake, as well as pathways from more distant recharge areas need to be considered and contaminant attenuation calculations undertaken.

It is important to consider the possibility of preferential pathways that allow groundwater to move faster than on average, for example in paleo channels, karst systems and fractured rock. While fast moving flow can provide significantly higher dilution, it can allow microbial pathogens and other contaminants to move more quickly through the system. These pathways have been identified from tracer tests over several decades around the country, including Hawke’s Bay and Canterbury with velocities of more than 200 m/day, but the Havelock North 2016 event provided a real example of how these pathways can provide for rapid contaminant transport.

For some sites, it may even be appropriate to undertake tracer tests. Tracer tests may be used to characterise the attenuation characteristics of non-conservative (benign bacteria), and conservative tracers (e.g. rhodamine, bromide, nickel-EDTA). Once the character of the groundwater body is known, site specific attenuation factors may be applied.

Monitoring of water quality and its variability may be used to determine the response to changing land uses, changing climate, and contaminating incidents. These responses are reflected in the statistics of the water quality and may then be used to determine the vulnerability of an intake to such changes. This is discussed further in the following section.

Groundwater age determination may also be used to assist a site-specific delineation, but as with all groundwater data, a clear understanding of the uncertainty with this is required. This is specifically outlined in the following section.

6.2.1 Age determination

Groundwater age refers to the time taken from when water enters the subsurface environment to travel through the groundwater system to a point where it can be sampled at a well. Any groundwater drawn from a well is made up of a distribution of water molecules of different ages, reflecting the varying travel pathways that the water has taken to reach the well.

The determination of groundwater age based on measurements of the concentration of tritium, chlorofluorocarbon and sulphur hexafluoride has become a popular means of assessing the risk of microbial contamination to a groundwater supply. This is because it is currently specified in the DWSNZ as a means of determining that a well is not directly affected by surface or climatic influences (bore water security criterion 1 in DWSNZ).

Water age determinations provide the most clear-cut means of meeting that criterion compared to the other options specified in the DWSNZ. If less than 0.005% of the water has been present in the aquifer for less than one year it is considered to comply with criterion 1.

GNS carry out analyses of tritium, chlorofluorocarbon and sulphur hexafluoride and report the mean residence time of the groundwater sample and whether or not the water less than one year old comprises less than 0.005% of the sample. However, in some instances this has been shown to not be a reliable method to avoid the risk of microbial contamination. Most notably this occurred in the August 2016 outbreak of gastroenteritis at Havelock North where the contaminated well was deemed to have been a secure water source, in part due to water age assessments undertaken in 2001 and 2011.

Callander et al. (2014) report other instances within New Zealand where groundwater sources were also deemed to be secure, in part due to water age assessments, but were subsequently found to show elevated E.coli detections.

The inaccuracy in the water age determinations is considered to be primarily due to:

- The analysis of water age distribution relies on very simple mixing models that do not reflect the heterogeneity of groundwater flow processes that exist in many groundwater systems.
- The recharge pattern of groundwater to a well will vary throughout the year. A discrete sample taken at a particular time will not reflect this variability in water age and may not occur at a time when the greatest proportion of young water may be reaching the well. Examples of situations when a greater proportion of young water (and microbial contaminants) may enter a well are:
  - during extreme rainfall events
  - due to excavation activities that allow rainfall or overland flow to breach protective soil and low permeability confining layers to reach a well intake screen much faster than would otherwise have been the case
  - the diversion of surface waterways or stormwater to allow surface water to infiltrate closer to a water supply well.
- The various compounds used to determine groundwater age may not give a consistent age and/or may be contaminated by human processes.

All these factors can lead to misleading conclusions being reached about the distribution of water ages at a particular well. For that reason it is considered that the prominence given to groundwater age (residence time) in the DWSNZ by the analysis of tritium, chlorofluorocarbon and sulphur hexafluoride is unhelpful and does not provide the certainty that is required for determining the robustness of a natural barrier to contamination.

Analyses of groundwater age can still provide a useful indication of the behaviour of a groundwater system, but should be judged alongside a conceptual understanding of the groundwater system and a monitoring history of indicators of surface influences including *E. coli*, total coliforms, nitrate, chloride and electrical conductivity. This monitoring information should be evaluated taking into consideration the timing of the sampling relative to significant recharge events and the potential risks created by excavations, overland flow or other activities (transient or permanent) that may influence groundwater movement towards a well.

Water-age determinations should not be given prominence over these other sources of information. Rather, all these sources of information are best considered together to determine the appropriate judgement about the robustness of the natural barriers to protect the groundwater source from contamination. Historical monitoring data and the conceptual hydrogeological understanding can be used to contribute to the site specific assessments of the source protection zones around groundwater community drinking-water wells.

6.3 Site specific surface water protection zones

For a surface water take, factors to be used for modifying a default source protection zone delineation to a site-specific one would include catchment properties such as climatic factors; topography; infiltration capacity of soil; rainfall/runoff correlation; mean flow; base flow evaluation; time of concentration[9]; potential for sediment removal; longitudinal dispersion characteristics of the water body up-stream of the intake; degree of dilution upstream of an intake; characteristic land use within the catchment and ease of direct access to water body.

Run-of-river reservoirs up-gradient of surface water intakes cannot be 'closed' against a contaminant flux but have the redeeming feature of being a substantial attenuating mechanism by dilution. In cases where the reservoir is not run-of-river, then it may be closed off until the contamination has passed.

Monitoring of water quality and its variability in response to events may also be useful to assist in assessing the vulnerability of an intake to such changes

6.4 Site specific conjunctive zones

Where groundwater and surface water interaction is occurring upstream or up-gradient of the supply, specific investigations to better understand the degree of interaction may be required. This could consist of water quality and level monitoring, general piezometric surveys, pumping tests designed to assess the interaction, measurements of groundwater and surface water level differences across of range of conditions including floods, and tracer tests.

[9] After a precipitation event, the time for water to flow through stream channels to the water supply intake.

7.0 Delineation flow charts

This section outlines the data requirements for default source protection zone delineation, and uses examples to show how delineation is carried out.

Theoretical example delineations based on the recommendations in the table below are provided in Appendix D.

7.1 Surface Water Zones

The process of delineating source protection zones for surface water intakes includes three principal steps, the results of which are specifications, preferably in the form of a map, for three zones as laid out in Figure 3.

- Intake zone (Zone 1)
- Intermediate source protection zone (Zone 2)
- The entire upstream catchment (Zone 3)

For this process, the information required is:

- an accurate map of all contributing surface water features
- an estimate of median surface water flow velocity, including for tributaries
- the upstream catchment watershed (boundary) (extending to a point 100 m downstream of the intake).

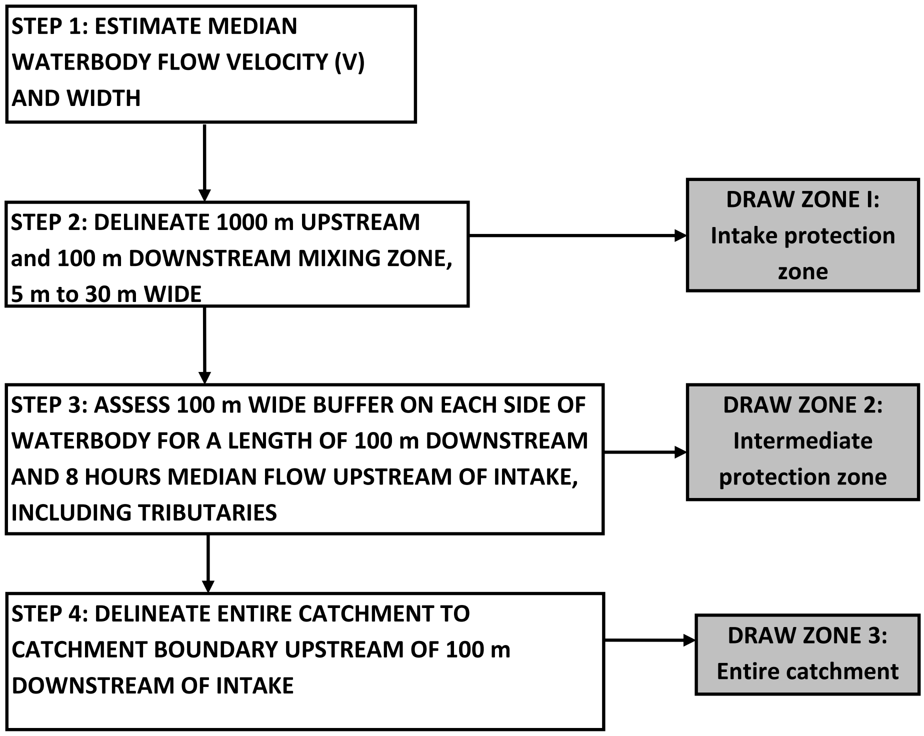


Figure 3: Default surface water source protection zone delineation process

7.2 Groundwater Zones

The process of delineating source protection zones for groundwater intakes includes three principal steps, the results of which are specifications, preferably in the form of a map, for three zones as laid out in Figure 4.

- Intake zone (Zone 1)
- Microbial source protection zone (Zone 2)
- The entire upstream catchment (Zone 3)

For this process, the information required is an estimate of:

- groundwater flow direction and uncertainty in direction
- hydraulic conductivity of the aquifer
- horizontal hydraulic gradient
- effective aquifer porosity
- mean long-term abstraction pumping rate
- composition and extent of low permeability confining strata and vertical gradients
- estimate of flow velocities through preferential pathways.

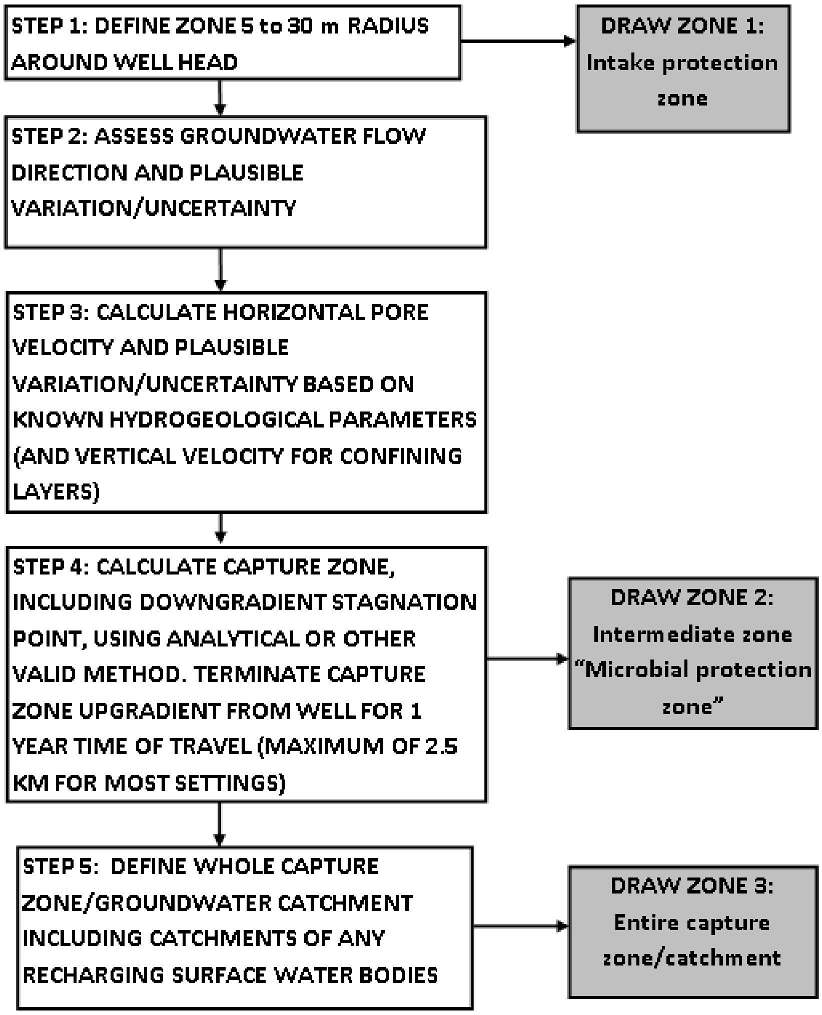


Figure 4: Default groundwater source protection zone delineation process

7.3 Conjunctive zones

As outlined previously, the term 'conjunctive' relates to situations where both hydraulically-connected groundwater and surface water are drawn into an intake. Where public drinking water supplies abstract water that is a combination of groundwater and surface water such as a gallery or a well that is receiving water from an adjacent surface water source, then source protection zones should be delineated for each component as if each were a single source using the above methods. In this case, there will be overlapping of the groundwater and surface water zones and these should first be defined separately.

7.4 Example delineations

Two delineation examples are described: one surface water and one groundwater. The examples use real data, but are not identified.

Groundwater example

- groundwater flow direction: towards 120°
- hydraulic conductivity of the aquifer: 0.001 m/s
- saturated thickness of the aquifer: 15 m
- horizontal hydraulic gradient: 0.003
- effective aquifer porosity: 0.2
- mean long-term abstraction pumping rate: 50 L/s
- preferential flow velocity (determined from tracer test): 50 m/day

Calculated distance for 1 year time of travel for average flow = 475 m

Calculated distance for 1 year time of travel through preferred flow paths at 50 m per day = 18.25 km (therefore, use maximum default distance of 2.5 km)

Calculated stagnation point = 177 m down-gradient from well

The calculated zones are as follows.

Zone 1: 30 m radius around well head

Zone 2: 177 m down-gradient; and a half-width of 280 m across gradient at the well extending 2.5 km up-gradient

Zone 3: 177 m down-gradient and a half-width of 280 m across gradient at the well extending to the up-gradient extent of the recharge zone.

The zone shapes calculated above are then broadened to allow for uncertainty in the flow direction and the downstream stagnation point, based on a broad and conservative hydrogeological judgement.

Surface water example

- median surface water flow velocity in river: 1 m/s
- location of the catchment basin boundary: 289 km upstream of intake
- area of the catchment basin: 18 650 km^2

Zone 1 intake protection is 1000 m by 30 m wide on both sides of the river

Zone 2 buffer strip is 8 hours at 1 m/s = 28.8 km long by 100 m width on both sides of the river

Zone 3 catchment is entire land area within catchment extending from a point 100 m downstream of the intake point

8.0 Conclusions

The definition of drinking-water source protection zones provides a context for considering management methods within these zones. These could include the use of planning rules for activities that may affect the quality of the source water at water supply intakes. Different default source protection zones have been defined, in recognition of two key mechanisms that help in the effective management of water supplies.

- The ability to respond to a contamination incident – i.e. the further away an incident occurs, the greater the time available to implement some avoidance or mitigation measure.
- The longer the travel path between a source of contamination and the water supply intake, the greater the natural attenuation of contaminants that occurs along that pathway.

Taking these factors into consideration, a three tiered approach to default source protection zones has been recommended to address both Priority 1 and 2 determinands in the DWSNZ. These could be considered for use as a spatial criterion within the NES.

Site specific investigations can be used to define alternative zones based upon an analysis of contamination risk, travel times and natural attenuation, taking into account the likely pathways of potential contaminants.

The most rigorous scrutiny of controls and management of activities is likely to occur in Zones 1 and 2, with a more general consideration in Zone 3. However, consideration of effects on water supply intakes from authorised activities and other hazards should apply in all three zones.

9.0 Glossary

Term / Acronym	Meaning
Absorption	Incorporation of a particle or molecule within a material
Adsorption	Adherence of particles or molecules to a material surface such as the surface of particles that make up the matrix of a groundwater system (e.g. gravel, sand, silt, clay)
Analytical model	Mathematical model of water flow and/or contaminant concentration by means of formulae. These models cannot easily take into account spatial variability of the medium in which the flow is occurring, although a sensitivity analysis can in part address this.
Aquifer	A thickness of strata from which water may be abstracted economically
Attenuation	Natural reduction in concentration of a substance or organism by processes including dilution, dispersion, adsorption, bio-degradation and chemical transformation
Areal extent of the zone of contribution to a discharging well	Two-dimensional representation (map view) of the zone of contribution to a discharging well
Bio-degradation	Reduction in the concentration of a material due to the activity of micro-organisms or plants
Catchment (surface water)	An area within which all surface water flows into one surface water body, sometimes referred to as a watershed
Chemical transformation	Reduction in the concentration of a compound due to processes of oxidation, reduction, or chemical reaction with other compounds
Confined aquifer	An aquifer overlain by relatively impermeable strata offering a measure of protection from contamination by surface activities
Conjunctive use	Combined use of hydraulically connected groundwater and surface water
Dispersion	The spreading out or decrease in contaminant concentration as a result of differences in fluid velocity and flow paths
DNAPL	Dense, non-aqueous phase liquid (e.g. chlorinated hydrocarbons such as TCE)
Flow path	A modelled line along which water travels from its source towards an abstraction point or discharge
Groundwater catchment	Strata containing groundwater, separated from other groundwater catchments by stream lines, no-flow and/or constant head boundaries.
Isochrone	Line marking the distance travelled to a well over a specific time period (e.g. 10 year isochrone)
LNAPL	Light, non-aqueous phase liquid
Log cycle removal	Reduction of contaminant – 1 cycle reduces concentration to 10% of original; 2 cycles to 1%, 3 cycles to 0.1%, etc.
Numerical model	A mathematical and graphical portrayal of a process determined from data input into the model and simplifying assumptions. Mathematical models are preceded by creating a conceptual model wherein the data and assumptions required by the model are understood.
Source water	Surface water or groundwater that is destined to enter an intake
Time of travel (TOT)	An estimate of the time taken for a water particle to move from one point to another. May be measured by means of dye or tracer tests, or mathematically modelled. An n year isochrone would mark the location of points from which it would take n years for groundwater to reach a well.
Tracer or dye test	A method whereby water is labelled by means of injecting dye into it and monitoring the progress of the tracer to wells and natural discharge points
Transmissivity	A measure of the ability of a saturated thickness of aquifer to transmit water
Unconfined aquifer	Aquifer in which the water table is not confined and is relatively unprotected from contamination by surface activities
Zone of contribution to a discharging well (ZOC)	A three-dimensional zone through which water travels to a discharging well or the surface expression of the three-dimensional boundary of the groundwater system that delineates the location of the water entering the groundwater system that eventually flows to a discharging well

Appendix A

Time of travel calculation method

Excerpt from Well Protection Toolkit Files: *Step Two – Define the Well Protection Area*[10][11]

STEP TWO | **APPENDICES**

Appendix 2.3 Formulas for Analytical Equations

For aquifers that have a uniform ambient water table slope, the distance of the capture zone boundary (X) down-gradient of the pumping well and the width (2Y) of the capture zone up-gradient of the pumping well can be calculated as follows (see Figure 2.9):

$$Y = \frac{Q}{2000\ T\ i} \qquad (2.2)$$

$$X = \frac{Y}{\pi} \qquad (2.3)$$

WHERE:

Y = the half width of the capture zone (m)

X = distance to the capture zone boundary down-gradient of the pumping well (m)

Q = pumping rate (L/s)

- estimated by averaging the volume of water pumped annually
- estimated by assuming the amount of water used is approximately 2270 L/d (500 Igal/d) per connection or per household
- estimates can be checked against the reported well capacity and the pump rating; the well can not be pumped at a higher rate than its capacity nor the capacity of the pump

T = transmissivity of the aquifer (m^2/s)

- measured by conducting a constant rate pumping test and measuring the drawdown in the water level in the aquifer
- transmissivity values may be available from the original groundwater consultant's report
- estimated from the well's specific capacity (see Driscoll, 1986[15])

[15] Driscoll, F.G., 1986. *Groundwater and Wells*. 2nd ed. Johnson Division, St. Paul, Minnesota. 1089 pp.

i = slope of the regional water table or hydraulic gradient under non-pumping conditions

- measured from water table or groundwater level contour maps
- often estimated from the local topographic slope

USE:

- Suitable for sand and gravel aquifers where conditions are uniform and there is sufficient information on the pumping rate, aquifer transmissivity, and water table slope;
- May not be suitable for fractured bedrock aquifers where groundwater flow occurs in discrete fractures.

The distance to the one-, five- and ten-year time of travel boundary in the capture zone can be estimated from the following formula:

$$d_{TOT} = \frac{t\ K\ i}{n} \qquad (2.4)$$

WHERE:

d_{TOT} = the distance representing the one-, five or ten-year time of travel (m),

t = specified time of travel (one, five, ten years),

K = hydraulic conductivity of the aquifer (m/y),

- hydraulic conductivity of the aquifer is the transmissivity divided by the aquifer thickness

i = slope of the water table or hydraulic gradient, and

- measured from water table or groundwater level contour maps
- often estimated from the local topographic slope

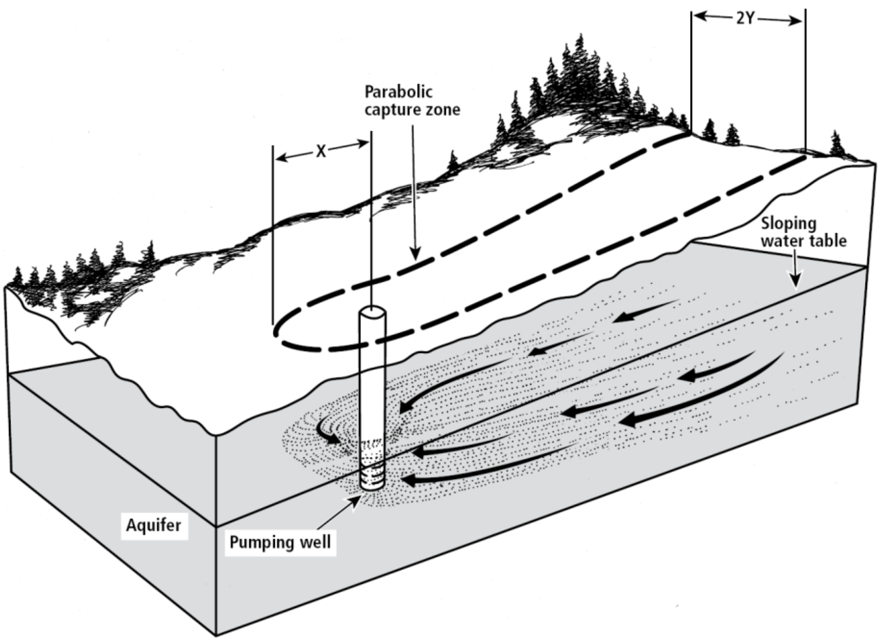
n = porosity of the aquifer.

- for sand and gravel aquifers, n can be assumed to be about 0.25

[10] From Well Protection Toolkit, a joint project of the Ministry of Environment, Lands and Parks, Ministry of Health and Ministry of Municipal Affairs; with support from Environment Canada and the B.C. Ground Water Association available at: http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/well_protection/pdfs/step2.pdf

[11] NZ supply specific water usage rates and porosity should be used

Figure 2.9 Capture Zone Determined from Analytical Equations



Appendix B

Literature review

1.0 Review process

A review of the literature concerning delineation of public drinking water supply protection zones available on the internet was undertaken and water resource managers from within New Zealand were contacted. The review results are tabulated in Table B-1 at the end of this Appendix for public drinking water supplies sourced from groundwater and Table B-2 for corresponding surface water sources, together with Table 2, Table 3 and Table 4 in Section 3.0 of the main report. These tables include the sources of information and brief details of what method was used to delineate the zones.

2.0 History of intake and source water protection

Both intake and wider source protection has been prioritised in many developed countries. The World Health Organisation [WHO] recommends the setting of national standards which include defining protection zones around water sources (WHO, 2011). Using defined zones as a method of protection has been developed in a number of countries. Commonly the whole capture area is considered, with degrees of restriction decreasing with distance from the point of abstraction.

Drinking water sources protection zones were pioneered in Germany and the USA with two contrasting approaches. Germany first enacted groundwater protection zones under the German Water Act 1957, and latter regulations for groundwater protection by the 1995 DVGW act (the German association for gas and water) under which regions often set more specific regulations. In 1986, as part of what was known as the 'Safe Drinking Water Act', the United States Environmental Protection Agency (US EPA) imposed a requirement on individual jurisdictions in the USA to develop wellhead and surface water protection programs that would define and protect the source areas around groundwater wells and reservoirs used for public drinking water purposes. Each state is now required to delineate source water protection areas and produce public assessments of current and future threats to water quantity and quality.

Since 1991 in New Zealand, legal protection of water quality and other aspects of source waters has been achieved under the Resource Management Act 1991 (RMA). Regional councils have responsibility, under s30(1)(c) of the RMA, to control land use and issue resource consents in order to protect water quality within a catchment. Regional plans, district plans and resource consents under the RMA are designed to assist the management of source water quality. In 1995, the Australia and New Zealand Environment and Conservation Council (ANZECC) produced a 'Guideline for Groundwater Protection in Australia'.

In 2002, the Ministry of Health published a set of guidelines regarding the creation of a Public Health Risk Management Plan for public drinking water supplies (now known as Water Safety Plans). The guidelines contain an appendix dealing with public drinking water source protection zones [12] (updated to refer to Water Safety Plans) but do not indicate a mechanism for delineating them, instead referring drinking water suppliers to their district or regional councils for advice.

A number of documents and web pages have been referenced in this review, but considerably more than this number have been viewed briefly but not specifically referenced because there is considerable overlap of content, especially in those dealing with the Source Water Assessment Program (SWAP) in the United States.

2.1 Drinking water source protection in New Zealand

In New Zealand, some regional councils have defined protection zones around drinking water intakes. For example, Waikato Regional Council produced a document in 2000 dealing with community groundwater supply protection (Hadfield & Nicole, 2000). It reviewed groundwater protection and described six methods of delineating groundwater catchments.

Similarly, in 2001 Environment Canterbury produced a review of rules associated with community water supply protection zones (PDP, 2001). Their review showed the need for a consistent approach to modelling of protection zones that took into account the risks associated with both normal and extraordinary land use activities and how these risks could be used to produce defensible zones. The report laid the technical groundwork for the dimensions of groundwater protection zones based on pathogen attenuation criteria.

In 2004, Environment Canterbury notified a proposed Natural Resources Regional Plan[13] in which public drinking water supply wells were surrounded by 'protection areas'. These are now incorporated into Schedule 1 of the Canterbury Land and Water Regional Plan as 'Community Drinking-water Protection zones' (ECan, 2017). These areas are varied in size and shape according to the depth of the well screen and the occurrence, or not, of any confining, or coastal confining strata overlying the aquifer. The size and shape of these protection zones relate to technical data developed relating to the survival of bacteria in groundwater. Environment Canterbury also describes rules that control or prohibit certain land use activities within a specific distance of a surface water supply intake. Environment Canterbury also manages activities via the Canterbury Land and Water Regional Plan within the general recharge area for the groundwater beneath Christchurch, known as the *"Christchurch Groundwater Protection Zone".*

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[12] Ministry of Health. 2014. Water Safety Plan Guide: Surface and groundwater sources, version 2, ref s1.1. Wellington: Ministry of Health.
[13] Variation 1 Proposed Natural Resources Regional Plan, Chapter 4: Water Quality; Environment Canterbury, July 2004, 320 p.

Explicit drinking water supply protection zones have been defined in the Greater Wellington Region and the Marlborough District. PDP (2012) applied a 3 zone approach to the zones in the Marlborough District. Groundwater protection zones and capture zones have been delineated in the Greater Wellington region using a 3 zone approach. Consequently, these zones have been defined as 'community drinking water supply protection areas' under the Proposed Natural Resources Plan for the Wellington Region (GWRC, 2015). A single zone approach for surface water protection zones was selected as a simplified approach to the 3 zones suggested by PDP and ESR (2005) guidelines where a 100 m wide buffer strip extending for a distance of 8 hour time-of-travel at median flow velocity (Thompson, 2015). These protection zones for surface water have also been incorporated into the Proposed Natural Resources Plan for the Wellington Region.

Other site-specific cases of drinking water supply protection zones include the delineation of community drinking water supplies in the Horizons Region (PDP, 2017a). Environment Southland uses a default protection zone of 250 m, and intends to include specific zones for each supply.

In some cases, regional councils apply particular controls or increased scrutiny to proposed activities within source protection zones that have been defined by the water supplier. For example, the Hawke's Bay Regional Council places increased emphasis on the consideration of effects from discharge activities proposed to occur within groundwater source protection zones that have been set by Hastings District Council in the Heretaunga Plains. These have been set by Tonkin and Taylor (2005) and include the following zones.

- Immediate protection zone (SPZ1) – a 5m setback zone around each well head to allow for specific control (by statute, regulation, planning rule) of activities within the immediate vicinity of the well heads.
- Microbial protection zone (SPZ2) - defined by analytic modelling that represents a 1 year groundwater travel time from the well field.
- Capture zone (SPZ3) – defined by a catchment or hydrogeological boundary, which in this case is based on a 10-year travel time.

2.2 Current international approaches for source water protection

Recent approaches to water source protection entail zones of protection from the wellhead or abstraction point to whole catchment assessment.

The Water Framework Directive (2000/60/EC) instigated the development of source water protection legislation in Europe whereby the 25 member states were required to define drinking water source protection areas (DWPAs). Development of safeguard zones may be established with takes using a partial or whole catchment approach to water source protection. Interpretation of the Water Directive Framework varies, however, many EU countries have adopted a

3 zone approach (refer to Table B-1). Some countries, including France and the UK, also include a fourth zone to be added under specific vulnerability conditions (refer to Table B-1). In Italy, Zone 3 is deemed the safeguard zone which encompasses the catchment area considering geological, hydrogeological, and geochemical data. The Water Framework Directive also requires identification of groundwater bodies that are intended for future drinking water use.

Delineation of source protection zones in the USA is determined by local jurisdictions depending on local conditions, as well as technical, financial, and human resources available within the jurisdictions. The US EPA recommends a three step approach to source water protection in which delineation is the first step, following by conducting an inventory of potential sources of contamination, and determination of the vulnerability of the water supply to contamination (EPA, 2018). Best practice guidelines by which states may delineate source water protection areas are recommended by the US EPA in the Trust for Public Land's 'Source Protection Handbook' (TLP & AWWA, n.d.). This takes a multi-barrier approach to providing safe drinking water starting with source protection.

Most states have completed water source assessments of their supplies. Time of travel (TOT) is the most commonly used approach to drinking water protection zones in the USA, and these are justified by the TOT providing a measure of time for a responsible agent to react and take remedial action to a pollution event.

There is an expanding consensus that solely using time of travel for delineation of water source protection zones may not address the stochastic variation of contaminants due to dispersion and heterogeneities within the aquifers (Chin, 2017; Frind, 2006). Alternate methods are proposed that consider well vulnerability. In the New Zealand context, it is important that all risks to supplies are considered in the setting of protection zones and in Water Safety Plans.

Wider assessment of water resources, particularly for groundwater, is commonly applied by consideration of the risk for the entire catchment. Switzerland, for example, distinguishes groundwater protection requirements based on the various categories of which water supply protection zones are a part (BUWL, 2004).

Each drinking water source's specificities determine its protection requirements. Most source areas for drinking water supplies may be divided into those represented by groundwater sources, and by surface water sources. However, some public drinking water supplies make conjunctive use of both groundwater and surface water. Under the Water Framework Directive, protection zones are defined based on classification of groundwater or surface water bodies. Groundwater sources are then divided into intergranular, karstic and fissured aquifer, while surface water bodies are divided into standing and flowing water bodies. Some countries divide source protection areas based upon the different characteristics of hydrogeological systems i.e. Slovenia, Croatia, Bosnia and

Herzegonia, Serbia and Montenegro have from 2 to 4 classifications based on aquifer type.

The Arab Guideline for delineation of groundwater protection areas distinguishes two approaches to aquifer protection for 'aquifers with either homogenous distribution of groundwater flow velocities', or 'heterogeneous distribution of groundwater flow velocities' (Margane, 2003). Croatia, Montenegro, Italy and Greece use technical division based on abstraction facilities.

Issues of catchment delineation are described in a USEPA (2005) report. This EPA document states: "*Conjunctive delineation of source water protection areas is the integrated delineation of the zone of ground-water contribution and the area of surface-water contribution to a public water supply. States that choose to consider the hydraulic connection between ground water and surface water when delineating a source water protection area, will afford themselves the opportunity to reduce contamination from ground-water and from surface-water sources"*. Conjunctive delineation therefore uses a mix of surface water and groundwater methods. Within New Zealand, examples of conjunctive use are common in a number of areas including Canterbury, Hawke's Bay and the Hutt Valley.

The common approach of using a zone of protection is to generally consider the whole capture zone for the drinking water supply, with decreasing degrees of protection or restrictions from the point of abstraction (WHO, 2006). For groundwater, commonly, delineation of the capture zone to the point of abstraction involves zonal categories to achieve the following levels of protection.

1) A zone immediately surrounding the abstraction point to prevent rapid ingress of contaminants to the well or damage to the wellhead.
2) A zone based on TOT required for necessary pathogen reduction to an acceptable level.
3) A zone based on TOT needed for dilution and effective attenuation of slowly degrading substances to an acceptable level.

Furthermore, an additional zone covering the whole catchment area is included to prevent long-term degradation of drinking water quality, unless this Zone 3 is defined this way.

A review of literature reveals that internationally, legislation and guidelines define 2 to 4 zones of protection for aquifers used for drinking water supply, or that may be needed for future drinking water supply. It is common to include the whole catchment in drinking water protection zones.

2.3 Unique New Zealand environments

New Zealand contains a number of different physical environments. One environment which has a rich groundwater resource is described briefly in this section. This is the sedimentary fan systems, common on the east coast of the South Island, and to a lesser extent in other areas including Hawke's Bay. The characteristics of this environment influence the extent to which overseas methods can be used to develop suitable catchment protection guidelines.

These coalescing fan systems developed during initiation of tectonic uplift prior, during and after the Pleistocene glaciation. The fans contain a mix of fluvio-glacial and alluvial deposits dominated by coarse grained sediment derived during periods of very high erosion and transport rate. The sedimentary strata are dominated by 'gravel' containing a matrix of sand, silt and clay dependent on the degree of post-deposition infill and sedimentary reworking. The fans have been built up to a degree that the rivers that feed them lose surface water into the permeable strata.

In these fans groundwater velocities can be fast (50 to 200 m/day), several orders of magnitude faster than equivalent velocities in alluvial and glacially derived fluvial aquifers developed in valleys that are typical of many overseas groundwater systems. In Canterbury, these fast groundwater flow systems and protection zones for wells have been described in the Natural Resources Regional Plan (ECan 2004) and subsequent documents. Corresponding, but slower groundwater flow systems and protection zones were described by Hadfield and Nicole (2001).

Unusual environments such as these sediment fans, and the occurrence in New Zealand of catchment environments involving karst, rocks in which groundwater flow is dominated by fracture systems, relatively unconsolidated recent volcanic strata and geothermal areas, indicate the degree of flexibility required for the successful deployment of source protection guidelines. It is apparent that source protection zones for New Zealand are best delineated for each source in a site-specific manner.

3.0 Groundwater sources

There are several methods by which a groundwater catchment area may be defined (Table B-3). Most methods include an implicit (rarely explicit) assumption that the longer groundwater flows underground, the more likely it is to be free from contamination by micro-organisms. The methods reviewed include[14]:

- definition of a circular arbitrary 'zone of contribution' (ZOC) of a specific radial distance from a well
- definition of a calculated 'zone of contribution' (ZOC) of a specific radial distance from a well
- definition of standardised shapes based on TOT and pumping conditions related to pathogen removal during groundwater flow
- definition of a non-circular ZOC of a specific length up-gradient of a well, that relates to analytical TOT calculations
- classical hydrogeological techniques including: hydrogeological mapping of flow systems, recharge and discharge areas, and dye tracing
- numerical groundwater flow modelling (e.g. using MODFLOW) of an abstraction and associated flow paths and corresponding TOT points.

These six categories are summarised in Figure 1 and Table 1 in Section 3.0 of this report.

The United Kingdom began establishing groundwater protection zones in the 1970's using simple standardised methods, but have since developed groundwater delineation methods to use either conceptual hydrogeological models or groundwater flow models. The approach chosen is based on data availability, the degree of understanding of the hydrogeological system, and importance of the water source (population size). The groundwater protection policy is advantaged by early establishment of a countrywide groundwater vulnerability assessment in the form of groundwater maps.

3.1 Time of travel concept

During the review process it became clear that use of the term 'time of travel' (TOT) involved very different parameters and gave very different results for groundwater and surface water protection delineation schemes.

The key difference is due to the fact that groundwater TOT definitions are based on expected attenuation (treatment/degradation) of micro-organisms and

[14] For the purposes of the review, local units of length or volume other than Système Internationale (SI) have been converted and, where appropriate, rounded.

compounds such as hydrocarbons. In contrast, surface water TOT definitions are primarily length-based, allowing sufficient warning time for action to be taken at a water treatment plant or intake.

TOT in both groundwater and surface water systems may be different for the different components. For example TOT in a karstic aquifer might be small when compared to that in a fine sandy aquifer; similarly, overland flow is fast in comparison to stream base flow.

Methods of protection zone delineation, most of which involve some TOT concept, are now described in more detail in order to illustrate their strengths, and weaknesses in a New Zealand context.

3.2 Fixed radius methods

As can be seen in Table B-1, the use of an arbitrary zone of contribution as shown in Figure 1a in Section 3.0 of the main report is rare. One apparent example is the State of Louisiana. A protection area of radius of 1 mile (1.6 km) applies to most wells in this state. More commonly used, is a calculated fixed radius zone of contribution, where efforts have been made to estimate the radial TOT to a well (Figure 1b in Section 3.0 of the main report). GNS have included this in their Groundwater Capture Zone GIS toolkit[15]. Concentric fixed radius distances, however, are regularly applied around the abstraction points to protect the source from immediate contaminants and to prevent damage to the wellhead. Neither of these two methods take into account groundwater flow direction or the effects of a confining layer.

3.3 Simplified variable shapes

Environment Canterbury defines the shape and size of ‘community drinking water supply protection zones’ around well heads. 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. Shape and size are related to perceived contamination risk, in that unconfined, and shallow screened wells have larger protection areas (up to 1 km long up-gradient, and up to 400 m around them in other directions (Figure 1c in Section 3.0 of the main report). Wells in confined aquifers that are screened at more than 70 m depth, have circular protection areas of 100 m radius. The sizes of the zones are based on assessment of required setback distances from wastewater discharge points (ECan Technical Report U01/104).

The method of individual well head protection zones deals primarily with near-field effects, protecting the wellhead and abstracted groundwater from localised contamination. In addition, larger scale protection for entire recharge areas are

[15] https://www.gns.cri.nz/Home/Our-Science/Environment-and-Materials/Groundwater/Database-and-tools/Groundwater-capture-zone-GIS-toolkit

applied, for example, the Christchurch Groundwater Protection Zone that is included in the Canterbury Land and Water Regional Plan.

Zones of contribution have also been delineated in for community drinking water supplies in the Horizons Region (PDP, 2017a). These zones are defined using standardised shapes based on water source type as follows.

1) For surface water sources, the land use 100 m either side of the waterbody, extending 1,000 m upstream and 100 m downstream of the intake point.
2) For shallow groundwater wells, a radius of 500 m around the well has been used, in addition to a zone extending 2 km upgradient with an allowance of 10 degrees for variation in the angle of groundwater flow.
3) For deep groundwater wells, a radius of 500 m has been used.

3.4 Analytical methods

A ZOC in a flowing groundwater system requires an analytical approach, which is briefly described in this section. Groundwater abstracted from a well located within a regional groundwater flow field travels to it in a complex way, only being radial in the zone immediately adjacent to the well (Figure 1d in Section 3.0 of the main report). Javandel and Tsang (1986), and others, showed how groundwater flow around each well, during periods of uniform abstraction, may be separated into two contrasting zones: a parabolic one within which groundwater will be abstracted by the well; the other, where groundwater will not flow into the well (Figure 1d). Outside this parabolic zone, groundwater may be slightly deflected towards the well during abstraction, but ultimately flows past the well. Recognition of this phenomenon is fundamental to water protection and has given rise to methods to protect groundwater from contamination in this parabolic zone of contribution (ZOC). The downstream apex of the parabola is a stagnation point, downstream of which all streamlines fail to arrive at the well (Figure 1d).

In addition to recognising that only groundwater lying within this ZOC will actually be abstracted, it is also possible to determine at what rate a water particle moves on its journey to the well. This has allowed the recognition of TOT zones or boundaries, representing volumes of groundwater of increasing ‘age’. The term ‘age’ simply means the time that would be taken for a notional particle of water at a specific location to enter the sub-surface environment and travel to a discharging well. Examples of jurisdictions that recommend this method to delineate catchment zones are ref 3 (the minimum required for large supplies) (British Columbia), and ref 15 (State of Maine).

Estimation of the shape of the parabolic function is a straightforward analysis using equations that are capable of being processed in a spreadsheet, but there are numerous software packages available to do this task, such as WHPA (created by the EPA), and WINFLOW (created by Scientific Software Group). In addition, GNS have included this in their Groundwater Capture Zone GIS toolkit[16]. These programs have been used to determine well protection areas from the geometry of streamlines converging upon an abstraction well. They are, however, based on the assumption that the aquifer systems are homogeneous with consistent groundwater flow direction and gradient. In reality, this is never the case, so the use of this approach must include an allowance for the variability and uncertainty associated with characterising the aquifer parameters.

A three zone approach for Marlborough District Council identifies site-specific groundwater protection areas for community water supply wells (PDP, 2012), based on knowledge of contaminant attenuation at that time. These zones include site-specific variation but are generally defined as follows. Zone 1 defines an intake zone around the wellhead. Zone 2 has been calculated based on TOT and a consideration of microbial removal. Zone 3 extends over a distance up-gradient of the well, where land use activities are likely to have a general impact on groundwater quality at the wellhead.

3.5 Hydrogeological investigations

Hydrogeologists commonly base their knowledge of the water resources of an area on a number of pieces of information, including hydrogeological mapping of flow systems, recharge and discharge areas, aquifer testing and in some cases tracer tests.

Flow systems in aquifers are assessed from knowledge of groundwater recharge sources such as rainfall and seepage from surface water bodies, the elevation and degree of discharge of groundwater into rivers and springs, aquifer test results and water levels in wells. In addition, tools such as tracer tests can be used to determine the discharge zone and TOT of groundwater from a specific area, which can be especially useful in karst terrain. Isotope (e.g. tritium and oxygen) and chemical tracer (e.g. sulphur hexafluoride) techniques on groundwater can be helpful to identify sources of recharge, provided they are not solely relied on.

These techniques may be used to delineate where water is recharging, how it moves sub-surface, and how long it takes to reach a target well. This information can then be used to delineate source protection zones based on specific time of travel, or attenuation, calculations.

3.6 Flow and transport modelling

There are a range of analytical methods that can be used to model contaminant attenuation in groundwater. Where analytical modelling is constrained, numerical groundwater flow modelling can be used. This covers a range of

[16] https://www.gns.cri.nz/Home/Our-Science/Environment-and-Materials/Groundwater/Database-and-tools/Groundwater-capture-zone-GIS-toolkit

techniques and scales, from those operating on a simple grid-based flow pattern, to complex assessments of aquifer variability and contaminant migration pathways. An analytical element model can also be used to assess more complex settings, as described in Moreau et al (2014a).

Many jurisdictions in the United States, Canada, Australia, and England and Wales use a sophisticated approach that attempts to deal with the natural variation in physical parameters that characterise groundwater systems. The German guideline DVWG W 101 explicitly calls for the use of numerical hydraulic models as the standard method for 50 day TOT for Zone 2 delineation.

Waikato Regional Council has used 1, 5, 10 and 20 year TOT to delineate zones for Matamata supply wells (Toews & Moreau, 2014). The intention of these zones is to inform policy for associated risks including microbial protection and land-use activities. GNS have applied this method in a number of other locations, as described in Moreau et al (2014b).

However, with the ability to model this natural variation comes the need for accurate data. In addition, the more sophisticated the modelling process, the more believable the results may be to the non-expert, perhaps creating a false sense of accuracy. It is important that the model be independently verified, and sensitivity analyses undertaken in order that a measured degree of confidence in the end result may be appreciated. Use of the Ministry for the Environment groundwater model audit guidelines shows how this may be achieved (Moore and Williams, 2002). Major drawbacks to the use of modelling are the requirement for much accurate data and the need for considerable manpower and computing resources.

The advantages of this modelling procedure are diverse: variations in water use; additional wells; seasonal changes in hydraulic gradient and direction of groundwater flow; areal variation in hydrogeological parameters can all be used to set up individual protection zones around wells (Figure 1e in Section 3.0 of the main report). Examples of such protection zones, with 1, 5, 10 and 20 year protection zones fanning out from a series of wells were documented in 2004 by the Ontario Ministry for the Environment in southern Ontario (Oxford, ref: 33). The United States Geological Survey (USGS) provides a variety numerical modelling tools applicable to delineation of groundwater protection zones.

In theory, the TOT zones can be extended outwards from the well, but with decreasing confidence regarding their boundaries. As a result, the parabolic zones, shown in Figure 1e, need to be flared in order to take into account the uncertainty or variation in groundwater flow direction associated with such long term predictions.

3.7 Commentary – Groundwater protection zones

Most of the techniques described here relate to protection zones determined by means of a TOT method. The reasoning behind this method is not at all well documented in the literature examined. Many jurisdictions apply a specific TOT protection zone without explicitly stating why this choice has been made.

TOT approaches are most realistic as they incorporate more specific empirical data than other methods. The science behind such an approach is that a groundwater TOT offers protection from contamination because of a number of processes: die-off of micro-organisms, adsorption of micro-organisms and chemical contaminants, dispersion and dilution of micro-organisms and chemical contaminants, bio-degradation and chemical transformation. These processes conspire to reduce the effects of a contaminant on its pathway from source, to a discharging public drinking water supply well. Groundwater TOT is, therefore, a way of ensuring that a sufficient number of these natural remediating or attenuating processes have been operative such that the resultant water quality is unlikely to exceed maximum acceptable values.

Limitations associated with TOT need to be considered as this approach does not specifically account for removal of contaminants through attenuation. This uncertainty may be addressed by consideration of tracer tests to acquire information about flow velocities and directions, hydraulic connections, and hydrodynamic dispersion (WHO, 2006). It is important that variations in flow velocity are considered.

In addition, there is often a further degree of conservatism built into the TOT zone because, in many cases, no allowance is made for the time taken for the contaminant to migrate down to the water in the aquifer of concern.

Details of these remediating or attenuating processes are generally not explicitly identified in the literature reviewed but are implicit in the methods used. Where attenuation has been recognised as a specific process (e.g. Ontario 2004), use of TOT zones is based on die-off of micro-organisms.

3.8 Vulnerability risk assessment

There is a growing consensus with using TOT as the sole measure for drinking water source protection as it does not infer the impact of a contaminant on water quality at a catchment scale (Chin, 2017; Molson & Frind, 2012). Vulnerability assessment regarding delineation of drinking water protection zones is a widely applied approach. Such vulnerability assessments can advance beyond conventional TOT methods by quantifying the impact of potential contamination sources within the whole capture zone or entire catchment (Huan et al, 2015; Frind, 2006). *“Risk should depend not only on advective travel time, but also on the nature of the source, the transport, and fate of the contaminant in the presence of dispersion and attenuation, and the interaction of the well with* *the flow system"*(Frind, 2006). There are a complex range of factors that can be considered for vulnerability assessment including preferential flow, transport in unsaturated media above the groundwater table, and velocity at breakthrough from the vadose-water table boundary (Neukum & Azzam, 2009; Stigter, et al. 2006). These factors, combined with the myriad of potential contaminant sources or activities can make for a rigorous risk assessment under which delineation of protection zones can be undertaken.

In France and the UK, vulnerability assessments can be used to determine regulations for the fourth zone of protection. The groundwater protection policy is advantaged by early establishment of a countrywide groundwater vulnerability assessment in the form of groundwater maps.

It is considered that a time of travel approach is reasonable for defining a default zone, provided this is done in a conservative manner allowing for preferential flow, but the site specific zone should ideally be based on a site specific consideration of sources, pathways and attenuation processes along these.

4.0 Surface water sources

The literature review indicated that there are several methods by which a catchment area may be defined for surface water sources (Table B-2). The methods all include an implication that surface water will usually be contaminated by microbes such as natural coliforms and those derived from agricultural and urban land use, including *Escherichia coli*; and may also become contaminated by other materials such as timber treatment chemicals, or hydrocarbons. The methods reviewed include:

- definition of a single ZOC that corresponds with the entire surface water catchment or watershed
- definition of a two zone system with a single ZOC that corresponds with the surface water body and includes a buffer zone adjacent to it, and an outer zone consisting of the remainder of the watershed
- definition of a three or more zone system, with two or more ZOCs represented by concentric buffer zones surrounding the surface water body, and the total watershed
- a complex, multi-zone approach based on land use.

Inner protection zones for surface water intakes relate to the need for warning time to shut off an intake, while outer zones relate to attenuation processes that may occur along contaminant pathways that lead to the surface water body. However, "*the TOT approach to surface water intakes is based on the amount of time it takes for a contaminant travelling at the same velocity as the stream and overland flow to reach the water intake point. The travel time method for surface water intakes does not define a protection zone; it is intended to directly protect* *water quality at the site of drinking water intake by providing an early warning system for contaminants deposited in or near upstream waters. The travel time between a surface water intake and an upstream location is dependent upon parameters such as stream discharge, overland flow discharge and contaminant characteristics. The intake-specific travel time, estimated through numerical modelling of stream and overland flow, would allow a drinking water treatment plant sufficient time (on the order of several hours) to take appropriate measures to avoid the intake of contaminated water or to bring additional treatment equipment on-line*" (Ontario 2004). This quote, derived from a large document produced in November 2004 as a result of the damage done by the Walkerton tragedy, summarises most if not all of the variables that are used to define the zones.

Countries under the Water Framework Direction commonly separate surface water bodies into flowing and standing water bodies for the purpose of delineation. Slovenia uses a specific distinction of surface water bodies based on retention time, where flowing water bodies are those with a retention time of 10 days.

The methods listed above are now described in more detail in order to illustrate their strengths, and weaknesses.

4.1 Single 'zone of contribution' (ZOC)

The single zone of contribution corresponds with the entire surface water catchment or watershed. Typically this method is used for small watershed areas, especially if land use is relatively benign, or has traditionally been restricted (e.g. State or Crown forest land, national park, conservation area).

However, in larger watersheds the imposition of inflexible regulations regarding land use over large areas may not be politically acceptable, with the result that a zoned approach is considered more practical, yet offering sufficient security of water quality and quantity.

4.2 Two zone ZOC

The inner zone of a two zone ZOC method of delineating surface water protection zones involves definition of a ZOC that corresponds with the intake (e.g. reservoir or main stem of river on which the intake occurs), and includes a buffer zone adjacent to the surface water body. A second zone includes the entire watershed.

An example of the two zone system is that operated in Massachusetts (Table B-2, ref. 24), where a buffer zone is drawn around any reservoir to a width of 400 feet (122 m). Around the contributing river and any tributaries there is a 200 feet buffer (61 m). Within this buffer, land uses and other activities are regulated. In addition to this zone of variable width, there is another zone delineated around tributaries and surface waters and on land within flood plains, over some aquifers, and within bordering vegetated wetlands, where certain activities are specifically prohibited. Figure 2 in Section 3.0 of the main report shows the layout of these different zones.

This type of protection zone delineation allows for variation in the width of a buffer zone, in part dependent on the significance of a waterway to catchment flow, and in part to surface topography within the catchment. It also recognises the fact that surface water and groundwater are commonly hydraulically connected and that the protection zone system should use a conjunctive approach.

Bosnia and Herzegovina use a two-zone delineation for flowing surface waters, but only near the intake. The first protects the intake zone with a 25 m fixed radius, while the second zone is a 50 m wide buffer strip from the river extending 1,000 m upstream.

4.3 Three or more ZOC

Creation of three or more 'zones of contribution' (ZOC) includes delineation of zones corresponding with the total watershed, and two or more concentric buffer sub-zones adjacent to the surface water body (Table B-2 ref. 10 & 51). Three zone systems offer more flexibility and different types are described here to illustrate this.

Australia has set up a series of Public Drinking Water Supply Areas (PDWSA) but these are planning tools that do not specifically state how they were delineated (ref: 12). The areas are termed 'Priority areas', in which different levels of environmental degradation are considered acceptable. Priority 1 areas may have no degradation; Priority 2 areas can have no increased risk of contaminating a water supply; and Priority 3 areas may have any pollution risk managed. There are also prohibited zones for a distance of 2 km around a reservoir high water level mark.

In contrast, the State of Wyoming in the USA (ref. 51) has set up a three zone delineation system in which the innermost zone or Zone 1 is 100 feet (30 m) radius of the water intake, Zone 2 is 15 miles (24 km) from the intake on the main stem of the river and all perennial tributaries (or 8 hour travel time at high flow), and includes a 1000 feet (305 m) buffer beyond perennial watercourse banks on the main stem and tributaries. A Zone 3 includes the remainder of the watershed.

Most protection zone delineation involves this three zone approach. Where surface or sheet flow in a catchment provides a significant proportion of the feed to a reservoir then a larger set back is appropriate. Differences between these delineation methods, and justification for the width of the innermost zone (30 m or 75 m) are not adequately explained in the literature. Aspects of soil type, topographic relief, rainfall might be expected to provide input necessary to delineate these zones, but details are implied, not described.

Italy and Slovenia use three zones for surface water protection zone delineation in flowing waters, where the first zones have fixed distances of 10 m and 100 m respectively. Italy defines the second zone by a minimum 200 m distance upstream of the intake point, with a width determined by expert risk assessment, while Slovenia uses a 20 day TOT. Both countries use expert judgement for site-specific delineation of the whole recharge area for Zone 3. This allows demarcation of zones within the watershed, representing TOT in a similar fashion to those in groundwater catchments but for different reasons. The TOT for surface water catchments represent an early warning system allowing resource managers to react to monitoring of water quality or spill events.

4.4 Integrated catchment management zone approach

An example of a complex approach to the creation of surface water protection zones is that in Table B-2, ref. 53, by the British Columbia (Canada) government. The process of delineation has been part of an integrated catchment management plan in which land and water uses, biodiversity, access, and watershed restoration all play a part, along with public consultation. There are two management zones around Haslam Lake that serves as the municipal water supply source for Powell River. The southern portion of the lake serves as the intake source of the municipal supply, and has a riparian Lake Management Zone of unspecified width, with strict criteria restricting land use activities. The northern portion of the lake has a narrower riparian buffer, and there are fewer restrictions on land use. The watercourse issuing from the lake has a riparian buffer of 100 m width.

This integrated catchment management approach is similar to the two zone system described previously, but the width of the innermost (riparian) buffer zone is not regionally specified, and is based on site-specific topography and land use. The advantages of an integrated catchment approach are that all aspects of a watershed are considered, but with the disadvantage of increased level of effort.

5.0 Conjunctive delineations

All groundwater is ultimately derived from surface water or rainfall recharge. However, some groundwater systems, such as those accessed by galleries or wells adjacent to rivers or lakes, receive recharge from surface water bodies. In addition, some surface water features, including springs, are derived from groundwater. This section of the review identifies examples of issues associated with conjunctive water resources (e.g. refs: 17, and 20) and how delineation takes into account the need for combined protection of the surface and groundwater resources.

Greece, Italy, Slovenia, Serbia, Bosnia and Herzegovina appear to have conjunctive classification of drinking water sources of surface and groundwater (Brenčič, 2016). This classification, however, does not translate through to delineation of conjunctive protection zones.

GNS Science used TOT to defined protection and capture zones in a conjunctive delineation of the Putaruru well field and Blue Spring on the Waihou River in the Waikato (Gusyev, et al., 2012). This study used available hydrogeological data combined with isotope tracers to estimate groundwater age to construct a numerical model to determine capture zones. There was a lack of aquifer data available, so the groundwater age data was relied on as a primary method of calibration for that study.

A two zone groundwater capture delineation approach also has been undertaken for 26 lake catchments in the Horizons Region (PDP, 2017b). This report uses two methods to delineate these zones; 1) the Recharge Balance approach, which defines the area of the aquifer immediately surrounding the lake, for which shallow groundwater flow is likely to be pulled towards the lake, and 2) the Uniform Flow approach, which aims to define the area of the aquifer which may provide groundwater flow into the lake. The surface water catchments were defined separately. While this study was not for drinking water protection, it provides a relevant example of conjunctive delineation methods.

An EPA document (EPA 2005) outlines considerations for conjunctive delineation of protection zones. For systems primarily supplied by surface water, the groundwater component should have been underground for sufficient time to reduce concentrations of any entrained toxic contaminants so that they will make an acceptably low level of contribution when mixed with the surface water. The area contributing to the surface water is the entire watershed, but groundwater contribution may come from a smaller, or larger area, depending on the geology and topography. The EPA document indicates that where a groundwater divide exists, marking the boundary of a groundwater catchment, the location of this divide may change with season and abstractive demand. This effect may be significant to delineation of groundwater catchments in general.

For systems primarily supplied by groundwater, the surface water component may well have a contrasting water quality that could compromise the total water quality. Under certain seasonal or demand conditions, the surface water contribution may change as a proportion of the total supply, with the result that the water quality also changes. Water intakes located beside or close to surface water bodies (e.g. galleries, bank infiltration units) will have predominantly surface water quality characteristics with a minor groundwater input. Therefore, delineation of protection zones around these types of intakes should be mindful of the surface water quality as well as the combined water quality.

Table B-1: Groundwater catchment delineation examples

Catchment definition method	Organisation (country)	Ref	Comments (requirements, criteria, assumptions, etc.)
Three zone plus special interest zone	Environment Agency (England and Wales; NRA 1995)	1	Zone 1: inner protection zone 50 days plus 50 m protection zone around well; Zone 2: outer protection zone 400 days or 25% of catchment area, whichever is larger; Zone 3: total catchment; Zone of special interest: Where local conditions require protection even if outside normal catchment area
Three zone	Environment and Heritage Service, Department of Environment (Northern Ireland)	2	Zone 1: inner protection zone 50 days plus 50 m protection zone around well; Zone 2: outer protection zone 400 days or 25% of catchment area, whichever is larger; Zone 3: total catchment
Two zone	British Columbia Water and Waste Association (BC, Canada)	3	Well protection zone: minimum 100 m around well; Capture zone: equivalent to zone of contribution; Site specific zone: dependent on contaminant source inventory.
Two zone	State Water Resources Control Board (California, USA)	4	**Zone A**: 2 year TOT; **Zone B**: 5 or 10 year TOT; Concentric zones, no allowance for regional flow
Time of travel zone	Alaska section of American Water Resources Association (USA)	5	No specific method described, but use of EPA guidebooks recommended
Two zone	City of Jacksonville, (Florida, USA)	6	**Buffer zone**: 200 foot; **Zone of contribution**: 2 years travel time
Modflow	Department of Health – Safe drinking water branch (Hawaii, USA)	7	Well site control zone: unspecified radius; Zone of capture: 2 years for microbiological components; Zone of capture: 10 years for chemical contaminants
Three zone	Ministry for the Environment (ON Canada)	8	Well buffer zone: 50 days TOT; Zone 1: 0 to 2 year saturated TOT; Zone 2: 2 to 10 year TOT; Zone **3**: 10 to 25 year TOT; Includes analytical model for calculating zone width and length.
DRASTIC + variety of methods	Department of Health, State of Washington (WA, USA)	9	6 month, 1 year, 5 year and 10 year TOT. Use of DRASTIC in association with analytical tools.
Three zone	Department of Environment, Western Australia (Australia)	10	Public Drinking Water Supply Area (PDWSA). Priority 1 (P1): No degradation; Priority 2 (P2): No increased risk; Priority 3 (P3): Pollution risk managed; Well head protection zones (WHPZ) P1 500 m; in P2 & P3 300 m.

Catchment definition method	Organisation (country)	Ref	Comments (requirements, criteria, assumptions, etc.)
Arbitrary fixed radius	Louisiana Department of Environmental Quality (USA)	11	Currently circular protection zones of 1 mile (1.6 km) around confined aquifers and 2 miles (3.2 km) around unconfined aquifers. Proposes 10 year TOT more complex models
Three zone	Australia and New Zealand Environment and Conservation Council (Australia)	12	Zone 1: 50 m radius (within well field); Zone 2: 10 years residence time; Zone 3: Greater than 10 years residence time
Dye tracing and mapping	USGS (USA)	13	Use of dye tracing to delineate 250 day and 3 year zones in Utah karst. Dye tracing may over-estimate travel times
Three zone	Wyoming Department of Environmental Quality (USA)	14, 30	Zone 1: WHPA1 extends to 200 day TOT; Zone 2: from WHPA 1 to 1000 day TOT; Zone 3: from WHPA2 to watershed boundary. Ref 30 contains different criteria 500 foot fixed radius, and then 2 year and 5 year TOT, including 1000 foot buffer zone around all perennial streams for 1 mile upstream of recharge area, or to point where stream becomes intermittent
Three zone	Maine Source Protection Section, (Maine USA)	15	Zone 1: 300 feet (91 m); Zone 2: 200 day TOT; Zone 3: 2500 day TOT; Sensitivity zone : 2500 day TOT; Zone dimensions dependent on population served
Single zone	Cape Cod Commission (Massachusetts, USA)	16	Complex zones of capture, no specifics given of how calculated. Protection areas account for 10% of land area on Cape Cod.
Single zone	Environmental Protection Agency (USA)	17	Useful overview, and delineation of conjunctive systems
Single zone	West Virginia Bureau for Public Health (USA)	18	Minimum TOT of 5 years, or flow boundaries, as appropriate. Use analytical procedures, mapping,
Three zone	City of Vancouver (Washington USA)	19	Draft Groundwater Protection Ordinance. GPD-1: includes 1, 5 and potentially 10 year TOT
Modelling	Nebraska Department of Environmental Quality (USA)	20	20 year TOT by modelling. Includes aspects of drought conditions affecting size and shape of area. Document also uses simple analytical method of creating well head protection area.
Three zone	Department of Environmental Quality, Oregon (USA)	21	For > 500 people 2, 5, and 10 year TOT; for <500 people, 2, 5, 15 year TOT. Two year zone considered outer limit of microbial influences. > 500 people, requires conceptual model, with other criteria and information requirements additional for larger populations. Data on conjunctive delineations.
Four zone	World Health Organisation	22	Useful review of methods, risk assessment and discussion

Catchment definition method	Organisation (country)	Ref	Comments (requirements, criteria, assumptions, etc.)
Two zone	Geological Survey of Ireland (Eire)	23	SI: inner protection area 100 day TOT SO: outer protection area = ZOC entire catchment area
Two zone	Iowa State Department of Environmental Protection (USA)	24	Inner zone 200 foot radius; Outer zone 2500 foot radius. Recommended criteria are TOT (2 years for microbiological; 5 years for chemical). Goes through 5 different methods of determining protection areas.
Variable method	South Dakota (USA)	25	Variable, depending on population size and land use.
Three zones by modelling	Amherst water supply, N S, Environment Canada (Canada)	26	Zone 1: 10 year TOT; Zone 2: 50 year delay; Zone 3: remaining area; Discussion on risk assessment
Four zones by modelling	Oxford water supply, ON, Environment Canada (Canada)	27	Zone 1: 2 year TOT; Zone 2: 5 year TOT; Zone 3: 10 year TOT; Zone 4: 25 year TOT Great maps of TOT zones.
Four zones by modelling	Edmundston water supply, NB, Environment Canada (Canada)	28	75 m buffer zone around all rivers and streams in watersheds providing potable water Zone 1: 100 day TOT; Zone 2: 5 year TOT; Zone 3: 5 to 25 year TOT; Good detail of why and how.
Standard shape	Environment Canterbury	29	Zone shape, size and orientation dependent on screen depth, groundwater flow direction, and status of aquifer confining layers (if any).
Three zone	Waikato Regional Council	30	Zone 1: 30 m; Zone 2: 100 TOT; Zone 3: 2 to 5 year TOT.
Three zone	Albanian government (Albania)	31	Zone 1: 15 to 100 m; Zone 2: expert judgement; Zone 3: expert judgement
Four zone	Drink Adria (Boznia & Herzegovina)	32	Zone 1: 10 m; Zone 2: 10 day TOT; Zone 3: 50 day TOT; Zone 4: expert judgement
Three zone	The Croatian Parliament (Croatia)	33	Zone 1: 10 m; Zone 2: 50 day TOT; Zone 3: 5 to 25 year TOT
Three zone	Greek government (Greece)	34	Zone 1: 10 – 20 m; Zone 2: 50 day TOT; Zone 3: expert judgement
Three zone	Italian government (Italy)	35	Zone 1: 10 m; Zone 2: 60 day TOT or 200 m; Zone 3: 365 day TOT
Three zone	Montenegro government (Montenegro)	36	Zone 1: 10 m; Zone 2: 10 m to over 50 m; Zone 3: expert judgement

Catchment definition method	Organisation (country)	Ref	Comments (requirements, criteria, assumptions, etc.)
Three zone	Slovenian government (Slovenia)	37	Capture area is an independent fenced zone; Zone 1: 50 day TOT; Zone 2: 400 day TOT; Zone 3: Recharge area
Three zone	Serbian government (Serbia)	38	Zone 1: 10 m; Zone 2: 50 day TOT; Zone 3: 200 day TOT
Three zone	DVGW act [the German association for gas and water] (Germany)	39	Zone 1: min 10 m; Zone2: 50 day TOT with minimum 100 m; Zone 3: recharge area
Three zone	French Government (France)	40	Zone 1: vague, often 30 m; Zone 2: vague, often 50 day TOT; Zone 3: optional
Three zone	Federal Office for environment, forest and landscape (Switzerland)	41	Zone 1: 10 m; Zone 2: 10 day TOT, minimum 100 m ; Zone 3: minimum greater than zones 1 and 2 combined.
Five zone	Ministry for Environment and Water (Hungary)	42	Inner protection zone: 20 day TOT; Outer protection zone: 6 month TOT; Hydrogeological protection zone A: 5 year TOT; Hydrogeological protection zone B: 50 year TOT; Hydrogeological protection zone C: total recharge area.
Three zone	Federal Ministry for Economic Cooperation & Development (Arab Region)	43	Zone 1: 10 m from wellhead and at least 20 m in the upstream direction of a spring; Zone 2: 50 day TOT, but not less than 100 m from intake point (Zone 2 is undefined for aquifers with heterogeneous distribution of groundwater flow; Zone 3: whole catchment area (may be divided into subzones A & B depending on aquifer flow velocities)
Three zone	Federal Institute for Geosciences and Natural Resources [BGR] (Jordan)	44	Zone 1:10 m downstream, 15 on both sides, 25 upstream of well and 50 m for spring; Zone 2: 50 day TOT or 2km upstream and 50 to 150 m downstream; Zone 3: whore recharge zone
Three zone	The Environmental Protection Agency (Ireland)	45	Zone 1: 0 to 10 m; Zone 2: 10 to 300 m; Zone 3: 300 – 1000 m
Three zone	Environmental and Land Management Ministry (Portugal)	46	Zone 1: undefined exclusion zone; Zone 2: 20 – 50 m for high permeability terrain, or 10 – 20 m for low permeability terrain, or 5 – 10 m for areas with >50 m of impermeable cove; Zone 3: 100 – 200 m
Three zone	Ministry of the Environment (Spain)	47	Zone 1: 24 hour; Zone 2:50 day TOT for ‘porous’ aquifers, or 100 day TOT for karstic aquifers; Zone 3: recharge area
Four zone	Turkish Environment Foundation (Turkey)	48	Zone 1: 50 m for porous aquifers and 100 m for karst aquifers; Zone 2: 50 – 250 m for porous aquifers and 100 – 500 m for karst aquifers; Zone 3: recharge area; Zone 4: catchment area

Table B-2: Surface water catchment delineation examples

Catchment definition method	Organisation (country)	Ref	Comments (requirements, criteria, assumptions, etc.)
Reservoir protection zone	Department of Environment, Western Australia (Australia)	10	Public Drinking Water Supply Area (PDWSA) Priority 1 (P1): No degradation Priority 2 (P2): No increased risk Priority 3 (P3): Pollution risk managed Prohibited zones: 2 km around high water level of a reservoir (RPZ)
Two zone	Massachusetts Department of Conservation and Recreation (USA)	24	Within 400 feet of the reservoirs and 200 feet of tributaries and surface waters (the "Primary Protection Zone"), any alteration is prohibited. "Alteration" includes a variety of activities, such as construction, excavation, grading, paving, and dumping. Generation, storage, disposal or discharge of pollutants is also prohibited in the Primary Zone. Between 200 and 400 feet of tributaries and surface waters, and on land within flood plains, over some aquifers, and within bordering vegetated wetlands (the "Secondary Protection Zone"), certain activities are specifically prohibited. These include storage, disposal or use of toxic, hazardous, and certain other materials; alteration of bordering vegetated wetlands; more dense development; and other activities.
Three zone	South Dakota Department of Environment and Natural Resources (USA)	25	Zone A: 10 river miles upstream of intake and 0.5 mile buffer around water body and its adjacent aquifer Zone B: 25 mile radius from intake Zone C: remaining watershed
Two zone	Albanian government (Albania)	31	Flow waters: Zone 1: 10 m fencing around capture facility Zone 2: 200 m in upstream and downstream direction (no defined width)
Two zone	Drink Adria (Bosnia & Herzegovina)	32	Standing waters: Zone 1: fenced zone; Zone 2: 50 m from edge of water body at high water stage; Zone 3: minimum 100 m from zone 2; Stream/feed source protection if required. Flowing waters: Zone 1: 25m; Zone 2: 1000 m upstream, 50 m from banks based on 100 year high flow

Two zone (standing water) One zone (flowing water)	The Croatian Parliament (Croatia)	33	Standing waters: Zone 1: 10 m from water body from high water level; Zone 2: 100 m from water body at high water stage; Zone 3: recharge area Flowing waters: Zone 1: 10 m around capture facility
Three zone (independent for surface and flowing waters)	Italian government (Italy)	35	Standing waters: Zones 1 & 2: Up to 200 m from edge of water body; Zone 3: expert judgement Flowing waters: Zone 1: 10 m around capture facility; Zone 2: at least 200 m upstream (width determined by risk calculations) Zone 3: expert judgement
Three zone	Montenegro government (Montenegro)	36	Zone 1: 10 m; Zone 2: 100 m from water body at high water level; Zone 3: 50 m from stream or feed source
Three zone	Slovenian government (Slovenia)	37	Zone 1: 100 m; Zone 2: 20 day TOT; Zone 3: recharge area
Three zone	Serbian government (Serbia)	38	Zone 1: Water body extending 10 m from lake edge at high water level; Zone 2: 500 m; Zone 3: recharge area
Three zone	University of California Agricultural Extension Service (USA)	50	Zone A: 400 feet from reservoir and primary streams, 200 foot from tributaries Zone B: 2500 foot (762 m) from intake Zone C: remainder of watershed.
Three zone	State of Wyoming (USA)	51	Zone 1: 100 foot radius of intake Zone 2: 15 miles from intake on main stem and all perennial tributaries (or 8 hour TOT at high flow). Includes 1000 foot beyond perennial stream banks of main stem and tributaries Zone 3: remaining watershed
Three zone	Department of Environment and Local Government, New Brunswick (Canada)	52	Zone A: the watercourses specifically identified on plans Zone B: 75 metre setback Zone C: balance of watershed
Complex multi-zone	Powell River water supply, BC, Environment Canada (Canada)	53	Three zone, complex division; 100 m buffer on each side of creek, rest of watershed.

Appendix C

Contaminant types and attenuation

1.0 Contaminant types and attenuation

Technical delineation of source protection zones requires knowledge of the types of contaminants that are likely to occur in the vicinity of a supply. Typical contaminants arising from various activities are described in Table 6 in Section 4.1 of the report. Many land uses share similar or identical suites of potential contaminants. For example, agricultural land uses involving agricultural livestock, rural and lifestyle dwellings are all characterised by having nitrate, phosphorus and microbes as potential contaminants, to differing degrees and differing also in their relative proportion of point and non-point source discharges.

Transport of contaminants in surface water and groundwater systems comes with considerable uncertainties resulting from the lack of precise site-specific knowledge of the factors that control the physical processes of flow and contaminant attenuation.

An indication of how these natural processes affect contaminant migration can be achieved by numerical assessments of the migration and attenuation processes and by monitoring actual concentration reductions at increasing distances from contamination source areas.

Processes of dilution, dispersion, adsorption, sedimentation, filtration, die-off, degradation and chemical transformation with transport of contaminants in water are reviewed in this section. These numerical examples also serve as the technical backing for the time-of-travel (TOT) and distance criteria used to delineate catchment protection zones.

1.1 Microorganisms

A variety of pathogenic microorganism can be present in sources such as human sewage and agricultural wastewaters in the form of bacteria, protozoa, and viruses. The presence or absence and concentration of these microorganisms in human wastewater is highly variable and depends on the number of contributing people infected in a population.

Analytical modelling can be used to estimate the appropriate time of travel or flow distances to indicate the likely range of these factors in real groundwater systems. Prior to entering the saturated groundwater flow system there will have been contamination reduction in the vadose (unsaturated) zone, primarily determined by soil type and thickness.

The Drinking Water Standards for New Zealand 2005 (DWSNZ) use *Escherichia coli* (E. *coli*) bacteria as an indicator of faecal contamination. The DWSNZ require at least a 5 log reduction in the concentration of protozoa for water that is considered ‘high’ risk’, but do not specify a required reduction for viruses. Viruses, however, can present the greatest health concern and are present in groundwater contaminated by human wastewater. Viruses have longer survival times in soil and water than bacteria, such as E. *coli* which is used an indicator of faecal contamination. Viruses are more infectious than bacteria and protozoa, meaning that fewer virus particles are required to be ingested to cause infection.

The reduction of microorganisms in the soil and vadose zones prior to reaching groundwater is dependent of a myriad of biological and physical conditions including microorganism properties, soil type, preferential flow-paths, soil chemistry, presence of organic matter and hydrological conditions, which affect the transport and attenuation of microorganisms. Pang (2009) describes removal rates of microorganisms in the subsurface under various hydrogeological conditions in an extensive review of New Zealand and international literature. She concludes that microbial removal rates for most soil types are generally in the order of 10 log per m, this could be as little as 10^{-1} log per m for clayey soil, clay loam and clayey silt loam.

Microbial removal in aquifers is much more variable than in the soil and vadose zones, and log removal of microorganisms in fast flowing uncontaminanted gravel aquifers can be as little as 10^{-2} log per m. It is also noted, that under specific conditions of continuous effluent loading, aquifers may exhaust their capababilities to achieve such reduction. Pore-water velocity is the greatest contributing factor for affecting microbial removal rates in aquifers. Pang (2009, p. 1548) states that *"pore-size exclusion in heterogenous large-pore aquifers and retardation in low-flow aquifers could lead to the velocities of microbial travers being quite different from those of conservative solute tracers".*

These removal rates can be applied to delineation of groundwater protection zones through the derivation of setback distance requirements. The USEPA and the Dutch drinking water regulations sets out criterion of no more than 1 in 10^4 microbiologically caused illness per year (achieved to 95% certainty) which equates to a maximum allowable value (MAV) of 2 x 10^{-7} viruses / L. This same infection criterion was applied by Blaschke et al. (2016) to determine setback distances between on-site wastewater treatment systems and drinking water wells against virus contamination in alluvial aquifers. A dose-response relationship was used with expected concentrations of virus particles in raw wastewater to determine a concentration in drinking water of ≤ 3.4 x 10^{-7} total virus particles/L to fulfil the criterion. A value of 2 virus particles was determined from the literature as the minimum infectious dose based on rotavirus infectivity. A resulting 12 log reduction of enteric virus particles was determined to be necessary. Modelled results found setback distances ranging 39 – 144 m in sand aquifers, 66 – 289 m in gravel aquifers, and 1 – 2.5 km in coarse gravel aquifers. These results, however, do not agree with Schijven, et al.(2006), where protection zones ranging 206 – 418 m were determined to achieve the same 10^{-4} per person per year risk of infection. In terms of time of travel (TOT), these distances equate to 1 – 2 years. Table C-1 gives a comparison of comparison of previously reported setback distances based on virus transport.

Under the specific context of New Zealand hydrogeological conditions, Moore et al (2010), model setback distances for on-site wastewater treatment systems to groundwater wells based on the current knowledge of microbial transport. They use an even more conservative approach, requiring an overall 16.2 $\log_{10}$ for rotavirus to achieve the same 10^{-4} per person per year infection risk. These guidelines use a 2.7 $\log_{10}$ reduction assuming reduction in the septic tank, disposal field and 1 m of underlying soil, therefore requiring a 13.5 $\log_{10}$ in the vadose and aquifer. For coarse gravel aquifers, the calculated setback distances translate to very large distances in terms of average TOT.

The necessary reduction in microorganisms required to achieve the infection risk criterion of 10^{-4} per person per year can translate into extensive and sometime impractical requirements for protection zones. Smaller protection zones are possible if further proof of reduction in virus concentration is demonstrated either through enhanced removal through unsaturated zone transport, or if there are more attachment sites present to aid removal (Schijven et al., 2006). Additional reduction can also be achieved by application of an appropriate treatment level for the wastewater discharge.

Table C-1: Previously reported setback distances in groundwater based on virus transport (adapted from Blaschke et al., 2016, Table 2, p 283)

Reference	Aquifer media and study area	Reduction in concentration	Criteria	Reduction mechanisms	Method	Setback distance (m)
Yates and Yates (1989)	Tucson Basin, unspecific aquifer	7 $\log_{10}$ reduction in viruses	-	Inactivation	Modeling	15 – 300
Berger (1994)	Sandy loam, groundwater 10–15 °C	11 $\log_{10}$ reduction in viruses	<2 × 10^{-7} virus/L so that virus infection <10^{-4}/p/y	Inactivation	Modeling	160 – 325
Pang et al. (2004)	Uncontaminated pumice sand aquifer, Rotorua, New Zealand	10 $\log_{10}$ reduction in viruses for drinking water 5 $\log_{10}$ reduction in E. coli for recreation water	<1 virus/100 L in drinking water <126 E. coli/100 mL for recreation water	Total removal	Modeling	48
Gunnarsdottir et al. (2013)	Coarse aquifer media at 5 °C	9 $\log_{10}$ reduction in Noroviruses	<1.8 × 10^{-7} virus/L so that virus infection <10^{-4}/p/y	Total removal	Modeling	900
Pang et al. (2005a); Pang et al. (2005b)	Sand and gravel aquifers	7 $\log_{10}$ reduction in viruses and faecal bacteria	zero virus/100 L, zero faecal bacteria/100 mL	Total removal	Experimental	33 – 3889[17]
Schijven and Hassanizadeh (2002); Schijven et al. (2006)	Sand aquifer, the Netherlands	9 $\log_{10}$ reduction in viruses	<1.8 × 10^{-7} virus/L so that virus infection <10^{-4}/p/y	Total removal	Modeling	153 – 357 206 – 418
van der Wielen et al. (2006)	Oxic and anoxic sand aquifers, the Netherlands	8.8 $\log_{10}$ reduction of Enterovirus and 9.3 log10 reduction of Reovirus	virus infection <10^{-4}/p/y	Total removal	Modeling	54 – 84 oxic aquifer, 276 anoxic aquifer

[17] Larger distance related to contaminated aquifers

van der Wielen et al. (2008)	Anoxic coarse sand aquifer, the Netherlands	-	$<1.2 \times 10^{-6}$ virus/L so that virus infection $<10^{-4}$/p/y	Total removal	Modeling	110
Abbaszadegan et al. (2003)	Limestone aquifer, USA	Samples that were tested positive with cell culture and RT-PCR were analysed for the distance to a source of contamination			Experimental	1000
Masciopinto et al. (2007)	Fractured limestone aquifer, Italy	-	-	-	Experimental & modeling	3000
Masciopinto et al. (2008)	Fractured limestone aquifer, Italy	7 $\log_{10}$ reduction in viruses	Simulated lowest removal rate 0.1±0.06 d^{-1}, groundwater velocity V= 50 m/d	Total removal	Modeling	8000 ± 4800
Moore et al. (2010)	Various hydrogeological settings, New Zealand	16.2 $\log_{10}$ for rotavirus or 11.1 $\log_{10}$ for heptatis A virus	$<7.9 \times 10^{-7}$ rotavirus or $<2.0 \times 10^{-6}$ hepatitis A virus	Total removal	Modeling	Various. Refer to log reduction Table 1 – 50 in guideline
Kvitsand et al. (2015)	Norwegian riverbank fieldsite	8.7 $\log_{10}$ reduction in viruses	$<1.8 \times 10^{-7}$ virus/L so that virus infection $<10^{-4}$/p/y	Dilution, dispersion, irreversible attachment	Modeling	174
Blaschke (2016)	Sand, gravel and coarse gravel aquifers, the Netherlands	12 $\log_{10}$ reduction in viruses	$\leq 3.4 \times 10^{-7}$ virus/L so that virus infection $<10-4$/p/y	Total removal	Modeling	39 – 114 m in sand aquifers. 66 – 289 in gravel aquifers. 1 – 2.5 km in coarse gravel aquifers

1.2 Hydrocarbon

In groundwater, hydrocarbon spillages are physically distributed as soil gas, separate phase, and dissolved in water. Within the groundwater environment, microbial and redox reactions degrade hydrocarbons. In addition, hydrocarbons are likely to adhere to clay-sized particles and be trapped in minute pore spaces by surface tension.

In groundwater systems, unless concentrations or quantities of hydrocarbon are very low, separate phase hydrocarbons may exist, floating on the groundwater table. Separate phase hydrocarbons represent biochemical oxygen demand (BOD), and have the ability to lower the redox potential in the groundwater, making other materials more soluble, especially metals such as iron and arsenic.

Examples of hydrocarbon discharge, such as from a leaking storage tank, into groundwater systems indicate that natural attenuation plays an important role in controlling down-gradient water quality. Two examples (Vidovich *et al.* 2001), involving over 10 000 litres of gasoline in each, indicated that dissolved gasoline was monitored at concentrations of concern in wells up to 150 m from the spill, and at lower levels (down to detection level) up to 450 m from the source. The zone of affected groundwater is limited to a few hundred metres down gradient from the spill.

In flowing surface water, hydrocarbons attenuate by a combination of evaporation, dispersion and dilution. A spill of about 10 000 litres of diesel in the Heathcote River, Christchurch, in February 2005 travelled a length of 15 km within hours. Whilst much of the diesel was pumped out of the river, mopped up or evaporated, had gasoline (petrol) been spilled, the discharged material would have evaporated more quickly, but also dissolved into the flowing water more readily. Therefore, competing mechanisms of attenuation by evaporation and dilution characterise hydrocarbons of contrasting composition.

1.3 Dissolved chemicals

Experiments and documented examples of nitrate and chloride plumes emanating from sources such as landfills support the theoretical basis for our understanding of how dispersion and degradation occurs in groundwater systems.

Groundwater containing dissolved contaminant chemicals such as nitrate, chloride, arsenic and agricultural chemicals is relatively common, though the concentrations are rarely of concern except in localised areas. A range of mechanisms attenuate chemical concentrations in groundwater. For example, although nitrate is a conservative chemical, its concentration in downward-migrating nitrogen-rich water from the soil layer will be reduced on reaching the water table by mixing with flowing groundwater, provided background concentrations are lower. In contrast, positively charged chemicals such as metal ions (Cu, Zn, As) are readily adsorbed onto negatively charged surfaces of sedimentary particles within the subsurface environment. Biological or chemical transformation in addition to dispersion and filtration can reduce concentrations even further.

Examples of migration of pesticides in the groundwater zone includes work carried out in Waikato. There, dieldrin has been previously recorded at levels of 3 times the MAV, reflecting its persistence and historical use.

Exceedances of the MAV for nitrate-nitrogen at a number of sites around New Zealand indicate that non-point source nitrate contamination is not being attenuated sufficiently to reduce concentrations in groundwater to acceptable levels. Dispersion is in general not an effective attenuation mechanism for nitrate in non-point-source discharge situations. This is partly due to the loading of the groundwater system with nitrate, and the slow groundwater flow velocities. Nitrate concentrations require a catchment-wide approach to management.

These examples show that whilst attenuation of contaminants can and does occur, the degree of attenuation is largely dependent on the rate of groundwater flow. In slow flowing groundwater systems, dissolved contaminants may pose a problem through not being flushed from beneath the site of contamination and accumulate there with little attenuation down-gradient. In fast flowing groundwater systems, contaminants are rapidly flushed from beneath the site and down-gradient concentrations can quickly attenuate. However, the resulting concentrations may still pose a risk to down-gradient receptors.

1.4 Soluble metals, entrained micro-organisms and sediment

Sediment is not itself toxic but may decrease the efficiency of water disinfection processes for surface water or groundwater takes with a high degree of hydraulic connection to surface water by increasing turbidity. Furthermore, in flowing surface water, metals and other conservative dissolved contaminants, as well as entrained micro-organisms, are likely to attenuate by dispersion, dilution, or adsorption onto suspended sediment, which then may settle to the stream bed. Where adsorption is the chief means of contaminant removal, there is a risk that the material could be re-suspended during the next fresh or flood and again become mobilised towards a water supply intake.

Flowing water is unlikely to allow suspended sediment to settle, therefore most intakes of drinking water require removal by filtration. Protection zones will not prevent periods of high turbidity, but good management practices on land use within a catchment can reduce this, for example for forestry and earthworks.

1.5 Attenuation as a mechanism for achieving target reduction

The preceding examples indicate the various processes of natural attenuation that can operate to reduce contaminant concentrations prior to water abstraction for drinking water supplies.

Monitoring of actual contaminated sites, and associated modelling indicate that the time of travel (TOT) concept, representing a distance-related mechanism, can in cases achieve the desired concentration reduction by means of natural attenuation processes.

As a conclusion to this section, the following management principles follow from the nature of the physico-chemical processes involved in attenuation.

- Both generic and site-specific protection zone delineation mechanisms should take into account natural attenuation to reduce contaminant loads received at public water supply intakes.
- Delineation of catchment zones must also provide response time for water supply operators to close intakes and find substitute supplies

Appendix D

Theoretical default protection examples

MINISTRY FOR THE ENVIRONMENT - TECHNICAL GUIDELINES FOR DRINKING WATER SOURCE PROTECTION ZONES

FIGURE 1 : DRINKING WATER PROTECTION ZONES: RIVER EXAMPLE

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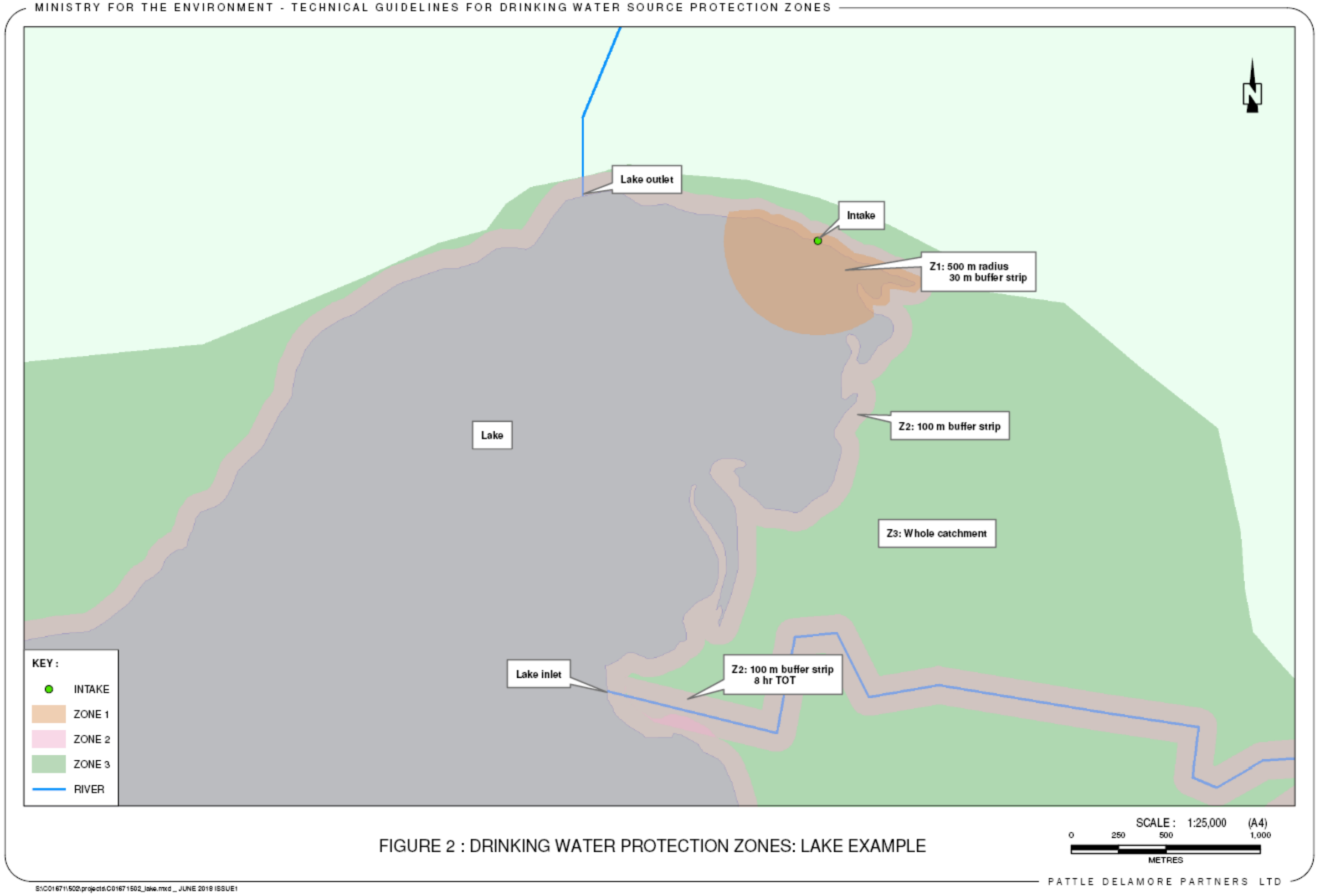

FIGURE 2 : DRINKING WATER PROTECTION ZONES: LAKE EXAMPLE

FIGURE 3 : DRINKING WATER PROTECTION ZONES: CONJUNCTIVE ZONE

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