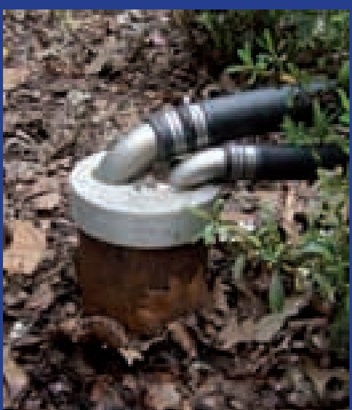
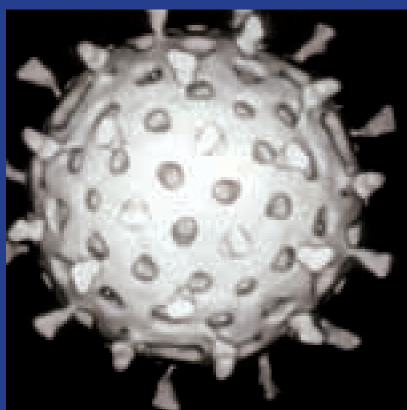
ESR

Guidelines for separation distances based on virus transport between on-site domestic wastewater systems and wells





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Supported by envirolink

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Summary

PART 1

The Issue

The discharge of domestic wastewater to ground and the proximate abstraction of groundwater for domestic purposes can contaminate drinking water. Regional councils need to consider these situations when implementing the National Environmental Standard (NES) for Sources of Human Drinking Water (NZ Government, 2007). Separation distances between wastewater discharges and groundwater abstractions must be established to reduce the likelihood of contamination. Some regional councils have specified separation requirements based on the transport of bacteria. Others have separation requirements with an uncertain scientific basis, and yet others have no separation requirements. Importantly, none of the existing separation distances allow for the influence of different subsurface materials on the transportation of viruses through the ground.

Using bacterial rather than viral transport as the basis for guidelines is a shortcoming for two main reasons. The survival characteristics of viruses favour their transportation over long distances in aquifers, and their high infectivity means they can cause disease, even though their numbers may have been substantially reduced during transport. Further, virus concentrations are reduced more effectively by some subsurface materials than others. The use of arbitrary separation distances that take no account of differences in these materials may over- or under-protect water resources.

Consequently, there is a need for a tool that establishes separation distances that are safe with respect to the more robust pathogens such as viruses, and can be used in different hydrogeological settings throughout New Zealand.

The Guidelines

The *Guidelines for Separation Distances Based on Virus Transport between On-site Domestic Wastewater Systems and Wells* (the Guidelines) calculates separation distances for domestic on-site wastewater treatment systems based on virus movement and removal in the subsurface environment. The document provides a process and tables of calculated data, which, in conjunction with the specifics of a particular location, allow safe minimum separation distances (or the required log reduction in virus concentration) to be estimated.

The guidelines establish scientifically defensible separation distances under a range of conditions throughout New Zealand. This flexibility is achieved by taking account of the extent to which different factors influence reductions in virus concentration. The factors include: the type and thickness of soil; the thickness of the vadose zone and the nature of the materials comprising it; and the nature of the materials comprising the aquifer.

Uncertainty is always associated with these types of calculation. This is due to the stochastic nature of subsurface processes, the intrinsic variability of the physical parameters required in the modelling, and the paucity of data on which to base estimates of modelling parameters. The Guidelines takes account of the uncertainty and present modelling results at a 95% level of confidence. This is done through stochastic modelling, using Monte Carlo techniques that allow modelling parameters

to take a range of values. This approach provides model outputs with a distribution of values from which a guideline can be obtained with the required level of confidence.

Development of the Guidelines

The guidelines were developed by taking account of the reduction in virus concentrations that occur in the sewage tank, the disposal field and soil, the vadose zone and the groundwater. The overall reduction in virus concentration that has to be achieved by the four components of the system was established from the initial virus concentration entering the sewage tank, and the maximum acceptable virus concentration in the groundwater at the well. The latter concentration was calculated to result in an annual probability of infection of 1 in 10,000. The United States Environmental Protection Agency (USEPA) uses this probability to establish water quality requirements, and it has been adopted internationally by other jurisdictions.

Adenoviruses, enteroviruses, hepatitis A virus, noroviruses and rotaviruses were considered as the basis for calculating the overall reduction in virus calculation that must be achieved. These viruses and virus groups were chosen because of their potential for waterborne transmission. The final separation distances given in the Guidelines are based on rotavirus and hepatitis A virus. Rotaviruses were selected because they are among the most infectious viruses and are shed at the greatest concentrations by infected individuals. Consequently, the degree of reduction they must undergo is the greatest. Hepatitis A virus was selected because the consequences for an individual of infection by this virus can be the most severe. Providing separation distances for rotaviruses and hepatitis A virus gives regional councils the flexibility to select the basis on which they set their separation distances.

The complexity of the calculations, and in some instances the lack of data on which to base the calculations, required assumptions to be made to make the problem of modelling tractable. These are discussed in Section 5.8. The Guidelines also have limitations, discussed in Section 6. These arise because of the assumptions made and the scope of work encompassed by the project specifications.

PART 2

Who should use the Guidelines

The guidelines are useful to several types of organisation.

i) **Regional councils** for informing the development of policies and rules in regional plans; implementation of the NES for Sources of Human Drinking Water; and informing actions for implementing the National Policy Statement for Freshwater Management.

ii) **District councils** for informing the development of rules within their district plans and the implementation of the requirements of the Local Government Act 2002 and the Building Act 1994.

iii) **Drinking water supply authorities** for implementing those parts of the Health [Drinking Water] Amendment Act 2007 (HDWAA) that require water suppliers to protect their source waters from contamination.

iv) **Public health agencies** for implementing their powers and responsibilities under the HDWAA relating to contamination of water supply source waters.

v) **On-site wastewater system manufacturers and providers** for evaluating the efficacy required of their systems in order that separation distances can be reduced to meet the Guidelines.

How to use the Guidelines

The flexibility that allows consideration of different subsurface materials and different vadose zone depths created a large number of tables that contain the modelling results. While the processes by which these results were obtained are complex, the use of the results to derive a separation distance for a particular location is not. Section 8 of this document provides *pro forma* templates that guide the user through the calculations to a final separation distance or calculation of the overall decimal log (log_{10}) reduction in virus concentration if that is required. Worked examples are provided.

PART 3

The Technical Appendix

Part 3 of the Guidelines explains the details of the modelling approach used to develop the guideline values presented in Part 2. In doing this it aims to:

- allow the approach taken to be assessed, thereby supporting the scientific defensibility of the guideline information provided in Part 2
- provide information that will allow this work to be extended when more data become available, thereby broadening the applicability of the guidelines and increasing their robustness.

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PART 1

Development of the Guidelines

PART 1 – Development of the Guidelines

1 Introduction

The *Guidelines for Separation Distances Based on Virus Transport Between On-site Domestic Wastewater Systems and Wells* (the Guidelines) has been developed in recognition of the need for pragmatic tools to identify areas and specific locations where the discharge from an on-site domestic wastewater system could pose a risk to the quality of drinking water. The document provides a process and tables of calculated data, which, in conjunction with the specifics of a particular location, allow a safe minimum separation distance or the required $\log_{10}$ reduction in virus concentration, to be estimated.

The Guidelines can assist regional councils and other organisations to consider and establish scientifically defensible separation distances between the discharges from on-site domestic wastewater disposal systems and shallow wells used for drinking water.

The separation distances have generally been calculated from worst-case scenarios based on the likely presence of viruses in wastewater, virus transport in soils, subsurface media and groundwater in a range of hydrogeological settings found in New Zealand. However, there are some instances where more typical values have been selected to yield results applicable to a much greater portion of the country. Where a council considers that the input parameter values used in the modelling are inapplicable to an aquifer in their region, they may wish to use the Guidelines for preliminary guidance and modify the separation distance given their knowledge of the particular aquifer.

The development of the Guidelines has combined findings from relevant international literature, with the best available field data, analytical methods and mathematical modelling approaches, to produce a technically robust tool with direct application for use throughout New Zealand.

The Guidelines is in three parts.

- Part 1 – Provides background on why the guidelines have been developed, and an outline of how the Guidelines have been developed.
- Part 2 – Gives guidance on the use of the Guidelines: who might use the document, and how to use it, based on *pro forma* worksheets supported by worked examples.
- Part 3 – Provides discussion on the technical details of the modelling and literature data that form the basis of the Guidelines.

Users of the Guidelines are assumed to have a basic understanding of the operation of on-site wastewater systems. For those without this knowledge, publications such as the Auckland Regional Council's Technical Report No.58 (TP58) *On-site wastewater Systems: Design and Management Manual*, or Northland Regional Council's on-line guide to *Septic Tanks and Sewage Systems*[1], may be helpful.

[1] http://www.nrc.govt.nz/Resource-Library-Summary/Publications/Waste/Septic-tanks-and-sewerage-systems/

2 What is the issue?

Aquifers are sources of drinking water for many households and communities in New Zealand. All regions of New Zealand have groundwater resources that are used as sources of domestic water for some dwellings. About 50,000 wells are registered on regional council databases as used for domestic water supplies, and it is likely that this is only about half of the total number of wells used for domestic supplies, as many are not registered[2].

There are about 270,000 on-site domestic wastewater systems in New Zealand[3]. Most households that have a private water supply well also have an on-site wastewater system. The well and the on-site wastewater system for a dwelling are often located in close proximity to the dwelling, and to each other. The wells and on-site domestic wastewater systems of neighbours may be close by, particularly in small rural settlements and areas of rural-residential housing and lifestyle blocks. Domestic wells generally access shallow groundwater, or where deeper groundwater is the source of supply, this is usually from an unconfined aquifer. In both situations the water quality is vulnerable to contaminants discharged from on-site domestic wastewater systems.

The drinking water taken from private domestic wells in New Zealand is, in almost all instances, not treated before use. Many small community water supplies do not have water treatment. A survey of a sample of small water supplies (serving less than 500 people in residences, small institutions and commercial users such as schools, marae, hospitals, hotels and restaurants, all located outside urban areas) undertaken for the Ministry of Health in 2002, showed that half of small water supplies are sourced from groundwater, but that only one-third of these systems had any form of treatment for microbiological contaminants[4].

For a developed country, New Zealand has some of the highest notifiable disease rates for diseases that are potentially waterborne, e.g. campylobacteriosis (159.9 cases/100,000 population[5]). Furthermore, such rates are likely to be under-reported by a factor of between 10 and 100. This was adversely commented on by the OECD in 2007[6].

A wide range of disease-causing microorganisms (pathogens) can be present in sewage. Three broad classes of pathogens are recognised as being a threat to human health: bacteria (e.g. *Campylobacter*), protozoa (e.g. *Cryptosporidium*) and viruses (e.g. hepatitis A virus). The presence or absence of these organisms in sewage depends on the number of infected people in the contributing population. In large populations common pathogens will almost always be present. In dwellings with on-site wastewater treatment and disposal systems, there may be extended periods during which pathogens are absent in the sewage because none of the occupants are infected. However, a household with infected occupants will produce sewage effluent that contains pathogens.

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2 Personal communications and data from groundwater staff of 11 regional councils and three unitary authorities.

3 *Proposed National Environmental Standard for On-site Wastewater Systems Discussion Document* Ministry for the Environment July 2008.

4 *New Zealand Small Water Systems Surveys* New Zealand Water Environment Research Foundation, August 2002.

5 *ESR New Zealand Public Health Surveillance Report*, June 2009, Vol. 7, ESR, available at: http://www.surv.esr.cri.nz/surveillance/NZPHSR.php

6 *OECD Environmental Performance Review of New Zealand*, OECD 2007.

The pathogens in faecal matter present a range of health risks, but viruses present the greatest health concern because they:

- are present in groundwater contaminated by sewage
- are environmentally robust so are expected to survive longer in the soil and water environment than bacteria. Longer survival may mean viruses remain infective after being carried longer distances than other pathogens in groundwater
- are highly infectious, more so than bacteria or protozoa. Ingestion of a very small number of viruses can cause infection, although the infective dose depends on the virus species
- can be resistant to disinfection processes, and have been detected in drinking water that met acceptable specifications for treatment and levels of conventional indicator organisms.

On-site domestic wastewater systems are designed to process human excreta and domestic wastewater. A wide variety of systems is in use in New Zealand including conventional septic tanks, aerated treatment units, sand filters, and constructed wetlands. Most on-site domestic wastewater systems discharge the effluent from the treatment system into land where further treatment occurs due to adsorption to soil particles and microbially-mediated processes. Land application systems include: field-tiles, boulder pits, absorption trenches, absorption or evapo-transpiration beds, mounds, surface or sub-surface irrigation.

Viruses in wastewater adsorbed to soil and subsurface media can be transported in water as it passes through these materials into the groundwater. The number of viruses in the wastewater will be reduced as it moves through the soil and sub-surface media. However, investigations show that significant concentrations of viruses may still enter groundwater, and be carried along with it.

The nature of soil and aquifer environments varies throughout New Zealand. The risk of groundwater contamination from viruses in wastewater from on-site domestic wastewater systems varies with these environments. The Guidelines considers a range of soil types and hydrogeological settings and provides separation distances to achieve an acceptable level of risk of infection from viruses in untreated drinking water sourced from shallow groundwater.

3 Scope of the Guidelines

The Guidelines:

- determines the target reduction in virus concentration necessary between the sewage tank and the abstracting well to reduce the virus concentration to an acceptable level
- calculates the reductions in virus concentrations predicted for a range of vadose and saturated zone hydrogeological conditions at differing groundwater depths and separation distances
- provides guidance on determining the adequacy of an existing separation distance, and determining an adequate separation distance for a proposed development
- provides guidance on the virus reduction efficiency required in wastewater treatment systems where separation distances cannot be achieved.

The scope of the Guidelines is limited to addressing the potential impact on drinking water quality in nearby shallow wells from viruses discharged from an on-site domestic wastewater treatment system serving one household. While the likelihood of viruses being present in the sewage from a dwelling is low, the infection of other household members or neighbours through their drinking water source can have significant consequences for those infected. Implementation of the Guidelines will ensure that, in the event of an outbreak of a viral waterborne disease, people who rely on a domestic well water supply will be adequately protected from infection at least 95% of the time.

A range of hydrogeological settings found in New Zealand is described, and separation distances are calculated based on the best available information for each setting. However, the data available vary in quantity and quality across the range of hydrogeological settings. Poor data increase the uncertainty in the separation distance calculations. Consequently, the poor data for some hydrogeological settings are reflected in correspondingly greater separation distances.

On-site domestic wastewater systems vary in their effectiveness at reducing virus concentrations in the wastewater. The Guidelines provides conservative generic estimates of virus removal by two types of wastewater system, but does not assess the effectiveness of existing or future wastewater systems to remove viruses.

Note:
The Guidelines DOES NOT address impacts on groundwater quality from:

- clusters of on-site domestic wastewater systems or
- community sewage treatment and discharge systems or
- a well pumping more water than would be used in a single dwelling.

The Guidelines CANNOT be used to establish separation distances between a well and

- multiple on-site domestic wastewater systems or
- on-site wastewater systems discharging sewage effluent collected from more than a single dwelling or
- on-site wastewater systems discharging sewage effluent collected from facilities such as schools, hospitals, marae, restaurants and camp grounds.

4 The viruses

4.1 Introduction

Well water is more likely to be contaminated by viruses than by bacteria from an on-site wastewater system. The greater infectivity of viruses contributes further to the health risk posed by viruses. For these reasons, the calculations in the Guidelines protect against viruses as well as bacteria.

A waterborne virus and four potentially waterborne virus families were considered for the Guidelines: adenoviruses, enteroviruses, hepatitis A virus, noroviruses and rotaviruses. These were selected because the international literature[7] and public health authorities recognise them as actual, or potential, waterborne viruses that could cause illnesses in New Zealand, including non-bacterial gastroenteritis and hepatitis A.

This section provides basic information about the five virus groups, including the symptoms of any associated illness following infection[8]. Advice should be sought from the appropriate district health board if further information about viruses is required.

4.2 Adenoviruses

Adenoviruses infect a wide range of mammals, birds and amphibians, as well as humans. The types of the virus that infect humans are about 80–90 nm (10^{-9} m) in diameter. Information about the prevalence of adenoviruses in drinking water sources is very limited.

These viruses cause a range of infections of the gastrointestinal tract, respiratory tract, urinary tract and the eyes, and are an important source of childhood gastroenteritis. They most commonly cause respiratory illness, but enteric (intestinal) adenoviruses are a major cause of gastroenteritis worldwide.

The diversity of adenoviruses species means that infection is possible by a number of routes. Consuming food or water contaminated by the virus may be an important source of gastro-enteric illness, although there is no substantial evidence supporting this transmission route. Epidemics of febrile disease (disease characterised by fever) with conjunctivitis are associated with waterborne transmission of some adenovirus types through contact recreation (e.g. inadequately chlorinated swimming pools and small lakes).

The infective dose is believed to be low. Infants and children are the most susceptible to adenovirus infections, many of which are asymptomatic. Immunocompromised people are especially susceptible to severe complications of adenovirus infection.

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[7] For example, *Guidelines for Drinking-water Quality,* Vol.1, *Recommendations,* 3rd Ed, World Health Organization, Geneva, 2004.

[8] The information is summarised from the WHO *Guidelines for Drinking-water Quality* (WHO, 2004) and the following:
CDC, #1 http://www.cdc.gov/ncidod/dvrd/revb/respiratory/eadfeat.htm, accessed 26-11-08.
CDC, #2, http://www.cdc.gov/ncidod/dvrd/revb/enterovirus/non-polio_entero.htm, accessed 26-11-08.
CDC, #3, http://www.cdc.gov/ncidod/dvrd/revb/gastro/norovirus-factsheet.htm accessed 26-11-08.
CDC, #4, http://www.cdc.gov/rotavirus/about_rotavirus.htm, accessed 26-11-08.

Adenoviruses are exceptionally resistant to disinfection processes, most notably ultraviolet (UV) irradiation.

4.3 Enteroviruses

Enteroviruses include several members that infect humans: poliovirus, coxsackievirus, echovirus and enterovirus. Other enteroviruses infect non-human animals. Enteroviruses are among the smallest known viruses, being 20–30 nm (10^{-9} m) in diameter.

The enteroviruses are the second most common causes of human infection (common cold viruses are the most common). They cause a broad range of illnesses, from mild fever to myocarditis, meningoencephalitis, poliomyelitis, herpangina, diabetes, hand-foot-and-mouth disease and neonatal multi-organ failure. The virus can persist in chronic conditions such as polymyositis, dilated cardiomyopathy and chronic fatigue syndrome.

Most enterovirus infections, particularly in children, are asymptomatic, but still lead to the excretion of large numbers of viruses, which may cause clinical disease in other individuals. Usually there are no long-term complications.

Predominant routes of transmission are by person-to-person contact and inhalation of airborne viruses or respiratory droplets. Transmission from drinking water could also be important, but this has not yet been confirmed. Waterborne transmission of enteroviruses (coxsackievirus A16 and B5) has been epidemiologically confirmed for only two outbreaks, and these were associated with children bathing in lake water in the 1970s.

Enteroviruses have been detected in drinking water supplies that met accepted specifications for treatment, disinfection and levels of conventional indicator organisms.

Immunity is imparted by infection, but is specific to a particular type of enterovirus.

4.4 Hepatitis A virus

The hepatitis A virus is the same shape and size as the enteroviruses, i.e. 20–30 nm (10^{-9} m) in diameter. Hepatitis A is very infectious. The virus enters the bloodstream via the intestinal tract and is carried to the liver where it may cause severe damage to liver cells.

In as many as 90% of cases, particularly children, infection may cause little, if any, liver damage and may pass without clinical symptoms. Illness has a sudden onset and includes symptoms of fever, malaise (feeling vaguely unwell), nausea, anorexia, abdominal discomfort and eventually jaundice. Repair of the liver damage is slow and may incapacitate the patient for six weeks or more. The mortality rate from Hepatitis A infection is less than 1%, but in general the severity of the illness increases with age, with mortality being highest in those over 50 years of age. Infection imparts lifelong immunity.

There is strong evidence that water contaminated with faeces is a common source of the virus. Evidence for infection through drinking water is the strongest of all the viruses.

4.5 Norovirus

Norovirus is a member of the calicivirus family. Noroviruses are 25–40 nm (10^{-9} m) in diameter. They are a major cause of gastroenteritis in all age groups, and are believed to be the most common cause of non-bacterial gastroenteritis outbreaks.

Symptoms of gastroenteritis from norovirus infection include nausea, vomiting and abdominal cramps. Usually about 40% of infected individuals present with diarrhoea, and some have fever, chills, headache and muscular pain. Gastrointestinal symptoms are usually mild and last from 24–72 h.

The primary transmission route of noroviruses is faecal-oral (faecal particles of one host are transmitted to the mouth of another). Transmission also occurs by person-to-person contact, and through airborne particles of vomit contaminating surfaces or entering the mouth and being swallowed. There is no evidence of infection through the respiratory system. Outbreaks of norovirus illness have been associated with contaminated drinking water, ice, water on cruise ships and recreational waters. However in the USA, of the outbreaks of norovirus reported between July 1997 and June 2000, only 3% were determined to be waterborne, while 57% were foodborne.

Susceptibility is widespread, and the infective dose is very low. Volunteer studies have shown that long-term immunity is variable. Immunity may be strain-specific and lasts only a few months.

4.6 Rotavirus

Rotavirus are spherical with a diameter of about 60–80 nm (10^{-9} m). Some subgroups of the genus specifically infect humans, while others infect a range of animals other than humans. Human rotaviruses are the most important single cause of infant death in the world. Typically they are responsible for 50–65% of cases of acute gastroenteritis of hospitalised children.

Acute infection has an abrupt onset of severe watery diarrhoea with fever, abdominal pain and vomiting. It is occasionally associated with severe dehydration and death in young children, if the infection is not appropriately treated. Diarrhoea caused by rotavirus is generally more severe than that caused by other agents. Symptoms last for three to eight days. Infection is seasonal in temperate climates. The rate peaks during the cooler months.

The virus is transmitted by the faecal-oral route. Person-to-person transmission and inhalation of airborne viruses seem to be much more important routes of infection than ingestion in food or water.

Susceptibility to infection is greatest between 6 and 24 months of age. By 3 years of age most individuals have acquired immunity to further infection.

There is some evidence that rotaviruses are more resistant to disinfection than other enteric viruses and *Escherichia coli*. As a result, *E. coli* measurements may not be a reliable indicator of the presence or absence of rotaviruses..

4.7 Viruses selected for separation distance assessment

Of the waterborne viruses considered in Sections 4.2.1-4.2.5, only hepatitis A virus and rotavirus were selected for the simulation modelling used to develop the recommendations in the Guidelines. This was to simplify the decisions required in using the Guidelines.

Rotavirus is highly infectious, and shed at high concentrations in the faeces of an infected individual. These characteristics mean that, all other things being equal, the separation distances required to reduce rotavirus to a satisfactory level will be greater than for any other virus considered. The calculation of separation distances based on rotavirus, therefore, will ensure satisfactory protection against *all* the viruses considered.

It is possible that for *some* hydrogeological settings, the separation distances calculated on the basis of rotavirus are impracticable. In these cases the calculation of separation distances based on one of the other viruses is required. From consideration of Sections 4.2-4.6 hepatitis A virus was selected because of the more severe illness it can cause: damage to the liver, the prolonged period for the liver to heal, and its estimated 1% mortality rate.

The calculation of separation distances based on hepatitis A virus, therefore, will ensure satisfactory protection against the most severe illness, but may not provide the same level of protection against the viruses that produce less severe illnesses.

Thus, the Guidelines provide the user with the information needed for deciding about the trade-off between the separation distance and the potential consequences of infection (also see Section 8.2). <u>The user should consult with the appropriate district health board if considering basing the calculation on hepatitis A virus.</u>

5 How have the Guidelines been developed?

5.1 Introduction

Viruses can survive sewage treatment processes, and be transported in water moving down through the soil and the unsaturated material beneath, then laterally with groundwater flow. The concentration of viruses is reduced at each stage of the transportation process. If groundwater containing viruses is abstracted from a well used for domestic water supply, the viruses can be ingested via drinking water, food washed in the water or water used for hygiene purposes. Once ingested, the viruses may cause illness in the new host.

The development of the Guidelines includes an estimation of the reduction in virus concentrations in each of four components of the virus transport process, based on a review of the international literature and experimental data from New Zealand (Fig. 5.1)

1. the sewage tank (wastewater treatment tank)
2. the wastewater disposal field and the soil beneath the disposal field
3. the unsaturated (vadose) zone above the water table and
4. the groundwater as it flows through the aquifer.

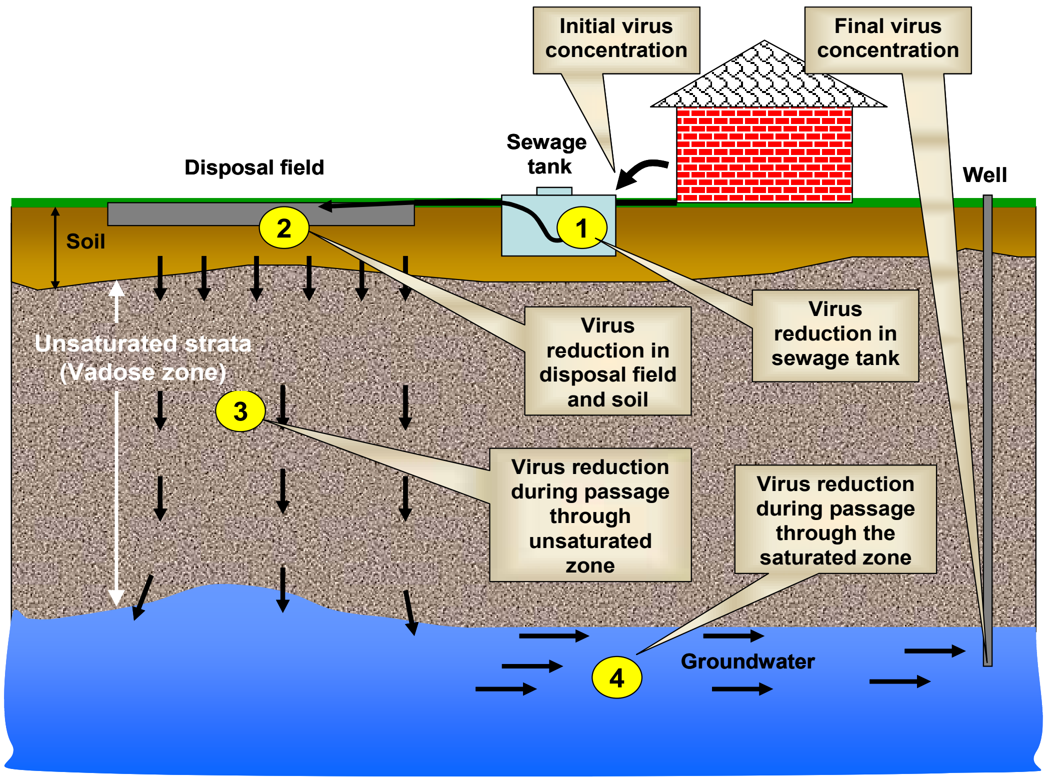


Fig. 5.1 **Components of virus removal between the sewage tank and abstraction point. Note: well is directly down gradient of the disposal field.**

The initial concentration of viruses entering the sewage tank and the maximum acceptable concentration in the well water determine the overall reduction that must be achieved.

The procedure by which these four pieces of information are brought together is set out in the worksheets provided in Section 8.4.

This section outlines how the Guidelines were developed, including background on the project team.

5.2 The project team

The project team consisted of seven members who together brought to the project expertise in the areas of groundwater science, groundwater modelling, drinking water quality, planning, and the needs and workings of regional councils.

Catherine Moore (ESR/Butler Partners[9]) has 19 years of experience in groundwater modelling as a researcher and groundwater consultant, and from a regional council perspective (Environment Canterbury). She recently completed a PhD on the incorporation of uncertainty analysis into groundwater modelling and its implication for groundwater management, and has taken workshops on incorporating this approach into groundwater management in New Zealand.

Chris Nokes (ESR) has 25 years of experience as a water quality scientist and has worked in the areas of drinking water quality, water treatment and water supply risk management. As a member of the Ministry of Health's Expert Committee on Drinking-Water Quality he has been involved with the preparation of two editions of the *Drinking-water Standards for New Zealand* (DWSNZ) and guidelines for their interpretation. He has also developed support material for the NES for sources of human drinking water for the Ministry for the Environment.

Barry Loe (Loe, Pearce & Associates) is a resource management consultant. His 24 years of experience in water quality and land management includes development of regional council policy and regulation of land and water use. Barry ensured that the requirements of regional council planners were taken into consideration in preparing the Guidelines.

Murray Close (ESR) has 30 years of experience in groundwater quality research. He has been involved in many collaborative projects, including the current Integrated Research for Aquifer Protection project. His current interests are determination and modelling of groundwater contamination, regional and national assessments of groundwater quality, vadose zone processes, and the impact of land use on groundwater quality.

Liping Pang (ESR) has 23 years of experience in groundwater quality research. She has carried out research on groundwater contamination from septic tanks and has estimated setback distances from septic tanks in selected groundwater systems. She has developed a methodology for considering the cumulative impact of septic tanks on groundwater quality.

Viv Smith (ESR[10]) has 19 years of experience in groundwater quality investigations, contaminated site management, and development of strategic projects within regional

[9] Affiliation at the start of the project was with Lincoln Ventures Limited.
[10] Affiliation at the start of the project was with Environment Waikato.

councils and with other agencies. At the time that she and Catherine conceived of the project Viv was a Programme Manager and the Strategic Waste Co-ordinator at Environment Waikato. Her project role was to ensure regular and effective contact with regional council personnel and delivery of a product with a council-friendly format.

Susie Osbaldiston (Northland Regional Council) is a groundwater management specialist, and joined the team as the regional councils' champion to assist in maintaining the linkage between the project and councils.

5.3 Required virus reduction

5.3.1 Introduction

Section 5.1 outlined the four components of the virus transport process in which virus reduction can be achieved. To determine whether the combined level of reduction is satisfactory, the required level of virus reduction must be calculated. This is virus-specific and requires two pieces of information:

i) the number of viruses initially in the wastewater

ii) the tolerable concentration in the well water.

Division of i) by ii) provides the reduction factor required, and by taking the logarithm ($base_{10}$) of this factor the required overall log_{10} reduction in virus concentration was calculated.

5.3.2 How many viruses could be in wastewater?

To determine the reduction in virus concentrations that must be achieved to meet the desired risk of infection, the virus concentration in the wastewater entering the sewage tank and the tolerable virus concentration in the drinking water must be known.

Determining the virus concentrations in domestic wastewater from a single dwelling is based on what is known about virus concentrations in human faeces. The approach is depicted in Fig. 5.2. Details of the data required for the train of calculations shown in Fig. 5.2 are given in Part 3: Technical Appendix.

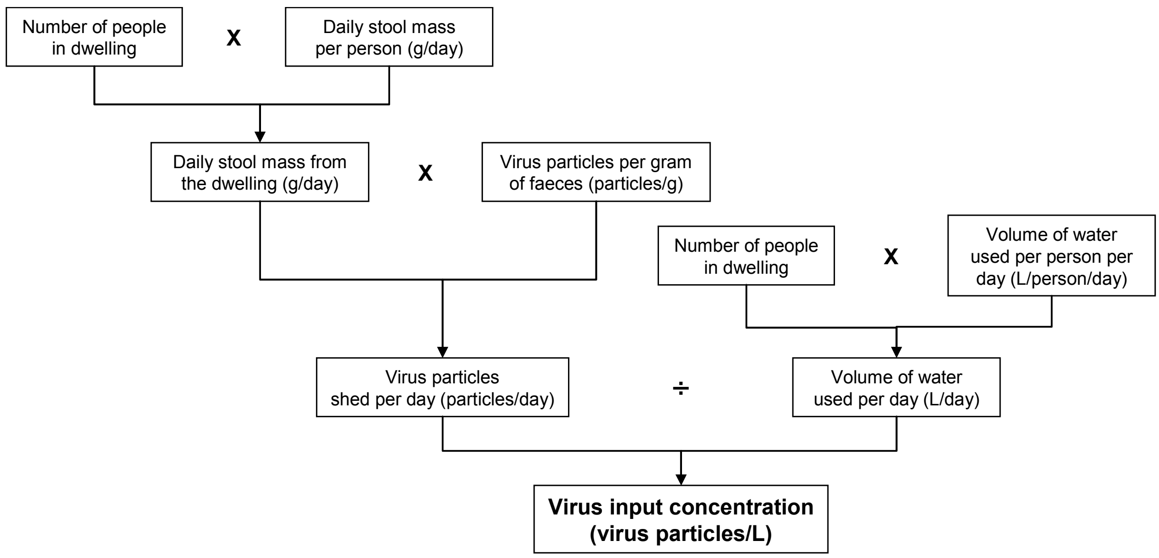


Fig. 5.2 Algorithm showing the data requirements and their relationship in the calculation of the virus concentration entering a sewage tank from an infected household

Sampling directly from on-site domestic wastewater systems is impracticable because of the need to sample when at least one resident is infected, knowing when this is occurring, and being able to cover the suite of viruses of interest.

5.3.3 What virus concentrations in drinking water can be tolerated?

Fig. 5.3 shows an overview of the approach to determining the tolerable virus concentration in the drinking water.

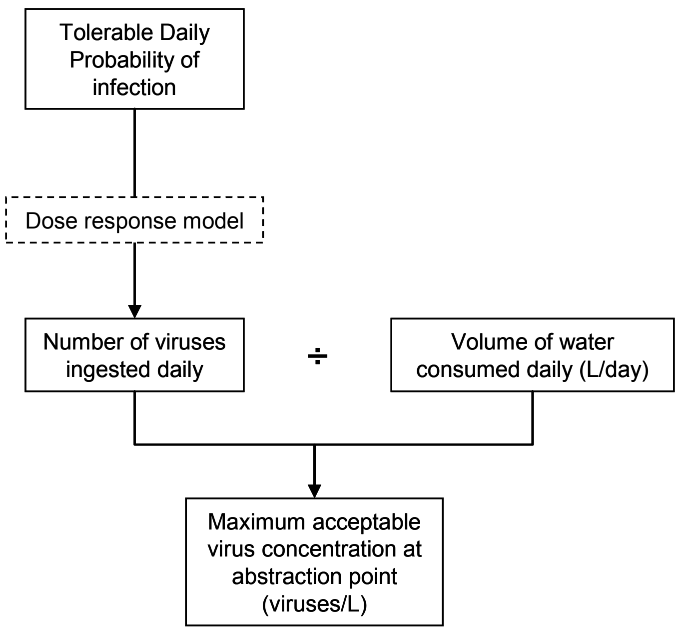


Fig. 5.3 Algorithm for calculating the tolerable virus concentration in water in a well

5.3.3.1 Tolerable probability of infection

In 1989, the USEPA set requirements for the removal of *Giardia* by water treatment plants to meet a tolerable probability of microbiologically-caused infection of 1 in 10^4 per year, i.e. no more than one person in a population of 10,000 becoming ill from waterborne pathogens per year. This target was based on an analysis of waterborne disease outbreak data gathered until that time. The data showed that in each reported outbreak of giardiasis[11], at least 0.5% (i.e. 50 in 10,000 people) were infected. The USEPA stated:

"*EPA believes that public water supplies should provide much greater protection than simply that necessary to avoid this level of risk from waterborne disease. EPA believes that providing treatment to ensure less than one case of microbiologically caused illness per year per 10,000 people is a reasonable goal.*"

Note that this statement refers to *illness*, but it is the probability of *infection* that the USEPA finally used to determine the water treatment requirements. The distinction is important because not everyone infected becomes ill. As a result, a target based on infection probability is more protective than one based on the probability of illness.

Although some concern has been expressed in the international literature that the tolerable infection probability of 1 in 10^4 is too conservative, this probability limit has been widely adopted internationally as the yard stick when evaluating tolerable pathogen loadings in drinking water. Although originally derived from giardiasis statistics (the number of people reported to have become ill through infection by *Giardia*), this probability is used for pathogen infection in general. For these reasons, this probability of infection has been used in the development of the Guidelines.

5.3.3.2 Dose-response models

Dose-response models are the mathematical expressions that relate the number of infective organisms ingested by an individual to the likelihood of that individual becoming infected. The dose required to infect an individual depends on the species of pathogenic organism. Moreover, individuals possess differing levels of resistance to infection. Thus a specific dose that will cause infection cannot be given; infection of an individual has to be expressed as a probability.

The mathematical forms of the dose-response relationships appropriate for the viruses of interest in the Guidelines are described in the Technical Appendix.

5.3.3.3 Drinking water consumption

The World Health Organization, when undertaking microbiological risk calculations for drinking water uses a volume of 1 L per person for the daily consumption of *unboiled* water. This volume is approximate because factors such as body mass, climate, physical activity and culture determine the volume of water an individual requires. Data from two New Zealand surveys have been used for the water consumption values in this modelling; the details of the distribution of values used are given in the Technical Appendix. The New Zealand surveys show a median daily consumption of 600 mL unboiled water for people older than 15 years, with a 95th percentile of 2,100 mL.

[11] The gastrointestinal disease resulting from infection by the protozoan, *Giardia.*

5.4 Virus removal in the sewage tank

Very little information about the reduction in virus concentrations that occurs in the sewage tank is available. Two values for the removal of viruses in sewage tanks are given in Section 8.6.1 for two generic categories of treatment system: primary and secondary treatment systems.

No Monte Carlo modelling was undertaken for virus removal in sewage tanks. A single value only is used for whichever treatment system is the closest approximation to the tank at the site.

5.5 Virus removal in the disposal field and soil

5.5.1 Removal in the disposal field

Guidance in calculating the reduction in virus concentration in three types of disposal field is given in the Guidelines: conventional trench; shallow dripper; and mound. The distribution aggregate medium in the disposal field, and sand, in the case of the mound, contribute to virus removal. The reduction in virus concentration in the disposal field (a $\log_{10}$ value) is calculated by multiplying the depth of aggregate the wastewater passes through (in metres) by the virus removal rate per metre ($\log_{10}$/m).

This calculation excludes the virus removal that occurs in soil surrounding, or below, the sparge lines[12] of the disposal field.

5.5.2 Removal in soil

The extent to which soil horizons can reduce the microbial loading of wastewater percolating through them depends on such factors as their composition, structure and depth. Only removal in the soil is considered in this part of the modelling.

Estimates of virus removal in New Zealand soils were made on the basis of two studies of bacteriophage (viruses that infect bacteria)[13,14]. The first study reported spatial removal rates ($\log_{10}$ reduction/metre) for bacteriophage in a small number of specific soils. These soils did not encompass all soil types in New Zealand. To obtain a greater coverage of New Zealand soils, data from a second study were used. By combining information from the two datasets, estimates of spatial removal rates for generic New Zealand soil types (based on the New Zealand Soil Classification) were made.

The removal rates for the specific soils and the generic soil types are given in Section 8.6.2. Details of the estimations are given in Section A4 Part 3. Multiplication of these removal rates ($\log_{10}$/m) by the soil thickness gives the extent of virus reduction in the soil (a $\log_{10}$ value).

12 Wastewater distribution lines with fine holes along their length through which the wastewater is fed into the soil.

13 Pang L, McLeod M, Aislabie J, Simunek J, Close M, Hector R, 2008, Modelling transport of microbes in ten undisturbed soils under effluent irrigation, *Vadose Zone J.,* 7, 97-111.

14 McLeod M, Aislabie J, Ryburn J, McGill, 2008, Regionalizing potential for microbial bypass flow through New Zealand soils, *J. Environ. Qual.*, 37, 1959-1967.

5.6 Virus removal in the vadose and saturated zones

5.6.1 Hydrogeological settings

Separation distances between on-site domestic wastewater systems and domestic wells have been developed for a range of hydrogeological settings found in New Zealand. The types of aquifers and associated vadose zone materials for which the Guidelines provide separation distances are:

- Alluvial gravel
- Alluvial sand
- Coastal sand
- Pumice sand
- Sandstone and non-karstic limestone
- Karstic and fractured rock (e.g. basalt and schist).

The Guidelines also consider the following additional vadose zone materials:

- Silt
- Clay
- Ash
- Peat.

5.6.2 Vadose zone modelling

Contaminant transport was modelled using a one-dimensional transport model. Two models were run in parallel for these calculations: the first described matrix flow and the second, the flow through macropores.

An unsaturated vadose zone might provide substantial virus removal. However, the vadose zone under a disposal field is unlikely to be unsaturated, and this will influence the extent to which it removes viruses. The level of the groundwater may be many metres below the disposal field, but continual effluent discharge will result in saturated flow conditions dominating the flow of water and microbes. It generally takes 24 hours of drainage for a "soil" to return to nominal field capacity[15], so that effluent from a normally functioning sewage tank will be moving in hydraulic conditions above field capacity for most of the time.

The models were run in conjunction with @RISK®[16] (software providing Monte Carlo calculation capability) to allow some input parameters to take a range of values. The input value ranges selected and the reasons for their selection are discussed in Section A5. The outputs produced by the Monte Carlo simulations were distributions of possible $\log_{10}$ reductions in virus concentration predicted to be achieved within the vadose zone.

A value for the $\log_{10}$ reduction in virus concentration in the vadose zone at the 95% confidence level can be obtained from this distribution. However, a more accurate determination of the combined removal in the vadose and saturated zones is obtained

[15] Field capacity is the water content held in soil.
[16] Palisade Corporation,798 Cascadilla St., Ithaca, NY USA 14850.

if the final distributions of both sets of calculations are combined in a Monte Carlo calculation. This properly takes account of the combined uncertainties.

5.6.3 Saturated zone modelling

Fig. 5.4 depicts the steps in modelling the saturated zone.

In brief, groundwater flow and virus transport were modelled using MODFLOW[17] and MT3D[18] software packages, respectively. These modelling packages require hydraulic properties (hydraulic conductivity and porosity) of the aquifer materials and removal rates, amongst other things, as inputs. The heterogeneous nature of most aquifer systems means that their hydraulic properties vary randomly throughout the aquifer, and cannot be analytically calculated. Instead, stochastic (probabilistic) approaches have to be used for modelling.

Wherever possible, field data were used to determine the hydraulic property fields to use for modelling each type of aquifer. The field data consisted of regional scale (tens of kilometres) measurements of hydraulic properties, obtained from regional council pump-test data, and small scale (tens of metres) measurements, obtained from ESR tracer tests. Variograms[19] summarise the spatial variability of these field data.

Using the mean values of hydraulic conductivity and porosity from field data (supplemented with literature information, as necessary), and variogram descriptions adjusted to represent the predictive model scale, the PEST[20] utility FIELDGEN was used to generate multiple realisations of fields for both parameters for each aquifer type. All of these realisations are considered to be equally likely representations of the aquifer characteristics, given the available data.

[17] McDonald, M.G. and Harbaugh, A.W. (1988). A modular three-dimensional finite-difference ground-water flow model. USGS Techniques of Water Resources Investigations, Book 6, Chapter A1. Washington DC.
[18] Chunmiao Zheng and P. Patrick Wang (2006). A modular three-dimensional multispecies transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. (Release DoD_3.50.A) by Department of Geological Sciences Department of Mathematics University of Alabama, Tuscaloosa, Alabama 35487-0338.
[19] A variogram is a mathematical description of how the differences in the value of a property at two locations, changes with the separation between the locations.
[20] Doherty J, 2007, PEST: Model independent Parameter Estimation. Version 11. Downloadable from www.sspa.com

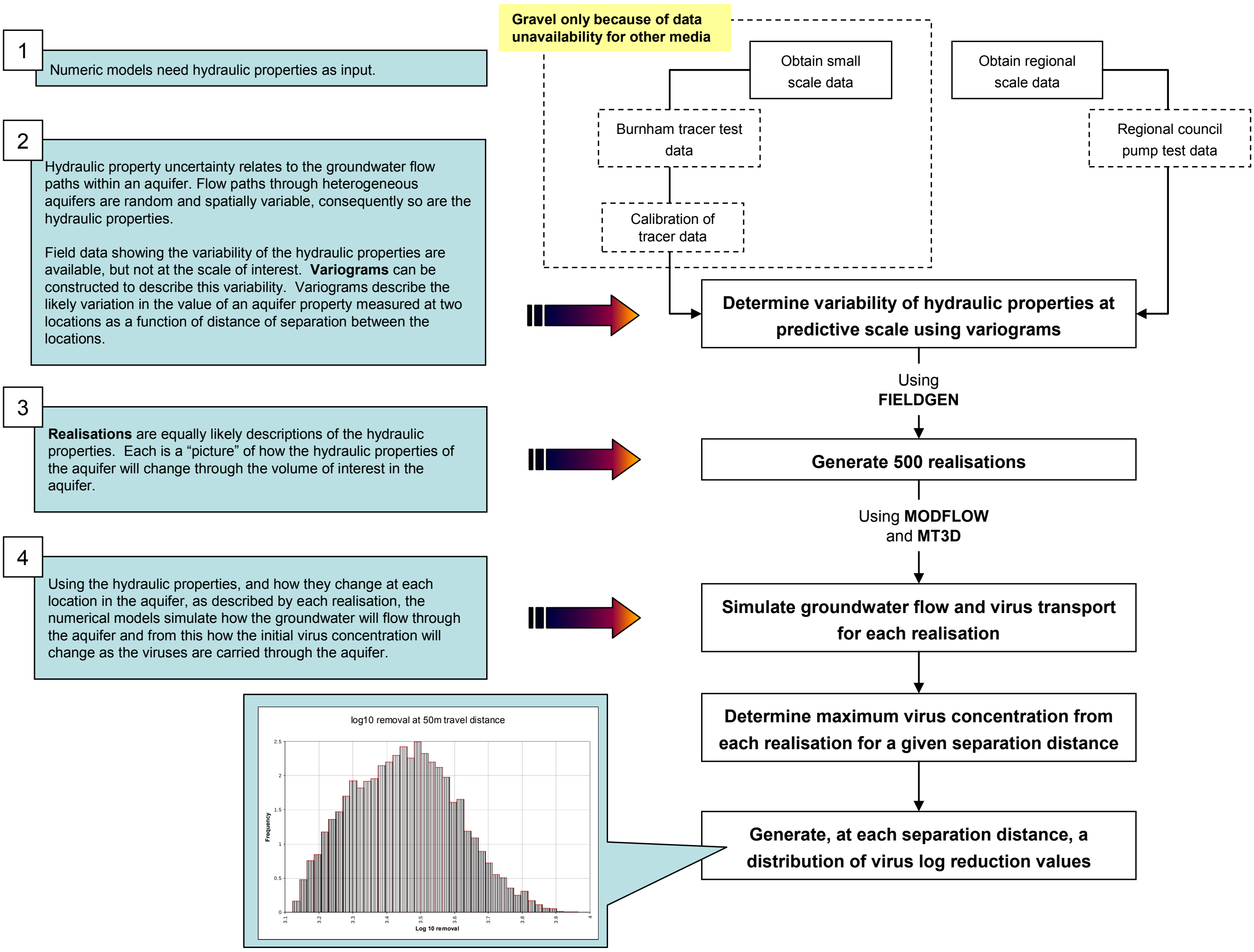


Fig. 5.4 Overview of the saturated zone modelling

MODFLOW and MT3D modelling software packages simulated groundwater flow and then contaminant transport within each flow field on the basis of the parameter realisation pairs generated.

The concentrations of viruses at a range of distances down-gradient of the discharge were investigated, and the maximum concentration at each specified distance recorded. This was repeated for each model simulation based on a new parameter realisation pair. The maximum concentration values were collated into a concentration distribution. This distribution described the range of, and the most likely, concentration reductions that can be achieved as the contaminant is dispersed within the groundwater flow down-gradient of the discharge.

The concepts and the modelling detail are discussed in Section A6 in Part 3.

5.7 Sensitivity analysis

A sensitivity analysis aims to determine how variation in the output of a model is influenced by variation in the model's input parameters.

Three major groups of input components influence the removal of viruses in sewage discharges, namely, the processes in the septic/tank disposal system (including transport through soil), transport through the vadose zone, and transport through the saturated zone.

The relative importance of each of these three components depends on the combination of components. At shallower depths, the component with the strongest influence on the overall virus removal is transport through the saturated zone. However, as the water table becomes deeper, the model outputs become increasingly affected by the characteristics of the vadose zone. In all situations the changes in the sewerage system parameters are the least significant in influencing the model's output.

In both the vadose and saturated zones, the output concentration reduction is most dependent on the removal rate parameter for the hydrogeological setting, and in comparison, the importance of transport processes is significantly less.

The factors affecting sensitivity are discussed in more detail in Section A1.3.

5.8 Assumptions

A reasonable degree of complexity was incorporated into this work to account for the most significant contributors to the uncertainty of virus transport, that is, the source concentrations and the contaminant transport velocity (where the variability of the contaminant transport velocity is largely caused by the orders of magnitude variability in hydraulic conductivities encountered at many sites). Nevertheless, to make the problem of modelling the movement of contaminants through the subsurface manageable a number of simplifying assumptions are necessary. These assumptions, and their rationales, are listed below.

a) **All occupants of a dwelling are infected at the same time and shed viruses in their faeces at the same time**. This is a worst-case situation and results in conservative (longer) separation distance estimates.

b) **Once the occupants of a dwelling are infected with a pathogenic virus, virus-contaminated wastewater will be discharged for 50 days.** The estimates of infection probability and the transport of viruses through the vadose and saturated zones are based on this figure.

   This period covers the range of shedding periods (time that the faeces of an infected person contains the virus) typically reported for the five virus types listed in Section 4. However, there have been reports of infants and children shedding for up to six months. As such instances appear to occur infrequently, this much longer shedding period was not incorporated into the modelling. Should shedding occur for this period, the level of protection will be less than the level intended.

c) **The drawdown from pumping of a domestic well is insufficient to significantly affect the rate at which viruses are carried to the well.** Domestic-purpose wells typically pump no more than 10–20 m^3 of water per day, pumping intermittently at low rates, such that the groundwater flow field is not altered significantly (especially when compared with the four orders of magnitude variability often encountered with groundwater velocities). However, in some circumstances a domestic well may also be used for other purposes requiring high-capacity pumping. In this situation, pumping could significantly affect groundwater velocity, and the impact of this would need to be assessed on a case-by-case basis.

d) **Rainfall fluctuations have no effect on either the rate at which viruses are carried into the ground, or dilution of the viruses**. Average rainfall recharge rates are insignificant when compared with the effluent field flux. Furthermore, modelling of the effluent through the unsaturated and soil strata is already essentially occurring in saturated conditions, and so transport removal rates would not be greatly affected by high rainfall events. However, occasionally high rainfall events may result in greater virus numbers moving through the unsaturated zone due to failure of the disposal field. In many cases, it is expected that these spikes in fluxes will be averaged out by the time the discharge reaches groundwater. Unfortunately, this may not always be the case, particularly where the vadose zone is thin and is composed of very permeable strata. While it is beyond the scope of the Guidelines to assess the range of possible system failures that may occur around the country, these could be assessed in particular areas if necessary as an adjunct to this work.

e) **On-site wastewater disposal systems are operated in accordance with TP58**[21]. While this may not be true, this is the best basis for selecting such modelling inputs as infiltration rate.

f) **Discharge of the disposal field into the ground is continuous**. In practice, the level of discharge will fluctuate. Effluent disposal fields are correctly designed so that they are intermittently unsaturated to facilitate microbial removal. Assuming a continuous discharge over an outbreak period will tend to protect water quality.

g) **Bacteriophage (viruses that infect bacteria) have similar transport properties in subsurface media to pathogenic viruses.** A number of bacteriophage types were selected to indicate virus transport properties. This assumption is necessary to allow any attempt at this modelling, because in many situations data for the transport of specific pathogenic viruses do not exist. While this is a focus of current research, we are unaware of any data that show there is a systematic difference in the generic behaviour of pathogenic viruses and the indicator bacteriophages used herein.

h) **The soil and vadose zone directly below the disposal field are constantly saturated.** The modelling has been undertaken assuming the maximum typical effluent disposal design flux of 10-50 mm/day. This flux is more than three orders of magnitude greater than most rainfall recharge rates. This has effectively (and conservatively) led to the assumption of constant saturation conditions. However, ideally the effluent disposal field is designed to provide unsaturated conditions to facilitate greater microbial removal – refer to f) above.

i) **The well screen is 2 m long.** Screen lengths can vary, but this is considered typical for most domestic supply wells.

j) **The aquifer is 5 m thick.** Aquifer thickness is variable. However, we have adopted a rule of thumb for domestic well low pumping rates, whereby an

[21] *On-site Wastewater Systems: Design and Management Manual*, 3rd Ed, Auckland Regional Council Technical Publication No. 58 (TP58), 2004.

aquifer thickness of at least twice the minimum likely well screen length (2 m) contributes groundwater into the well. This assumption will be very conservative wherever wells are located some distance from the septic tank or they are screened well below the water table, as vertical mixing at depths greater than 5 m could be expected in these circumstances. These wells will be over-protected by the guidelines.

k) **Water is abstracted at the water table depth.** As in j), where a well is screened substantially below the water table, contaminants introduced at the top of the saturated zone will be greatly diluted by the time they reach the screen depth. These wells will be over-protected by the guidelines.

l) **The "affected" well is directly down-gradient of the disposal field.** Separation distances based on the Guidelines will ensure adequate protection for all well waters, irrespective of their orientation with respect to the wastewater source and groundwater flow direction. Wells that are not down-gradient of the disposal field on the flowline will be over-protected. Note, however, that pumping from the "affected" well could alter flowlines and gradients, this is not taken into account by the model.

m) **The wastewater disposal field is 10 m x 10 m**[22]. The rationale for this assumption is explained in Section A6.6.1.1.

This project contains many modelling components. Some of the components have been verified with field measurements, e.g. the component addressing virus indicator transport through alluvial gravel aquifers. However, many other components simply represent our estimate on the basis of the best available data.

[22] The size of the disposal field can vary from 20 m^2 to 200 m^2 depending on the wastewater distribution system used – the 100m^2 used is considered a reasonable average size.

6 Limitations of the Guidelines

Limitations in the guidelines arise from two sources:

- technical - resulting from the assumptions that have to be made to make the modelling problem tractable (as discussed in Section 5.8)
- non-technical – the work is outside the scope of the project.

The limitations of the Guidelines are:

a) The guidelines are only valid for single dwellings. The volumes of wastewater discharged, and numbers of viruses in the wastewater when a household is infected, are based on New Zealand statistics for dwelling occupancy. The Guidelines cannot be reliably used when much larger numbers of people are contributing to the discharge, such as a rural school or marae. Wastewater from a larger number of people will contain larger numbers of viruses (in the event of infection) and larger separation distances will be required to provide an adequate reduction in virus numbers.

b) The guidelines protect groundwater wells against a *single* on-site wastewater disposal system. Cumulative effects of more than one disposal system are not taken into account.

c) The guidelines are generic. The *ranges* of data were used as inputs for the modelling to encompass typical values for modelling, not unusual, or specific, situations. The guidelines are designed to provide adequate protection in at least 95% of cases. This means that there will be many situations in which the calculated separation distances over-protect groundwater. This is unavoidable.

d) The guidelines are not appropriate for wells drawing from confined aquifers. The modelling assumes that wastewater percolates through the vadose zone directly into the groundwater. A confining layer prevents this. Use of the Guidelines where the aquifer is confined will result in separation distances that over-protect the groundwater quality at the abstracting well.

e) The guidelines cannot take account of the malfunction of components of the system. For example, the model assumes even discharge of the wastewater over the area of the disposal field. If a shallow dripper system becomes clogged somewhere within the dripper line and the discharge occurs over a small area, the modelling cannot take account of how this might affect the quality of water at the well.

f) The level of protection provided by the guidelines is based on the range of *typical* shedding periods. The guidelines do not take account of infrequent situations where prolonged shedding may occur (see Section 5.8 b).

g) Estimates of virus removal are provided for only two generic categories of on-site wastewater treatment systems. This is primarily because of a scarcity of data on the removal of viruses in proprietary wastewater treatment systems.

h) Deterministic approaches (in which the input values are fixed) were adopted for the simulation of virus reduction in the on-site domestic wastewater system (e.g. sewage tank) and in the disposal field and soil. In contrast, probabilistic approaches utilising Monte Carlo sampling methods were considered important for the vadose and saturated zone modelling.

i) Verification of the guidelines has not been possible. Ideally, the accuracy of the predictions of a model should be verified by empirical testing via aquifer sampling. Verification testing is impracticable in this case. It would require discharging pathogenic viruses into the ground at concentrations that a household of infected occupants would produce. Moreover, a number of sites with suitable orientation and separation of disposal field and well would have to be found, and well water sampled and monitored for days or months.

j) Model outputs are not presented for separation distances less than 40 m. The accuracy of the modelling results at shorter distances is questionable because of the grid size used in the model. A finer grid size would have resulted in model runs times that were unworkable. As the minimum existing separation distances set by councils are of the order of 30–40 m, this limitation was considered acceptable. The exception to this 40 m limit is a 20 m minimum separation distance suggested for pumice sand. The calculated virus reductions are so high in this case, that despite the large calculation uncertainties, 20 m is still considered a conservative estimate of a satisfactory separation distance.

k) The accuracies of the calculated virus removals and separation distances that can be achieved through the use of the Guidelines are influenced by the accuracy of the data on which the calculations are based (see Section 8.3).

The separation distances and log reduction values that can be calculated with the assistance of this document are *guidelines*, not regulations, based on the best available knowledge.

Regional council users have identified three situations that cannot presently be addressed by the Guidelines. These are recorded here to guide future guideline development:

- circumstances in which separation distances less than 40 m may be satisfactory – this would require the use of a modelling grid finer than the 10m x 10m x 5m grid used in this work
- separation distances for bores drawing water for community water supplies – drawdown effects would need to be incorporated into the model to take account of the greater cone of depression created by the demand of a community supply
- situations in which more than one waste disposal field may affect a bore – model modification to take account of cumulative effects would be required.

Part 2 – Using the Guidelines

PART 2

Using the Guidelines

PART 2 Using the Guidelines

7 Who should use the Guidelines?

Table 7.1 Organisations that may find the Guidelines useful

Organisation	Applications
Regional councils and unitary authorities	• Developing policies and rules for regional plans • Resource consent processing • Implementing the National Environmental Standard for Sources of Human Drinking Water 2007
District councils	• Developing district plans • Implementing the Local Government Act 2002 • Implementing the Building Act 1994
Drinking water supply authorities	• Implementing the Health [Drinking water] Amendment Act 2007
Public health agencies	• Implementing their powers and responsibilities under the Health [Drinking water] Amendment Act 2007
On-site wastewater system manufacturers and providers	• Improving the efficacy of their systems
Land use planning and wastewater consultants	• Location of wells and on-site wastewater systems
Well drillers and on-site wastewater system installers	• Location of wells and on-site wastewater systems

7.1 Regional councils

The functions of a regional council under the Resource Management Act 1991 (RMA) include controlling the use of land to maintain and enhance the quality of water, and controlling the discharge of contaminants from an on-site wastewater system.

The Guidelines can identify locations or areas of a region, where the proximity of existing discharges and wells may be actually or potentially having adverse effects on drinking water quality. The Guidelines can also be used to assess the risk to water quality from a new discharge from an on-site wastewater system, and the threat to water quality in a new well in proximity to on-site domestic wastewater systems.

7.1.1 Regional plans, regional rules & resource consents

The Guidelines can inform the development of policies and rules in regional plans that control discharges from on-site domestic wastewater systems, and the installation of wells for drinking water.

The information provided in the Guidelines can be used to assess the extent to which adverse effects of a discharge can be internalised within a property, and the extent to which a discharge is likely to have a potential adverse effect on water quality.

Most regional plans regulate the discharge from on-site domestic wastewater systems to land, and contain regional rules to authorise the discharge from both existing[23] and new[24] systems as a permitted activity, no resource consent required, subject to conditions specified in the rules. This authority is required under section 15(1)(b) of the RMA in situations where the contaminants discharged to land may enter water (groundwater or surface water).

Some regional plans have rules with conditions requiring separation distances between new on-site domestic wastewater system discharges to land and drinking water supply wells. However, many regional plans authorise discharges from existing and new discharge systems without any conditions requiring separation from a well.

Where regional plan rules require a separation distance from a well, these generally require that the discharge from the on-site wastewater system must be separated from a domestic well by between 20–50 m, depending on the particular regional plan. These separation distances have been imposed generally without substantive scientific basis or specific consideration of the sensitivity of groundwater to contamination at the location of the discharge. Where separation distances have been based on some scientific evidence of contaminant transport, they relate to bacteria.

The development of the Guidelines has shown that, in many instances, bacteria-based separation distances will be insufficient to protect drinking water quality from viruses discharged in domestic wastewater, and that the potential for viruses to be present in groundwater should be recognised in many more situations than is currently the case.

Most regional plans have rules controlling the use of land for the installation of bores to abstract groundwater. This is usually a permitted activity. While a regional council offers no guarantee about the quality of the groundwater that a well accesses, taking into account the proximity of on-site wastewater discharges when a well is installed will reduce the potential for adverse effects on human health.

The Guidelines can be used to avoid reverse sensitivity effects[25] developing from new wells being located where the water quality may be affected by an existing discharge.

Regional rules could include conditions that implement the separation distances recommended by the Guidelines, or set treatment standards for viruses in on-site domestic wastewater systems to achieve the reduction in virus numbers needed to reach the acceptable level of risk for the available separation distance.

Where resource consent is required for the discharge from a domestic on-site wastewater system, the Guidelines can be used in the assessment of effects on the

[23] Existing when a plan is notified.
[24] Installed after a plan has been notified.
[25] The impact of a new installation on an existing installation.

environment of the discharge, particularly the potential effect on users of domestic wells accessing groundwater that may be affected by viruses in the discharge.

7.1.2 National Environmental Standard for Sources of Human Drinking Water 2007

The Resource Management (NES for Sources of Human Drinking Water) Regulations 2007 primarily applies to protecting drinking water quality for supplies servicing more than 500 people. The Regulations restrict granting discharge permits and water permits, and place limitations on permitted activity rules, for activities upstream of a water supply intake that may detrimentally affect the quality of the water supply to the extent that it would not meet the DWSNZ[26], or if these standards are already not met, not increase the concentration of a determinand[27] by more than "a minor amount". While the Regulations set minimum requirements, consent authorities are free to make them more stringent.

The DWSNZ does not have compliance criteria for viruses; however, it advises the following:

> *Water that is sourced from a catchment in which there is human activity, in particular one with a sewage contamination upstream of the drinking-water abstraction point, is likely to contain some human-pathogenic viruses. It is possible some of the present water treatment options may not remove or inactivate all human-pathogenic viruses. However, insufficient information exists regarding the removal or inactivation of viruses through the various processes used in drinking-water treatment. Consequently, while the DWSNZ do not include viral criteria, it is intended they will be included in a future standard when the effectiveness of viral removal or inactivation by water treatment processes is better understood.*
>
> *It is considered that if no human effluent is in the catchment, viruses will not pose a risk to public health.*
>
> *Note that some forms of water treatment are known to be less effective at removing or killing viruses than others. For example, filtration without coagulation is not as effective at removing viruses as are coagulation and filtration, and UV treatment is less effective at killing viruses than the other disinfectants recognised in the DWSNZ. The UV disinfection criteria in section 5.16 may not provide adequate protection against viruses.*

Further, the draft of the *Guidelines for Drinking-water Quality Management for New Zealand*[28] states:

> *In the absence of any MAVs[29] for viruses in the current DWSNZ it should be understood that if they are specifically sought, they should not be detected.*

[26] *Drinking-water Standards for New Zealand 2005 (Revised 2008),* Ministry of Health, ISBN 978-0-478-31809-8, or available on the Ministry's website http://www/moh.govt.nz/water/
[27] A term used in the NES to mean a health-significant contaminant.
[28] Draft *Guidelines for Drinking-water Quality Management for New Zealand*, Ministry of Health, October 2005, available at http://www.moh.govt.nz/moh.nsf/indexmh/drinking-water-publications
[29] MAV – maximum acceptable value.

Should the DWSNZ in future contain viral criteria, the Guidelines (this document) may assist with assessing broadly:

- the risk posed by on-site domestic wastewater systems in the groundwater catchment of the drinking water supply well, and
- the nature of sewage treatment and disposal systems that would be needed in the groundwater catchment to ensure compliance with the DWSNZ.

However, the Guidelines are limited to consideration of a low capacity pumping well supplying a single dwelling and will not accurately predict the virus transport in groundwater where the groundwater flow field has been significantly altered by the high capacity pumping that would be required for a community water supply to more than 500 people. In such situations, the impact of pumping would need to be assessed on a case-by-case basis.

7.1.3 National Policy Statement for Freshwater Management

A proposed National Policy Statement for Freshwater Management was publicly notified in September 2008, with submissions being heard by the Board of Inquiry during 2009. The Board has reported to the Minister with recommendations for the content of the policy statement.

The proposed National Policy Statement for Freshwater Management requires regional councils to: set fresh water (including groundwater) quality standards, manage demand for freshwater resources, including discharges to water, to ensure domestic supply for the future, and protect against the degradation of freshwater resources from discharges.

The Guidelines identifies the potential for viruses in discharges from on-site domestic wastewater systems to adversely affect water quality and human health. The potential for these contaminants to be present in groundwater in catchments where there are on-site domestic wastewater systems has not been well recognised in the past. Implementation of a National Policy Statement for Freshwater Management will require recognition of viruses in groundwater with appropriate management responses.

7.2 District councils

7.2.1 District plans

Subdivision planning needs to take account of sewage servicing and water supply for the dwellings. The location of wells and on-site domestic wastewater systems needs to recognise the potential for viruses from the wastewater systems to affect the quality of water taken from supply wells.

Some district councils have rules in district plans controlling the use of land for on-site wastewater treatment. Such provisions should recognise the potential effects of viruses in the wastewater, and the ability of on-site domestic wastewater systems to reduce viruses in the wastewater.

7.2.2 Water and sanitary assessments - Local Government Act 2002

Section 125 of the Local Government Act 2002 requires territorial authorities to periodically undertake assessments of water and other sanitary services in their district.

The requirements of these assessments include:

- exploring the risk to the community from the absence of services, such as reticulated sewage or water supply
- reviewing the quality of drinking water and wastewater
- considering current and future demand for services, the options to provide services, and the health and environmental impact of discharges.

The Guidelines can contribute to the risk assessment process by indicating the likely presence of a contaminant in wastewater that could threaten the quality of drinking water and public health depending upon the relative positions of wastewater discharges and domestic water supply wells.

7.2.3 Building Act 2004, Building Regulations and Building Code Compliance

The Building Act 2004, through the New Zealand Building Code (NZBC), sets mandatory provisions for building work. NZBC Clause G12 Water Supply seeks to safeguard people from illness caused by contaminated water by ensuring that water is potable and the supply system is protected from contamination. Clause G13 Foul Water states that an on-site wastewater system must be constructed "*to avoid the likelihood of contamination of any potable water supplies*" and "*to avoid the likelihood of contamination of soils, groundwater, and waterways except as permitted under the Resource Management Act 1991*."

The Guidelines can assist local authorities to ensure these provisions can be complied with.

7.3 Drinking water supply authorities

The Health (Drinking Water) Amendment Act 2007 (HDWAA) introduced new provisions to the Health Act 1956. The provisions require drinking water suppliers to comply with the HDWAA within a defined timeframe. Compliance includes: preparing and implementing public health risk management plans, which must identify any public health risks associated with the water supply; mechanisms for preventing these risks arising; and ways to reduce and eliminate those risks if they arise. Drinking water suppliers are required to take reasonable steps to protect the water supply from contamination.

Clause 69(u)(i) of the HDWWA states:

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

The discharge of wastewater from on-site domestic wastewater systems could pose a risk to a drinking water supply. The Guidelines provides a means of identifying the risk of viral contamination of the water supply from on-site wastewater discharges in the catchment of a groundwater-sourced water supply. Appropriate wastewater treatment and separation distances are mechanisms that can be implemented to reduce the public health risks to the water supply.

7.4 Public health agencies

It is an offence under the Health Act 1956 to act in a way that is likely to contaminate the source water of a drinking water supply. A medical officer of health has powers to enforce the Health Act 1956, including assessing potential contamination of a water supply, and issuing compliance orders to prevent or remedy risks to public health from the water supply.

The identification of the risk of contamination of drinking water supplies from viruses in domestic wastewater, and the separation distances needed between on-site domestic wastewater systems and domestic water supply wells can assist to reduce the risk of contamination of drinking water by viruses to a satisfactory level.

7.5 On-site wastewater system manufacturers and providers

The effectiveness of on-site wastewater treatment systems is often evaluated by measuring the reduction in the amount of solid organic matter in the effluent, either as suspended solids (SS) or biochemical oxygen demand (BOD). The microbiological quality of wastewater is typically assessed using indicator bacteria (faecal coliforms or *E. coli*), and the disinfection systems are designed based on bacterial reduction. As noted in the DWSNZ, some forms of disinfection may be less effective than others at killing viruses.

Where the separation distances recommended in the Guidelines between on-site wastewater discharges and domestic wells cannot be achieved, the risk of infection can be reduced by improving the quality of the wastewater entering groundwater, by treating the wastewater. Therefore, an opportunity exists for on-site domestic wastewater systems to be designed that increase the effectiveness of virus removal.

7.6 Consultants for land development, well drillers and wastewater system installers

The planning for, and development of, land with dwellings serviced by individual or small community wells and on-site domestic wastewater systems, needs to ensure adequate separation distances are provided between the water supply and waste disposal systems. The Guidelines can be used in the design and layout of a development, or individual installations, to ensure that on-site wastewater discharges do not pose a threat to drinking water quality.

8 How to use the Guidelines

8.1 Introduction

The guidelines resulting from this work cannot be summarised in a single table. This is a consequence of providing the flexibility to take account of different soil types, hydrogeological settings, and vadose zone thicknesses, amongst other things. Using the Guidelines requires a series of calculation steps and reference to tables of data generated from the modelling.

To assist the user, the calculations are set out in *pro forma* worksheets with accompanying worked examples.

8.2 Guidance on virus selection

The separation distances and log reductions contained in this section have been calculated using the infection probabilities for two viruses or virus groups: rotavirus and hepatitis A virus. The reasons for doing this are explained in Section 4.7. Selection of the virus to use as the basis for the calculation is the first step in determining a satisfactory separation distance. This document does not direct the user in selecting the virus on which to base their calculations, a council must decide for itself which is appropriate for their conditions. However, the following may assist a council in reaching this decision:

Rotavirus *should* be selected as the basis for the calculation, if a council:

a) wishes to provide a high level of protection for its residents against infection by *all* of the key water-borne viruses, OR

b) is uncertain about which virus to chose – this follows the precautionary principle of taking the most protective action when there is uncertainty.

Hepatitis A virus *could* be used for the basis of the calculation, if a council believes:

- that the protection provided by using rotavirus is excessive, OR, the separation distances calculated using rotavirus are impracticable, AND
- that while infection by hepatitis A virus should be avoided, the health consequences of infection by the other key water-borne viruses can be tolerated.

<u>The decision to base the calculation on hepatitis A virus should be made in consultation with the appropriate district health board</u>.

8.3 Data collection

To undertake the calculations contained in the worksheets the user has to provide values for several input parameters. Availability of this information will vary from region to region and probably areas with regions. Table 8.1 provides suggestions for sources of the information required for the calculations.

Table 8.1 Guide to possible sources of information and default values for parameter values required for the calculations

Information	Possible sources of the information	Default value
Information regarding the wastewater treatment system and its disposal field	• System plans • System designer • Previous property owners • Company that installed the system • Consenting authority • Consult TP58	If uncertain of dimensions of the disposal field, assume the recommended values given in TP58
Soil thickness and classification	• Bore logs from wells in the area may give an indication of likely soil thickness – regional council • Soil maps and database- Landcare Research • Soil maps and descriptions – regional council	If uncertain of soil thickness, assume 1 m
Depth to groundwater Vadose zone geology Saturated zone geology	• Bore logs from wells in the area may give an indication of depth to groundwater - regional council • Area peizometric maps – possibly regional council • Geological maps	

The user will achieve the most accurate results from the model if the input values are as accurate as possible. However, if the detailed assessment of a site to determine such parameters as groundwater depth is impracticable, *estimates* of the groundwater depth using cheaper, less detailed techniques could be used for the calculations. This is because of the input parameters that determine the model output for a given hydrogeological setting, the removal rates that have been obtained from the scientific literature are the most important (see Section A1.3). Correctly establishing the hydrogeological setting is clearly an important step in determining a satisfactory separation distance.

8.4 Indicative guidelines for key hydrogeological settings

Based on information from regional councils about typical hydrogeological settings and vadose zone thicknesses, Table 8.2 provides broad guidance on the separation distances needed to remove the most infectious viruses. A 2.7 $\log_{10}$ reduction in virus concentration before the effluent leaves the disposal field is assumed based on: treatment by septic tank (0.6 $\log_{10}$), disposal by conventional trench (0.1 $\log_{10}$) and approximately 1 m of soil achieving a 2.0 $\log_{10}$ reduction in virus concentration. An overall $\log_{10}$ reduction of 16.2 is required to protect against rotavirus, therefore, after the other log reductions have been taken into account a 13.5 $\log_{10}$ reduction must be achieved by passage through the vadose zone and aquifer.

Should the detailed calculations using the worksheets in Section 8.5 show that a practicable separation distance cannot achieve a satisfactory virus reduction, one or more of the following should be considered:

- Modifying the treatment system, including introducing disinfection
- Changing to a disposal system that will achieve improved virus removal
- Increasing the depth of the bore. The calculated values assume abstraction at the water table, so increasing the screen depth below the water table level will achieve greater dilution and therefore reduction in the virus concentration
- Where possible, relocating the disposal field or bore so that the bore is up-gradient of the disposal field – the calculations assume the worst-case situation of the bore being directly down-gradient of the disposal field.

Table 8.2 Separation distances that will achieve satisfactory removal of the most infectious viruses.

Hydrogeological Settings		**Vadose Zone thickness (m)**				
Aquifer	**Vadose Zone**	2 m	5 m	10 m	20 m	30 m
Gravel	Gravel	[grey]	[grey]	[grey]	[grey]	[grey]
	Sand (alluvial)	[grey]	[grey]	[grey]	[red]	[yellow]
	Silt	[grey]	[grey]	[grey]	[yellow]	[yellow]
Sand (alluvial)	Gravel	[grey]	[grey]	[orange]	[orange]	[orange]
	Sand (alluvial)	[grey]	[red]	[red]	[yellow]	[yellow]
	Silt	[grey]	[red]	[red]	[yellow]	[yellow]
	Ash	[grey]	[red]	[red]	[yellow]	[yellow]
	Pumice sand	[red]	[orange]	[yellow]	[yellow]	[yellow]
Karstic or Fractured Rock	Gravel	[grey]	[grey]	[grey]	[grey]	[grey]
	Sand (alluvial)	[grey]	[grey]	[grey]	[orange]	[yellow]
	Silt	[grey]	[grey]	[grey]	[orange]	[yellow]
	Ash	[grey]	[grey]	[grey]	[orange]	[yellow]
	Pumice sand	[grey]	[grey]	[yellow]	[yellow]	[yellow]

Key:		
	Possible within 50 m	[yellow]
	Possible within 100 m	[orange]
	Possible within 300 m	[red]
	Requires 300 m or more separation	[grey]

8.5 Worksheets and examples

There are two situations in which the data produced by the modelling might be needed:

1. where the separation distance between a disposal field and a well is already known, and the adequacy of the separation needs to be checked, e.g., a well is proposed to be sited a given distance from an on-site domestic wastewater system and this distance needs to be checked.
2. where the required reduction in virus concentration is known and the separation distance needed to achieve this has to be determined, e.g., a rural sub-division is planned for an area and guidance on the minimum separation between wastewater disposal systems and neighbouring wells is needed.

Two different worksheets are provided in this section to assist in using the Guidelines in either of these ways. The information used is the same in both cases, but viewed differently near the end of the calculation. Each sheet guides the user as to which data are needed for the calculation, how to perform the calculation, and which tables need to be accessed for modelling results that are required in the calculation. All the necessary tables are gathered into Section 8.6.

After each worksheet, a worked example is provided.

Worksheet No.1 To calculate the log_{10} reduction in virus concentration achieved by the separation distance

Worksheet No.1 is used to determine whether the proposed distance between a wastewater disposal field and a well is adequate.

Step 1 Identify the target log reduction required.

From Table I choose the virus to be used in the calculation and enter the log_{10} reduction required in **Box A**

Table I

	Log_{10} reduction required
Rotavirus	**16.2**
Hepatitis A virus	**11.1**

A	

Step 2 Determine the log reduction achievable by the wastewater treatment system

From Table II choose the type of treatment system and enter its log reduction achievable in **Box B**

Table II

	Log_{10} reduction achievable
Primary treatment system (septic tank)	**0.6**
Secondary treatment system (AWTS[30])	**1.0**

B	

Step 3 Determine any additional log reduction if disinfection is used

If chlorination or UV disinfection is used, enter "**1.0**" in **Box C,** otherwise enter "**0**".

C	

Step 4 Calculate the log reduction achievable in the disposal field and soil

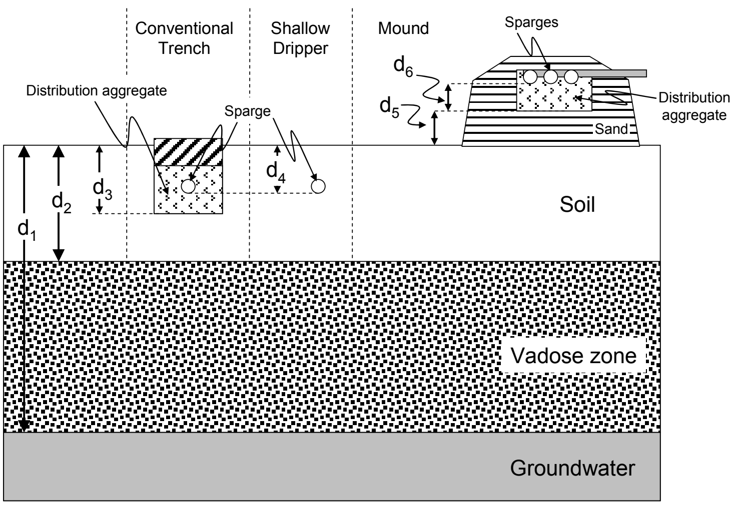


Fig. I

[30] Proprietary aerated wastewater treatment system

1 Choose the type of disposal field

2 From Fig. I write down the dimensions in Table III in metres.

Table III (no data needed in shaded cells).

Dimension (metres)	*Conventional Trench*	*Shallow Dripper*	*Mound*
d_1			
d_2			
d_3			
d_4			
d_5			
d_6			

3 In Table IV write down the soil type and its log_{10} reduction (see **Table 8.6** or **Table 8.7** in Section 8.6.2 of the Guidelines).

Table IV

Soil type	*Reduction log_{10}/m*

This is value **a** in Table V

4 Carry out the calculations in Table V for the disposal system in use. There will be only one result in **Box D**. [Grey shaded cells do not need to be filled.]

Table V (no data needed in shaded cells).

Reduction in distribution aggregate						
	Conventional Trench		*Shallow Dripper*		*Mound*	
Distribution aggregate	*Calculation*	*Result*	*Calculation*	*Result*	*Calculation*	*Result*
Pea gravel	**0.36 x (d_3-d_4)**				**0.36 x d_6**	
Sand	**0.49 x (d_3-d_4)**				**0.49 x d_6**	
Reduction in sand						
					0.49 x d_5	
Reduction in soil						
	a x (d_2-d_3)		**a x (d_2-d_4)**		**a x d_2**	
Sum the above Result column for the disposal system in use to give the **total log_{10} reduction** in **Box D**						
D			**OR**		**OR**	

Step 5 Determine the log reduction achieved in the vadose and saturated zones

1 Write the vadose zone and saturated zone (aquifer) materials in Table VI. Possible materials are given in Section 8.6.3 of the Guidelines.

Table VI

	Material	*Vadose Zone thickness **(d_1-d_2)***
Vadose zone		
Saturated zone		

2 Calculate the vadose zone thickness (use the values d_1 and d_2 from Table III), and write it in Table VI.

3 Use the catalogue in **Table 8.8** and the vadose and saturated zone materials written in Table VI to find the table needed in Section 8.6.3.

4 Read the $\log_{10}$ reduction from the table as shown in Fig.II.

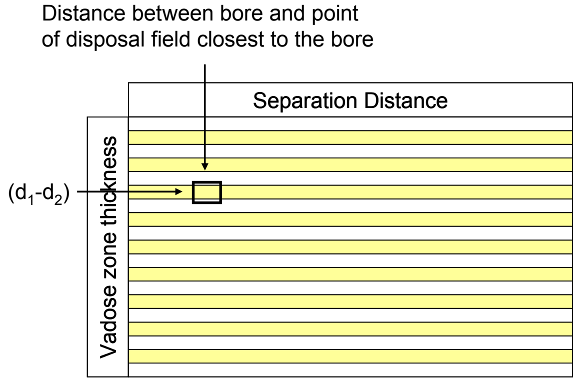


Fig. II

The calculated vadose zone thickness and separation distance may not exactly match the values given in the vertical and horizontal scales of the table. Read from the row and column with the closest value.

5 Write the $\log_{10}$ reduction in **Box E** of Table VII.

Step 6 Calculate the over all log reduction and compare this against the required log reduction

1 Transfer data from **Boxes A, B, C** and **D** to Table VII

2 Subtract **Boxes B, C, D** and **E** from **Box A** and write the result in **Box F**

Table VII

A	
B	
C	
D	
E	

F	

Interpretation:

Value of F	Interpretation
0 or – ve	Separation distance is satisfactory
+ve	Separation distance needs to be increased or additional treatment installed

Worked Example for Worksheet 1

Worksheet No. 1 is used to determine whether the proposed distance between a wastewater disposal field and a well is adequate.

The situation:

The owner of a rural block wishes to install a new septic tank with a conventional trench system for disposal of the wastewater from the house. He proposes installing the disposal field 50 m from a neighbour's existing domestic water supply well. This well abstracts groundwater at a depth of 15 m below ground.

The regional council has adopted the Guidelines as the basis for estimating satisfactory separation distances. Further, the council has decided to use the separation distances required to reduce hepatitis A virus concentrations, rather than rotavirus. It has chosen hepatitis A because it believes that protection from the possibly severe consequences of infection by hepatitis A virus is important, while the consequences of infection by rotavirus are, in New Zealand, not severe enough to justify the large separation distances that protecting against this virus might require.

The question:

Is the proposed separation distance between the disposal field and the well sufficient to adequately protect against contamination of the drinking water of the neighbour, should an outbreak of hepatitis A occur in the household?

Information Needed:	For this example
What type of wastewater treatment system is used?	Conventional septic tank
Does the wastewater receive additional disinfection before discharge?	No
What type of disposal system is used?	Conventional trench
How deep is the trench?	0.4 m
How deep is the sparge (the wastewater distribution pipe) under the ground?	0.2 m
What type of aggregate is used?	Builders' mix
What is the depth of soil on the site?	1.2 m
What is the soil classified as under the NZSC system?	Brown soil
What is the depth to groundwater?	15 m
What is predominant material in the vadose zone?	Alluvial sand
What is the aquifer material?	Alluvial gravel

Worksheet No.1 — To calculate the $\log_{10}$ reduction in virus concentration achieved by the separation distance

Worksheet No.1 is used to determine whether the proposed distance between a wastewater disposal field and a well is adequate.

Step 1 Identify the target log reduction required.

From Table I choose the virus to be used in the calculation and enter the $\log_{10}$ reduction required in **Box A**

Table I

	Log_{10} reduction required
Rotavirus	**16.2**
Hepatitis A virus	**11.1**

A	11.1

RC is basing its calculations on hepatitis A virus

Step 2 Determine the log reduction achievable by the wastewater treatment system

From Table II choose the type of treatment system and enter its log reduction achievable in **Box B**

Table II

	Log_{10} reduction achievable
Primary treatment system (septic tank)	**0.6**
Secondary treatment system (AWTS[31])	**1.0**

B	0.6

Treatment is by septic tank

Step 3 Determine any additional log reduction if disinfection is used

If chlorination or UV disinfection is used, enter "**1.0**" in **Box C,** otherwise enter "**0**".

C	0

No additional disinfection in use.

Step 4 Calculate the log reduction achievable in the disposal field and soil

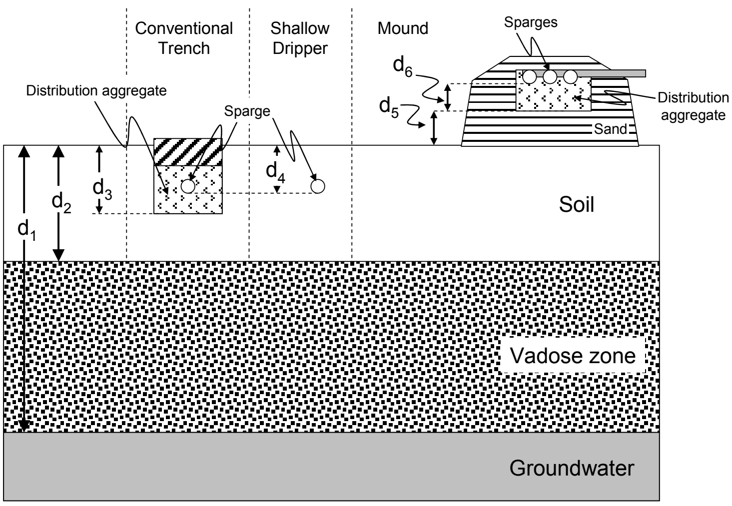


Fig. I

[31] Proprietary aerated wastewater treatment system

1 Choose the type of disposal field

2 From Fig. I write down the dimensions in Table III in metres.

Table III (no data needed in shaded cells)

Dimension (metres)	*Conventional Trench*	*Shallow Dripper*	*Mound*
d_1	**15**		
d_2	**1.2**		
d_3	**0.4**		
d_4	**0.2**		
d_5			
d_6			

This example is for a conventional trench system therefore data are not required for either of the other systems.

Depth to groundwater

Thickness of soil also depth to vadose zone

Depth to bottom of trench

Depth of the disposal pipes (sparge pipes) under the ground

3 In Table IV write down the soil type and its $\log_{10}$ reduction (see **Table 8.6** or **Table 8.7** in Section 8.6.2 of the Guidelines).

Table IV

Soil type	*Reduction $\log_{10}$/m*
Brown soil	**2.0**

This is value **a** in Table V

NZSC Feature	Virus removal $\log_{10}$ m^{-1}
Organic soils	1.0
•	•
Brown soils	2.0
•	•
Allophanic soils	2.5

4 Carry out the calculations in Table V for the disposal system in use. There will be only one result in **Box D**. [Grey ...]

Table V (no data needed in shad...

Builders' mix is sometimes used as the aggregate. Gravel is a better approximation to builders' mix than sand.

Values for "d_3" and "d_4" come from Table IV. "0.36" is the $\log_{10}$/m reduction for viruses in pea gravel. The calculation yields a value of 0.072, which is rounded up to give a result to one decimal place.

Reduction in distribution aggrega...						
	Conventio...		*Shallow Dripper*			
Distribution aggregate	*Ca...ation*	*Result*	*Calculation*		*Ca...*	
Pea gravel	**0.36 x (d_3-d_4)**	**0.1**			**0.36 x d_6**	
Sand	**0.49 x (d_3-d_4)**				**0.49 x d_6**	
Reduction in sand						
Reduction in soil						
	a x (d_2-d_3)	**1.6**	**a x (d_2-d_4)**		**a x d_2**	
Sum the above Result column for the disposal system in use to give the **total $\log_{10}$ reduction** in **Box D**						
D		**1.7**	**OR**		**OR**	

Values for "d_2" and "d_3" come from Table III, and the value for "a" is from Table IV.

Step 5 Determine the log reduction achieved in the vadose and saturated zones

1 Write the vadose zone and saturated zone (aquifer) materials in Table VI. Possible materials are given in Section 8.6.3 of the Guidelines.

Table VI

	Material	*Vadose Zone thickness* ***(d_1-d_2)***
Vadose zone	**Coarse sand**	**13.8**
Saturated zone	**Gravel**	

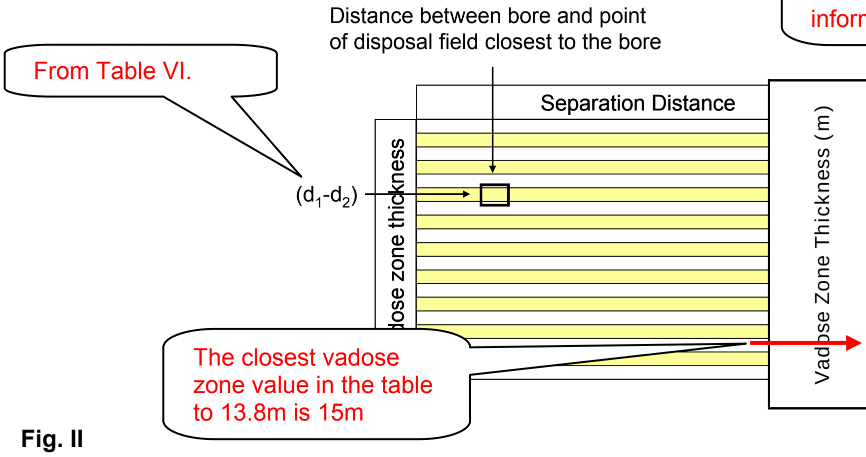
Values for "d_1" and "d_2" come from Table III. The difference is (15-1.2) 13.8m.

2 Calculate the vadose zone thickness (use the values $\mathbf{d_1}$ and $\mathbf{d_2}$ from Table III), and write it in Table VI.

3 Use the catalogue in **Table 8.8** and the vadose and saturated zone materials written in Table VI to find the table needed in Section 8.6.3.

4 Read the $\log_{10}$ reduction from the table as shown in Fig.II.

Separation distance from “The Situation” information.



Vadose Zone Thickness (m)	Separation Distance (m)		
	40	50	60
1	1.9	2.0	2.0
2	2.5	2.6	2.6
3	3.1	3.2	3.2
4	3.7	3.7	3.8
5	4.2	4.3	4.3
6	4.7	4.8	4.9
7	5.2	5.3	5.4
8	5.7	5.9	5.9
9	6.4	6.5	6.5
10	6.9	7.0	7.0
15	9.9	10.0	10.0
20	12.9	12.9	13.0
25	15.8	16.0	16.1

Fig. II

The calculated vadose zone thickness and separation distance may not exactly match the values given in the vertical and horizontal scales of the table. Read from the row and column with the closest value.

5 Write the $\log_{10}$ reduction in **Box E** of Table VII.

Step 6 Calculate the over all log reduction and compare this against the required log reduction

1 Transfer data from **Boxes A, B, C** and **D** to Table VII

2 Subtract **Boxes B, C, D** and **E** from **Box A** and write the result in **Box F**

Table VII

A	**11.1**
B	**0.6**
C	**0**
D	**1.7**
E	**10.0**

Data copied from “Boxes” earlier in the form.

F	**-1.2**

The negative result indicates that there is adequate separation to protect against hepatitis A virus (see “Interpretation” table below)

Interpretation:

Value of F	Interpretation
0 or – ve	Separation distance is satisfactory
+ve	Separation distance needs to be increased or additional treatment installed

Worksheet No.2 To calculate the separation distance needed to achieve a specified $\log_{10}$ reduction in virus concentration

Worksheet No.2 is used to determine what separation distance between a wastewater disposal field and a well is needed to provide adequate protection for the well-water quality.

Step 1 Identify the target log reduction required.

From Table I choose the virus to be used in the calculation and enter the $\log_{10}$ reduction required in **Box A**

Table I

	Log_{10} reduction required
Rotavirus	**16.2**
Hepatitis A virus	**11.1**

A	

Step 2 Determine the log reduction achievable by the wastewater treatment system

From Table II choose the type of treatment system and enter its $\log_{10}$ reduction achievable in **Box B**

Table II

	Log_{10} reduction achievable
Primary treatment system (septic tank)	**0.6**
Secondary treatment system (AWTS[32])	**1.0**

B	

Step 3 Determine any additional log reduction if disinfection is used

If chlorination or UV disinfection is used, enter "**1.0**" in **Box C,** otherwise enter "**0**".

C	

Step 4 Calculate the log reduction achievable in the disposal field and soil

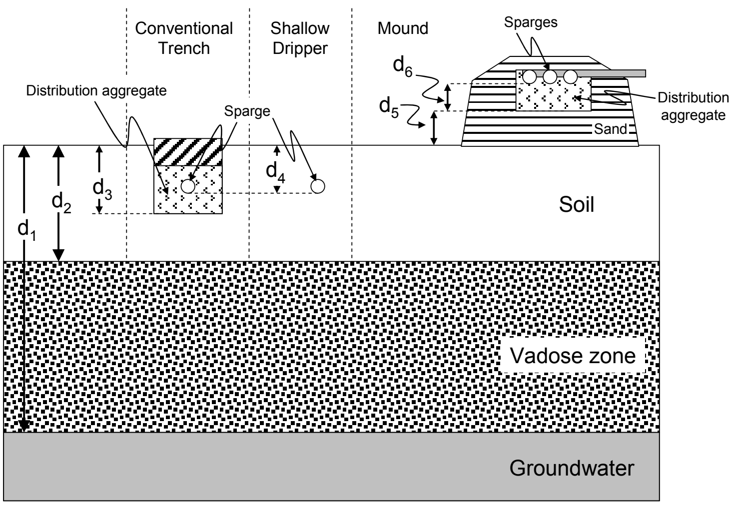


Fig. I

[32] Proprietary aerated wastewater treatment system

1 Choose the type of disposal field

2 From Fig. I write down the dimensions in Table III in metres.

Table III (no data needed in shaded cells).

Dimension (metres)	*Conventional Trench*	*Shallow Dripper*	*Mound*
d_1			
d_2			
d_3			
d_4			
d_5			
d_6			

3 In Table IV write down the soil type and its $\log_{10}$ reduction (see **Table 8.6** or **Table 8.7** in Section 8.6.2 of the Guidelines).

Table IV

Soil type	*Reduction $\log_{10}$/m*

This is value **a** in Table V

4 Carry out the calculations in Table V for the disposal system in use. There will be only one result in **Box D**. [Grey shaded cells do not need to be filled.]

Table V (no data needed in shaded cells).

Reduction in distribution aggregate						
	Conventional Trench		*Shallow Dripper*		*Mound*	
Distribution aggregate	*Calculation*	*Result*	*Calculation*	*Result*	*Calculation*	*Result*
Pea gravel	**0.36 x (d_3-d_4)**				**0.36 x d_6**	
Sand	**0.49 x (d_3-d_4)**				**0.49 x d_6**	
Reduction in sand						
					0.49 x d_5	
Reduction in soil						
	a x (d_2-d_3)		**a x (d_2-d_4)**		**a x d_2**	
Sum the above Result column <u>for the disposal system in use</u> to give the **total $\log_{10}$ reduction** in **Box D**						
D			**OR**		**OR**	

Step 5 Calculate the overall log reduction required

1 Transfer data from **Boxes A, B, C** and **D** to Table VI

2 Subtract **Boxes B, C** and **D** from **Box A** and write this result in **Box E.**

Table VI

A	
B	
C	
D	

E		This is the total log_{10} reduction required.

Step 6 Determine the separation distance needed to achieve the required log reduction (E)

1 Write the vadose zone and saturated zone (aquifer) materials at the site in Table VII. Possible materials are given in Section 8.6.4 of the Guidelines.

Table VII

	Material	*Vadose Zone thickness* ***(d_1-d_2)***
Vadose zone		
Saturated zone		

2 Calculate the vadose zone thickness (use the values $\mathbf{d_1}$ and $\mathbf{d_2}$ from Table III), and write it in Table VII.

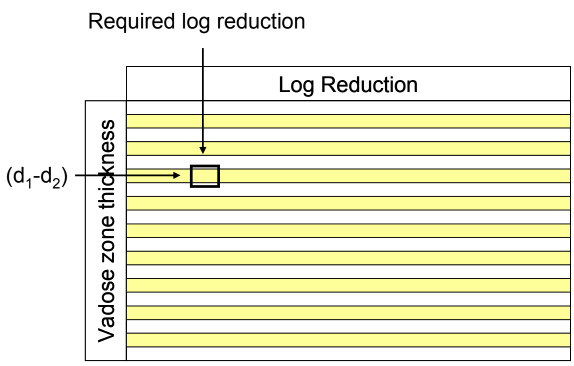


Fig. II

3 Use the catalogue in **Table 8.9** and the vadose and saturated zone materials written in Table VI to find the table needed in Section 8.6.4.

4 Read the log_{10} reduction from the table as shown in Fig.II.

The calculated vadose zone depth and required log_{10} reduction may not exactly match the values given in the vertical and horizontal scales of the table. Read from the row and column with the closest value.

5 Write the separation distance in the box below

Separation Distance required (m)	

Worked Example for Worksheet 2

Worksheet No. 2 is used to determine what the separation distance between a wastewater disposal field and a bore should be.

The situation:

A regional council has decided to base its separation distance requirements on the calculations for rotavirus contained in the Guidelines. It has chosen rotavirus as the basis for the calculations because it knows that by ensuring protection from rotavirus, protection will also be achieved for the other viruses considered most likely to be a concern in water, including hepatitis A virus. This decision means that the separation distance between a disposal field and well must be able to achieve a $\log_{10}$ reduction in virus concentration of at least a 16.2

A consent applicant is wishing to sink a new well close to his neighbour's boundary. His neighbour's wastewater disposal field is not far from the boundary. The neighbour's wastewater undergoes treatment by an aerated wastewater treatment system before UV treatment and discharge into the ground.

The question:

What separation distance between his neighbour's disposal field and his proposed well does the consent applicant need to adequately protect against contamination of his drinking water, should an outbreak caused by a waterborne virus occur in his neighbour's household?

Information Needed:	For this example
What type of wastewater treatment system is used?	Proprietary aerated wastewater treatment system
Does the wastewater receive additional disinfection before discharge?	UV
What type of disposal system is used?	Shallow dripper
How deep is the sparge (the wastewater distribution pipe) under the ground?	0.1 m
What is the thickness of soil on the site?	1.2 m
What is the soil classified as under the NZSC system?	Organic soil
What is the depth to groundwater?	10 m
What is predominant material in the vadose zone?	Alluvial sand
What is the aquifer material?	Alluvial sand

Worksheet No.2 To calculate the separation distance needed to achieve a specified $\log_{10}$ reduction in virus concentration

Worksheet No.2 is used to determine what separation distance between a wastewater disposal field and a well is needed to provide adequate protection for the well-water quality.

Step 1 Identify the target log reduction required.

RC is basing its calculations on rotavirus

From Table I choose the virus to be used in the calculation and enter the $\log_{10}$ reduction required in **Box A**

Table I

	Log_{10} reduction required
Rotavirus	**16.2**
Hepatitis A virus	**11.1**

A	16.2

Step 2 Determine the log reduction achievable by the wastewater treatment sys

Treatment is by aerated wastewater treatment system

From Table II choose the type of treatment system and enter its $\log_{10}$ reduction achievable in **Box B**

Table II

	Log_{10} reduction achievable
Primary treatment system (septic tank)	**0.6**
Secondary treatment system (AWTS[33])	**1.0**

B	1.0

Step 3 Determine any additional log reduction if disinfection is used

Additional disinfection is by UV

If chlorination or UV disinfection is used, enter "**1.0**" in **Box C,** otherwise enter "**0**".

C	1.0

Step 4 Calculate the log reduction achievable in the disposal field and soil

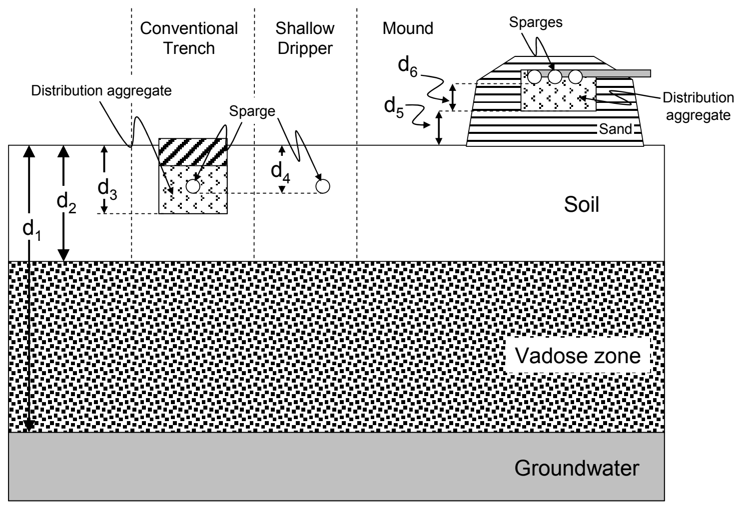


Fig. I

[33] Proprietary aerated wastewater treatment system

1 Choose the type of disposal field

2 From Fig. I write down the dimensions in Table III in metres.

Table III (no data needed in shaded cells).

Dimension (metres)	*Conventional Trench*	*Shallow Dripper*	*Mound*
d_1		**10**	
d_2		**1.2**	
d_3			
d_4		**0.1**	
d_5			
d_6			

Depth to groundwater

Thickness of soil

Depth of dripper line

3 In Table IV write down the soil type and its $\log_{10}$ reduction (see **Table 8.6** or **Table 8.7** in Section 8.6.2 of the Guidelines).

NZSC Feature	Virus removal $\log_{10}\ m^{-1}$
Organic soils	1.0
•	•
Brown soils	2.0
•	•
Allophanic soils	2.5

Table IV

Soil type	*Reduction $\log_{10}/m$*
Organic soil	**1.0**

This is value **a** in Table V

4 Carry out the calculations in Table V for the disposal system in use. There will be only one result in **Box D**. [Grey shaded cells do not need to be filled.]

Table V (no data needed in shaded cells).

Reduction in distribution aggregate						
	Conventional Trench		*Shallow Dripper*		*Mound*	
Distribution aggregate	*Calculation*	*Result*	*Calculation*	*Result*	*Calculation*	
Pea gravel	**0.36 x (d_3-d_4)**				**0.36 x d_6**	
Sand	**0.49 x (d_3-d_4)**				**0.49 x d_6**	
Reduction in sand						
					0.49 x d_5	
Reduction in soil						
	a x (d_2-d_3)		**a x (d_2-d_4)**	**1.1**	**a x d_2**	
Sum the above Result column <u>for the disposal system in use</u> to give the **total $\log_{10}$ reduction** in **Box D**						
D			**OR**	**1.1**	**OR**	

"d_2" and "d_4" are obtained from Table .III, "a" is from Table IV. The result is 1.1.

Step 5 Calculate the overall log reduction required

1 Transfer data from **Boxes A, B, C** and **D** to Table VI

2 Subtract **Boxes B, C** and **D** from **Box A** and write this result in **Box E.**

Table VI

A	**16.2**
B	**1.0**
C	**1.0**
D	**1.1**

E	**13.1**

This is the total $\log_{10}$ reduction required.

Data are copied from boxes earlier in the form.

This value (16.2 -1 -1.1) will be used to look up the separation distance in the table in Step 6

Step 6 Determine the separation distance needed to achieve the required log reduction (E)

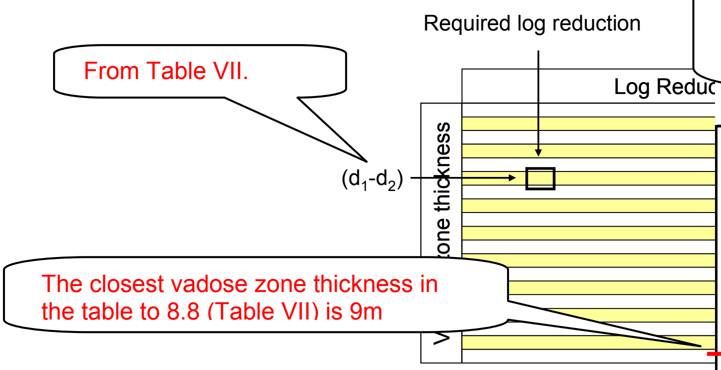
1 Write the vadose zone and saturated zone (aquifer) materials at the site in Table VII. Possible materials are given in Section 8.6.4 of the Guidelines.

Table VII

	Material	*Vadose Zone thickness* ***(d_1-d_2)***
Vadose zone	**Coarse sand**	**8.8**
Saturated zone	**Coarse sand**	

Values for "d_1" and "d_2" come from Table III. The difference (10 - 1.2)

2 Calculate the vadose zone thickness (use the values $\mathbf{d_1}$ and $\mathbf{d_2}$ from Table III), and write it in Table VII.



Vadose Zone Thickness (m)	Log reduction 12.0	12.5	13.0	13.5
1	303	322	341	360
2	282	296	314	332
3	260	273	286	298
4	231	247	261	275
5	212	227	241	256
6	188	198	213	229
7	171	185	195	207
8	145	158	181	189
9	125	141	155	170
10	105	116	138	147
15		47	55	64
20				

Fig. II

3 Use the catalogue in **Table 8.9** and the vadose and saturated zone materials written in Table VI to find the table needed in Section 8.6.4.

4 Read the $\log_{10}$ reduction from the table as shown in Fig.II.

The calculated vadose zone depth and required $\log_{10}$ reduction may not exactly match the values given in the vertical and horizontal scales of the table. Read from the row and column with the closest value.

5 Write the separation distance in the box below

Separation Distance required (m)	**155**

To protect users of the well water against viral infection, the new well must be at least 155 m away from the disposal field.

8.6 Data tables

8.6.1 Virus reduction in on-site treatment systems and their disposal fields

Table 8.3 Log_{10} reductions achievable by on-site treatment systems

Disposal system type	Log_{10} reduction achievable
Primary treatment system (septic tank)	0.6
Secondary treatment system (AWTS[34])	1.0

Table 8.4 Log_{10} reduction achievable by additional disinfection

Disinfection Process	Log_{10} reduction achievable
Chlorination	1.0
UV irradiation	1.0

Table 8.5 Log_{10} reduction achievable by distribution aggregate in disposal fields

Type of aggregate	Log_{10} reduction achievable
Pea gravel (assume this value when builders' mix is used)	0.36
Sand	0.49

[34] Proprietary aerated wastewater treatment system

8.6.2 Virus reduction in soil

Users will need to determine the soil type or the generic soil order present on the site of the on-site sewage disposal area. This information is usually available from the regional council, or Landcare Research.

If the soil at the site is listed in Table 8.6, use the virus removal rate from that table, otherwise select the soil order classification in Table 8.7 and use that removal rate.

Table 8.6 Virus reduction for specific soil types

Soil Identification	Virus removal log_{10}/m
Netherton clayey soil	1.0
Hamilton clay	1.8
Waikiwi silt loam	2.3
Waikoikoi silt loam	2.3
Lismore shallow silt loam over gravels	2.0
Templeton silt loam	2.0
Manawatu fine sandy loam	3.0
Waitarere sandy recent soil	2.5
Atiamuri pumice soil	16.6
Waihou allophanic soil	20

Table 8.7 Virus reduction for generic soil orders

NZSC Feature	Virus removal log_{10}/m
Organic soils	1.0
Ultic soils	1.0
Granular soils	1.0
Melanic soils	1.0
Podzol soils	1.0
Gley soils	1.0
Brown soils	2.0
Pallic soils	2.0
Oxidic soils	2.0
Raw & Recent soils	2.5
Semiarid soils	2.5
Pumice soils	16
Allophanic soils	20

8.6.3 Virus reduction in vadose and saturated zones – find log_{10} reduction

This section contains tables that give log reductions for a specified vadose zone thickness and separation distance. Each table is for a different combination of vadose zone and saturated zone materials. The materials that have been modelled are:

Vadose zone

- Alluvial gravel
- Alluvial sand
- Coastal sand (fine)
- Pumice sand
- Sandstone and non-karstic limestone
- Silts
- Clay
- Ash
- Peat
- Karstic and fractured rock (e.g. basalt and schist).

Saturated zone

- Alluvial gravel
- Alluvial sand
- Coastal sand (fine)
- Pumice sand
- Sandstone and non-karstic limestone
- Karstic and fractured rock (e.g. basalt and schist).

The minimum separation distance provided in these tables is 40 m. In general, separation distances are only provided up to those giving slightly more than 16.2 log_{10} virus reduction (maximum required for rotavirus).

The tables with pumice sand as the saturated zone medium have been omitted as virus removals are very high and separation distances are short. **A separation distance of 20 m will provide an adequate log reduction in these cases (the worksheet calculation is unnecessary)** to allow for source zone protection and prevent the possibility of direct transport of viruses down the disturbed media around the well.

Table 8.8 catalogues the table numbers in this section and the vadose zone/saturation zone material hydrogeological settings to which they refer.

Table 8.8 Log_{10} reduction table catalogue

	Vadzose Zone Material	Saturated Zone Material
Log Reduction Table 1	Gravel	Gravel
Log Reduction Table 2	Gravel	Alluvial Sand
Log Reduction Table 3	Gravel	Coastal Sand
Log Reduction Table 4	Gravel	Sandstone/Non-karstic Limestone
Log Reduction Table 5	Gravel	Karstic and Fractured Rock
Log Reduction Table 6	Alluvial Sand	Gravel
Log Reduction Table 7	Alluvial Sand	Alluvial Sand
Log Reduction Table 8	Alluvial Sand	Coastal Sand
Log Reduction Table 9	Alluvial Sand	Sandstone/Non-karstic Limestone
Log Reduction Table 10	Alluvial Sand	Karstic and Fractured Rock
Log Reduction Table 11	Coastal Sand	Gravel
Log Reduction Table 12	Coastal Sand	Alluvial Sand
Log Reduction Table 13	Coastal Sand	Coastal Sand
Log Reduction Table 14	Coastal Sand	Sandstone/Non-karstic Limestone
Log Reduction Table 15	Coastal Sand	Karstic and Fractured Rock
Log Reduction Table 16	Pumice Sand	Gravel
Log Reduction Table 17	Pumice Sand	Alluvial Sand
Log Reduction Table 18	Pumice Sand	Coastal Sand
Log Reduction Table 19	Pumice Sand	Sandstone/Non-karstic Limestone
Log Reduction Table 20	Pumice Sand	Karstic and Fractured Rock
Log Reduction Table 21	Sandstone/Non-karstic Limestone	Gravel
Log Reduction Table 22	Sandstone/Non-karstic Limestone	Alluvial Sand
Log Reduction Table 23	Sandstone/Non-karstic Limestone	Coastal Sand
Log Reduction Table 24	Sandstone/Non-karstic Limestone	Sandstone/Non-karstic Limestone
Log Reduction Table 25	Sandstone/Non-karstic Limestone	Karstic and Fractured Rock

	Vadzose Zone Material	Saturated Zone Material
Log Reduction Table 26	Silt	Gravel
Log Reduction Table 27	Silt	Alluvial Sand
Log Reduction Table 28	Silt	Coastal Sand
Log Reduction Table 29	Silt	Sandstone/Non-karstic Limestone
Log Reduction Table 30	Silt	Karstic and Fractured Rock
Log Reduction Table 31	Clay	Gravel
Log Reduction Table 32	Clay	Alluvial Sand
Log Reduction Table 33	Clay	Coastal Sand
Log Reduction Table 34	Clay	Sandstone/Non-karstic Limestone
Log Reduction Table 35	Clay	Karstic and Fractured Rock
Log Reduction Table 36	Ash	Gravel
Log Reduction Table 37	Ash	Alluvial Sand
Log Reduction Table 38	Ash	Coastal Sand
Log Reduction Table 39	Ash	Sandstone/Non-karstic Limestone
Log Reduction Table 40	Ash	Karstic and Fractured Rock
Log Reduction Table 41	Peat	Gravel
Log Reduction Table 42	Peat	Alluvial Sand
Log Reduction Table 43	Peat	Coastal Sand
Log Reduction Table 44	Peat	Sandstone/Non-karstic Limestone
Log Reduction Table 45	Peat	Karstic and Fractured Rock
Log Reduction Table 46	Karstic and Fractured Rock	Gravel
Log Reduction Table 47	Karstic and Fractured Rock	Alluvial Sand
Log Reduction Table 48	Karstic and Fractured Rock	Coastal Sand
Log Reduction Table 49	Karstic and Fractured Rock	Sandstone/Non-karstic Limestone
Log Reduction Table 50	Karstic and Fractured Rock	Karstic and Fractured Rock

Log Reduction Table 1 **Vadose zone: Gravel - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Separation Distance (m)													
	40	50	60	80	100	150	200	250	300	400	500	600	800	1000
1	1.5	1.6	1.6	1.7	1.9	2.0	2.3	2.5	2.6	2.9	3.2	3.4	3.8	4.2
2	1.7	1.8	1.8	2.0	2.1	2.3	2.6	2.7	2.9	3.2	3.5	3.7	4.1	4.5
3	1.9	2.0	2.1	2.2	2.3	2.5	2.9	3.0	3.2	3.5	3.7	4.0	4.4	4.8
4	2.1	2.2	2.2	2.4	2.5	2.7	3.1	3.2	3.4	3.7	4.0	4.2	4.7	5.1
5	2.3	2.4	2.4	2.6	2.7	2.9	3.3	3.4	3.6	3.9	4.2	4.4	4.9	5.4
6	2.4	2.5	2.6	2.8	2.9	3.1	3.5	3.6	3.8	4.1	4.5	4.7	5.2	5.6
7	2.6	2.7	2.8	2.9	3.1	3.3	3.6	3.8	4.0	4.3	4.6	4.8	5.3	5.8
8	2.8	2.8	2.9	3.0	3.2	3.4	3.8	4.0	4.2	4.5	4.8	5.0	5.6	6.1
9	2.9	3.0	3.0	3.2	3.4	3.7	4.0	4.1	4.3	4.7	5.0	5.2	5.7	6.3
10	3.1	3.2	3.2	3.4	3.5	3.8	4.2	4.3	4.5	4.8	5.2	5.5	6.0	6.4
15	3.7	3.9	3.9	4.0	4.2	4.5	5.0	5.1	5.3	5.7	6.0	6.2	6.9	7.4
20	4.5	4.6	4.6	4.8	4.9	5.3	5.7	5.9	6.1	6.6	6.9	7.2	7.8	8.3
25	5.2	5.3	5.3	5.5	5.7	5.9	6.5	6.7	7.0	7.3	7.7	8.1	8.6	9.3
30	5.9	5.9	6.1	6.3	6.4	6.8	7.3	7.4	7.8	8.1	8.5	8.8	9.6	10.1
35	6.6	6.7	6.8	6.9	7.2	7.6	8.1	8.3	8.6	9.1	9.4	9.7	10.5	11.0
40	7.4	7.6	7.7	7.9	8.0	8.4	8.9	9.0	9.4	9.9	10.4	10.7	11.3	12.1
45	8.2	8.4	8.5	8.7	8.9	9.2	9.8	10.0	10.3	10.8	11.3	11.6	12.3	12.9
50	9.1	9.1	9.2	9.4	9.6	10.1	10.7	10.8	11.1	11.6	12.1	12.4	13.0	14.0
55	9.9	10.0	10.1	10.4	10.4	10.8	11.4	11.7	11.9	12.4	12.9	13.3	14.2	14.7
60	10.7	10.9	10.8	11.0	11.2	11.6	12.3	12.4	12.9	13.3	13.5	14.5	15.0	15.7
65	11.5	11.7	11.6	11.9	12.2	12.5	13.1	13.4	13.7	14.1	14.6	15.2	16.1	16.9
70	12.4	12.4	12.5	12.8	13.0	13.3	14.2	14.3	14.6	15.2	15.6	16.0	17.0	17.8
75	13.1	13.3	13.4	13.5	13.8	14.2	14.9	15.1	15.4	15.9	16.7	16.6	17.4	18.5
80	13.9	14.1	14.1	14.2	14.5	14.9	15.7	15.9	16.3	16.6	17.2	17.5	18.5	19.3

Log Reduction Table 2 Vadose zone: Gravel - Saturated zone: Alluvial Sand

Vadose Zone Thickness (m)	Separation Distance (m)															
	40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
1	3.0	3.3	3.6	3.9	4.3	4.6	4.8	5.4	6.0	6.6	7.1	8.1	9.7	11.5	14.2	16.9
2	3.3	3.6	3.9	4.2	4.6	5.0	5.1	5.7	6.3	7.0	7.4	8.4	10.0	11.8	14.5	17.3
3	3.5	3.9	4.2	4.5	4.9	5.3	5.4	6.1	6.6	7.3	7.7	8.7	10.2	12.2	14.7	17.6
4	3.8	4.2	4.5	4.8	5.2	5.6	5.7	6.3	7.0	7.5	8.0	9.0	10.7	12.5	15.1	17.9
5	4.1	4.4	4.8	5.1	5.5	5.8	6.0	6.6	7.2	7.9	8.4	9.3	10.9	12.8	15.4	18.1
6	4.3	4.7	5.1	5.4	5.8	6.1	6.3	6.9	7.6	8.2	8.7	9.8	11.3	13.0	15.7	18.6
7	4.5	4.9	5.2	5.6	6.1	6.4	6.7	7.4	7.9	8.5	9.0	10.0	11.5	13.5	15.9	18.7
8	4.7	5.1	5.5	5.8	6.3	6.8	6.9	7.5	8.1	8.8	9.2	10.3	11.9	13.8	16.2	19.1
9	4.9	5.3	5.7	6.0	6.6	7.0	7.1	7.9	8.5	9.1	9.6	10.5	12.3	14.0	16.6	19.5
10	5.0	5.5	5.9	6.4	6.8	7.2	7.3	8.1	8.7	9.4	9.9	10.9	12.4	14.3	16.9	19.9
15	5.9	6.4	6.9	7.3	7.9	8.4	8.6	9.3	10.0	10.7	11.2	12.3	14.3	15.7	18.6	21.4
20	6.6	7.3	7.9	8.3	8.8	9.3	9.6	10.4	11.4	12.1	12.6	13.8	15.3	17.3	20.0	23.0
25	7.3	8.1	8.7	9.2	9.7	10.2	10.6	11.4	12.4	13.3	13.6	15.0	16.6	18.9	21.8	24.6
30	8.2	8.9	9.5	10.0	10.9	11.2	11.7	12.4	13.4	14.3	15.0	16.4	18.0	20.3	23.0	26.1
35	8.9	9.7	10.4	10.8	11.6	12.0	12.5	13.6	14.4	15.2	16.2	17.5	19.5	21.6	24.5	27.8
40	9.7	10.5	11.2	11.7	12.3	13.0	13.4	14.6	15.4	16.4	17.0	18.9	20.7	23.0	26.1	29.5
45	10.6	11.4	11.9	12.7	13.4	13.8	14.5	15.5	16.5	17.6	18.1	19.8	22.0	24.0	27.8	30.7
50	11.5	12.2	12.8	13.4	13.9	14.7	15.2	16.3	17.5	18.4	19.5	20.6	23.1	25.5	28.7	31.9
55	12.2	13.1	13.7	14.4	15.1	15.8	16.3	17.3	18.4	19.6	20.4	21.6	24.3	26.8	30.1	33.5
60	13.2	13.8	14.5	15.1	15.9	16.2	17.1	18.3	19.2	20.7	21.4	23.0	25.3	27.6	32.0	35.2
65	13.9	14.7	15.5	15.9	16.7	17.4	17.9	18.9	20.2	21.3	22.2	23.8	26.4	28.9	32.0	36.8
70	14.7	15.5	16.2	16.8	17.6	18.4	19.0	20.2	21.3	22.9	23.4	25.0	27.4	29.6	34.2	38.2
75	15.4	16.2	17.1	17.6	18.4	19.2	19.7	21.0	22.3	23.1	24.3	26.1	28.5	31.5	34.7	39.1
80	16.4	17.2	17.8	18.3	19.3	20.1	20.3	21.6	23.1	24.1	25.3	26.9	29.4	32.3	36.2	40.4

Log Reduction Table 3 Vadose zone: Gravel - Saturated zone: Coastal Sand

	Separation Distance (m)												
Vadose Zone Thickness (m)	40	50	60	70	80	90	100	120	140	160	180	200	250
1	4.0	4.8	5.3	6.3	7.1	8.0	8.6	11.2	12.8	15.4	17.0	19.3	25.8
2	4.3	5.1	5.6	6.7	7.4	8.2	8.9	11.6	13.1	15.7	17.3	19.6	26.1
3	4.6	5.4	5.9	6.9	7.6	8.5	9.2	11.8	13.4	16.1	17.6	20.0	26.5
4	4.8	5.6	6.2	7.2	7.9	8.9	9.6	12.2	13.7	16.4	18.0	20.2	26.8
5	5.0	5.9	6.4	7.5	8.2	9.2	9.8	12.5	14.1	16.7	18.2	20.6	27.0
6	5.2	6.1	6.7	7.7	8.5	9.4	10.2	12.8	14.3	16.9	18.6	21.0	27.5
7	5.4	6.3	6.9	8.0	8.8	9.8	10.4	13.0	14.7	17.3	18.9	21.1	27.7
8	5.6	6.6	7.1	8.3	9.0	9.9	10.6	13.2	14.8	17.6	19.2	21.6	28.1
9	5.8	6.8	7.3	8.5	9.1	10.2	10.9	13.6	15.2	17.8	19.6	21.9	28.3
10	6.0	7.0	7.5	8.7	9.5	10.5	11.0	13.7	15.5	18.2	19.9	22.1	28.6
15	6.7	7.8	8.5	9.7	10.6	11.6	12.4	15.0	16.8	19.4	21.3	23.6	30.0
20	7.5	8.6	9.4	10.5	11.5	12.7	13.5	16.1	18.0	20.7	22.7	25.0	31.5
25	8.2	9.4	10.1	11.4	12.4	13.6	14.3	17.2	19.2	21.9	23.8	26.3	32.6
30	8.9	10.2	10.9	12.3	13.3	14.5	15.4	18.1	20.2	23.0	24.8	27.6	34.3
35	9.7	11.1	11.8	13.1	14.1	15.4	16.2	18.9	21.3	23.9	26.3	28.6	35.5
40	10.5	11.7	12.8	13.9	15.2	16.5	17.1	20.3	22.3	25.1	27.1	29.8	36.7
45	11.4	12.6	13.5	14.9	16.0	17.2	18.1	20.9	23.2	26.3	28.3	30.9	37.9
50	12.1	13.3	14.4	15.6	16.8	18.1	18.9	21.8	24.2	27.2	29.3	32.1	39.2
55	13.0	14.4	15.1	16.5	17.6	19.1	19.9	22.6	25.3	28.0	30.6	33.1	40.0
60	13.8	15.0	15.8	17.2	18.6	19.7	20.7	23.5	26.3	29.1	31.5	34.2	41.4
65	14.6	16.1	16.7	18.3	19.2	21.1	21.4	24.5	26.9	30.2	32.4	35.2	42.2
70	15.4	16.7	17.6	19.1	20.0	21.9	22.3	25.5	28.0	30.8	33.0	36.2	43.6
75	16.3	17.5	18.3	19.7	21.1	22.4	23.1	26.4	28.8	31.7	34.5	37.0	44.1
80	17.1	18.4	19.2	20.6	22.0	23.2	24.1	27.2	30.0	32.6	35.3	37.8	45.9

Log Reduction Table 4 Vadose zone: Gravel - Saturated zone: Sandstone and Non-karstic Limestone

Vadose Zone Thickness (m)	Separation Distance (m)					
	40	50	60	70	80	90
1	9.2	11.1	13.1	15.2	16.4	18.6
2	9.5	11.4	13.5	15.5	16.7	18.9
3	9.9	11.7	13.8	15.8	16.9	19.3
4	10.2	12.1	14.1	16.1	17.4	19.5
5	10.5	12.5	14.3	16.4	17.8	19.7
6	10.9	12.6	14.9	16.8	18.0	20.2
7	11.3	13.0	15.1	17.2	18.6	20.5
8	11.5	13.4	15.3	17.3	18.8	20.8
9	11.9	13.5	15.8	17.9	19.0	21.1
10	12.0	14.0	16.0	18.0	19.4	21.5
15	13.5	15.7	17.5	19.6	21.0	23.0
20	15.3	16.9	19.2	21.4	22.8	24.6
25	16.9	18.8	21.2	22.7	24.1	26.4
30	18.4	20.1	22.4	24.8	26.5	28.4
35	19.8	21.9	24.1	26.7	27.5	29.8
40	21.3	23.6	25.8	27.9	29.4	31.3

Log Reduction Table 5 Vadose zone: **Gravel** - Saturated zone: **Karstic and Fractured Rock**

	Separation Distance (m)														
Vadose Zone Thickness (m)	40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	0.6	0.6	0.7	0.8	1.1	1.3	1.6	1.9	2.2	2.9	3.4	4.1	6.6	12.9	19.3
2	0.8	0.9	1.0	1.1	1.4	1.6	1.9	2.2	2.5	3.2	3.8	4.4	7.0	13.3	19.6
3	1.0	1.1	1.2	1.4	1.7	1.9	2.2	2.6	2.8	3.6	4.1	4.8	7.3	13.6	20.0
4	1.2	1.3	1.4	1.7	2.0	2.2	2.6	2.9	3.2	3.8	4.5	5.1	7.6	13.9	20.2
5	1.4	1.5	1.6	1.9	2.3	2.5	2.9	3.2	3.5	4.2	4.8	5.5	8.0	14.3	20.7
6	1.5	1.7	1.8	2.1	2.5	2.8	3.1	3.5	3.9	4.4	5.1	5.8	8.2	14.6	20.7
7	1.7	1.9	2.0	2.2	2.6	3.0	3.4	3.7	4.1	4.8	5.4	6.0	8.6	15.0	21.5
8	1.9	2.1	2.2	2.4	2.9	3.2	3.7	4.1	4.4	5.2	5.7	6.5	9.0	15.3	21.4
9	2.0	2.2	2.3	2.6	3.1	3.4	3.9	4.3	4.7	5.4	6.1	6.8	9.2	15.7	21.7
10	2.1	2.4	2.5	2.8	3.4	3.6	4.1	4.5	4.8	5.8	6.3	7.0	9.6	15.8	22.2
15	2.9	3.0	3.3	3.6	4.2	4.6	5.2	5.7	6.2	7.0	7.9	8.7	11.3	17.5	24.0
20	3.6	3.9	4.0	4.4	5.1	5.5	6.1	6.7	7.4	8.5	9.2	10.1	12.8	19.4	25.4
25	4.2	4.6	4.6	5.3	5.8	6.5	7.1	7.9	8.3	9.4	10.5	11.2	14.4	20.8	27.5
30	4.9	5.2	5.4	5.9	6.7	7.3	8.1	8.8	9.3	10.5	11.6	12.4	16.1	22.3	28.8
35	5.8	6.0	6.2	6.7	7.5	8.0	9.0	9.6	10.3	11.7	12.8	13.5	17.5	24.3	30.7
40	6.5	6.7	7.1	7.5	8.6	9.1	9.9	10.8	11.5	12.8	14.1	15.0	18.7	25.9	32.5
45	7.3	7.7	7.9	8.4	9.3	10.0	10.8	11.6	12.5	13.7	15.1	16.5	20.2	27.5	34.3
50	8.2	8.4	8.8	9.1	10.2	10.7	11.7	12.6	13.4	14.9	16.2	17.2	21.4	29.3	35.4
55	9.0	9.4	9.5	9.9	10.8	11.7	12.5	13.5	14.2	15.8	17.5	18.4	22.8	30.9	38.2
60	9.7	10.0	10.3	10.7	11.7	12.3	13.7	14.5	15.4	16.9	18.2	19.7	24.3	33.0	38.7
65	10.6	10.8	11.1	11.6	12.5	13.2	14.2	15.5	16.3	18.1	19.6	20.9	25.4	34.5	40.5
70	11.5	11.7	11.9	12.4	13.6	14.1	15.3	16.2	17.5	18.7	20.2	21.4	26.6	36.1	42.9
75	12.2	12.5	12.6	13.2	14.2	14.9	16.1	17.1	18.1	19.9	21.2	22.9	27.2	37.1	45.2
80	13.1	13.3	13.5	13.9	14.9	15.7	16.9	18.1	19.0	20.6	22.5	23.6	29.0	38.4	46.1

Log Reduction Table 6 **Vadose zone: Alluvial Sand - Saturated zone: Gravel**

		Separation Distance (m)													
		40	50	60	80	100	150	200	250	300	400	500	600	800	1000
Vadose Zone Thickness (m)	1	1.9	2.0	2.0	2.2	2.3	2.4	2.8	2.9	3.0	3.4	3.6	3.9	4.3	4.7
	2	2.5	2.6	2.6	2.8	2.9	3.1	3.4	3.6	3.7	4.0	4.3	4.6	5.0	5.4
	3	3.1	3.2	3.2	3.4	3.5	3.7	4.1	4.2	4.4	4.7	4.9	5.2	5.7	6.1
	4	3.7	3.7	3.8	3.9	4.0	4.3	4.7	4.8	5.0	5.3	5.6	5.9	6.4	6.8
	5	4.2	4.3	4.3	4.5	4.6	4.9	5.3	5.4	5.6	6.0	6.3	6.5	7.0	7.5
	6	4.7	4.8	4.9	5.0	5.2	5.4	5.9	6.0	6.2	6.5	6.9	7.1	7.6	8.1
	7	5.2	5.3	5.4	5.6	5.7	5.9	6.4	6.6	6.8	7.1	7.4	7.7	8.3	8.8
	8	5.7	5.9	5.9	6.1	6.2	6.5	7.0	7.1	7.4	7.7	8.0	8.3	8.8	9.4
	9	6.4	6.5	6.5	6.7	6.8	7.1	7.6	7.7	7.9	8.2	8.7	8.9	9.5	10.1
	10	6.9	7.0	7.0	7.2	7.4	7.6	8.2	8.3	8.5	8.9	9.3	9.6	10.1	10.7
	15	9.9	10.0	10.0	10.3	10.3	10.7	11.3	11.4	11.8	12.1	12.4	12.8	13.5	14.0
	20	12.9	12.9	13.0	13.2	13.3	13.7	14.2	14.4	14.8	15.3	15.6	16.1	16.7	17.3
	25	15.8	16.0	16.1	16.3	16.5	16.8	17.5	17.7	17.8	18.3	18.9	19.2	20.0	20.6
	30	18.7	18.9	18.8	19.0	19.4	19.6	20.1	20.5	20.9	21.2	21.6	22.1	23.2	23.5
	35	21.5	21.7	21.8	21.9	22.1	22.4	23.0	23.3	23.8	24.1	24.7	25.1	25.9	26.5

Log Reduction Table 7 **Vadose zone: Alluvial Sand - Saturated zone: Alluvial Sand**

		Separation Distance (m)															
		40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
Vadose Zone Thickness (m)	1	3.4	3.8	4.1	4.3	4.7	5.1	5.3	5.9	6.4	7.1	7.5	8.5	10.1	11.9	14.6	17.4
	2	4.2	4.5	4.8	5.1	5.5	5.8	6.1	6.6	7.2	7.9	8.3	9.4	10.8	12.6	15.4	18.3
	3	4.8	5.2	5.5	5.8	6.2	6.7	6.8	7.4	8.0	8.7	9.2	10.0	11.6	13.6	16.2	18.9
	4	5.5	5.9	6.2	6.6	7.0	7.4	7.5	8.2	8.7	9.4	9.9	11.0	12.6	14.4	17.0	19.6
	5	6.1	6.5	6.9	7.2	7.8	8.1	8.2	9.0	9.5	10.2	10.7	11.6	13.3	15.0	17.8	20.8
	6	6.6	7.1	7.5	7.9	8.4	8.7	9.0	9.6	10.3	11.0	11.6	12.6	14.1	15.8	18.7	21.1
	7	7.3	7.8	8.3	8.6	9.1	9.4	9.7	10.3	11.0	11.7	12.2	13.3	14.9	16.9	19.7	22.3
	8	7.8	8.4	8.8	9.2	9.7	10.1	10.3	11.0	11.8	12.6	13.0	14.1	15.7	17.6	20.3	23.0
	9	8.4	9.0	9.4	9.8	10.3	10.8	11.1	11.8	12.5	13.2	13.8	14.9	16.5	18.4	21.1	24.0
	10	9.1	9.6	10.1	10.6	11.1	11.6	11.8	12.7	13.2	14.1	14.5	15.6	17.4	19.4	21.9	24.7
	15	12.1	12.7	13.3	13.8	14.5	14.9	15.3	16.3	16.8	17.8	18.4	19.6	21.4	23.3	26.2	29.5
	20	15.2	15.9	16.5	17.2	17.6	18.2	18.6	19.7	20.4	21.5	22.0	23.4	25.4	27.3	30.4	33.6
	25	18.2	18.8	19.6	20.0	20.7	21.3	22.0	22.6	23.7	24.9	25.5	27.1	29.2	31.1	34.6	37.7
	30	21.1	21.7	22.4	23.0	23.6	24.2	25.0	26.2	26.8	27.9	29.1	30.3	32.5	35.0	38.5	41.6

Log Reduction Table 8 **Vadose zone: Alluvial Sand - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Separation Distance (m) 40	50	60	70	80	90	100	120	140	160	180	200	250
1	4.4	5.3	5.8	6.9	7.5	8.4	9.1	11.7	13.3	15.9	17.5	19.8	26.2
2	5.1	6.0	6.5	7.6	8.3	9.2	9.8	12.5	14.0	16.7	18.2	20.6	27.0
3	5.8	6.7	7.3	8.2	9.0	9.8	10.6	13.2	14.8	17.5	19.0	21.3	27.8
4	6.4	7.3	7.9	9.0	9.7	10.7	11.3	14.0	15.7	18.1	19.9	22.2	28.7
5	7.0	8.0	8.6	9.7	10.3	11.5	12.1	14.7	16.3	19.1	20.7	23.0	29.4
6	7.6	8.5	9.2	10.2	11.1	12.1	12.7	15.4	17.0	19.6	21.4	23.7	30.2
7	8.1	9.1	9.8	10.9	11.7	12.8	13.4	16.0	17.9	20.5	22.2	24.5	31.1
8	8.6	9.7	10.3	11.6	12.4	13.4	14.2	16.7	18.5	21.0	22.9	25.1	31.7
9	9.3	10.4	11.0	12.2	13.0	14.1	14.8	17.5	19.3	21.9	23.6	26.0	32.6
10	9.8	10.9	11.7	12.9	13.7	14.8	15.4	18.1	20.0	22.7	24.3	26.7	33.3
15	12.9	14.1	14.9	16.0	17.0	18.3	19.0	21.6	23.7	26.5	28.3	30.9	37.4
20	16.0	17.1	18.0	19.3	20.3	21.5	22.3	25.0	27.4	29.9	31.9	34.6	41.2
25	19.0	20.1	20.8	22.3	23.4	24.5	25.4	28.1	30.4	33.3	35.1	38.4	45.2
30	21.7	23.1	23.8	25.2	26.2	27.8	28.3	31.1	33.6	36.4	38.8	41.4	48.5

Log Reduction Table 9 **Vadose zone: Alluvial Sand - Saturated zone: Sandstone and Non-karstic Limestone**

Vadose Zone Thickness (m)		Separation Distance (m)					
		40	50	60	70	80	90
	1	9.7	11.6	13.7	15.7	16.8	19.1
	2	10.4	12.4	14.3	16.4	17.6	19.8
	3	11.3	13.1	15.2	17.2	18.6	20.5
	4	12.0	13.8	16.1	18.1	19.4	21.4
	5	13.0	14.7	17.0	18.9	20.3	22.2
	6	13.6	15.7	17.8	19.6	21.1	22.8
	7	14.5	16.5	18.5	20.8	21.8	24.0
	8	15.5	17.6	19.3	21.6	22.7	24.6
	9	16.2	18.2	20.2	22.4	23.4	25.5
	10	16.9	19.2	20.9	23.3	24.2	26.5
	15	21.5	23.3	25.6	27.7	29.3	31.0

Log Reduction Table 10 Vadose zone: Alluvial Sand - Saturated zone: Karstic and Fractured Rock

		Separation Distance (m)														
		40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
Vadose Zone Thickness (m)	1	1.0	1.1	1.1	1.3	1.5	1.8	2.1	2.4	2.7	3.3	4.0	4.7	7.1	13.3	19.8
	2	1.6	1.7	1.8	2.0	2.3	2.5	2.9	3.2	3.5	4.1	4.8	5.4	7.9	14.4	20.8
	3	2.2	2.3	2.5	2.7	3.0	3.2	3.6	3.9	4.3	5.0	5.5	6.3	8.7	15.1	21.3
	4	2.7	2.9	3.0	3.3	3.7	3.9	4.3	4.7	5.1	5.7	6.4	7.0	9.6	16.1	22.2
	5	3.3	3.5	3.6	3.8	4.3	4.6	5.1	5.5	5.9	6.6	7.2	7.9	10.4	16.7	22.9
	6	3.8	3.9	4.1	4.5	5.0	5.3	5.8	6.3	6.6	7.3	8.2	8.8	11.2	17.7	24.0
	7	4.3	4.5	4.6	5.1	5.6	5.9	6.4	7.0	7.2	8.0	8.8	9.5	12.1	18.4	24.5
	8	4.8	5.0	5.3	5.5	6.2	6.6	7.1	7.6	8.0	8.8	9.5	10.3	12.9	19.0	25.4
	9	5.4	5.6	5.8	6.2	6.8	7.2	7.8	8.2	8.8	9.5	10.4	11.1	13.7	20.1	26.4
	10	6.0	6.2	6.4	6.8	7.4	7.7	8.5	9.0	9.4	10.3	11.2	11.8	14.6	21.2	27.3
	15	9.1	9.2	9.4	9.7	10.7	11.2	11.8	12.4	12.9	14.0	15.0	16.1	18.8	25.6	31.7
	20	12.0	12.1	12.5	12.9	13.7	14.2	15.1	15.9	16.6	17.8	18.7	19.9	23.3	30.5	36.9
	25	14.9	15.2	15.4	15.8	16.8	17.4	18.3	19.1	19.8	21.2	22.2	23.7	27.3	34.7	41.4
	30	17.8	18.1	18.3	18.7	19.8	20.3	21.3	22.1	23.1	24.4	25.8	27.0	30.8	38.9	45.7
	35	20.7	20.9	21.1	21.5	22.5	23.1	24.3	25.1	26.2	27.7	28.9	30.3	34.3	42.6	49.9

Log Reduction Table 11 Vadose zone: Coastal Sand - Saturated zone: Gravel

Vadose Zone Thickness (m)	Separation Distance (m)													
	40	50	60	80	100	150	200	250	300	400	500	600	800	1000
1	2.2	2.3	2.3	2.5	2.6	2.8	3.1	3.3	3.4	3.7	4.0	4.3	4.7	5.1
2	3.0	3.1	3.2	3.3	3.4	3.7	4.1	4.1	4.3	4.6	4.9	5.2	5.7	6.2
3	3.8	3.8	3.9	4.1	4.2	4.5	4.9	5.0	5.2	5.5	5.8	6.1	6.6	7.1
4	4.5	4.6	4.7	4.8	4.9	5.2	5.7	5.8	6.0	6.4	6.6	7.0	7.5	8.1
5	5.2	5.3	5.4	5.5	5.7	6.0	6.5	6.6	6.8	7.2	7.5	7.8	8.3	8.9
6	5.9	6.0	6.0	6.3	6.4	6.8	7.2	7.4	7.7	7.9	8.3	8.6	9.3	9.8
7	6.6	6.8	6.8	7.0	7.1	7.5	8.0	8.1	8.5	8.7	9.2	9.4	10.0	10.6
8	7.3	7.4	7.5	7.6	7.8	8.1	8.7	8.9	9.1	9.5	9.8	10.2	10.8	11.5
9	8.0	8.2	8.2	8.4	8.5	8.9	9.5	9.7	9.9	10.3	10.7	10.9	11.6	12.2
10	8.8	8.9	9.0	9.2	9.4	9.7	10.2	10.3	10.7	11.1	11.5	11.7	12.5	13.1
15	12.6	12.7	12.6	13.0	13.1	13.5	14.2	14.3	14.6	15.1	15.4	15.7	16.7	17.2
20	16.3	16.5	16.6	16.8	17.0	17.3	18.0	18.2	18.7	19.1	19.5	20.0	20.8	21.4
25	20.0	20.0	20.2	20.5	20.6	20.9	21.6	22.1	22.3	22.9	23.4	23.7	24.2	25.4

Log Reduction Table 12 Vadose zone: **Coastal Sand** - Saturated zone: **Alluvial Sand**

		Separation Distance (m)															
		40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
Vadose Zone Thickness (m)	1	3.8	4.1	4.5	4.8	5.1	5.5	5.6	6.4	7.0	7.6	8.0	9.0	10.6	12.4	15.0	17.8
	2	4.9	5.3	5.6	5.9	6.4	6.7	6.9	7.5	8.2	8.7	9.3	10.2	11.7	13.7	16.3	19.0
	3	5.7	6.2	6.6	7.0	7.4	7.9	8.0	8.7	9.4	9.8	10.5	11.5	13.0	14.9	17.6	20.2
	4	6.6	7.0	7.5	7.9	8.4	8.9	9.0	9.8	10.5	11.1	11.6	12.6	14.2	16.1	18.6	21.6
	5	7.4	7.9	8.4	8.8	9.4	9.9	10.1	10.9	11.5	12.2	12.8	13.9	15.4	17.4	20.0	22.7
	6	8.1	8.7	9.1	9.7	10.3	10.8	10.9	11.8	12.6	13.2	13.9	14.9	16.6	18.6	21.3	24.1
	7	8.8	9.5	10.1	10.5	11.0	11.6	11.8	12.7	13.5	14.2	14.7	16.0	17.5	19.6	22.5	25.5
	8	9.6	10.2	10.7	11.3	11.9	12.4	12.7	13.8	14.4	15.2	15.7	17.0	18.8	20.9	23.5	26.3
	9	10.4	11.0	11.6	12.1	12.8	13.4	13.6	14.6	15.4	16.4	16.9	17.9	20.1	21.9	24.9	27.9
	10	11.0	11.8	12.4	12.9	13.5	14.0	14.7	15.6	16.3	17.3	17.9	19.1	21.0	23.1	25.9	29.2
	15	14.9	15.6	16.3	16.9	17.5	18.4	18.7	19.6	20.8	21.9	22.5	24.0	26.0	28.4	31.6	35.2
	20	18.8	19.4	20.2	20.9	21.6	22.2	22.9	23.9	24.9	26.3	27.1	28.6	31.2	33.3	37.3	40.7
	25	22.5	23.1	24.0	24.7	25.2	26.1	26.6	27.8	28.8	29.8	30.8	32.9	35.5	37.8	42.1	45.9

Log Reduction Table 13 **Vadose zone: Coastal Sand - Saturated zone: Coastal Sand**

		Separation Distance (m)											
		40	50	60	70	80	90	100	120	140	160	180	200
Vadose Zone Thickness (m)	1	4.8	5.6	6.2	7.2	7.9	8.9	9.5	12.1	13.7	16.3	17.9	20.3
	2	5.8	6.7	7.2	8.3	9.1	10.0	10.6	13.3	14.9	17.5	19.1	21.6
	3	6.6	7.6	8.2	9.3	10.0	11.1	11.7	14.4	16.1	18.7	20.4	22.7
	4	7.5	8.5	9.1	10.2	11.1	12.1	12.8	15.3	17.2	19.8	21.5	23.7
	5	8.2	9.3	10.0	11.2	12.0	13.1	13.6	16.4	18.3	20.8	22.6	25.1
	6	9.0	10.1	10.8	12.0	12.8	14.0	14.7	17.3	19.3	22.1	23.9	26.2
	7	9.7	10.9	11.6	12.8	13.8	15.1	15.6	18.3	20.6	23.1	24.7	27.3
	8	10.5	11.6	12.3	13.6	14.6	15.8	16.4	19.2	21.2	24.1	25.6	28.2
	9	11.1	12.4	13.2	14.3	15.4	16.7	17.5	20.2	22.3	24.9	26.8	29.3
	10	11.9	13.2	13.8	15.1	16.2	17.4	18.3	21.0	23.0	25.9	27.8	30.2
	15	15.6	17.0	17.8	19.1	20.3	21.6	22.4	25.2	27.8	30.3	32.6	35.3
	20	19.5	20.6	21.6	23.0	24.2	25.7	26.4	29.4	31.8	34.8	37.1	39.7
	25	23.2	24.4	25.0	26.7	28.1	29.5	30.5	33.4	36.0	38.5	41.0	43.6

Log Reduction Table 14 **Vadose zone: Coastal Sand - Saturated zone: Sandstone and Non-karstic Limestone**

Vadose Zone Thickness (m)	Separation Distance (m) 40	50	60	70	80	90
1	10.2	12.0	14.1	16.1	17.4	19.5
2	11.2	13.3	15.4	17.5	18.4	20.5
3	12.7	14.5	16.5	18.5	20.0	22.0
4	13.9	15.7	17.6	19.9	21.0	23.1
5	15.2	17.0	19.3	21.0	22.7	24.5
6	16.4	18.4	20.6	22.4	23.9	25.9
7	17.6	19.6	21.6	23.9	25.0	27.4
8	18.9	20.8	22.8	25.4	26.3	28.4
9	20.2	22.0	24.2	26.3	27.6	29.8
10	21.3	23.4	25.3	27.2	28.5	31.1

Log Reduction Table 15 **Vadose zone: Coastal Sand - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Separation Distance (m)														
	40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	1.3	1.4	1.5	1.7	2.0	2.2	2.5	2.8	3.1	3.8	4.4	5.2	7.7	13.8	20.2
2	2.1	2.3	2.4	2.6	3.0	3.3	3.7	4.0	4.3	5.0	5.7	6.3	8.7	15.2	21.3
3	2.9	3.1	3.2	3.5	3.9	4.3	4.7	5.2	5.6	6.3	6.9	7.6	10.1	16.3	22.7
4	3.6	3.8	4.0	4.3	4.9	5.2	5.8	6.1	6.7	7.5	8.1	9.0	11.5	17.7	23.9
5	4.4	4.6	4.7	5.1	5.7	6.1	6.5	7.2	7.6	8.6	9.3	10.0	12.5	19.1	25.6
6	5.1	5.3	5.5	5.8	6.5	6.9	7.5	8.2	8.6	9.7	10.3	11.1	13.8	20.6	26.4
7	5.8	6.0	6.2	6.6	7.2	7.8	8.6	9.0	9.5	10.7	11.4	12.4	15.3	21.6	28.1
8	6.4	6.7	6.9	7.4	8.0	8.5	9.2	9.9	10.5	11.6	12.6	13.3	16.6	22.8	29.4
9	7.2	7.4	7.7	8.0	8.8	9.3	10.0	10.7	11.3	12.6	13.6	14.4	17.9	23.9	30.8
10	7.9	8.1	8.4	8.8	9.7	10.1	11.0	11.8	12.3	13.5	14.6	15.6	18.9	25.4	32.1
15	11.6	12.0	12.1	12.6	13.6	14.1	15.2	16.0	16.8	18.0	19.4	20.8	24.7	32.6	38.4
20	15.4	15.7	15.9	16.5	17.5	18.1	19.2	20.2	21.0	22.5	23.7	25.5	29.8	38.1	45.2
25	19.2	19.3	19.7	20.1	21.0	21.8	22.8	23.8	25.1	26.4	27.9	29.5	34.5	43.7	51.1
30	22.8	23.1	23.2	23.8	24.7	25.6	26.5	27.9	28.7	30.8	32.5	33.8	39.4	49.5	57.5

Log Reduction Table 16 Vadose zone: Pumice Sand - Saturated zone: Gravel

		Separation Distance (m)													
		40	50	60	80	100	150	200	250	300	400	500	600	800	1000
Vadose Zone Thickness (m)	1	3.3	3.4	3.5	3.6	3.8	4.0	4.3	4.5	4.6	4.9	5.3	5.5	5.9	6.4
	2	5.2	5.2	5.3	5.5	5.6	5.9	6.3	6.4	6.6	6.9	7.2	7.5	8.0	8.5
	3	7.0	6.9	7.1	7.2	7.4	7.7	8.1	8.1	8.5	8.8	9.2	9.5	10.0	10.5
	4	8.6	8.8	8.8	9.0	9.1	9.5	9.9	10.1	10.4	10.7	11.0	11.4	12.0	12.6
	5	10.3	10.4	10.5	10.7	10.8	11.2	11.7	11.8	12.1	12.6	12.9	13.2	13.7	14.4
	6	12.1	12.2	12.3	12.5	12.7	13.0	13.5	13.6	14.0	14.3	14.7	15.1	15.8	16.4
	7	13.9	14.0	14.0	14.2	14.2	14.7	15.3	15.5	15.7	16.1	16.5	16.9	17.5	18.4
	8	15.6	15.6	15.7	16.0	16.1	16.5	17.1	17.1	17.6	18.1	18.5	18.7	19.5	20.2
	9	17.3	17.5	17.5	17.8	17.9	18.2	18.8	18.9	19.3	19.7	20.3	20.5	21.3	21.9
	10	19.0	19.1	19.2	19.4	19.6	20.0	20.6	20.7	21.0	21.4	21.9	22.4	23.2	23.8
	15	27.8	27.9	27.9	28.2	28.4	28.7	29.4	29.6	30.0	30.5	31.1	31.4	32.5	33.0

Log Reduction Table 17 **Vadose zone: Pumice Sand - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Separation Distance (m)															
	40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
1	5.1	5.5	5.8	6.2	6.6	6.9	7.0	7.7	8.2	8.9	9.5	10.4	12.0	13.6	16.5	19.3
2	7.1	7.6	8.0	8.4	8.9	9.2	9.5	10.2	10.7	11.5	11.8	13.0	14.5	16.4	19.1	21.7
3	9.0	9.6	10.0	10.4	11.0	11.6	11.7	12.4	13.1	13.8	14.4	15.5	17.0	18.9	21.5	24.5
4	10.8	11.4	12.0	12.4	13.1	13.4	13.7	14.5	15.2	16.2	16.7	17.7	19.3	21.5	24.3	27.2
5	12.6	13.2	13.8	14.4	14.9	15.5	15.8	16.6	17.5	18.3	18.8	20.1	21.9	23.8	26.6	29.8
6	14.4	15.0	15.8	16.3	16.8	17.4	17.8	18.8	19.5	20.7	21.1	22.6	24.5	26.3	29.3	32.3
7	16.2	17.0	17.5	18.2	18.8	19.4	19.6	20.7	21.6	22.7	23.0	24.5	26.5	28.8	31.9	34.6
8	18.0	18.7	19.3	19.9	20.5	21.2	21.6	22.5	23.3	24.7	25.2	26.8	28.6	30.9	34.1	37.3
9	19.7	20.4	21.1	21.8	22.3	22.8	23.3	24.4	25.4	26.2	27.4	28.7	31.1	32.7	36.5	40.1
10	21.3	22.1	22.9	23.5	23.9	24.8	25.2	26.2	27.2	28.7	29.3	30.6	32.8	35.3	39.0	42.4

Log Reduction Table 18 **Vadose zone: Pumice Sand - Saturated zone: Coastal Sand**

		Separation Distance (m)											
		40	50	60	70	80	90	100	120	140	160	180	200
Vadose Zone Thickness (m)	1	6.0	6.9	7.5	8.6	9.3	10.2	10.9	13.5	15.0	17.7	19.3	21.6
	2	8.1	9.2	9.7	10.7	11.7	12.6	13.2	15.9	17.5	20.2	22.0	24.1
	3	9.9	11.0	11.7	12.8	13.7	14.8	15.5	18.2	20.0	22.6	24.2	26.5
	4	11.7	12.8	13.7	14.9	15.6	17.0	17.5	20.2	22.1	25.0	26.6	28.9
	5	13.4	14.6	15.3	16.6	17.6	18.7	19.5	22.3	24.3	26.8	28.9	31.4
	6	15.3	16.4	17.2	18.5	19.4	20.8	21.4	24.5	26.5	29.0	31.0	33.6
	7	17.0	18.1	19.0	20.3	21.4	22.7	23.4	26.1	28.3	31.2	33.4	35.7
	8	18.7	19.9	20.7	22.0	23.2	24.4	25.1	28.2	30.4	33.1	35.3	38.1
	9	20.4	21.7	22.6	23.9	24.9	26.3	27.0	30.0	32.2	35.0	37.2	40.2
	10	22.2	23.4	24.3	25.5	26.8	28.2	29.0	32.0	34.2	36.8	39.0	42.1

Log Reduction Table 19 Vadose zone: Pumice Sand - Saturated zone: Sandstone and Non-karstic Limestone

		Separation Distance (m)					
		40	50	60	70	80	90
Vadose Zone Thickness (m)	1	11.6	13.4	15.3	17.5	18.8	21.1
	2	14.2	16.1	18.1	20.0	21.5	23.7
	3	16.7	18.8	20.7	22.7	24.4	25.9
	4	19.4	21.3	23.6	25.7	26.8	28.4
	5	21.7	24.2	26.1	28.1	29.5	31.4
	6	24.3	26.8	28.4	30.8	32.3	34.3
	7	26.7	28.9	30.9	33.6	34.6	36.8
	8	29.5	31.4	33.8	35.8	37.1	39.2
	9	31.7	34.1	36.4	38.1	39.7	42.0
	10	33.7	35.8	38.5	40.7	42.4	44.4

Log Reduction Table 20 Vadose zone: Pumice Sand - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Separation Distance (m)														
	40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	2.4	2.6	2.7	2.9	3.3	3.5	3.9	4.3	4.6	5.2	5.8	6.5	8.9	15.2	21.6
2	4.3	4.4	4.6	4.9	5.4	5.7	6.1	6.7	7.2	7.8	8.4	9.0	11.6	18.1	24.2
3	6.0	6.2	6.4	6.7	7.4	7.7	8.2	8.7	9.3	10.3	11.0	11.7	14.2	20.6	26.8
4	7.7	8.0	8.2	8.6	9.2	9.6	10.4	10.9	11.5	12.5	13.4	14.2	17.0	23.1	29.5
5	9.5	9.7	9.9	10.3	11.1	11.6	12.3	13.0	13.4	14.7	15.6	16.6	19.7	25.7	32.1
6	11.2	11.5	11.6	12.2	12.9	13.6	14.1	15.0	15.7	16.7	18.0	18.5	22.3	28.2	35.3
7	12.9	13.2	13.5	13.9	14.8	15.3	16.3	17.1	17.5	18.8	20.2	21.1	24.4	31.4	37.3
8	14.6	14.9	15.1	15.5	16.5	17.2	17.9	18.8	19.4	20.9	22.2	23.3	26.5	33.9	40.4
9	16.4	16.7	16.9	17.4	18.3	18.9	19.8	20.6	21.4	22.9	24.1	25.3	29.3	36.9	43.1
10	18.1	18.4	18.6	19.1	20.2	20.6	21.8	22.4	23.2	24.9	25.7	27.2	31.4	39.3	45.6
15	26.8	27.1	27.4	28.0	28.9	29.7	30.7	31.7	32.6	34.3	35.9	37.6	42.5	51.6	59.5

Log Reduction Table 21 Vadose zone: Sandstone - Saturated zone: Gravel

Vadose Zone Thickness (m)	Separation Distance (m)													
	40	50	60	80	100	150	200	250	300	400	500	600	800	1000
1	1.2	1.3	1.3	1.5	1.6	1.7	2.0	2.2	2.3	2.6	2.9	3.1	3.5	3.9
2	1.2	1.3	1.3	1.5	1.6	1.7	2.1	2.2	2.3	2.6	2.9	3.1	3.5	3.9
3	1.2	1.3	1.4	1.5	1.6	1.7	2.1	2.2	2.4	2.7	2.9	3.2	3.6	3.9
4	1.3	1.4	1.4	1.5	1.7	1.8	2.1	2.3	2.4	2.7	3.0	3.2	3.6	4.0
5	1.3	1.4	1.4	1.6	1.7	1.8	2.1	2.3	2.4	2.7	3.0	3.2	3.6	4.0
6	1.3	1.4	1.4	1.6	1.7	1.8	2.2	2.3	2.4	2.8	3.0	3.2	3.7	4.0
7	1.4	1.4	1.5	1.6	1.7	1.9	2.2	2.3	2.5	2.8	3.1	3.3	3.7	4.1
8	1.4	1.5	1.5	1.7	1.8	1.9	2.2	2.4	2.5	2.8	3.1	3.3	3.7	4.1
9	1.4	1.5	1.5	1.7	1.8	1.9	2.3	2.4	2.5	2.8	3.1	3.3	3.7	4.1
10	1.4	1.5	1.6	1.7	1.8	1.9	2.3	2.4	2.6	2.9	3.1	3.4	3.8	4.1
15	1.6	1.7	1.7	1.9	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
20	1.7	1.8	1.8	2.0	2.1	2.2	2.6	2.7	2.8	3.2	3.4	3.7	4.0	4.4
25	1.8	1.9	2.0	2.1	2.2	2.3	2.7	2.9	3.0	3.3	3.6	3.8	4.2	4.6
30	2.0	2.1	2.1	2.3	2.4	2.5	2.9	3.0	3.1	3.4	3.7	3.9	4.3	4.7
35	2.1	2.2	2.2	2.4	2.5	2.6	3.0	3.1	3.3	3.6	3.9	4.1	4.5	4.9
40	2.2	2.3	2.4	2.5	2.7	2.8	3.1	3.3	3.4	3.7	4.0	4.2	4.7	5.0
45	2.4	2.5	2.5	2.7	2.8	2.9	3.3	3.4	3.6	3.9	4.1	4.4	4.8	5.2
50	2.5	2.6	2.6	2.8	2.9	3.1	3.4	3.6	3.7	4.0	4.3	4.5	5.0	5.4
55	2.7	2.7	2.8	2.9	3.1	3.2	3.6	3.7	3.9	4.2	4.4	4.7	5.1	5.5
60	2.8	2.9	2.9	3.1	3.2	3.3	3.7	3.8	4.0	4.3	4.6	4.8	5.3	5.6
65	2.9	3.0	3.0	3.2	3.3	3.5	3.9	4.0	4.1	4.5	4.7	5.0	5.4	5.8
70	3.0	3.1	3.2	3.3	3.4	3.6	4.0	4.1	4.3	4.6	4.9	5.1	5.5	6.0
75	3.2	3.2	3.3	3.4	3.6	3.8	4.1	4.3	4.4	4.7	5.0	5.3	5.7	6.1
80	3.3	3.4	3.4	3.6	3.7	3.9	4.3	4.4	4.6	4.9	5.2	5.4	5.9	6.3

Log Reduction Table 22 Vadose zone: **Sandstone** - Saturated zone: **Alluvial Sand**

Vadose Zone Thickness (m)	Separation Distance (m)															
	40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
1	2.7	3.0	3.3	3.6	4.0	4.3	4.5	5.1	5.7	6.4	6.8	7.8	9.3	11.2	13.8	16.6
2	2.7	3.0	3.3	3.6	4.0	4.4	4.5	5.1	5.7	6.4	6.8	7.8	9.4	11.2	13.8	16.7
3	2.8	3.1	3.4	3.6	4.1	4.4	4.6	5.2	5.7	6.4	6.9	7.9	9.4	11.2	13.9	16.7
4	2.8	3.1	3.4	3.7	4.1	4.4	4.6	5.2	5.8	6.4	6.9	7.9	9.5	11.3	13.9	16.7
5	2.8	3.1	3.4	3.7	4.1	4.5	4.6	5.2	5.8	6.5	6.9	7.9	9.5	11.3	13.9	16.7
6	2.8	3.1	3.4	3.7	4.1	4.5	4.6	5.3	5.8	6.5	7.0	7.9	9.5	11.3	13.9	16.8
7	2.9	3.2	3.5	3.8	4.2	4.5	4.7	5.3	5.8	6.5	7.0	8.0	9.6	11.4	14.0	16.8
8	2.9	3.2	3.5	3.8	4.2	4.5	4.7	5.3	5.9	6.5	7.0	8.0	9.6	11.4	14.0	16.8
9	2.9	3.2	3.5	3.8	4.2	4.6	4.7	5.4	5.9	6.6	7.0	8.0	9.6	11.4	14.0	16.9
10	2.9	3.3	3.5	3.8	4.3	4.6	4.7	5.3	5.9	6.6	7.1	8.0	9.6	11.5	14.0	16.9
15	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.2	9.8	11.6	14.2	17.0
20	3.2	3.5	3.8	4.1	4.5	4.9	5.0	5.6	6.2	6.9	7.3	8.3	9.8	11.7	14.4	17.2
25	3.4	3.7	4.0	4.3	4.7	5.0	5.2	5.8	6.4	7.1	7.5	8.5	10.0	11.9	14.6	17.3
30	3.5	3.8	4.1	4.5	4.9	5.1	5.4	5.9	6.5	7.2	7.7	8.6	10.2	12.0	14.7	17.5
35	3.7	4.0	4.3	4.6	5.0	5.3	5.5	6.1	6.7	7.4	7.8	8.8	10.4	12.3	14.9	17.6
40	3.8	4.1	4.4	4.7	5.2	5.5	5.6	6.3	6.8	7.5	7.9	9.0	10.5	12.3	15.0	17.8
45	4.0	4.3	4.6	4.9	5.3	5.6	5.8	6.4	7.0	7.7	8.2	9.1	10.7	12.5	15.2	17.9
50	4.1	4.5	4.7	5.0	5.5	5.8	6.0	6.6	7.2	7.7	8.3	9.3	10.9	12.6	15.3	18.1
55	4.2	4.6	4.9	5.2	5.6	5.9	6.1	6.8	7.4	8.0	8.5	9.4	11.0	12.9	15.4	18.3
60	4.4	4.8	5.1	5.4	5.8	6.1	6.3	6.9	7.5	8.2	8.5	9.6	11.2	12.9	15.6	18.5
65	4.6	4.9	5.2	5.5	6.0	6.2	6.4	7.1	7.6	8.3	8.8	9.7	11.3	13.1	15.8	18.5
70	4.7	5.1	5.4	5.7	6.1	6.4	6.6	7.3	7.8	8.4	8.9	9.9	11.5	13.3	15.9	18.7
75	4.9	5.2	5.5	5.8	6.3	6.6	6.8	7.4	7.9	8.6	9.1	10.0	11.6	13.5	16.1	18.9
80	5.0	5.4	5.7	5.9	6.4	6.8	6.9	7.6	8.1	8.9	9.3	10.2	11.7	13.7	16.4	19.2

Log Reduction Table 23 **Vadose zone: Sandstone - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Separation Distance (m)												
	40	50	60	70	80	90	100	120	140	160	180	200	250
1	3.7	4.5	5.0	6.1	6.7	7.7	8.3	10.9	12.5	15.1	16.7	19.1	25.5
2	3.7	4.5	5.0	6.1	6.8	7.7	8.3	10.9	12.5	15.2	16.7	19.1	25.5
3	3.8	4.6	5.1	6.1	6.8	7.7	8.4	11.0	12.6	15.2	16.7	19.1	25.6
4	3.8	4.6	5.1	6.1	6.8	7.7	8.4	11.0	12.6	15.2	16.8	19.2	25.6
5	3.8	4.6	5.1	6.2	6.9	7.8	8.4	11.0	12.6	15.2	16.8	19.2	25.6
6	3.8	4.6	5.2	6.2	6.9	7.8	8.5	11.1	12.6	15.3	16.8	19.2	25.6
7	3.9	4.7	5.2	6.2	6.9	7.8	8.5	11.1	12.7	15.3	16.9	19.2	25.7
8	3.9	4.7	5.2	6.3	6.9	7.9	8.5	11.1	12.7	15.3	16.9	19.2	25.7
9	3.9	4.7	5.2	6.3	7.0	7.9	8.5	11.2	12.7	15.4	16.9	19.3	25.7
10	4.0	4.7	5.3	6.3	7.0	7.9	8.6	11.1	12.7	15.4	17.0	19.3	25.8
15	4.1	4.9	5.4	6.5	7.1	8.0	8.7	11.3	12.9	15.5	17.1	19.4	25.9
20	4.2	5.0	5.6	6.6	7.3	8.2	8.9	11.5	13.0	15.7	17.3	19.6	26.0
25	4.4	5.2	5.7	6.8	7.4	8.3	9.0	11.6	13.2	15.9	17.4	19.7	26.2
30	4.5	5.3	5.8	6.9	7.6	8.5	9.1	11.8	13.3	16.0	17.5	20.0	26.3
35	4.7	5.5	6.0	7.0	7.7	8.7	9.3	11.9	13.4	16.1	17.7	20.0	26.5
40	4.8	5.6	6.1	7.2	7.9	8.9	9.4	12.0	13.7	16.3	17.9	20.3	26.6
45	5.0	5.8	6.3	7.3	8.1	9.0	9.6	12.2	13.7	16.4	18.0	20.3	26.8
50	5.1	6.0	6.5	7.5	8.2	9.1	9.8	12.4	13.9	16.6	18.2	20.5	26.9
55	5.3	6.1	6.6	7.6	8.4	9.2	9.9	12.5	14.2	16.8	18.4	20.7	27.1
60	5.4	6.2	6.8	7.8	8.5	9.4	10.1	12.7	14.3	16.9	18.5	20.9	27.3
65	5.6	6.4	6.9	8.0	8.7	9.6	10.3	12.9	14.4	17.1	18.7	21.0	27.4
70	5.7	6.6	7.1	8.1	8.9	9.7	10.4	13.0	14.6	17.2	18.8	21.1	27.7
75	5.8	6.7	7.2	8.3	9.0	9.9	10.6	13.2	14.8	17.4	19.0	21.3	27.7
80	6.0	6.8	7.3	8.4	9.1	10.1	10.7	13.4	14.9	17.5	19.2	21.5	28.0

Log Reduction Table 24 **Vadose zone: Sandstone** - Saturated zone: **Sandstone and Non-karstic Limestone**

Vadose Zone Thickness (m)	Separation Distance (m)					
	40	50	60	70	80	90
1	8.9	10.8	12.8	14.9	16.2	18.2
2	8.9	10.8	12.8	14.9	16.2	18.3
3	9.0	10.9	12.9	14.9	16.2	18.3
4	9.0	10.9	12.9	15.0	16.2	18.3
5	9.0	10.9	13.0	15.0	16.2	18.3
6	9.1	10.9	13.0	15.0	16.3	18.4
7	9.0	10.9	13.0	15.1	16.3	18.4
8	9.1	11.0	13.0	15.0	16.3	18.4
9	9.1	11.0	13.1	15.1	16.4	18.4
10	9.2	11.0	13.1	15.1	16.4	18.5
15	9.3	11.2	13.2	15.3	16.6	18.6
20	9.4	11.4	13.4	15.5	16.7	18.8
25	9.6	11.6	13.5	15.5	16.8	18.9
30	9.7	11.6	13.7	15.8	17.0	19.1
35	9.9	11.8	13.8	15.9	17.2	19.2
40	10.2	11.9	14.0	16.2	17.3	19.4
45	10.3	12.2	14.2	16.1	17.5	19.5
50	10.4	12.3	14.3	16.3	17.6	19.7
55	10.5	12.4	14.5	16.4	17.8	19.8
60	10.6	12.6	14.6	16.7	17.9	20.1
65	10.9	12.8	14.8	16.9	18.2	20.3
70	11.0	13.0	15.0	17.1	18.3	20.3
75	11.2	13.1	15.1	17.2	18.5	20.6
80	11.3	13.3	15.3	17.4	18.6	20.6

Log Reduction Table 25 **Vadose zone: Sandstone - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Separation Distance (m)														
	40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	0.3	0.3	0.4	0.5	0.8	1.0	1.3	1.6	1.9	2.6	3.2	3.8	6.4	12.6	19.0
2	0.3	0.4	0.4	0.6	0.8	1.0	1.3	1.6	1.9	2.6	3.2	3.9	6.4	12.7	19.0
3	0.3	0.4	0.5	0.6	0.8	1.0	1.3	1.7	2.0	2.7	3.2	3.9	6.4	12.7	19.0
4	0.4	0.4	0.5	0.6	0.9	1.1	1.4	1.7	2.0	2.7	3.3	3.9	6.4	12.8	19.1
5	0.4	0.5	0.5	0.7	0.9	1.1	1.4	1.7	2.0	2.7	3.3	4.0	6.5	12.8	19.1
6	0.4	0.5	0.5	0.7	0.9	1.1	1.4	1.8	2.1	2.7	3.3	4.0	6.5	12.8	19.1
7	0.4	0.5	0.6	0.7	1.0	1.1	1.5	1.8	2.1	2.8	3.3	4.0	6.5	12.8	19.1
8	0.5	0.6	0.6	0.7	1.0	1.2	1.5	1.8	2.1	2.8	3.4	4.0	6.6	12.8	19.2
9	0.5	0.6	0.6	0.8	1.0	1.2	1.5	1.8	2.2	2.8	3.4	4.1	6.5	12.9	19.2
10	0.5	0.6	0.7	0.8	1.0	1.2	1.5	1.8	2.2	2.8	3.4	4.1	6.6	12.9	19.2
15	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.7	13.1	19.4
20	0.8	0.9	1.0	1.1	1.3	1.5	1.8	2.2	2.5	3.1	3.7	4.4	6.9	13.2	19.4
25	0.9	1.0	1.1	1.3	1.5	1.7	2.0	2.3	2.6	3.3	3.9	4.5	7.0	13.3	19.6
30	1.1	1.2	1.2	1.4	1.6	1.8	2.1	2.5	2.8	3.4	4.0	4.7	7.2	13.5	19.9
35	1.2	1.3	1.4	1.5	1.8	2.0	2.3	2.6	2.9	3.6	4.2	4.8	7.4	13.6	19.9
40	1.3	1.4	1.5	1.7	1.9	2.2	2.4	2.8	3.1	3.8	4.3	5.0	7.5	13.9	20.3
45	1.5	1.6	1.7	1.8	2.1	2.3	2.6	2.9	3.2	3.9	4.5	5.2	7.7	14.0	20.5
50	1.6	1.7	1.8	2.0	2.2	2.5	2.8	3.1	3.4	4.1	4.7	5.4	7.8	14.1	20.5
55	1.8	1.8	1.9	2.1	2.4	2.6	2.9	3.3	3.6	4.2	4.8	5.5	8.0	14.3	20.6
60	1.9	2.0	2.1	2.2	2.5	2.8	3.1	3.4	3.7	4.4	5.0	5.7	8.1	14.4	20.7
65	2.0	2.1	2.2	2.4	2.7	3.0	3.3	3.5	3.9	4.5	5.2	5.8	8.3	14.5	21.0
70	2.1	2.3	2.4	2.6	2.9	3.1	3.4	3.7	4.0	4.7	5.3	6.0	8.5	14.7	21.2
75	2.3	2.4	2.5	2.7	3.0	3.2	3.6	3.9	4.2	4.9	5.5	6.1	8.7	14.9	21.4
80	2.4	2.5	2.6	2.8	3.2	3.4	3.8	4.1	4.4	5.0	5.6	6.3	8.9	15.1	21.3

Log Reduction Table 26 **Vadose zone: Silt - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Separation Distance (m)													
	40	50	60	80	100	150	200	250	300	400	500	600	800	1000
1	2.0	2.1	2.1	2.3	2.4	2.5	2.8	3.0	3.1	3.4	3.7	3.9	4.3	4.7
2	2.7	2.7	2.8	2.9	3.1	3.2	3.6	3.7	3.9	4.2	4.5	4.7	5.1	5.5
3	3.3	3.4	3.5	3.6	3.7	3.9	4.3	4.4	4.6	4.9	5.2	5.5	5.9	6.3
4	4.0	4.1	4.1	4.3	4.4	4.6	5.0	5.1	5.3	5.6	5.9	6.2	6.6	7.0
5	4.6	4.7	4.7	4.9	5.0	5.2	5.6	5.7	5.9	6.2	6.6	6.8	7.3	7.8
6	5.2	5.3	5.3	5.5	5.6	5.9	6.3	6.4	6.6	6.9	7.3	7.5	8.0	8.5
7	5.8	5.8	5.9	6.1	6.3	6.5	6.8	7.0	7.2	7.5	7.8	8.2	8.7	9.1
8	6.4	6.5	6.5	6.7	6.8	7.1	7.5	7.7	7.8	8.2	8.4	8.8	9.2	9.8
9	7.0	7.0	7.1	7.3	7.4	7.7	8.1	8.2	8.5	8.8	9.1	9.4	9.9	10.4
10	7.5	7.6	7.7	7.8	8.0	8.3	8.7	8.8	9.0	9.4	9.7	10.0	10.5	11.0
15	10.6	10.7	10.8	11.0	11.1	11.4	11.8	12.0	12.2	12.6	12.9	13.2	13.8	14.2
20	13.9	14.0	14.0	14.3	14.4	14.8	15.3	15.5	15.8	16.4	16.6	16.9	17.4	18.2
25	17.1	17.3	17.2	17.5	17.7	17.9	18.6	18.7	19.2	19.6	19.9	20.3	21.0	21.6
30	20.2	20.2	20.3	20.6	20.8	21.0	21.7	21.8	22.3	22.6	23.0	23.7	24.1	25.0
35	23.3	23.3	23.5	23.7	24.0	24.2	24.7	25.0	25.3	25.7	26.1	26.6	27.5	28.2
40	26.4	26.5	26.5	26.8	26.9	27.3	27.9	28.3	28.4	29.0	29.3	30.0	30.8	31.3
45	29.4	29.4	29.4	29.7	29.8	30.2	31.0	31.1	31.4	31.9	32.4	33.0	33.7	34.4
50	32.2	32.4	32.5	32.6	32.8	33.1	33.9	34.1	34.4	34.9	35.7	36.0	36.7	37.7
55	35.3	35.4	35.6	35.6	35.8	36.2	37.0	37.0	37.5	38.3	38.5	38.9	39.9	40.7
60	38.3	38.4	38.3	38.5	38.9	39.1	39.8	40.0	40.5	41.0	41.5	42.1	43.0	43.9
65	40.9	41.1	41.1	41.5	41.6	42.1	42.8	42.9	43.3	43.9	44.4	45.1	45.8	46.8
70	44.0	44.2	44.3	44.6	44.6	45.0	45.6	46.0	46.4	47.0	47.2	48.0	49.2	49.7
75	46.9	47.0	47.2	47.3	47.5	47.7	48.5	48.9	49.3	50.0	50.4	51.2	51.8	52.3
80	49.7	49.8	49.9	50.1	50.3	50.7	51.5	51.7	52.2	52.8	53.6	53.7	55.0	55.5

Log Reduction Table 27 Vadose zone: Silt - Saturated zone: Alluvial Sand

Vadose Zone Thickness (m)	Separation Distance (m)															
	40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
1	3.5	3.8	4.1	4.4	4.8	5.2	5.3	5.9	6.5	7.2	7.6	8.6	10.2	12.0	14.6	17.5
2	4.3	4.6	4.9	5.2	5.7	6.0	6.1	6.8	7.4	8.0	8.5	9.5	11.0	12.9	15.5	18.2
3	5.1	5.4	5.7	6.0	6.5	6.8	7.0	7.6	8.2	8.8	9.3	10.3	11.9	13.7	16.4	19.2
4	5.7	6.2	6.5	6.8	7.3	7.6	7.8	8.3	9.0	9.6	10.1	11.2	12.7	14.6	17.1	20.1
5	6.4	6.9	7.2	7.5	8.0	8.3	8.5	9.3	9.9	10.4	10.9	11.9	13.6	15.4	18.0	20.8
6	7.1	7.6	7.9	8.3	8.8	9.0	9.3	10.0	10.5	11.3	11.7	12.7	14.3	16.2	18.8	21.7
7	7.7	8.2	8.6	8.9	9.4	9.8	10.0	10.8	11.3	12.2	12.6	13.6	15.2	17.0	19.7	22.2
8	8.3	8.8	9.2	9.6	10.2	10.6	10.8	11.5	12.0	12.9	13.3	14.3	15.9	17.6	20.3	23.3
9	9.0	9.4	9.9	10.3	10.7	11.3	11.5	12.2	12.7	13.4	13.9	14.9	16.6	18.5	21.3	24.1
10	9.6	10.1	10.5	10.9	11.5	11.9	12.1	12.8	13.5	14.2	14.8	15.9	17.3	19.1	22.1	24.7
15	12.7	13.2	13.9	14.2	14.7	15.1	15.5	16.1	17.1	17.7	18.5	19.3	21.0	22.8	25.8	28.6
20	16.2	16.9	17.6	18.0	18.7	19.3	19.7	20.4	21.5	22.3	23.1	24.2	26.3	28.2	31.3	34.5
25	19.4	20.1	20.8	21.5	22.0	22.6	23.2	24.0	25.1	25.8	26.7	28.2	30.2	32.3	35.4	39.0
30	22.5	23.1	24.0	24.6	25.2	25.8	26.3	27.5	28.3	29.7	30.2	31.9	33.6	36.2	39.6	43.0

Log Reduction Table 28 Vadose zone: Silt - Saturated zone: Coastal Sand

		Separation Distance (m)												
		40	50	60	70	80	90	100	120	140	160	180	200	250
Vadose Zone Thickness (m)	1	4.5	5.3	5.8	6.9	7.6	8.5	9.2	11.7	13.3	15.9	17.5	19.9	26.4
	2	5.3	6.1	6.7	7.7	8.4	9.4	10.0	12.6	14.1	16.8	18.4	20.6	27.1
	3	6.0	6.8	7.4	8.5	9.2	10.1	10.8	13.4	15.0	17.7	19.2	21.6	28.0
	4	6.7	7.6	8.2	9.3	9.9	10.9	11.5	14.0	15.7	18.3	20.0	22.3	28.8
	5	7.4	8.3	8.9	10.1	10.8	11.7	12.3	15.0	16.7	19.3	20.8	23.2	29.5
	6	8.0	9.0	9.6	10.7	11.5	12.4	13.0	15.7	17.4	20.1	21.6	24.0	30.4
	7	8.6	9.6	10.3	11.4	12.1	13.1	13.8	16.5	18.0	20.9	22.4	24.7	31.3
	8	9.3	10.3	10.9	11.9	12.7	13.9	14.6	17.1	18.8	21.4	23.1	25.4	32.1
	9	9.8	10.9	11.5	12.6	13.5	14.5	15.2	17.8	19.7	22.3	24.0	26.2	32.6
	10	10.4	11.5	12.2	13.3	14.1	15.3	16.0	18.4	20.3	22.9	24.6	27.1	33.4
	15	13.6	14.6	15.3	16.6	17.3	18.6	19.2	21.9	23.7	26.6	28.2	30.6	37.3
	20	17.0	18.3	19.0	20.2	21.2	22.4	23.2	26.3	28.2	31.1	32.9	35.6	42.1
	25	20.1	21.5	22.3	23.6	24.6	25.9	26.9	29.6	31.8	34.5	37.1	39.5	46.3
	30	23.3	24.4	25.6	26.6	27.9	29.2	30.0	32.8	34.9	38.1	40.2	42.8	50.0

Log Reduction Table 29 Vadose zone: Silt - Saturated zone: Sandstone and Non-karstic Limestone

		Separation Distance (m)					
		40	50	60	70	80	90
Vadose Zone Thickness (m)	1	9.8	11.6	13.6	15.7	17.0	19.0
	2	10.6	12.4	14.7	16.6	17.8	19.9
	3	11.4	13.3	15.4	17.4	18.7	20.7
	4	12.3	14.2	16.2	18.2	19.5	21.7
	5	13.2	15.0	17.2	19.1	20.2	22.6
	6	13.8	15.7	17.7	19.9	21.3	23.1
	7	14.7	16.6	18.7	20.6	22.1	24.0
	8	15.4	17.3	19.3	21.4	22.7	25.0
	9	16.3	18.3	20.2	22.4	23.6	25.5
	10	17.2	19.2	21.1	22.9	24.4	26.4
	15	20.8	22.8	24.9	27.1	28.4	30.3
	20	26.6	28.6	30.6	32.7	34.4	36.0

Log Reduction Table 30 Vadose zone: Silt - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Separation Distance (m)														
	40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	1.1	1.2	1.2	1.4	1.6	1.8	2.1	2.4	2.8	3.4	4.0	4.7	7.2	13.4	19.8
2	1.8	1.9	2.0	2.2	2.4	2.7	2.9	3.3	3.6	4.3	4.9	5.5	8.1	14.2	20.6
3	2.4	2.5	2.6	2.9	3.2	3.4	3.8	4.1	4.5	5.1	5.6	6.4	8.8	15.2	21.6
4	3.1	3.2	3.3	3.6	3.9	4.2	4.6	5.0	5.2	6.0	6.5	7.2	9.7	16.1	22.3
5	3.7	3.8	3.9	4.2	4.6	5.0	5.3	5.7	6.1	6.8	7.4	8.1	10.6	16.9	23.2
6	4.3	4.4	4.6	4.9	5.3	5.6	6.0	6.4	6.8	7.5	8.2	8.8	11.4	17.7	24.0
7	4.9	5.0	5.2	5.4	6.0	6.3	6.8	7.2	7.6	8.4	9.1	9.8	12.1	18.6	24.8
8	5.5	5.7	5.8	6.1	6.6	6.9	7.4	7.9	8.2	9.1	9.8	10.4	12.9	19.2	25.5
9	6.0	6.3	6.4	6.7	7.2	7.6	8.1	8.5	9.0	9.8	10.6	11.1	14.1	20.2	26.0
10	6.6	6.8	7.0	7.3	7.9	8.2	8.8	9.3	9.7	10.6	11.2	11.9	14.6	20.9	27.1
15	9.8	9.9	10.1	10.4	11.0	11.5	12.0	12.7	13.1	13.9	14.7	15.5	18.5	25.0	31.0
20	13.0	13.3	13.5	13.9	14.8	15.3	16.2	16.9	17.4	18.8	19.8	20.7	24.2	30.8	37.4
25	16.2	16.4	16.7	17.2	18.0	18.6	19.5	20.4	21.2	22.3	23.7	24.9	28.4	35.3	41.8
30	19.2	19.6	19.7	20.3	21.0	21.8	22.7	23.6	24.4	25.7	27.2	28.1	32.1	39.9	46.4
35	22.3	22.6	22.8	23.3	24.3	25.0	25.8	26.6	27.6	29.1	30.3	32.0	36.1	44.3	50.9

Log Reduction Table 31 Vadose zone: Clay - Saturated zone: Gravel

		Separation Distance (m)													
		40	50	60	80	100	150	200	250	300	400	500	600	800	1000
Vadose Zone Thickness (m)	1	2.6	2.7	2.7	2.8	2.9	3.1	3.5	3.6	3.7	4.1	4.3	4.6	5.0	5.4
	2	3.7	3.8	3.9	4.0	4.1	4.3	4.7	4.8	5.0	5.3	5.6	5.9	6.3	6.7
	3	4.8	4.9	5.0	5.1	5.2	5.5	5.9	6.0	6.2	6.5	6.8	7.0	7.5	8.0
	4	5.8	5.9	6.0	6.1	6.3	6.6	6.9	7.1	7.3	7.6	7.9	8.2	8.7	9.2
	5	6.8	7.0	7.0	7.2	7.4	7.6	8.0	8.1	8.4	8.7	9.1	9.3	9.8	10.3
	6	7.8	7.9	8.0	8.2	8.3	8.6	9.1	9.2	9.4	9.8	10.2	10.4	10.9	11.5
	7	8.9	9.0	9.0	9.2	9.3	9.6	10.2	10.3	10.4	10.8	11.2	11.5	12.0	12.4
	8	9.9	10.0	10.0	10.2	10.4	10.6	11.1	11.2	11.5	11.9	12.2	12.5	13.1	13.7
	9	10.9	10.9	11.0	11.2	11.4	11.6	12.2	12.3	12.6	12.9	13.2	13.5	14.1	14.6
	10	11.8	11.9	11.9	12.2	12.4	12.6	13.1	13.4	13.6	13.9	14.3	14.6	15.3	15.8
	15	16.8	16.9	17.1	17.2	17.3	17.7	18.2	18.3	18.6	19.1	19.5	19.8	20.3	21.1
	20	26.4	26.7	26.7	26.9	27.1	27.4	28.2	28.2	28.6	29.2	29.8	30.1	30.6	31.4

Log Reduction Table 32 Vadose zone: Clay - Saturated zone: Alluvial Sand

Vadose Zone Thickness (m)	Separation Distance (m)															
	40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
1	4.2	4.5	4.8	5.1	5.5	5.8	6.0	6.6	7.2	7.9	8.3	9.3	10.8	12.7	15.3	18.2
2	5.5	5.8	6.2	6.5	6.9	7.3	7.4	8.1	8.7	9.3	9.8	10.8	12.3	14.3	16.9	19.7
3	6.6	7.1	7.4	7.8	8.2	8.6	8.8	9.4	10.2	10.8	11.2	12.3	13.8	15.6	18.4	21.1
4	7.8	8.3	8.7	9.0	9.6	10.0	10.1	10.9	11.5	12.1	12.5	13.6	15.1	17.2	19.7	22.8
5	8.9	9.3	9.8	10.2	10.7	11.2	11.4	12.1	12.6	13.5	14.0	15.1	16.5	18.2	21.3	23.9
6	9.9	10.4	11.0	11.3	12.0	12.3	12.5	13.3	14.0	14.7	15.3	16.3	18.1	20.0	22.3	25.3
7	11.0	11.5	12.0	12.5	12.9	13.6	13.7	14.5	15.1	16.0	16.4	17.6	19.0	21.4	24.0	26.9
8	12.1	12.6	13.1	13.6	14.1	14.6	14.9	15.6	16.4	17.3	17.9	19.0	20.6	22.5	25.3	28.2
9	13.0	13.7	14.2	14.6	15.2	15.7	16.1	16.8	17.6	18.4	19.1	20.1	21.9	23.7	26.6	29.2
10	14.1	14.6	15.2	15.7	16.3	16.8	17.1	18.1	18.7	19.4	20.2	21.5	23.1	25.0	27.7	30.7
15	19.2	19.9	20.5	21.0	21.5	22.1	22.4	23.6	24.4	25.3	26.0	27.5	29.3	31.4	34.4	37.6
20	28.9	29.7	30.3	31.0	31.7	32.6	33.0	33.9	35.0	36.4	37.3	38.5	40.7	43.2	47.1	50.6

Log Reduction Table 33 Vadose zone: Clay - Saturated zone: Coastal Sand

Vadose Zone Thickness (m)	Separation Distance (m)											
	40	50	60	70	80	90	100	120	140	160	180	200
1	5.1	6.0	6.5	7.6	8.3	9.1	9.8	12.4	13.9	16.6	18.2	20.6
2	6.4	7.3	7.8	8.9	9.6	10.5	11.2	13.8	15.4	18.1	19.6	22.1
3	7.6	8.5	9.1	10.2	10.9	12.0	12.6	15.2	16.8	19.4	21.1	23.5
4	8.6	9.7	10.4	11.4	12.2	13.2	13.8	16.5	18.2	20.8	22.4	24.9
5	9.8	10.8	11.4	12.6	13.4	14.4	15.1	17.7	19.5	22.1	23.8	26.2
6	10.9	11.9	12.5	13.7	14.6	15.6	16.4	19.0	20.7	23.4	25.3	27.6
7	11.8	12.9	13.6	14.8	15.7	16.8	17.3	20.1	22.1	24.7	26.3	28.9
8	12.9	13.9	14.7	16.0	16.8	18.0	18.6	21.4	23.3	25.8	27.8	30.0
9	13.9	15.0	15.6	16.9	17.9	19.1	19.7	22.5	24.6	26.9	28.7	31.5
10	14.9	16.1	16.8	18.1	19.0	20.1	20.8	23.6	25.4	28.3	30.1	32.7
15	20.0	21.1	22.0	23.2	24.2	25.5	26.3	29.1	31.4	34.1	36.2	38.7
20	29.8	30.9	31.7	33.0	34.1	35.7	36.4	39.4	42.0	44.7	46.8	49.9

Log Reduction Table 34 Vadose zone: Clay - Saturated zone: Sandstone and Non-karstic Limestone

Vadose Zone Thickness (m)		Separation Distance (m)					
		40	50	60	70	80	90
	1	10.4	12.3	14.4	16.4	17.7	19.9
	2	11.9	13.8	15.8	18.0	19.3	21.3
	3	13.4	15.1	17.3	19.4	20.8	22.8
	4	14.8	16.8	18.8	20.8	22.1	24.1
	5	16.4	18.0	20.1	22.0	23.7	25.5
	6	17.6	19.5	21.6	23.8	24.9	27.0
	7	19.0	21.1	23.2	25.1	26.4	28.6
	8	20.3	22.4	24.4	26.5	27.8	29.9
	9	21.8	23.9	25.7	27.7	29.0	31.3
	10	23.0	25.0	27.0	29.4	30.9	32.9

Log Reduction Table 35 Vadose zone: Clay - Saturated zone: Karstic and Fractured Rock

		Separation Distance (m)														
		40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
Vadose Zone Thickness (m)	1	1.7	1.8	1.9	2.0	2.3	2.5	2.8	3.1	3.4	4.1	4.6	5.4	7.9	14.2	20.4
	2	2.8	2.9	3.0	3.3	3.6	3.9	4.2	4.6	4.9	5.6	6.2	6.9	9.3	15.7	22.1
	3	3.9	4.0	4.2	4.4	4.8	5.2	5.5	6.0	6.3	7.1	7.6	8.3	10.9	17.0	23.5
	4	4.9	5.1	5.2	5.5	6.0	6.4	6.8	7.3	7.6	8.4	9.1	9.7	12.5	18.6	25.1
	5	6.0	6.1	6.3	6.7	7.1	7.5	8.1	8.6	8.9	9.6	10.5	11.2	13.6	19.8	26.8
	6	7.0	7.1	7.3	7.7	8.2	8.7	9.2	9.7	10.0	11.2	11.9	12.6	15.4	21.5	27.9
	7	8.0	8.1	8.3	8.7	9.3	9.7	10.3	10.9	11.4	12.3	13.0	13.9	16.6	23.0	29.2
	8	8.9	9.2	9.4	9.7	10.4	10.8	11.5	12.1	12.5	13.5	14.4	15.1	18.0	24.3	30.5
	9	10.0	10.2	10.4	10.8	11.5	11.9	12.5	13.0	13.7	14.6	15.4	16.5	19.5	25.6	32.0
	10	10.9	11.2	11.4	11.8	12.6	12.9	13.7	14.2	14.7	15.9	16.8	17.5	20.6	27.3	33.4
	15	15.9	16.1	16.4	16.8	17.7	18.2	18.9	19.7	20.5	21.6	22.7	23.6	27.4	34.4	40.8
	20	25.7	25.9	26.2	26.6	27.6	28.2	29.2	30.4	31.2	32.7	34.1	35.7	39.3	47.6	55.0

Log Reduction Table 36 Vadose zone: Ash - Saturated zone: Gravel

		Separation Distance (m)													
		40	50	60	80	100	150	200	250	300	400	500	600	800	1000
Vadose Zone Thickness (m)	1	2.0	2.1	2.1	2.2	2.4	2.5	2.9	3.0	3.1	3.4	3.7	3.9	4.3	4.7
	2	2.6	2.8	2.8	2.9	3.1	3.2	3.6	3.7	3.9	4.2	4.5	4.7	5.1	5.5
	3	3.3	3.4	3.4	3.6	3.7	3.9	4.3	4.4	4.6	4.9	5.2	5.4	5.9	6.3
	4	3.9	4.0	4.0	4.2	4.3	4.5	4.9	5.0	5.2	5.5	5.8	6.1	6.6	7.0
	5	4.5	4.6	4.6	4.8	4.9	5.1	5.5	5.6	5.8	6.1	6.5	6.7	7.2	7.7
	6	5.1	5.2	5.2	5.3	5.5	5.7	6.1	6.3	6.5	6.8	7.1	7.4	7.8	8.4
	7	5.6	5.7	5.8	6.0	6.0	6.3	6.7	6.8	7.1	7.4	7.7	8.0	8.5	9.0
	8	6.2	6.3	6.4	6.5	6.7	6.9	7.3	7.5	7.7	8.0	8.3	8.5	9.2	9.6
	9	6.7	6.8	6.9	7.1	7.2	7.5	7.9	8.0	8.2	8.6	8.9	9.2	9.6	10.2
	10	7.3	7.4	7.5	7.6	7.8	8.1	8.5	8.6	8.8	9.1	9.5	9.8	10.4	10.8
	15	10.1	10.2	10.2	10.4	10.6	10.9	11.4	11.5	11.7	12.2	12.4	12.6	13.4	13.8
	20	13.2	13.3	13.3	13.6	13.7	14.2	14.6	14.7	15.2	15.5	15.9	16.2	16.8	17.6
	25	16.2	16.3	16.3	16.5	16.7	17.0	17.6	17.8	18.0	18.5	18.8	19.2	20.0	20.6
	30	19.0	19.2	19.3	19.4	19.5	19.9	20.6	20.8	21.1	21.4	22.1	22.5	23.0	23.9
	35	22.1	22.2	22.3	22.4	22.7	23.1	23.6	23.8	24.3	24.8	25.0	25.7	26.3	27.0

Log Reduction Table 37 Vadose zone: Ash - Saturated zone: Alluvial Sand

Vadose Zone Thickness (m)	Separation Distance (m)															
	40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
1	3.5	3.8	4.1	4.4	4.8	5.2	5.3	6.0	6.5	7.2	7.6	8.5	10.2	12.1	14.7	17.5
2	4.3	4.7	5.0	5.3	5.6	6.0	6.2	6.8	7.3	8.0	8.5	9.4	11.1	12.9	15.6	18.2
3	5.1	5.4	5.7	6.0	6.5	6.8	6.9	7.5	8.2	8.8	9.3	10.2	11.8	13.7	16.3	19.1
4	5.7	6.1	6.4	6.8	7.3	7.5	7.7	8.4	8.9	9.7	10.1	11.0	12.7	14.5	17.1	19.8
5	6.4	6.8	7.1	7.5	7.9	8.3	8.5	9.1	9.7	10.4	10.9	11.8	13.5	15.2	17.8	20.7
6	7.0	7.4	7.8	8.2	8.6	9.0	9.1	9.9	10.4	11.2	11.6	12.6	14.3	16.1	18.6	21.4
7	7.5	8.1	8.5	8.9	9.3	9.7	9.9	10.5	11.2	12.0	12.4	13.3	14.9	16.8	19.5	22.2
8	8.2	8.6	9.1	9.4	10.0	10.4	10.5	11.3	12.0	12.6	13.3	14.0	15.5	17.6	20.1	22.8
9	8.8	9.3	9.7	10.1	10.7	11.0	11.3	11.9	12.6	13.3	13.8	14.9	16.5	18.3	21.1	23.8
10	9.3	9.9	10.3	10.6	11.3	11.5	11.9	12.6	13.3	14.1	14.5	15.6	17.2	19.1	21.9	24.7
15	12.2	12.8	13.4	13.8	14.3	14.8	15.1	15.9	16.5	17.4	18.0	19.1	20.9	22.8	25.4	28.1
20	15.6	16.2	16.8	17.3	18.1	18.5	18.8	19.9	20.5	22.0	22.4	23.7	25.7	27.6	30.7	33.3
25	18.5	19.0	19.9	20.4	21.1	21.6	22.2	23.2	24.0	25.1	25.9	27.4	29.3	31.0	34.5	37.6
30	21.3	22.1	23.0	23.3	24.0	24.8	25.3	26.2	27.3	28.5	29.2	30.4	32.7	35.1	38.5	42.0

Log Reduction Table 38 Vadose zone: Ash - Saturated zone: Coastal Sand

Vadose Zone Thickness (m)	Separation Distance (m)													
	30	40	50	60	70	80	90	100	120	140	160	180	200	250
1	3.9	4.5	5.3	5.9	6.9	7.6	8.5	9.1	11.7	13.3	16.0	17.5	19.9	26.4
2	4.6	5.3	6.1	6.6	7.7	8.4	9.3	10.0	12.6	14.3	16.8	18.3	20.7	27.2
3	5.3	6.0	6.9	7.4	8.5	9.1	10.1	10.7	13.4	14.9	17.6	19.2	21.6	28.0
4	6.0	6.7	7.5	8.1	9.2	9.9	10.9	11.5	14.2	15.7	18.4	20.0	22.4	28.8
5	6.6	7.3	8.2	8.8	9.9	10.6	11.7	12.3	14.9	16.6	19.2	20.7	23.1	29.6
6	7.2	7.9	8.9	9.5	10.5	11.4	12.3	13.0	15.6	17.2	19.9	21.4	23.9	30.3
7	7.8	8.5	9.4	10.2	11.2	12.0	12.9	13.6	16.2	17.9	20.5	22.3	24.7	31.1
8	8.4	9.1	10.1	10.7	11.8	12.7	13.7	14.3	16.9	18.6	21.4	22.9	25.4	31.9
9	8.9	9.7	10.7	11.3	12.5	13.2	14.3	14.9	17.6	19.3	22.0	23.6	25.9	32.6
10	9.4	10.2	11.3	11.9	13.2	13.9	15.0	15.6	18.3	20.2	22.7	24.5	26.7	33.2
15	12.3	13.1	14.2	15.0	16.0	17.1	18.1	18.8	21.6	23.4	25.9	28.0	30.3	36.7
20	15.4	16.4	17.5	18.2	19.6	20.7	21.9	22.7	25.5	27.5	30.5	32.3	35.1	41.6
25	18.4	19.2	20.5	21.3	22.6	23.5	24.9	25.8	28.6	30.9	33.8	35.5	38.2	45.1
30	21.2	22.1	23.3	24.2	25.7	26.6	28.0	28.8	31.8	34.1	37.1	39.2	41.6	48.9

Log Reduction Table 39 Vadose zone: Ash - Saturated zone: Sandstone and Non-karstic Limestone

		Separation Distance (m)					
		40	50	60	70	80	90
Vadose Zone Thickness (m)	1	9.8	11.6	13.6	15.7	17.1	19.1
	2	10.7	12.5	14.6	16.5	18.0	19.8
	3	11.3	13.3	15.4	17.4	18.8	20.9
	4	12.2	14.0	16.2	18.1	19.4	21.6
	5	13.0	15.0	17.0	19.0	20.2	22.5
	6	13.7	15.7	17.8	19.6	21.3	23.1
	7	14.5	16.5	18.4	20.4	21.9	24.0
	8	15.4	17.3	19.3	21.2	22.5	24.9
	9	16.3	18.0	20.0	22.0	23.5	25.6
	10	17.0	18.9	20.9	22.9	24.1	26.2
	15	20.7	22.6	24.5	26.6	28.0	30.4

Log Reduction Table 40 Vadose zone: Ash - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Separation Distance (m) 40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	1.1	1.2	1.2	1.4	1.6	1.8	2.1	2.4	2.8	3.4	4.0	4.6	7.2	13.6	19.9
2	1.8	1.9	2.0	2.1	2.4	2.7	3.0	3.3	3.6	4.3	4.8	5.6	8.1	14.3	20.6
3	2.4	2.5	2.6	2.8	3.2	3.4	3.8	4.1	4.4	5.1	5.7	6.4	8.9	15.2	21.3
4	3.0	3.1	3.3	3.5	3.9	4.2	4.5	4.9	5.2	5.9	6.6	7.3	9.7	15.8	22.2
5	3.6	3.8	3.8	4.1	4.6	4.8	5.3	5.6	6.1	6.7	7.3	7.9	10.4	16.9	23.2
6	4.2	4.3	4.5	4.7	5.2	5.6	5.9	6.4	6.8	7.5	8.1	8.7	11.4	17.7	23.9
7	4.7	4.9	5.0	5.3	5.8	6.1	6.6	7.0	7.5	8.2	8.8	9.6	12.1	18.3	24.8
8	5.3	5.5	5.7	5.9	6.5	6.8	7.3	7.7	8.2	8.9	9.6	10.2	13.0	19.1	25.3
9	5.9	6.1	6.2	6.5	7.0	7.4	7.8	8.3	8.9	9.6	10.3	11.2	13.6	20.1	26.1
10	6.4	6.6	6.8	7.1	7.7	8.0	8.4	9.2	9.6	10.2	11.0	11.9	14.3	20.5	27.0
15	9.2	9.4	9.6	9.9	10.7	11.0	11.7	12.1	12.7	13.8	14.4	15.3	18.0	24.5	30.8
20	12.3	12.5	12.8	13.1	14.0	14.5	15.1	16.0	16.6	18.0	19.1	19.9	23.7	30.4	36.6
25	15.2	15.4	15.7	16.2	17.1	17.7	18.6	19.4	20.0	21.5	22.5	23.8	27.2	34.4	40.9
30	18.1	18.4	18.8	19.1	20.2	20.7	21.6	22.6	23.2	24.7	26.0	27.0	30.9	39.1	45.3
35	21.2	21.5	21.7	22.2	22.9	23.6	24.7	25.7	26.6	28.0	29.5	30.5	34.5	42.8	49.9

Log Reduction Table 41 Vadose zone: Peat - Saturated zone: Gravel

		Separation Distance (m)													
		40	50	60	80	100	150	200	250	300	400	500	600	800	1000
Vadose Zone Thickness (m)	1	2.1	2.2	2.2	2.4	2.5	2.6	3.0	3.1	3.3	3.6	3.8	4.1	4.5	4.9
	2	3.0	3.1	3.1	3.3	3.4	3.6	3.9	4.0	4.2	4.5	4.8	5.0	5.5	5.9
	3	3.8	3.9	4.0	4.1	4.2	4.5	4.8	4.9	5.1	5.4	5.7	6.0	6.4	6.9
	4	4.6	4.7	4.8	4.9	5.1	5.3	5.7	5.8	6.0	6.3	6.6	6.9	7.4	7.8
	5	5.5	5.5	5.6	5.7	5.9	6.1	6.6	6.7	6.9	7.2	7.5	7.8	8.3	8.7
	6	6.3	6.3	6.5	6.6	6.8	7.0	7.5	7.5	7.8	8.0	8.4	8.7	9.3	9.7
	7	7.1	7.3	7.3	7.5	7.6	7.9	8.3	8.5	8.6	9.0	9.3	9.6	10.2	10.6
	8	8.0	8.0	8.1	8.3	8.5	8.8	9.2	9.3	9.5	9.9	10.2	10.5	11.0	11.6
	9	8.8	8.9	9.0	9.1	9.3	9.6	10.1	10.2	10.4	10.8	11.2	11.4	12.0	12.5
	10	9.6	9.7	9.8	10.0	10.1	10.4	11.0	11.0	11.4	11.7	12.0	12.3	13.0	13.5
	15	13.7	13.8	13.8	14.1	14.2	14.4	15.1	15.3	15.5	16.0	16.3	16.5	17.3	17.7
	20	17.6	17.6	17.7	17.9	18.1	18.4	19.1	19.1	19.5	20.0	20.4	20.7	21.4	22.1
	25	21.4	21.4	21.4	21.7	21.9	22.1	22.9	23.0	23.4	23.9	24.5	24.6	25.4	25.7

Log Reduction Table 42 Vadose zone: Peat - Saturated zone: Alluvial Sand

		Separation Distance (m)															
		40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
Vadose Zone Thickness (m)	1	3.6	4.0	4.2	4.5	5.0	5.3	5.5	6.1	6.7	7.3	7.8	8.8	10.3	12.2	14.8	17.7
	2	4.7	5.0	5.3	5.6	6.0	6.4	6.5	7.1	7.7	8.4	8.8	9.9	11.5	13.2	15.8	18.7
	3	5.6	6.0	6.3	6.6	7.1	7.4	7.6	8.3	8.8	9.5	10.0	10.9	12.4	14.4	16.8	19.9
	4	6.5	6.9	7.3	7.6	8.1	8.5	8.7	9.3	9.9	10.6	11.0	12.0	13.7	15.5	18.1	20.8
	5	7.4	7.8	8.3	8.6	9.0	9.4	9.6	10.3	10.9	11.7	12.2	13.1	14.7	16.4	19.1	21.9
	6	8.3	8.7	9.2	9.5	10.1	10.6	10.7	11.4	12.0	12.7	13.1	14.3	15.9	17.6	20.3	23.4
	7	9.2	9.6	10.1	10.6	11.0	11.6	11.7	12.3	13.1	13.8	14.2	15.4	16.9	18.6	21.5	24.1
	8	10.1	10.6	11.1	11.5	11.9	12.5	12.7	13.4	14.2	15.0	15.6	16.4	18.2	19.9	22.5	25.4
	9	11.0	11.5	12.0	12.5	12.9	13.5	13.7	14.6	15.2	16.0	16.4	17.6	19.2	20.9	23.6	26.5
	10	11.9	12.5	13.0	13.3	13.9	14.4	14.7	15.4	16.3	17.0	17.4	18.5	20.4	22.3	25.2	27.9
	15	15.9	16.5	17.1	17.7	18.5	18.8	19.3	20.1	20.6	21.9	22.4	23.8	25.7	27.5	30.4	33.4
	20	19.9	20.5	21.3	21.8	22.6	22.9	23.6	24.6	25.5	26.2	27.2	28.6	30.3	32.5	35.7	38.8
	25	23.7	24.5	25.2	25.7	26.4	26.9	27.5	28.7	29.3	30.7	31.2	32.4	35.0	37.5	40.6	43.3

Log Reduction Table 43 Vadose zone: Peat - Saturated zone: Coastal Sand

Vadose Zone Thickness (m)	Separation Distance (m) 40	50	60	70	80	90	100	120	140	160	180	200
1	4.6	5.4	6.0	7.0	7.7	8.6	9.3	11.9	13.5	16.1	17.7	20.1
2	5.6	6.4	7.0	8.0	8.8	9.7	10.3	13.0	14.5	17.1	18.7	21.1
3	6.5	7.4	8.0	9.1	9.8	10.7	11.3	13.9	15.6	18.3	19.8	22.2
4	7.5	8.4	8.9	10.0	10.8	11.7	12.3	14.9	16.7	19.4	20.9	23.2
5	8.3	9.3	9.9	11.0	11.8	12.7	13.4	16.1	17.6	20.3	21.9	24.4
6	9.2	10.1	10.8	12.0	12.7	13.8	14.4	17.0	18.8	21.4	23.1	25.5
7	10.1	11.1	11.8	12.9	13.7	14.7	15.6	18.2	19.8	22.4	24.1	26.5
8	10.8	11.9	12.7	13.8	14.6	15.9	16.4	19.3	20.9	23.5	25.2	27.5
9	11.8	12.9	13.5	14.9	15.7	16.7	17.4	20.0	21.9	24.5	26.2	28.7
10	12.7	13.7	14.5	15.7	16.6	17.6	18.3	21.1	22.9	25.7	27.2	29.9
15	16.7	17.9	18.8	20.1	21.0	22.1	23.0	25.7	27.8	30.4	32.3	34.8
20	20.5	21.9	22.6	24.0	25.0	26.3	27.2	29.9	32.2	35.0	37.1	39.8

Log Reduction Table 44 Vadose zone: Peat - Saturated zone: Sandstone and Non-karstic Limestone

		Separation Distance (m)					
		40	50	60	70	80	90
Vadose Zone Thickness (m)	1	9.9	11.8	13.8	15.9	17.2	19.3
	2	10.9	12.9	14.8	17.0	18.2	20.3
	3	12.1	14.0	16.1	18.0	19.3	21.5
	4	13.2	15.1	17.1	19.3	20.5	22.4
	5	14.3	16.2	18.2	20.4	21.7	23.6
	6	15.4	17.3	19.3	21.5	22.8	24.8
	7	16.5	18.4	20.5	22.7	23.8	26.0
	8	17.6	19.7	21.9	23.6	25.0	27.2
	9	18.8	20.5	22.8	24.9	25.8	28.4
	10	19.9	21.9	23.8	26.4	27.5	29.3
	15	25.8	27.6	29.6	31.8	33.1	35.0

Log Reduction Table 45 Vadose zone: **Peat** - Saturated zone: **Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Separation Distance (m)														
	40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	1.2	1.3	1.4	1.5	1.8	2.0	2.3	2.6	2.9	3.6	4.2	4.8	7.3	13.6	19.9
2	2.1	2.2	2.3	2.5	2.8	3.0	3.3	3.7	3.9	4.6	5.2	5.9	8.4	14.7	21.2
3	2.9	3.1	3.2	3.4	3.8	4.0	4.4	4.7	5.1	5.7	6.3	7.0	9.5	15.9	22.1
4	3.7	3.9	4.0	4.3	4.7	5.0	5.4	5.8	6.1	6.8	7.5	8.2	10.6	17.0	23.3
5	4.6	4.7	4.9	5.2	5.6	6.0	6.3	6.8	7.2	7.9	8.7	9.2	11.9	18.1	24.2
6	5.4	5.5	5.8	6.0	6.6	6.9	7.3	7.8	8.2	8.9	9.8	10.5	12.8	19.5	25.7
7	6.2	6.4	6.6	6.9	7.5	7.8	8.3	8.9	9.3	10.0	10.7	11.4	14.0	20.2	26.7
8	7.1	7.3	7.5	7.8	8.4	8.7	9.3	9.9	10.3	11.2	11.9	12.7	15.2	21.5	28.0
9	8.0	8.1	8.3	8.6	9.3	9.7	10.3	10.8	11.3	12.3	13.1	13.8	16.4	23.0	29.0
10	8.7	8.9	9.2	9.6	10.3	10.5	11.3	11.7	12.4	13.4	14.1	14.8	17.6	23.8	30.4
15	12.7	13.1	13.2	13.7	14.4	15.0	15.6	16.3	16.9	18.1	19.1	20.1	23.0	29.6	36.2
20	16.7	16.9	17.1	17.6	18.6	19.1	19.9	20.7	21.4	22.7	23.9	25.0	28.5	35.7	41.7
25	20.4	20.7	21.0	21.4	22.3	22.9	23.8	24.8	25.3	26.9	28.3	29.7	33.0	40.4	47.2

Log Reduction Table 46 **Vadose zone: Karstic and Fractured Rock - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Separation Distance (m)													
	40	50	60	80	100	150	200	250	300	400	500	600	800	1000
1	1.2	1.3	1.3	1.4	1.5	1.7	2.0	2.1	2.3	2.6	2.8	3.1	3.5	3.9
2	1.2	1.3	1.3	1.5	1.6	1.7	2.0	2.2	2.3	2.6	2.9	3.1	3.5	3.9
3	1.4	1.5	1.5	1.6	1.8	1.9	2.2	2.4	2.5	2.8	3.1	3.3	3.7	4.1
4	1.4	1.5	1.5	1.7	1.8	1.9	2.3	2.4	2.5	2.8	3.1	3.3	3.7	4.1
5	1.5	1.6	1.7	1.8	1.9	2.1	2.4	2.5	2.7	3.0	3.2	3.5	3.9	4.3
6	1.6	1.7	1.7	1.8	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
7	1.6	1.7	1.7	1.8	1.9	2.1	2.4	2.5	2.7	3.0	3.3	3.5	3.9	4.3
8	1.6	1.7	1.7	1.8	2.0	2.1	2.4	2.6	2.7	3.0	3.2	3.5	3.9	4.3
9	1.6	1.7	1.7	1.8	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
10	1.6	1.6	1.7	1.8	2.0	2.1	2.4	2.5	2.7	3.0	3.3	3.5	3.9	4.3
15	1.6	1.7	1.7	1.8	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
20	1.6	1.7	1.7	1.8	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
25	1.6	1.7	1.7	1.8	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
30	1.6	1.7	1.7	1.9	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
35	1.6	1.7	1.7	1.9	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
40	1.6	1.7	1.7	1.9	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
45	1.6	1.7	1.7	1.9	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
50	1.6	1.7	1.7	1.9	2.0	2.1	2.4	2.6	2.7	3.0	3.3	3.5	3.9	4.3
55	1.6	1.7	1.7	1.9	2.0	2.1	2.5	2.6	2.7	3.0	3.3	3.5	3.9	4.3
60	1.6	1.7	1.7	1.9	2.0	2.1	2.5	2.6	2.7	3.0	3.3	3.5	3.9	4.3
65	1.6	1.7	1.7	1.9	2.0	2.1	2.5	2.6	2.7	3.1	3.3	3.5	3.9	4.3
70	1.6	1.7	1.7	1.9	2.0	2.1	2.5	2.6	2.7	3.0	3.3	3.5	4.0	4.3
75	1.6	1.7	1.7	1.9	2.0	2.1	2.5	2.6	2.7	3.1	3.3	3.6	4.0	4.3
80	1.6	1.7	1.7	1.9	2.0	2.1	2.5	2.6	2.8	3.1	3.3	3.6	4.0	4.3

Log Reduction Table 47 **Vadose zone: Karstic and Fractured Rock - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Separation Distance (m)															
	40	50	60	70	80	90	100	120	140	160	180	200	250	300	400	500
1	2.7	3.0	3.3	3.6	4.0	4.3	4.5	5.1	5.7	6.3	6.8	7.7	9.3	11.2	13.8	16.6
2	2.7	3.0	3.3	3.6	4.0	4.3	4.5	5.1	5.7	6.3	6.8	7.8	9.3	11.2	13.8	16.6
3	2.9	3.2	3.5	3.8	4.2	4.5	4.7	5.3	5.9	6.5	7.0	8.0	9.6	11.4	14.0	16.8
4	2.9	3.2	3.5	3.8	4.2	4.6	4.7	5.3	5.9	6.6	7.0	8.0	9.6	11.4	14.0	16.8
5	3.0	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.1	9.7	11.6	14.2	17.0
6	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.1	9.7	11.6	14.2	17.0
7	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.1	9.8	11.6	14.2	17.1
8	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.2	9.7	11.6	14.2	17.0
9	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.1	9.8	11.6	14.2	17.0
10	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.8	7.2	8.2	9.7	11.6	14.2	17.0
15	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.8	7.2	8.2	9.7	11.6	14.2	17.0
20	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.2	9.8	11.6	14.2	17.0
25	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.2	9.7	11.6	14.2	17.0
30	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.2	9.7	11.6	14.2	17.0
35	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.7	7.2	8.2	9.8	11.6	14.2	17.0
40	3.1	3.4	3.7	4.0	4.4	4.7	4.9	5.5	6.1	6.8	7.2	8.2	9.8	11.6	14.2	17.0
45	3.1	3.4	3.7	4.0	4.4	4.8	4.9	5.5	6.1	6.8	7.2	8.2	9.8	11.6	14.2	17.0
50	3.1	3.4	3.7	4.0	4.4	4.8	4.9	5.5	6.1	6.7	7.2	8.2	9.8	11.6	14.2	17.0
55	3.1	3.4	3.7	4.0	4.4	4.8	4.9	5.5	6.1	6.8	7.3	8.2	9.8	11.6	14.2	17.0
60	3.1	3.4	3.7	4.0	4.4	4.8	4.9	5.5	6.1	6.8	7.2	8.2	9.8	11.6	14.3	17.0
65	3.1	3.4	3.7	4.0	4.4	4.8	4.9	5.5	6.1	6.8	7.3	8.2	9.8	11.6	14.2	17.1
70	3.1	3.4	3.7	4.0	4.4	4.8	4.9	5.6	6.1	6.8	7.3	8.2	9.8	11.6	14.2	17.1
75	3.1	3.5	3.8	4.0	4.4	4.8	4.9	5.6	6.1	6.8	7.2	8.2	9.8	11.6	14.3	17.0
80	3.1	3.4	3.8	4.0	4.5	4.8	4.9	5.6	6.1	6.8	7.3	8.2	9.8	11.7	14.3	17.1

Log Reduction Table 48 **Vadose zone: Karstic and Fractured Rock - Saturated zone: Coastal Sand**

	Separation Distance (m)												
Vadose Zone Thickness (m)	40	50	60	70	80	90	100	120	140	160	180	200	250
1	3.7	4.5	5.0	6.0	6.7	7.6	8.3	10.9	12.5	15.1	16.7	19.0	25.5
2	3.7	4.5	5.0	6.1	6.7	7.6	8.3	10.9	12.5	15.1	16.7	19.0	25.5
3	3.9	4.7	5.2	6.3	6.9	7.8	8.5	11.1	12.7	15.3	16.9	19.2	25.7
4	3.9	4.7	5.2	6.3	7.0	7.9	8.5	11.1	12.7	15.4	16.9	19.3	25.7
5	4.1	4.9	5.4	6.4	7.1	8.0	8.7	11.3	12.9	15.5	17.1	19.4	25.8
6	4.1	4.9	5.4	6.5	7.1	8.0	8.7	11.3	12.9	15.5	17.1	19.4	25.9
7	4.1	4.9	5.4	6.4	7.1	8.0	8.7	11.3	12.9	15.5	17.0	19.5	25.9
8	4.1	4.9	5.4	6.5	7.1	8.1	8.7	11.3	12.9	15.5	17.1	19.4	25.9
9	4.1	4.9	5.4	6.5	7.1	8.0	8.7	11.3	12.9	15.5	17.1	19.4	25.9
10	4.1	4.9	5.4	6.5	7.1	8.0	8.7	11.3	12.9	15.5	17.1	19.4	25.9
15	4.1	4.9	5.4	6.5	7.1	8.0	8.7	11.3	12.9	15.5	17.1	19.5	25.9
20	4.1	4.9	5.4	6.4	7.1	8.0	8.7	11.3	12.9	15.5	17.1	19.4	25.9
25	4.1	4.9	5.4	6.5	7.1	8.1	8.7	11.3	12.9	15.5	17.1	19.5	25.9
30	4.1	4.9	5.4	6.4	7.1	8.1	8.7	11.3	12.9	15.5	17.1	19.5	25.9
35	4.1	4.9	5.4	6.5	7.2	8.0	8.7	11.3	12.9	15.5	17.1	19.5	25.9
40	4.1	4.9	5.4	6.5	7.1	8.1	8.7	11.3	12.9	15.5	17.1	19.4	25.9
45	4.1	4.9	5.4	6.5	7.2	8.1	8.7	11.3	12.9	15.5	17.1	19.4	25.9
50	4.1	4.9	5.4	6.5	7.2	8.1	8.7	11.3	12.9	15.5	17.1	19.4	25.9
55	4.1	4.9	5.4	6.5	7.2	8.1	8.7	11.3	12.9	15.5	17.1	19.5	25.9
60	4.1	4.9	5.4	6.5	7.2	8.1	8.7	11.3	12.9	15.6	17.1	19.5	25.9
65	4.1	4.9	5.4	6.5	7.2	8.1	8.7	11.3	12.9	15.6	17.1	19.5	25.9
70	4.1	4.9	5.5	6.5	7.2	8.1	8.8	11.4	12.9	15.6	17.1	19.5	25.9
75	4.2	5.0	5.5	6.5	7.2	8.1	8.8	11.4	13.0	15.6	17.1	19.5	25.9
80	4.2	5.0	5.5	6.5	7.2	8.1	8.8	11.4	12.9	15.6	17.1	19.5	26.0

Log Reduction Table 49 Vadose zone: **Karstic and Fractured Rock** - **Saturated zone: Sandstone and Non-karstic Limestone**

Vadose Zone Thickness (m)	Separation Distance (m)					
	40	50	60	70	80	90
1	8.9	10.8	12.8	14.8	16.1	18.2
2	8.9	10.8	12.8	14.9	16.1	18.2
3	9.1	11.0	13.0	15.0	16.3	18.4
4	9.1	11.0	13.0	15.1	16.3	18.4
5	9.3	11.2	13.2	15.3	16.5	18.6
6	9.3	11.2	13.2	15.2	16.5	18.6
7	9.3	11.2	13.2	15.2	16.5	18.6
8	9.2	11.2	13.2	15.3	16.5	18.6
9	9.3	11.2	13.2	15.3	16.6	18.6
10	9.3	11.2	13.2	15.3	16.5	18.6
15	9.3	11.2	13.2	15.2	16.5	18.6
20	9.3	11.2	13.2	15.2	16.5	18.6
25	9.3	11.2	13.2	15.3	16.5	18.6
30	9.3	11.2	13.2	15.3	16.5	18.6
35	9.3	11.2	13.2	15.3	16.5	18.6
40	9.3	11.2	13.2	15.3	16.6	18.6
45	9.3	11.2	13.2	15.3	16.5	18.6
50	9.3	11.2	13.2	15.3	16.6	18.6
55	9.3	11.2	13.2	15.3	16.6	18.6
60	9.3	11.2	13.2	15.3	16.6	18.6
65	9.3	11.3	13.2	15.3	16.6	18.7
70	9.3	11.3	13.3	15.3	16.5	18.7
75	9.4	11.3	13.2	15.4	16.6	18.6
80	9.3	11.2	13.3	15.3	16.6	18.7

Log Reduction Table 50 Vadose zone: **Karstic and Fractured Rock** - Saturated zone: **Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Separation Distance (m)														
	40	50	60	80	100	150	200	250	300	400	500	600	1000	2000	3000
1	0.3	0.3	0.4	0.5	0.8	1.0	1.3	1.6	1.9	2.6	3.1	3.8	6.3	12.6	18.9
2	0.3	0.3	0.4	0.5	0.8	1.0	1.3	1.6	1.9	2.6	3.2	3.8	6.3	12.6	19.0
3	0.5	0.5	0.6	0.7	1.0	1.2	1.5	1.8	2.1	2.8	3.4	4.0	6.5	12.9	19.2
4	0.5	0.6	0.6	0.8	1.0	1.2	1.5	1.8	2.2	2.8	3.4	4.1	6.6	12.8	19.2
5	0.6	0.7	0.8	0.9	1.1	1.3	1.7	2.0	2.3	3.0	3.5	4.2	6.7	13.0	19.3
6	0.6	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	2.9	3.5	4.2	6.7	13.0	19.4
7	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.7	13.0	19.3
8	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.5	4.2	6.7	13.0	19.3
9	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.5	4.2	6.7	13.0	19.4
10	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.2	6.7	13.0	19.4
15	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.2	6.8	13.0	19.4
20	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.7	13.0	19.4
25	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.2	6.7	13.1	19.4
30	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.7	13.0	19.4
35	0.7	0.7	0.8	0.9	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.8	13.1	19.4
40	0.7	0.8	0.8	1.0	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.2	6.7	13.0	19.4
45	0.7	0.8	0.8	1.0	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.2	6.8	13.0	19.4
50	0.7	0.8	0.8	1.0	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.8	13.0	19.4
55	0.7	0.8	0.8	1.0	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.8	13.1	19.4
60	0.7	0.8	0.8	1.0	1.2	1.4	1.7	2.0	2.3	3.0	3.6	4.3	6.8	13.0	19.4
65	0.7	0.8	0.8	1.0	1.2	1.4	1.7	2.0	2.4	3.0	3.6	4.3	6.8	13.1	19.4
70	0.7	0.8	0.8	1.0	1.2	1.4	1.7	2.0	2.4	3.0	3.6	4.3	6.8	13.1	19.4
75	0.7	0.8	0.9	1.0	1.2	1.4	1.7	2.1	2.4	3.0	3.6	4.3	6.8	13.1	19.4
80	0.7	0.8	0.9	1.0	1.2	1.4	1.8	2.1	2.4	3.0	3.7	4.3	6.8	13.1	19.4

8.6.4 Virus reduction in vadose and saturated zones – find separation distance

This section contains tables that give minimum separation distances for a specified vadose zone thickness and required $\log_{10}$ reduction. Each table is for a different combination of vadose zone and saturated zone materials. The materials that have been modelled are:

Vadose zone

- Alluvial gravel
- Alluvial sand
- Coastal sand (fine)
- Pumice sand
- Sandstone and non-karstic limestone
- Silts
- Clay
- Ash
- Peat
- Karstic and fractured rock (e.g. basalt and schist).

Saturated zone

- Alluvial gravel
- Alluvial sand
- Coastal sand (fine)
- Pumice sand
- Sandstone and non-karstic limestone
- Karstic and fractured rock (e.g. basalt and schist).

Unlike the tables in Section 8.6.3, these tables contain areas of blank cells. These are the result of two limits placed on the data provided. A lower limit of 40 m is placed on the calculations because of the unacceptably high level of uncertainty in model calculations at these shorter distances. Also, an upper limit of 1,000 m is set on the separation distance, as distances greater than this are likely to be deemed impracticable.

Blank cells below the cells containing numbers should be interpreted as a 40m separation distance. Blank cells above the cells containing numbers indicate a distance greater than 1,000m.

The tables with pumice sand as the saturated zone medium have been omitted. A default separation distance of 20m should be used in these cases (the worksheet calcaulation is unnecessary).

Table 8.9 Separation distances table catalogue

(Large tables are split into (a) and (b)).

	Vadzose Zone Material	Saturated Zone Material
Separation Distances Table 1	Gravel	Gravel
Separation Distances Table 2	Gravel	Alluvial Sand
Separation Distances Table 3	Gravel	Coastal Sand
Separation Distances Table 4	Gravel	Sandstone/Non-karstic Limestone
Separation Distances Table 5	Gravel	Karstic and Fractured Rock
Separation Distances Table 6	Alluvial Sand	Gravel
Separation Distances Table 7	Alluvial Sand	Alluvial Sand
Separation Distances Table 8	Alluvial Sand	Coastal Sand
Separation Distances Table 9	Alluvial Sand	Sandstone/Non-karstic Limestone
Separation Distances Table 10	Alluvial Sand	Karstic and Fractured Rock
Separation Distances Table 11	Coastal Sand	Gravel
Separation Distances Table 12	Coastal Sand	Alluvial Sand
Separation Distances Table 13	Coastal Sand	Coastal Sand
Separation Distances Table 14	Coastal Sand	Sandstone/Non-karstic Limestone
Separation Distances Table 15	Coastal Sand	Karstic and Fractured Rock
Separation Distances Table 16	Pumice Sand	Gravel
Separation Distances Table 17	Pumice Sand	Alluvial Sand
Separation Distances Table 18	Pumice Sand	Coastal Sand
Separation Distances Table 19	Pumice Sand	Sandstone/Non-karstic Limestone
Separation Distances Table 20	Pumice Sand	Karstic and Fractured Rock
Separation Distances Table 21	Sandstone/Non-karstic Limestone	Gravel
Separation Distances Table 22	Sandstone/Non-karstic Limestone	Alluvial Sand
Separation Distances Table 23	Sandstone/Non-karstic Limestone	Coastal Sand
Separation Distances Table 24	Sandstone/Non-karstic Limestone	Sandstone/Non-karstic Limestone
Separation Distances Table 25	Sandstone/Non-karstic Limestone	Karstic and Fractured Rock

	Vadzose Zone Material	Saturated Zone Material
Separation Distances Table 26	Silt	Gravel
Separation Distances Table 27	Silt	Alluvial Sand
Separation Distances Table 28	Silt	Coastal Sand
Separation Distances Table 29	Silt	Sandstone/Non-karstic Limestone
Separation Distances Table 30	Silt	Karstic and Fractured Rock
Separation Distances Table 31	Clay	Gravel
Separation Distances Table 32	Clay	Alluvial Sand
Separation Distances Table 33	Clay	Coastal Sand
Separation Distances Table 34	Clay	Sandstone/Non-karstic Limestone
Separation Distances Table 35	Clay	Karstic and Fractured Rock
Separation Distances Table 36	Ash	Gravel
Separation Distances Table 37	Ash	Alluvial Sand
Separation Distances Table 38	Ash	Coastal Sand
Separation Distances Table 39	Ash	Sandstone/Non-karstic Limestone
Separation Distances Table 40	Ash	Karstic and Fractured Rock
Separation Distances Table 41	Peat	Gravel
Separation Distances Table 42	Peat	Alluvial Sand
Separation Distances Table 43	Peat	Coastal Sand
Separation Distances Table 44	Peat	Sandstone/Non-karstic Limestone
Separation Distances Table 45	Peat	Karstic and Fractured Rock
Separation Distances Table 46	Karstic and Fractured Rock	Gravel
Separation Distances Table 47	Karstic and Fractured Rock	Alluvial Sand
Separation Distances Table 48	Karstic and Fractured Rock	Coastal Sand
Separation Distances Table 49	Karstic and Fractured Rock	Sandstone/Non-karstic Limestone
Separation Distances Table 50	Karstic and Fractured Rock	Karstic and Fractured Rock

Separation Distances Table 1a **Vadose zone: Gravel - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1	154	263	438	650	902									
2	81	184	334	507	746	996								
3	46	146	250	415	601	835								
4		95	190	340	503	721	961							
5		69	163	280	434	628	843							
6		46	129	204	359	519	735	958						
7			93	182	302	477	663	872						
8			76	160	255	402	582	777	972					
9			53	124	198	344	498	717	905					
10				100	177	306	453	605	797					
15					76	151	199	347	489	683	850			
20						45	112	177	280	384	544	696	870	
25								84	156	197	299	447	566	765
30									57	116	171	258	372	501
35											85	140	190	283
40												44	98	159
45														64
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 1b **Vadose zone: Gravel - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
15														
20														
25	913													
30	649	776	955											
35	380	525	673	792	987									
40	239	322	427	538	700	849	982							
45	120	177	254	347	449	576	716	865						
50		89	141	186	286	385	479	623	792	899				
55			54	115	167	210	315	422	532	655	765	918		
60					80	138	180	264	326	479	547	599	801	937
65							87	149	194	267	370	478	571	676
70								57	103	160	190	285	368	468
75										83	127	172	232	317
80											46	97	158	189

Separation Distances Table 2a **Vadose zone: Gravel - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction													
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	40	57	72	86	107	123	140	156	176	188	199	213	228	243
2		46	62	77	92	112	129	146	160	181	191	202	218	234
3			53	70	82	103	117	135	151	169	186	196	210	226
4			45	61	74	88	110	127	141	158	178	189	199	214
5				53	67	81	98	115	133	148	164	183	194	207
6				45	58	72	87	107	123	137	153	171	185	195
7				40	53	67	78	93	109	125	143	160	181	190
8					47	60	73	84	102	120	137	151	170	186
9					42	54	69	78	90	111	125	141	158	176
10						50	61	73	85	105	118	133	149	165
15							43	51	62	73	81	96	111	125
20									46	54	63	74	84	97
25										42	49	57	66	76
30												44	51	60
35													41	48
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 2b **Vadose zone: Gravel - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction													
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1	257	271	285	299	318	337	355	374	393	412	430	448	466	485
2	250	264	277	291	306	325	344	363	383	402	419	437	455	473
3	242	257	270	283	295	313	333	353	373	392	411	428	445	462
4	229	244	259	273	287	302	321	340	359	378	397	415	433	451
5	222	238	253	266	279	292	307	327	346	366	385	404	423	441
6	208	223	239	254	269	284	299	317	336	355	373	392	410	427
7	200	216	233	249	262	275	288	302	322	343	364	384	404	422
8	195	207	222	238	253	266	280	293	310	330	350	370	391	409
9	189	199	213	227	241	255	270	285	300	319	338	357	376	395
10	182	192	203	220	236	252	265	278	292	307	326	346	365	384
15	139	153	171	185	194	204	217	229	242	256	274	292	310	327
20	110	121	132	144	158	175	186	195	207	224	241	256	268	280
25	86	97	110	122	132	142	153	171	185	192	200	215	231	247
30	70	76	84	96	110	123	133	143	154	166	180	187	194	203
35	54	62	72	79	90	100	109	118	130	143	154	165	175	184
40	43	49	56	66	75	82	89	102	111	119	131	142	152	162
45			45	52	61	68	75	82	93	101	111	121	130	140
50					47	55	63	71	81	87	97	106	114	123
55						43	49	56	64	71	78	86	94	104
60								45	53	61	68	75	84	94
65									42	48	54	61	71	77
70											44	51	58	65
75												41	47	53
80														42

Separation Distances Table 3a **Vadose zone: Gravel - Saturated zone: Coastal Sand**

		Log reduction													
		4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5
Vadose Zone Thickness (m)	1	40	46	54	62	67	72	79	85	90	98	103	107	111	114
	2		43	49	58	63	68	75	82	87	94	100	104	108	112
	3			45	51	61	66	71	78	84	90	97	102	106	110
	4			42	48	57	63	68	74	81	86	92	99	103	107
	5				46	52	61	65	70	77	83	88	95	101	105
	6				43	49	56	63	68	74	80	86	91	97	102
	7				41	46	53	61	65	70	77	82	87	93	100
	8					44	49	58	63	67	73	80	85	91	98
	9					42	47	54	61	66	70	78	83	88	94
	10					40	45	51	59	64	69	74	80	85	90
	15							42	47	53	60	64	68	73	79
	20									44	49	55	61	65	70
	25										42	47	52	58	63
	30											40	44	48	54
	35													42	46
	40														40
	45														
	50														
	55														
	60														
	65														
	70														
	75														
	80														

Separation Distances Table 3b **Vadose zone: Gravel - Saturated zone: Coastal Sand**

		Log reduction													
		11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
Vadose Zone Thickness (m)	1	118	124	130	136	142	145	149	153	157	161	167	174	180	184
	2	116	120	126	132	138	143	147	151	155	158	164	170	176	182
	3	114	118	122	129	135	141	145	148	152	156	159	165	172	178
	4	111	115	118	124	130	137	142	146	150	153	157	162	168	174
	5	109	113	116	120	127	133	139	143	147	151	155	158	164	170
	6	106	110	114	118	122	129	136	141	145	149	153	157	161	167
	7	104	108	112	116	120	126	132	138	143	146	150	154	158	162
	8	103	107	111	114	118	123	130	136	141	145	149	152	156	160
	9	101	104	108	112	115	119	125	131	138	143	146	150	154	158
	10	100	104	107	111	115	118	123	129	135	140	144	148	151	155
	15	84	89	95	101	105	108	112	116	120	125	131	137	142	146
	20	75	80	84	89	94	100	104	108	112	116	119	124	130	135
	25	67	71	76	81	85	89	95	101	105	108	112	115	119	123
	30	60	64	68	72	77	82	86	90	95	101	104	108	112	116
	35	49	56	61	65	70	74	79	83	87	91	97	102	106	109
	40	44	48	53	57	62	66	71	75	79	83	86	90	99	103
	45		41	45	49	55	60	64	67	71	75	80	84	88	93
	50				44	48	52	57	61	65	69	73	78	82	85
	55					40	44	47	52	58	63	66	70	75	79
	60							42	46	50	56	61	65	69	72
	65									43	46	49	56	62	65
	70										41	45	49	54	59
	75												41	45	50
	80														43

Separation Distances Table 4 **Vadose zone: Gravel - Saturated zone: Sandstone and Non-karstic Limestone**

Vadose Zone Thickness (m)	Log reduction 9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
1	42	44	47	49	52	55	57	60	62	64	67	69	73	77
2	40	43	45	48	50	53	55	58	60	63	65	68	70	74
3		41	43	46	49	51	54	56	59	61	64	66	69	72
4			42	44	47	50	52	55	57	60	62	65	67	70
5			40	42	45	48	50	53	56	58	61	63	66	68
6				41	44	47	50	52	54	56	58	60	63	66
7					41	44	47	50	52	55	57	60	62	64
8					40	43	45	48	50	53	56	58	61	64
9						41	44	47	50	52	54	56	59	61
10						40	42	45	48	50	53	55	57	60
15									40	42	44	47	49	52
20													41	44
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 5a **Vadose zone: Gravel - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction													
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1	264	342	423	509	581	659	739	819	899	979				
2	214	298	368	445	527	608	688	768	848	928				
3	162	237	321	387	481	557	631	710	789	868	948			
4	107	190	262	350	426	503	579	659	741	824	906	989		
5	87	152	217	305	374	449	526	597	677	757	837	917	997	
6	74	99	186	252	323	410	486	555	628	712	797	881	966	
7	60	94	152	216	283	351	427	513	597	675	752	830	908	985
8	47	83	122	184	242	315	380	463	540	607	687	766	846	925
9	41	72	97	162	213	272	338	410	489	562	638	720	802	884
10		60	86	127	187	244	318	372	445	529	597	675	753	831
15			47	73	94	137	184	230	277	334	401	458	515	574
20					62	83	98	146	194	233	270	309	356	405
25						48	71	88	114	150	189	224	265	318
30							42	63	83	95	123	160	193	228
35									50	73	88	100	151	176
40											58	80	89	98
45												45	64	83
50														53
55														
60														
65														
70														
75														
80														

Separation Distances Table 5b   Vadose zone: Gravel - Saturated zone: Karstic and Fractured Rock

		Log reduction													
		9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5
Vadose Zone Thickness (m)	1														
	2														
	3														
	4														
	5														
	6														
	7														
	8														
	9	966													
	10	909	987												
	15	643	720	797	874	951									
	20	474	533	585	655	732	808	884	961						
	25	364	410	457	505	570	634	698	761	825	889	952			
	30	270	319	360	402	446	489	551	614	667	720	774	827	880	933
	35	203	240	277	314	350	386	429	476	533	600	650	700	750	800
	40	143	175	203	232	264	301	340	379	417	454	491	544	604	658
	45	94	114	149	182	215	246	273	298	341	384	422	458	493	528
	50	73	87	96	131	166	190	218	247	275	304	338	372	408	447
	55		59	81	92	109	138	168	199	224	248	287	321	352	383
	60			51	70	86	96	127	158	176	194	219	248	278	308
	65					56	75	89	100	134	163	189	212	232	253
	70							62	81	90	99	144	168	188	212
	75								50	74	87	97	125	156	176
	80										61	82	92	105	135

Separation Distances Table 6a **Vadose zone: Alluvial Sand - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
1	162	288	453	666	920									
2		126	221	387	574	812								
3			101	189	325	523	723	961						
4				92	176	296	469	651	853					
5					79	166	279	411	606	805				
6						82	156	258	395	544	747	947		
7							71	158	220	354	522	709	890	
8								72	153	204	331	489	681	861
9									62	136	190	327	464	619
10										55	115	182	295	429
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 6b **Vadose zone: Alluvial Sand - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
1														
2														
3														
4														
5														
6														
7														
8														
9	805	968												
10	578	758	935											
15		49	124	177	258	373	523	659	798	989				
20								61	127	179	259	341	481	576
25														52
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 7a   Vadose zone: **Alluvial Sand** - Saturated zone: **Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction													
	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
1	42	57	74	87	108	125	142	156	178	190	200	215	231	246
2			50	66	81	97	115	132	149	166	183	193	205	221
3				44	60	75	87	107	122	140	154	172	188	199
4					40	53	67	80	99	114	131	148	165	181
5							49	62	75	87	107	121	141	154
6								47	59	72	82	101	117	132
7									44	55	68	79	92	110
8										44	53	66	77	87
9											41	50	62	73
10													48	59
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 7b **Vadose zone: Alluvial Sand - Saturated zone: Alluvial Sand**

		Log reduction													
		10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0
Vadose Zone Thickness (m)	1	260	274	288	303	322	341	360	379	398	416	434	451	469	487
	2	238	254	268	282	296	314	332	350	369	387	405	422	439	456
	3	215	231	247	260	273	286	298	316	335	354	373	392	411	429
	4	190	200	215	231	247	261	275	289	303	323	342	361	380	400
	5	172	187	198	212	227	241	256	271	285	300	318	335	353	371
	6	146	160	177	188	198	213	229	246	261	276	290	306	323	340
	7	126	140	154	171	185	195	207	222	238	252	265	277	290	304
	8	105	121	133	145	158	181	189	198	212	228	244	258	272	285
	9	84	97	111	125	141	155	170	184	193	204	219	234	249	262
	10	68	79	89	105	116	133	147	158	180	189	198	211	225	239
	15					47	55	64	73	80	91	103	114	129	144
	20											45	52	60	68
	25														
	30														
	35														
	40														
	45														
	50														
	55														
	60														
	65														
	70														
	75														
	80														

Separation Distances Table 8a **Vadose zone: Alluvial Sand - Saturated zone: Coastal Sand**

		Log reduction													
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5
Vadose Zone Thickness (m)	1	47	54	62	67	72	80	85	91	99	103	107	111	115	119
	2		44	50	60	65	69	76	82	88	95	101	105	109	113
	3			42	48	56	63	68	74	80	86	92	99	103	107
	4				41	46	53	61	66	70	78	83	88	95	101
	5					40	45	50	59	64	69	75	81	86	91
	6							44	50	57	63	68	73	78	84
	7								44	49	56	62	66	71	77
	8									43	48	54	61	65	69
	9										42	46	52	60	64
	10											42	47	52	57
	15														
	20														
	25														
	30														
	35														
	40														
	45														
	50														
	55														
	60														
	65														
	70														
	75														
	80														

Separation Distances Table 8b **Vadose zone: Alluvial Sand - Saturated zone: Coastal Sand**

		Log reduction													
		12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5
Vadose Zone Thickness (m)	1	124	130	137	142	145	149	153	157	161	167	173	180	184	189
	2	116	120	127	133	140	144	147	151	155	159	164	171	177	182
	3	111	115	118	124	130	136	141	145	149	153	157	161	167	173
	4	105	109	113	116	120	126	132	138	143	147	151	155	159	164
	5	99	103	107	111	115	118	124	130	136	141	145	149	152	156
	6	89	96	102	106	109	113	117	121	127	133	140	144	147	151
	7	83	87	94	101	104	108	112	116	120	125	130	135	140	144
	8	75	81	86	92	98	103	106	110	114	118	123	129	135	140
	9	68	73	80	85	89	96	101	105	109	113	116	120	126	131
	10	62	67	72	78	83	87	93	100	104	108	112	116	120	124
	15			41	45	49	55	61	66	70	75	80	84	88	93
	20									40	44	49	54	60	64
	25														
	30														
	35														
	40														
	45														
	50														
	55														
	60														
	65														
	70														
	75														
	80														

Separation Distances Table 9 **Vadose zone: Alluvial Sand - Saturated zone: Sandstone and Non-karstic Limestone**

		Log reduction													
		11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
Vadose Zone Thickness (m)	1	47	49	52	54	57	59	62	64	66	69	72	77	81	83
	2	43	45	48	51	53	56	59	61	63	66	68	71	75	79
	3		41	44	47	49	52	54	57	59	61	64	66	69	72
	4			40	43	45	48	51	53	55	57	59	62	64	67
	5					40	43	46	49	51	53	56	58	60	63
	6							42	44	47	49	52	54	56	59
	7								40	43	45	48	50	53	55
	8										40	43	45	47	50
	9												42	44	47
	10													41	43
	15														
	20														
	25														
	30														
	35														
	40														
	45														
	50														
	55														
	60														
	65														
	70														
	75														
	80														

Separation Distances Table 10a Vadose zone: Alluvial Sand - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Log reduction													
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	349	427	505	578	656	736	817	897	977					
2	223	304	384	460	536	615	694	773	852	931				
3	104	185	261	334	404	498	566	640	722	803	885	966		
4	59	90	161	224	289	366	445	522	596	674	752	830	909	987
5		52	87	126	192	254	321	391	470	541	610	689	769	849
6			54	81	106	173	223	282	355	422	480	556	640	722
7				48	77	97	156	207	251	336	401	462	528	601
8					48	80	95	143	190	242	305	366	433	506
9						46	70	91	127	178	225	273	327	397
10								66	87	113	168	204	254	309
15														65
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 10b **Vadose zone: Alluvial Sand - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction													
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1														
2														
3														
4														
5	929													
6	804	886	968											
7	679	757	835	913	991									
8	565	631	708	785	862	939								
9	455	517	589	664	740	816	892	968						
10	364	419	476	547	626	698	771	844	917	989				
15	86	96	130	175	218	257	306	352	398	448	499	547	595	666
20					42	61	83	95	132	168	196	225	254	291
25											44	64	84	94
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 11a **Vadose zone: Coastal Sand - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
1	80	181	326	498	711	956								
2			115	193	355	526	724	926						
3				73	151	259	406	564	750	975				
4						111	182	295	454	613	794	966		
5							72	146	210	344	491	684	858	
6								53	109	174	271	414	565	721
7										79	152	207	316	461
8											60	127	182	287
9													98	155
10														57
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 11b **Vadose zone: Coastal Sand - Saturated zone: Gravel**

	Log reduction													
Vadose Zone Thickness (m)	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
1														
2														
3														
4														
5														
6	885													
7	629	785	959											
8	404	560	714	871										
9	212	317	452	632	778	941								
10	117	180	274	378	512	670	803	976						
15								86	152	185	284	385	545	664
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 12a **Vadose zone: Coastal Sand - Saturated zone: Alluvial Sand**

	Log reduction													
Vadose Zone Thickness (m)	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
1		46	61	76	90	110	125	141	156	180	190	200	215	231
2				44	58	72	84	104	120	135	152	170	185	196
3						46	58	70	82	100	115	129	145	165
4								50	60	71	81	98	112	126
5									42	52	63	74	83	95
6											46	56	67	75
7												43	49	58
8														47
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 12b **Vadose zone: Coastal Sand - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction													
	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0
1	246	261	275	289	305	324	343	362	380	399	417	435	453	471
2	210	226	242	257	270	283	296	313	332	351	370	389	407	426
3	181	191	201	218	234	251	264	277	290	304	322	340	359	377
4	140	157	176	188	199	213	228	243	257	271	284	298	317	336
5	110	124	140	154	169	184	193	203	220	236	252	265	277	290
6	84	102	114	126	138	152	168	183	192	203	217	232	246	259
7	70	79	88	104	115	127	140	154	171	184	192	200	216	234
8	56	65	73	83	93	105	115	127	143	154	170	184	192	200
9	42	50	58	68	76	84	97	108	117	129	142	152	163	181
10			46	53	62	72	79	89	97	107	118	132	144	154
15										41	48	55	63	72
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 13a **Vadose zone: Coastal Sand - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5
1	42	48	56	63	68	74	81	86	92	100	104	108	112	115
2			42	48	56	63	67	72	78	84	90	98	103	107
3					44	49	57	63	67	73	80	84	89	96
4						40	45	50	58	63	68	73	79	84
5								42	47	53	60	64	69	74
6									40	45	49	56	61	66
7											43	47	52	59
8												40	45	49
9														43
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 13b **Vadose zone: Coastal Sand - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5
1	119	125	131	138	142	146	150	154	158	162	169	175	181	185
2	110	114	118	123	129	135	141	145	149	152	156	160	167	173
3	102	106	110	113	117	122	127	133	139	143	147	151	154	158
4	89	96	102	105	109	113	117	122	127	132	137	142	146	150
5	80	85	89	98	103	106	110	113	117	121	126	131	137	141
6	70	77	82	86	90	97	102	106	110	114	118	122	127	132
7	64	68	72	77	81	85	90	98	103	106	110	114	117	121
8	56	62	65	69	74	79	83	87	93	101	104	108	111	115
9	47	51	58	63	67	71	76	81	85	89	94	100	104	108
10	41	45	48	55	62	65	69	74	78	83	87	91	97	101
15									43	46	50	56	61	65
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 14 Vadose zone: **Coastal Sand** - Saturated zone: **Sandstone and Non-karstic Limestone**

	Log reduction													
Vadose Zone Thickness (m)	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	45	47	50	52	55	57	60	62	64	67	69	73	77	80
2		41	44	46	48	51	53	56	58	61	63	65	68	70
3					41	44	47	50	52	55	57	60	63	65
4							41	43	46	49	51	54	57	59
5										42	44	47	50	52
6												41	43	46
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 15a Vadose zone: Coastal Sand - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Log reduction													
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	349	427	505	578	656	736	817	897	977					
2	223	304	384	460	536	615	694	773	852	931				
3	104	185	261	334	404	498	566	640	722	803	885	966		
4	59	90	161	224	289	366	445	522	596	674	752	830	909	987
5		52	87	126	192	254	321	391	470	541	610	689	769	849
6			54	81	106	173	223	282	355	422	480	556	640	722
7				48	77	97	156	207	251	336	401	462	528	601
8					48	80	95	143	190	242	305	366	433	506
9						46	70	91	127	178	225	273	327	397
10								66	87	113	168	204	254	309
15														65
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 15b Vadose zone: Coastal Sand - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Log reduction													
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1														
2														
3														
4														
5	929													
6	804	886	968											
7	679	757	835	913	991									
8	565	631	708	785	862	939								
9	455	517	589	664	740	816	892	968						
10	364	419	476	547	626	698	771	844	917	989				
15	86	96	130	175	218	257	306	352	398	448	499	547	595	666
20					42	61	83	95	132	168	196	225	254	291
25											44	64	84	94
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 16a **Vadose zone: Pumice Sand - Saturated zone: Gravel**

	Log reduction													
Vadose Zone Thickness (m)	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
1	59	152	266	420	593	832								
2					78	162	269	418	602	791	997			
3								54	117	188	304	454	610	808
4												80	152	218
5														
6														
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 16b **Vadose zone: Pumice Sand - Saturated zone: Gravel**

	Log reduction													
Vadose Zone Thickness (m)	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0
1														
2														
3	986													
4	330	486	622	803	970									
5	60	124	181	285	389	534	712	884						
6					80	143	197	306	449	587	726	878		
7								61	127	172	259	369	491	629
8												83	146	193
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 17a **Vadose zone: Pumice Sand - Saturated zone: Alluvial Sand**

		Log reduction													
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5
Vadose Zone Thickness (m)	1		50	66	78	97	114	131	148	163	181	191	202	218	233
	2						48	59	73	83	100	114	132	148	159
	3										49	60	71	80	89
	4													43	51
	5														
	6														
	7														
	8														
	9														
	10														
	15														
	20														
	25														
	30														
	35														
	40														
	45														
	50														
	55														
	60														
	65														
	70														
	75														
	80														

Separation Distances Table 17b **Vadose zone: Pumice Sand - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction													
	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5
1	249	265	280	296	312	330	347	364	382	399	417	435	453	470
2	183	192	201	217	233	249	262	276	289	303	322	341	359	378
3	109	122	136	151	167	183	191	200	216	233	250	263	276	289
4	60	71	79	92	106	119	134	146	156	172	186	197	210	225
5			46	55	63	72	82	90	105	117	129	141	152	167
6						41	51	57	65	74	83	93	104	114
7										44	50	60	68	75
8													41	48
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 18a   Vadose zone: **Pumice Sand** - Saturated zone: **Coastal Sand**

	Log reduction													
Vadose Zone Thickness (m)	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
1	45	52	60	64	69	76	82	88	94	100	104	108	112	116
2					44	49	56	63	68	73	78	84	89	96
3								41	45	50	58	63	67	72
4												43	47	52
5														
6														
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 18b Vadose zone: **Pumice Sand** - Saturated zone: **Coastal Sand**

	Log reduction													
Vadose Zone Thickness (m)	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5	19.0	19.5	20.0
1	120	127	134	140	144	148	151	155	159	164	170	176	182	186
2	102	106	109	113	117	121	127	133	140	144	147	151	155	159
3	78	83	87	93	100	104	108	111	115	119	124	129	135	140
4	58	63	67	71	79	83	87	91	99	103	107	111	115	118
5	41	45	49	56	61	65	69	74	79	84	88	93	100	103
6					42	46	51	57	62	66	70	75	81	84
7									45	49	55	60	64	68
8												43	47	52
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 19 **Vadose zone: Pumice Sand - Saturated zone: Sandstone and Non-karstic Limestone**

Vadose Zone Thickness (m)	Log reduction													
	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1			42	45	48	51	53	56	58	61	63	66	68	70
2								41	44	47	50	52	55	57
3													41	44
4														
5														
6														
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 20a   Vadose zone: **Pumice Sand** - Saturated zone: **Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction 3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	86	149	213	288	368	446	523	597	679	762	844	927		
2				55	83	118	183	232	283	353	433	515	593	672
3							41	67	88	117	176	228	273	316
4											50	75	92	133
5														42
6														
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 20b Vadose zone: Pumice Sand - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Log reduction													
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1														
2	752	831	911	990										
3	369	427	494	572	652	731	811	890	970					
4	175	213	256	298	350	403	458	514	574	640	711	782	853	923
5	65	86	98	139	178	214	253	305	346	387	437	492	543	593
6				50	74	90	109	143	192	224	252	288	334	384
7							44	60	82	94	124	162	187	215
8											53	78	89	100
9														44
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 21 **Vadose zone: Sandstone - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
1	87	195	363	553	796									
2	82	191	354	542	782									
3	78	187	345	529	771									
4	74	183	338	518	755									
5	72	178	325	503	737									
6	67	174	321	493	724	986								
7	65	169	307	479	712	969								
8	60	166	303	468	695	956								
9	50	162	289	459	680	939								
10	46	158	278	449	669	926								
15		115	225	399	598	851								
20		83	190	350	538	777								
25		66	171	311	475	706	969							
30		43	140	248	423	628	881							
35			99	201	372	559	800							
40			77	181	328	497	722	985						
45			56	160	277	448	658	899						
50			40	121	228	387	582	809						
55				91	192	344	522	748						
60				71	171	298	470	670	913					
65				49	153	256	414	606	843					
70					117	209	371	538	783					
75					89	181	326	490	707	945				
80					70	161	284	440	642	869				

Separation Distances Table 22a Vadose zone: Sandstone - Saturated zone: Alluvial Sand

Vadose Zone Thickness (m)	Log reduction													
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	50	67	80	100	116	134	149	166	184	194	207	223	239	254
2	49	66	79	98	116	133	149	165	183	194	206	222	238	253
3	48	65	79	97	114	131	148	164	183	193	205	221	237	253
4	47	64	78	95	114	131	147	162	182	193	205	220	236	251
5	46	63	77	93	113	130	146	162	182	192	203	219	235	251
6	45	62	77	91	112	128	145	160	181	191	202	218	234	250
7	45	61	76	90	111	128	145	160	181	191	202	217	233	248
8	44	60	75	89	109	127	144	159	180	190	201	217	232	248
9	42	59	74	88	109	125	143	158	178	189	200	215	231	246
10	42	58	74	87	109	125	142	157	176	189	199	215	231	247
15		53	70	83	103	120	137	153	171	186	196	210	226	242
20		49	66	79	97	115	132	148	164	183	194	206	223	239
25		44	60	76	89	110	127	144	157	180	190	201	217	233
30			56	71	85	105	123	139	154	173	187	198	212	227
35			51	67	81	99	115	133	149	166	184	195	208	223
40			46	62	76	91	111	128	145	159	182	191	200	217
45			41	57	72	86	106	122	141	155	172	186	197	212
50				51	69	81	101	117	134	151	170	185	195	207
55				47	63	78	94	112	128	144	160	181	192	204
60				42	58	73	86	107	123	141	156	179	189	198
65					53	71	81	102	118	136	152	169	185	195
70					48	64	78	94	111	129	147	165	182	192
75					45	59	74	88	108	124	142	156	175	188
80						54	71	83	102	118	137	151	167	185

Separation Distances Table 22b **Vadose zone: Sandstone - Saturated zone: Alluvial Sand**

		Log reduction													
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
Vadose Zone Thickness (m)	1	268	281	295	312	331	350	369	388	407	425	443	461	478	496
	2	267	280	294	311	330	349	368	387	406	424	441	459	477	495
	3	266	280	293	310	329	348	367	386	405	423	440	458	476	494
	4	265	278	292	308	327	346	365	384	403	421	440	458	476	494
	5	265	279	292	308	327	346	365	384	403	421	439	457	475	493
	6	263	277	291	306	325	345	364	384	403	420	438	456	473	491
	7	262	276	290	305	324	343	362	382	401	419	437	455	473	491
	8	262	276	290	305	324	343	362	381	400	418	436	454	472	490
	9	261	274	288	302	322	341	360	379	398	416	434	451	469	487
	10	260	274	287	300	320	340	359	379	398	416	433	451	468	486
	15	257	270	284	297	316	335	354	373	393	411	429	446	464	482
	20	254	267	281	294	310	328	347	366	385	403	421	440	458	476
	25	249	262	275	289	303	322	341	360	379	398	417	435	453	472
	30	243	257	271	285	299	317	336	355	374	393	411	428	446	464
	35	239	254	267	280	293	309	328	347	366	385	403	422	440	459
	40	233	250	264	278	292	308	326	345	364	382	401	419	437	455
	45	227	243	258	272	286	300	319	338	357	375	394	412	430	448
	50	223	238	253	268	282	297	314	333	352	371	390	408	426	443
	55	220	236	251	264	277	290	305	325	345	364	384	404	421	439
	60	212	228	244	259	273	287	302	321	340	359	378	397	414	432
	65	208	224	240	255	269	283	296	314	333	352	371	390	408	427
	70	202	218	234	249	263	277	291	307	326	345	364	383	402	420
	75	199	214	230	246	260	273	287	300	319	339	358	377	396	414
	80	196	210	226	242	257	269	282	294	310	329	348	367	386	404

Separation Distances Table 23a **Vadose zone: Sandstone - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5
1	44	50	60	65	69	76	83	88	95	101	105	109	113	117
2	43	50	59	64	69	76	83	88	95	101	105	109	113	117
3	43	49	58	64	69	76	82	88	94	101	105	109	113	116
4	43	49	58	64	69	75	82	87	94	101	105	109	112	116
5	42	49	58	64	68	75	82	87	93	101	104	108	112	116
6	42	48	57	63	68	74	81	87	93	100	104	108	112	116
7	42	48	56	63	68	74	81	86	93	100	104	108	112	116
8	41	47	56	63	67	73	81	86	92	100	104	107	111	115
9	41	47	55	62	67	73	80	86	92	99	103	107	111	115
10	40	47	55	62	67	73	80	85	91	99	103	107	111	115
15		45	52	61	66	70	78	84	90	97	102	106	110	114
20		43	50	59	64	69	76	83	88	95	101	105	109	113
25		42	48	56	63	67	74	81	86	92	100	104	108	112
30			46	53	62	66	71	79	84	90	98	103	107	110
35			44	50	60	65	70	77	83	88	95	102	105	109
40			42	49	57	63	68	74	81	86	92	100	104	108
45			40	47	54	62	67	72	79	85	90	98	103	107
50				45	51	60	65	70	77	83	89	96	102	106
55				43	49	58	64	69	75	82	87	94	101	105
60				41	48	55	62	67	73	80	85	91	99	103
65					45	52	61	66	70	77	83	89	96	102
70					44	49	59	64	69	75	82	87	94	101
75					42	48	56	62	67	73	80	86	91	99
80					40	46	53	62	66	71	78	84	89	96

Separation Distances Table 23b **Vadose zone: Sandstone - Saturated zone: Coastal Sand**

	Log reduction													
Vadose Zone Thickness (m)	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	121	127	134	140	144	148	151	155	159	165	171	178	183	187
2	121	127	133	140	144	147	151	155	159	164	171	177	182	187
3	120	127	133	139	143	147	151	155	158	164	170	177	182	186
4	120	126	133	139	143	147	151	155	158	164	170	176	182	186
5	120	126	132	139	143	147	151	154	158	163	170	176	182	186
6	120	126	132	138	143	147	150	154	158	163	169	176	181	186
7	119	125	132	138	143	146	150	154	158	163	169	175	181	185
8	119	125	131	138	142	146	150	154	157	162	168	175	181	185
9	119	124	131	137	142	146	150	153	157	162	168	175	181	185
10	119	125	131	137	142	146	150	153	157	161	168	174	180	185
15	117	122	129	135	141	145	148	152	156	160	166	172	179	184
20	116	120	127	133	140	144	147	151	155	159	164	170	177	182
25	115	119	125	131	138	142	146	150	154	157	162	168	174	181
30	114	118	123	130	136	141	145	149	153	156	160	167	173	180
35	113	117	121	128	134	141	144	148	152	155	159	165	171	178
40	112	116	120	126	132	138	143	146	150	154	158	162	169	175
45	111	115	119	124	131	137	142	146	150	153	157	161	167	173
50	109	113	117	122	128	134	140	144	148	152	155	159	165	171
55	109	113	116	121	126	132	138	143	146	150	154	158	163	169
60	107	111	115	119	124	130	136	142	146	149	153	157	162	168
65	106	109	113	117	121	128	134	141	144	148	152	156	160	165
70	105	109	112	116	120	126	133	139	143	147	151	155	158	164
75	103	107	111	115	119	124	130	136	141	145	149	153	157	162
80	102	106	109	113	117	121	128	134	141	145	148	152	156	160

Separation Distances Table 24 Vadose zone: **Sandstone** - Saturated zone: **Sandstone and Non-karstic Limestone**

	Log reduction													
Vadose Zone Thickness (m)	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	51	53	56	58	61	63	66	68	71	75	79	82	84	87
2	51	53	56	58	61	63	66	68	71	75	79	82	84	86
3	51	53	56	58	61	63	65	68	70	74	78	81	84	86
4	51	53	56	58	60	63	65	68	70	74	78	81	84	86
5	50	53	55	58	60	63	65	68	70	74	78	81	84	86
6	50	53	55	58	60	63	65	67	70	74	78	81	83	86
7	50	53	55	58	60	62	65	67	70	74	78	81	83	86
8	50	52	55	57	60	62	65	67	70	74	77	81	83	86
9	50	52	55	57	60	62	65	67	69	73	77	81	83	85
10	50	52	55	57	59	62	64	67	69	73	77	81	83	85
15	49	52	54	57	59	61	64	66	69	71	75	79	82	84
20	48	51	53	56	58	61	63	65	68	70	74	78	81	84
25	47	50	52	55	57	60	63	65	68	70	74	78	81	83
30	47	50	52	54	57	59	61	64	66	69	72	76	80	82
35	46	48	51	53	56	58	61	63	66	68	71	75	78	81
40	45	48	50	53	55	58	60	62	65	67	69	73	77	81
45	44	47	49	52	54	57	59	62	64	67	69	73	76	80
50	43	46	48	51	54	56	59	61	64	66	69	72	75	79
55	43	45	48	50	53	55	58	60	63	66	68	71	75	78
60	42	44	47	49	52	55	57	60	62	64	67	69	73	77
65	40	43	46	48	51	54	56	59	61	63	66	68	71	75
70	40	43	45	48	50	53	55	58	60	62	65	67	70	74
75		41	44	47	49	52	54	57	59	62	64	66	69	72
80		41	43	46	48	51	54	56	59	61	63	66	68	71

Separation Distances Table 25 **Vadose zone: Sandstone - Saturated zone: Karstic and Fractured Rock**

	Log reduction													
Vadose Zone Thickness (m)	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1	313	387	471	549	625	704	784	863	943					
2	308	383	465	544	620	700	780	859	939					
3	303	377	460	540	615	696	776	857	937					
4	300	373	456	536	609	689	769	849	929					
5	294	369	449	530	606	686	766	846	926					
6	290	368	447	526	601	681	760	840	920	1000				
7	287	362	442	524	599	679	760	840	920					
8	281	356	434	517	595	674	753	832	912	991				
9	276	352	429	513	590	670	750	831	912	992				
10	273	350	427	508	582	661	741	821	901	982				
15	251	325	401	483	558	635	716	797	879	960				
20	227	307	381	461	538	613	694	776	857	938				
25	206	283	358	437	521	598	678	758	838	918	998			
30	179	253	334	410	497	573	652	731	811	890	970			
35	152	233	310	385	467	547	625	703	782	860	939			
40	112	208	287	362	442	523	595	676	757	838	919	1000		
45	93	182	264	339	415	498	574	652	731	810	889	968		
50	83	158	235	315	392	468	545	624	705	786	867	947		
55	68	125	216	289	367	449	528	601	681	761	842	922		
60	52	97	183	263	343	424	503	575	653	734	815	895	976	
65		86	155	245	315	393	472	555	636	714	792	871	949	
70		74	131	210	299	373	450	528	606	685	764	843	921	
75		60	105	187	266	341	412	503	578	655	735	814	893	972
80		47	89	161	239	317	396	487	558	629	707	785	863	941

Separation Distances Table 26a **Vadose zone: Silt - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1	43	153	261	427	634	883								
2			91	189	338	505	737	976						
3				66	161	272	436	622	863					
4					40	126	208	377	546	751	986			
5							98	188	318	482	676	890		
6								81	168	272	426	597	813	996
7									72	153	253	394	558	736
8										61	134	207	352	517
9											45	114	183	315
10													107	177
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 26b **Vadose zone: Silt - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5
1														
2														
3														
4														
5														
6														
7	970													
8	695	893												
9	465	636	836											
10	298	430	608	806	992									
15					86	160	256	381	539	702	894			
20											54	113	168	254
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 27a **Vadose zone: Silt - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction													
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1		40	56	72	85	107	123	139	154	176	188	198	212	228
2				46	62	76	92	111	127	144	159	180	190	201
3						53	69	81	101	116	134	150	167	184
4							46	61	74	87	108	125	141	157
5								43	54	68	79	98	112	127
6										49	61	74	89	105
7											46	58	71	82
8												44	54	67
9														52
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 27b **Vadose zone: Silt - Saturated zone: Alluvial Sand**

	Log reduction													
Vadose Zone Thickness (m)	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1	244	259	272	286	299	318	337	356	376	395	413	430	447	465
2	217	234	250	263	276	290	304	323	343	362	382	401	420	438
3	194	207	222	238	253	267	281	295	312	330	348	366	384	402
4	175	187	197	211	227	244	258	272	285	298	317	337	357	377
5	144	163	182	191	202	217	232	247	261	275	289	304	323	343
6	119	138	152	169	186	196	209	225	241	256	269	283	296	313
7	99	113	128	144	156	175	188	199	213	228	243	258	272	287
8	76	87	106	120	139	151	167	185	194	206	222	238	253	268
9	62	74	85	100	115	132	148	162	182	192	203	218	233	248
10	48	59	72	79	96	112	126	141	154	170	184	193	203	221
15							45	54	64	77	88	101	117	128
20														44
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 28a **Vadose zone: Silt - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5
1		40	46	54	62	66	72	79	85	90	98	103	107	110
2				43	49	57	63	68	75	81	86	92	100	104
3						46	53	61	65	70	77	83	89	96
4							43	49	57	63	68	74	81	86
5								41	47	53	61	65	70	76
6										45	50	59	64	68
7											44	49	56	62
8												42	47	54
9													42	47
10														41
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 28b **Vadose zone: Silt - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	114	118	123	130	136	142	145	149	153	157	161	167	174	180
2	108	112	116	119	125	132	138	143	146	150	154	158	162	169
3	102	105	109	113	117	121	127	133	140	144	147	151	155	159
4	92	99	104	108	112	116	120	126	132	138	142	146	150	154
5	82	88	95	101	105	109	113	116	120	126	132	138	142	146
6	74	80	86	92	100	104	107	111	115	118	123	130	136	141
7	67	72	79	84	89	95	101	105	109	113	116	120	127	133
8	61	66	71	77	82	87	92	99	103	107	111	115	120	125
9	52	59	64	69	74	80	85	90	98	103	106	110	114	118
10	45	51	58	63	67	72	79	83	88	93	100	104	108	112
15							44	49	55	61	65	69	76	81
20													40	44
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 29 **Vadose zone: Silt - Saturated zone: Sandstone and Non-karstic Limestone**

	Log reduction													
Vadose Zone Thickness (m)	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	47	49	52	54	57	59	62	64	67	69	72	76	80	82
2	42	45	48	50	53	55	57	59	62	64	67	69	73	78
3		40	43	46	48	51	53	56	58	60	63	65	68	71
4				41	44	46	49	52	54	57	59	62	64	66
5						42	45	47	50	52	55	57	59	61
6							41	44	46	49	52	54	57	59
7									41	44	47	50	52	54
8										40	43	46	48	51
9												41	43	46
10														42
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 30a **Vadose zone: Silt - Saturated zone: Karstic and Fractured Rock**

	Log reduction													
Vadose Zone Thickness (m)	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1	178	259	338	417	497	575	655	734	813	893	972			
2	64	115	208	283	359	437	518	599	675	751	827	903	979	
3		49	87	159	234	303	385	474	549	622	704	786	868	950
4				75	110	190	252	334	404	501	570	645	725	806
5					66	95	156	223	283	354	433	516	587	666
6						56	85	131	197	261	329	396	469	546
7							47	83	99	167	227	291	351	413
8								42	73	97	161	211	268	335
9										66	92	138	187	244
10											62	86	110	174
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 30b **Vadose zone: Silt - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction													
	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5
1														
2														
3														
4	886	967												
5	747	829	910	991										
6	625	702	780	857	935									
7	488	562	642	728	815	901	987							
8	388	459	535	611	690	770	850	929						
9	295	363	428	487	577	652	719	787	854	921	989			
10	221	275	335	389	464	539	610	684	758	831	905	979		
15			54	83	99	146	202	237	289	349	409	474	537	598
20										60	81	93	120	160
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 31a **Vadose zone: Clay - Saturated zone: Gravel**

	Log reduction													
Vadose Zone Thickness (m)	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	116	208	373	564	790									
2			78	170	299	463	657	880						
3					70	154	250	413	592	795				
4							63	141	226	379	541	722	925	
5									57	126	199	341	483	686
6											56	135	192	322
7													54	129
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 31b **Vadose zone: Clay - Saturated zone: Gravel**

		Log reduction													
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
Vadose Zone Thickness (m)	1														
	2														
	3														
	4														
	5	880													
	6	456	645	823											
	7	186	320	443	601	795									
	8	61	124	190	306	432	588	776	946						
	9			61	125	183	283	435	596	756	949				
	10					65	127	187	277	427	574	721	880		
	15														
	20														
	25														
	30														
	35														
	40														
	45														
	50														
	55														
	60														
	65														
	70														
	75														
	80														

Separation Distances Table 32a **Vadose zone: Clay - Saturated zone: Alluvial Sand**

	Log reduction													
Vadose Zone Thickness (m)	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1				50	66	79	101	116	133	149	166	184	194	208
2						41	54	70	82	102	118	133	150	168
3									48	63	75	87	107	123
4											44	56	69	79
5													43	54
6														
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 32b **Vadose zone: Clay - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction													
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1	224	240	255	268	281	294	311	330	350	369	389	407	425	442
2	184	194	208	224	241	255	268	281	293	309	327	346	365	384
3	135	151	171	186	195	208	224	240	255	269	283	296	313	332
4	91	110	125	141	156	178	189	199	214	230	247	259	271	283
5	65	76	87	103	117	136	149	161	180	190	199	215	233	250
6	42	52	60	73	81	100	113	127	140	154	170	184	194	206
7				50	59	69	82	89	107	120	136	148	159	182
8						47	57	69	77	88	104	118	130	142
9								47	56	67	77	86	97	111
10										47	56	65	75	84
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 33a **Vadose zone: Clay - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5
1				44	51	60	65	69	76	83	88	95	101	105
2						41	46	53	62	66	71	79	84	90
3									44	50	58	64	68	74
4											43	48	55	61
5													42	47
6														
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 33b **Vadose zone: Clay - Saturated zone: Coastal Sand**

	Log reduction													
Vadose Zone Thickness (m)	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	109	113	117	121	127	134	140	144	148	152	155	159	165	171
2	97	102	106	110	114	117	122	129	135	141	144	148	152	156
3	81	86	91	99	103	107	111	115	119	124	130	136	141	145
4	66	71	78	83	88	95	101	105	109	112	116	120	126	132
5	53	61	65	69	75	81	86	92	98	103	107	111	115	119
6	41	46	51	59	64	68	73	79	84	89	95	101	105	109
7			41	46	51	59	64	68	72	78	83	88	94	101
8					41	46	51	57	62	66	70	76	82	86
9							41	46	50	58	63	67	71	76
10									41	45	49	56	62	66
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 34 **Vadose zone: Clay - Saturated zone: Sandstone and Non-karstic Limestone**

Vadose Zone Thickness (m)	Log reduction													
	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	43	46	48	51	53	56	58	61	63	66	68	71	75	78
2			40	43	46	49	51	54	56	59	61	63	66	68
3						41	44	46	49	52	54	56	59	61
4									41	44	46	49	51	54
5												40	44	47
6														
7														
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 35a **Vadose zone: Clay - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction													
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1	78	143	231	313	381	471	548	618	699	779	860	940		
2			55	92	164	233	314	381	468	547	620	701	782	864
3					48	86	127	195	254	320	383	473	555	632
4							45	77	104	165	218	280	345	408
5									43	70	97	152	195	243
6											43	70	92	131
7														68
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 35b **Vadose zone: Clay - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction													
	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5
1														
2	945													
3	710	788	866	944										
4	490	566	641	714	787	859	932							
5	309	385	445	503	571	647	729	812	894	976				
6	183	232	299	341	383	442	512	587	659	732	804	876	948	
7	90	125	173	214	259	314	367	426	495	554	616	691	765	840
8	42	66	88	108	163	203	244	295	349	402	455	510	583	653
9			41	64	85	99	161	204	247	284	331	387	450	510
10					42	65	86	98	155	189	232	283	327	367
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 36a **Vadose zone: Ash - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	258	427	638	888										
2	88	186	340	508	737	977								
3		69	163	276	442	639	855							
4			54	142	238	398	564	774						
5					115	199	362	500	712	926				
6						99	183	308	472	662	864			
7							91	175	282	423	599	808	993	
8								83	161	261	402	584	751	956
9									74	143	239	366	536	745
10										64	136	206	351	492
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 36b **Vadose zone: Ash - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1														
2														
3														
4														
5														
6														
7														
8														
9	926													
10	668	843												
15		91	162	254	366	536	699	855						
20								75	132	186	280	392	528	697
25														76
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 37a **Vadose zone: Ash - Saturated zone: Alluvial Sand**

	Log reduction													
Vadose Zone Thickness (m)	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
1		56	72	85	105	122	139	155	174	188	199	214	229	244
2			46	62	77	90	111	128	146	159	180	191	203	218
3					54	69	81	102	118	133	149	167	184	196
4						47	62	75	91	108	125	143	156	175
5							43	56	71	82	101	116	132	148
6									52	65	78	90	110	125
7										48	61	73	85	104
8											47	57	72	80
9												44	55	68
10													43	53
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 37b   Vadose zone: Ash - Saturated zone: Alluvial Sand

	Log reduction													
Vadose Zone Thickness (m)	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0
1	258	272	285	298	317	336	356	375	394	412	430	448	465	483
2	233	248	262	276	289	304	322	341	359	378	396	415	434	453
3	210	225	240	255	268	281	294	311	330	349	368	387	406	424
4	189	200	215	230	245	259	273	286	299	319	338	358	378	397
5	164	182	193	205	220	235	250	265	280	294	311	330	349	368
6	143	156	175	188	197	211	226	241	256	270	284	298	317	336
7	119	133	147	161	181	193	206	221	237	252	266	280	293	309
8	99	113	127	141	157	171	185	199	215	232	249	261	273	285
9	77	90	107	122	137	151	168	183	192	203	218	234	249	263
10	66	75	90	104	118	131	144	157	180	189	198	213	229	245
15					45	54	63	74	84	96	110	123	139	151
20												46	55	64
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 38a **Vadose zone: Ash - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5
1			46	53	61	66	72	79	85	91	98	103	107	111
2				43	48	58	63	68	74	81	87	93	99	104
3					40	46	52	61	66	70	78	84	89	97
4							44	50	59	64	69	75	81	86
5								42	47	54	62	67	72	79
6									41	46	52	60	65	70
7											45	51	58	63
8												44	49	56
9													43	48
10														43
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 38b **Vadose zone: Ash - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	114	118	123	130	136	142	145	149	153	156	160	167	173	180
2	107	111	115	119	125	131	137	142	146	150	154	158	163	169
3	102	106	110	113	117	122	128	135	141	144	148	152	155	159
4	92	100	104	107	111	115	119	124	130	137	142	146	149	153
5	84	89	96	102	106	109	113	117	121	127	133	139	143	147
6	76	82	87	92	100	104	108	112	115	119	125	131	137	142
7	68	74	80	85	91	98	103	107	111	114	118	123	129	135
8	62	67	72	78	83	88	95	101	105	109	113	117	121	127
9	55	61	66	70	77	82	87	93	101	104	108	112	116	119
10	47	53	60	65	69	75	81	86	90	98	103	106	110	114
15						44	49	54	60	65	70	75	79	84
20												41	46	50
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 39 Vadose zone: **Ash** - Saturated zone: **Sandstone and Non-karstic Limestone**

	Log reduction													
Vadose Zone Thickness (m)	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	47	49	52	55	57	60	62	64	67	69	72	76	80	82
2	42	45	47	50	52	55	57	60	62	65	67	70	73	77
3		41	43	46	49	51	53	56	58	61	63	66	68	71
4				41	44	47	50	52	55	57	59	62	64	67
5						42	45	47	50	53	55	58	60	63
6							41	44	46	49	51	54	56	58
7									42	45	48	50	53	55
8										41	43	46	48	51
9												41	44	47
10														43
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 40a Vadose zone: Ash - Saturated zone: Karstic and Fractured Rock

Vadose Zone Thickness (m)	Log reduction													
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
1	180	259	335	411	498	578	657	736	815	893	972			
2	60	117	206	283	355	436	525	590	667	747	826	906	985	
3		48	91	162	234	311	384	467	544	616	697	777	858	938
4			41	81	116	196	268	344	419	491	560	635	716	798
5					71	97	168	229	293	365	443	527	615	697
6						63	92	142	212	267	331	402	490	565
7							57	87	129	187	253	305	373	448
8								51	83	102	167	219	281	347
9									46	78	98	158	218	265
10										45	73	93	152	205
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 40b **Vadose zone: Ash - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction 9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5
1														
2														
3														
4	879	961												
5	778	860	942											
6	640	716	793	870	946									
7	522	586	662	742	821	901	981							
8	415	482	565	644	715	787	859	931						
9	313	384	459	525	581	653	736	818	900	982				
10	238	288	370	438	497	558	624	705	785	865	946			
15		55	82	95	148	188	238	282	326	373	433	508	568	635
20								48	72	89	103	148	190	222
25														53
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 41a   Vadose zone: Peat - Saturated zone: Gravel

Vadose Zone Thickness (m)	Log reduction													
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	206	376	564	811										
2	44	130	244	398	580	808								
3			67	156	267	419	608	835						
4					94	176	296	466	650	855				
5						45	117	194	333	490	681	884		
6								65	152	235	383	535	702	906
7										86	166	261	399	561
8												103	177	292
9													62	133
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 41b **Vadose zone: Peat - Saturated zone: Gravel**

Vadose Zone Thickness (m)	Log reduction													
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1														
2														
3														
4														
5														
6														
7	737	938												
8	420	590	807	961										
9	194	316	458	640	814	996								
10	85	159	251	345	497	654	813	999						
15									76	157	194	293	412	587
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 42a Vadose zone: Peat - Saturated zone: Alluvial Sand

	Log reduction													
Vadose Zone Thickness (m)	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
1		51	69	80	99	117	134	151	168	184	194	207	224	240
2				51	68	81	100	116	133	149	166	183	193	204
3						50	66	78	94	112	129	146	160	180
4							40	52	66	78	90	110	126	143
5									42	54	67	81	94	112
6											45	56	69	79
7													47	58
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 42b **Vadose zone: Peat - Saturated zone: Alluvial Sand**

	Log reduction													
Vadose Zone Thickness (m)	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0
1	256	269	282	296	313	332	351	370	389	407	425	442	459	477
2	220	236	251	265	279	293	310	330	349	368	387	406	424	441
3	191	202	219	236	252	265	278	291	306	326	346	366	387	406
4	157	181	191	200	215	230	245	259	273	287	301	320	339	359
5	127	142	155	173	187	197	211	227	243	258	273	288	304	322
6	88	109	124	140	155	176	187	195	207	222	238	253	268	282
7	69	79	88	110	125	138	152	171	185	193	203	220	236	252
8	48	58	71	81	90	108	123	136	148	161	177	190	202	216
9		41	50	59	69	81	90	107	119	134	148	160	182	190
10				42	50	60	73	82	93	108	122	134	147	161
15												41	49	58
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 43a **Vadose zone: Peat - Saturated zone: Coastal Sand**

	Log reduction													
Vadose Zone Thickness (m)	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5
1			44	51	60	65	70	77	83	88	95	101	105	109
2					45	51	60	65	70	77	83	88	95	101
3							45	51	60	65	69	76	82	88
4								40	46	52	61	65	70	76
5										42	47	53	61	66
6												43	48	55
7														44
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 43b Vadose zone: Peat - Saturated zone: Coastal Sand

Vadose Zone Thickness (m)	Log reduction													
	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	113	117	122	128	134	140	144	148	151	155	159	165	171	178
2	105	109	113	116	120	127	133	140	144	148	151	155	159	165
3	95	101	105	109	113	117	121	127	133	138	143	147	150	154
4	82	88	95	101	105	109	113	117	121	126	132	138	142	146
5	70	76	82	88	94	101	104	108	112	116	119	125	132	138
6	62	66	71	77	83	87	93	101	104	108	112	116	120	125
7	49	56	62	66	71	77	83	88	93	99	103	107	111	115
8	41	46	51	57	63	67	72	78	83	87	92	101	104	108
9			42	46	52	60	64	67	72	78	83	88	94	101
10					43	48	54	60	64	68	73	79	84	89
15													42	46
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 44 Vadose zone: **Peat** - Saturated zone: **Sandstone and Non-karstic Limestone**

	Log reduction													
Vadose Zone Thickness (m)	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	46	48	51	53	56	58	61	63	66	68	71	75	78	81
2	40	43	45	48	50	53	56	58	61	63	65	68	70	74
3				42	45	47	50	53	55	57	60	62	65	67
4						42	44	47	50	52	55	57	59	62
5								41	44	46	49	51	54	57
6										41	43	46	48	51
7													42	45
8														
9														
10														
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 45a **Vadose zone: Peat - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction													
	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
1	240	313	383	467	550	630	709	787	866	945				
2	80	153	228	310	388	464	541	619	698	778	857	936		
3		46	87	153	220	292	368	448	529	606	684	763	842	921
4				60	91	151	208	280	357	432	505	572	649	733
5						69	94	155	216	276	343	409	478	563
6							47	80	98	157	217	272	336	407
7									55	84	103	171	215	262
8											62	86	111	173
9												43	71	90
10														53
15														
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 45b **Vadose zone: Peat - Saturated zone: Karstic and Fractured Rock**

Vadose Zone Thickness (m)	Log reduction													
	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
1														
2														
3	999													
4	817	902	986											
5	645	720	795	869	944									
6	467	530	596	682	770	858	946							
7	328	396	466	538	613	689	766	842	918	994				
8	217	261	318	375	442	514	577	651	732	812	893	973		
9	121	174	220	268	317	371	428	491	556	626	703	781	858	936
10	75	92	143	179	223	271	310	362	418	489	556	624	697	770
15								48	72	89	110	151	190	226
20														
25														
30														
35														
40														
45														
50														
55														
60														
65														
70														
75														
80														

Separation Distances Table 46 **Vadose zone: Karstic and Fractured Rock - Saturated zone: Gravel**

		Log reduction													
		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
Vadose Zone Thickness (m)	1		92	199	373	566	811								
	2		89	196	367	558	802								
	3		61	167	304	475	699	960							
	4		49	163	289	462	683	943							
	5			127	237	406	611	865							
	6			121	232	405	608	858							
	7			123	234	402	606	859							
	8			119	231	403	601	863							
	9			120	231	403	607	860							
	10			119	232	401	602	862							
	15			120	230	399	599	860							
	20			115	230	399	604	851							
	25			115	224	395	599	852							
	30			114	225	398	595	851							
	35			110	223	396	599	848							
	40			111	224	394	592	843							
	45			106	220	392	592	845							
	50			104	220	395	593	845							
	55			102	215	387	586	837							
	60			102	215	388	583	837							
	65			100	208	384	581	833							
	70			98	208	385	582	827							
	75			98	206	377	575	823							
	80			95	203	378	570	819							

Separation Distances Table 47a **Vadose zone: Karstic and Fractured Rock - Saturated zone: Alluvial Sand**

Vadose Zone Thickness (m)	Log reduction 3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
1	51	68	81	101	117	135	150	168	185	195	208	224	240	255
2	50	67	80	101	117	134	150	167	184	195	207	223	239	254
3	44	60	75	89	110	127	144	159	180	190	200	216	232	248
4	43	60	75	88	109	126	143	157	178	189	200	215	231	247
5		54	71	84	105	121	138	153	172	187	197	212	228	243
6		54	71	84	104	120	137	153	172	187	197	211	227	243
7		54	71	83	104	120	138	153	172	186	197	211	227	242
8		54	71	84	105	121	138	153	172	187	197	211	227	243
9		54	71	83	104	120	138	153	172	187	197	211	226	242
10		54	71	84	104	120	138	153	172	187	197	211	226	242
15		54	71	84	104	121	137	152	171	187	197	211	227	243
20		53	71	83	104	120	138	153	171	186	196	210	226	242
25		54	71	84	104	120	137	152	170	186	197	211	227	243
30		53	70	83	104	120	137	153	171	186	196	210	226	242
35		53	70	83	103	120	138	153	170	186	196	210	225	240
40		53	70	83	103	120	137	152	171	186	196	210	225	241
45		53	70	83	103	119	137	152	171	186	196	210	226	242
50		53	69	83	103	119	137	153	171	186	196	209	225	241
55		53	69	82	103	119	137	152	169	185	196	209	225	241
60		52	69	82	102	119	136	152	170	186	196	210	226	242
65		52	69	82	102	118	136	152	169	185	195	209	225	241
70		52	69	82	102	118	136	152	169	185	195	209	225	241
75		51	68	82	102	118	135	151	169	185	195	209	225	241
80		52	68	81	102	118	135	151	168	185	195	209	224	240

Separation Distances Table 47b   Vadose zone: Karstic and Fractured Rock - Saturated zone: Alluvial Sand

Vadose Zone Thickness (m)	Log reduction 10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
1	268	282	296	313	332	351	370	389	408	426	444	461	479	497
2	268	281	295	312	331	350	370	389	407	425	443	461	479	496
3	262	276	289	304	323	342	362	381	400	418	436	454	471	489
4	261	275	288	302	322	341	360	380	399	417	435	453	471	488
5	258	271	285	298	316	336	355	374	393	411	429	447	465	483
6	257	271	285	298	316	335	354	373	392	410	428	446	464	483
7	257	271	285	298	317	336	355	374	394	412	429	446	464	481
8	257	271	284	298	316	335	354	373	393	411	429	447	465	483
9	256	270	284	298	316	335	355	374	393	412	429	447	465	483
10	257	271	284	298	317	336	355	374	393	411	429	447	465	483
15	257	271	284	298	316	335	354	373	392	410	428	446	464	482
20	257	270	284	298	316	336	355	375	394	412	430	447	465	482
25	257	270	284	297	315	334	354	373	392	411	428	446	464	482
30	257	270	284	297	315	335	354	374	393	411	429	447	465	482
35	255	270	284	298	316	335	354	373	392	411	428	446	463	481
40	256	270	284	298	316	335	353	372	391	410	427	445	463	481
45	256	270	283	296	314	333	353	372	391	410	428	446	463	481
50	256	270	283	297	315	334	354	373	392	411	428	446	464	481
55	256	270	283	297	315	334	353	373	392	410	428	446	464	481
60	256	270	283	297	314	333	352	371	389	408	426	444	462	481
65	256	269	283	296	314	333	353	372	391	410	427	445	463	480
70	256	269	283	297	315	334	353	373	392	410	427	445	462	479
75	256	270	283	297	314	333	352	371	390	409	427	445	463	481
80	255	268	282	295	313	332	351	371	390	408	426	444	461	479

Separation Distances Table 48a **Vadose zone: Karstic and Fractured Rock - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5
1	44	51	60	65	70	77	83	89	96	102	105	109	113	117
2	44	50	60	65	69	77	83	88	95	101	105	109	113	117
3	41	48	56	63	67	73	81	86	92	100	104	108	111	115
4	41	47	55	62	67	73	80	86	92	99	103	107	111	115
5		45	53	61	66	71	78	84	90	97	103	106	110	114
6		45	52	61	66	71	78	84	90	97	102	106	110	114
7		45	52	61	66	71	78	84	90	97	102	106	110	114
8		45	52	61	66	71	78	84	89	97	102	106	110	114
9		45	52	61	66	71	78	84	90	97	102	106	110	114
10		45	52	61	66	71	78	84	90	97	102	106	110	114
15		45	52	61	66	71	78	84	90	97	102	106	110	114
20		45	52	61	66	71	78	84	90	97	102	106	110	114
25		45	52	61	66	70	78	84	89	97	102	106	110	114
30		45	52	61	66	71	78	84	89	97	102	106	110	114
35		45	52	61	65	70	78	84	90	97	102	106	110	114
40		45	52	61	66	71	78	84	89	97	102	106	110	114
45		45	52	61	65	70	78	84	89	97	102	106	110	114
50		45	52	61	65	70	78	84	89	96	102	106	110	114
55		45	52	61	65	70	78	84	89	96	102	106	110	114
60		45	52	61	65	70	78	84	89	96	102	106	110	114
65		45	51	61	65	70	77	84	89	96	102	106	110	114
70		45	51	60	65	70	77	83	89	96	102	106	109	113
75		44	51	60	65	70	77	83	89	96	102	106	109	113
80		44	51	60	65	70	77	83	89	96	102	105	109	113

Separation Distances Table 48b **Vadose zone: Karstic and Fractured Rock - Saturated zone: Coastal Sand**

Vadose Zone Thickness (m)	Log reduction													
	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
1	121	128	134	140	144	148	152	155	159	165	172	178	183	187
2	121	128	134	140	144	148	152	155	159	165	171	178	183	187
3	119	125	131	138	142	146	150	154	158	162	169	175	181	185
4	119	124	131	137	142	146	150	153	157	162	168	175	181	185
5	118	123	129	135	141	145	149	152	156	160	166	173	179	184
6	118	123	129	135	141	145	149	152	156	160	166	173	179	184
7	118	123	129	135	141	145	148	152	156	160	166	173	179	184
8	118	123	129	136	141	145	149	152	156	160	166	173	179	184
9	118	123	129	135	141	145	149	152	156	160	166	173	179	184
10	118	123	129	135	141	145	149	152	156	160	166	173	179	184
15	118	122	129	135	141	145	148	152	156	160	166	172	179	183
20	118	123	129	135	141	145	148	152	156	160	166	173	179	184
25	118	123	129	135	141	145	148	152	156	160	166	173	179	184
30	118	123	129	135	141	145	148	152	156	160	166	173	179	184
35	118	122	129	135	141	144	148	152	156	160	166	172	179	183
40	118	122	129	135	141	145	148	152	156	160	166	172	179	183
45	118	122	129	135	141	144	148	152	156	160	166	172	179	183
50	117	122	128	135	141	144	148	152	156	160	166	172	179	183
55	117	122	128	135	140	144	148	152	156	160	166	172	179	183
60	117	122	129	135	141	144	148	152	156	159	166	172	178	183
65	117	122	128	135	140	144	148	152	156	159	165	172	179	183
70	117	121	128	134	141	144	148	152	156	160	166	172	178	183
75	117	122	128	134	140	144	148	152	156	159	165	172	178	183
80	117	122	128	134	140	144	148	152	155	159	165	172	178	183

Separation Distances Table 49 **Vadose zone: Karstic and Fractured Rock - Saturated zone: Sandstone and Non-karstic Limestone**

		Log reduction													
		11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
Vadose Zone Thickness (m)	1	51	54	56	59	61	63	66	68	71	75	79	82	84	87
	2	51	54	56	58	61	63	66	68	71	75	79	82	84	87
	3	50	53	55	57	60	62	65	67	70	74	77	81	83	86
	4	50	52	55	57	60	62	65	67	70	73	77	81	83	86
	5	49	52	54	56	59	61	64	66	69	72	76	80	82	85
	6	49	52	54	56	59	61	64	66	69	72	76	80	82	85
	7	49	52	54	57	59	61	64	66	69	72	76	80	82	85
	8	49	52	54	57	59	62	64	66	69	72	76	80	82	85
	9	49	52	54	57	59	61	64	66	69	72	76	80	82	85
	10	49	52	54	56	59	61	64	66	69	72	76	80	82	85
	15	49	51	54	56	59	61	64	66	69	72	76	80	82	85
	20	49	51	54	56	59	61	64	66	69	72	76	80	82	85
	25	49	52	54	57	59	61	64	66	69	72	76	80	82	85
	30	49	52	54	56	59	61	64	66	69	72	76	80	82	85
	35	49	51	54	56	59	61	64	66	69	72	76	80	82	85
	40	49	51	54	56	59	61	64	66	69	72	76	79	82	84
	45	49	51	54	56	59	61	64	66	69	72	76	80	82	85
	50	49	52	54	57	59	61	64	66	69	72	76	80	82	85
	55	49	51	54	56	59	61	64	66	69	72	76	79	82	85
	60	49	51	54	56	59	61	64	66	69	72	75	79	82	84
	65	49	51	54	56	59	61	64	66	69	72	75	79	82	84
	70	49	51	54	56	59	61	64	66	68	71	76	80	82	84
	75	49	51	54	56	59	61	64	66	68	71	75	79	82	85
	80	49	51	54	56	59	61	64	66	68	71	75	79	82	84

Separation Distances Table 50 **Vadose zone: Karstic and Fractured Rock - Saturated zone Karstic and Fractured Rock**

		Log reduction													
		2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
Vadose Zone Thickness (m)	1	317	392	475	552	628	708	788	868	948					
	2	314	388	472	550	626	706	786	866	945					
	3	281	358	438	520	593	673	754	834	915	995				
	4	276	352	431	514	589	668	748	827	907	987				
	5	253	331	405	495	568	644	724	805	885	966				
	6	253	333	409	492	566	643	723	803	883	962				
	7	254	330	403	488	563	640	720	800	881	961				
	8	250	330	407	493	566	643	722	802	881	961				
	9	252	331	407	492	566	643	723	803	884	964				
	10	252	330	404	488	565	643	723	803	883	963				
	15	250	329	405	489	564	641	721	800	880	960				
	20	247	328	404	489	563	639	720	800	881	961				
	25	249	331	405	489	565	643	723	804	884	964				
	30	250	329	405	489	563	640	721	802	882	963				
	35	249	327	401	489	563	640	720	800	880	960				
	40	246	326	399	487	564	641	721	801	881	961				
	45	247	326	399	486	563	640	719	797	876	955				
	50	250	327	402	487	561	636	716	795	875	955				
	55	244	327	400	483	561	639	718	797	876	955				
	60	244	324	397	482	560	637	716	795	873	952				
	65	243	321	396	480	557	635	715	795	875	955				
	70	243	321	396	479	556	633	712	791	870	949				
	75	241	320	394	479	555	630	712	793	874	955				
	80	241	321	393	475	553	630	710	789	869	948				

Part 3 – Technical appendix

Part 3 – Technical appendix

PART 3

Technical Appendix

PART 3 – Technical appendix

A1 Introduction

A1.1 Overview

This technical appendix explains the modelling approach used to develop the guideline values presented in Part 2. It aims to:

- allow an assessment of the approach taken, thereby supporting the scientific defensibility of the guideline information provided in Part 2
- provide information that will allow this work to be extended when more data become available, thereby broadening the applicability of the guidelines and increasing their robustness[35].

The information in Part 3 is ordered as follows:

Section A2: Discusses how the required $\log_{10}$ reduction in virus concentration was determined.

Section A3: Discusses literature values for the $\log_{10}$ reduction in virus concentration occurring in the sewage tank and its disposal field, and which of these values are recommended for the calculation.

Section A4: Discusses literature values available for the $\log_{10}$ reduction in virus concentration achievable in different soil types in New Zealand.

Section A5: Describes the approach taken to model virus reduction in the vadose zone, the values selected for input parameters, and the reasons for these selections.

Section A6: Describes the approach taken to model virus reduction in the saturated zone, the concepts involved in the modelling, the values selected for input parameters, and the reasons for these selections.

Appendices 1, 2 and 3 tabulate the stool mass dataset, virus dataset, which includes concentrations of viruses in faeces and their shedding period, and dose-response parameter values. These are the datasets used to carry out the calculations described in Section A2.

No new experimental work was undertaken during this project. The modelling is based solely on virus removal data from the scientific literature, and hydraulic properties derived from pump-test data obtained from New Zealand's regional councils and unitary authorities. Where required, the validity of the approaches developed for assessing the predictive uncertainties associated with some aquifer types has been assessed by experts external to the project team.

Fig. A1 gives an overview of the components used in determining the separation distances and the data required.

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[35] It is not the intention that Part 3 alone will allow a user to generate the guideline values from scratch. Some of the software used is not commercially available, and expertise in the use of the more sophisticated modelling is required.

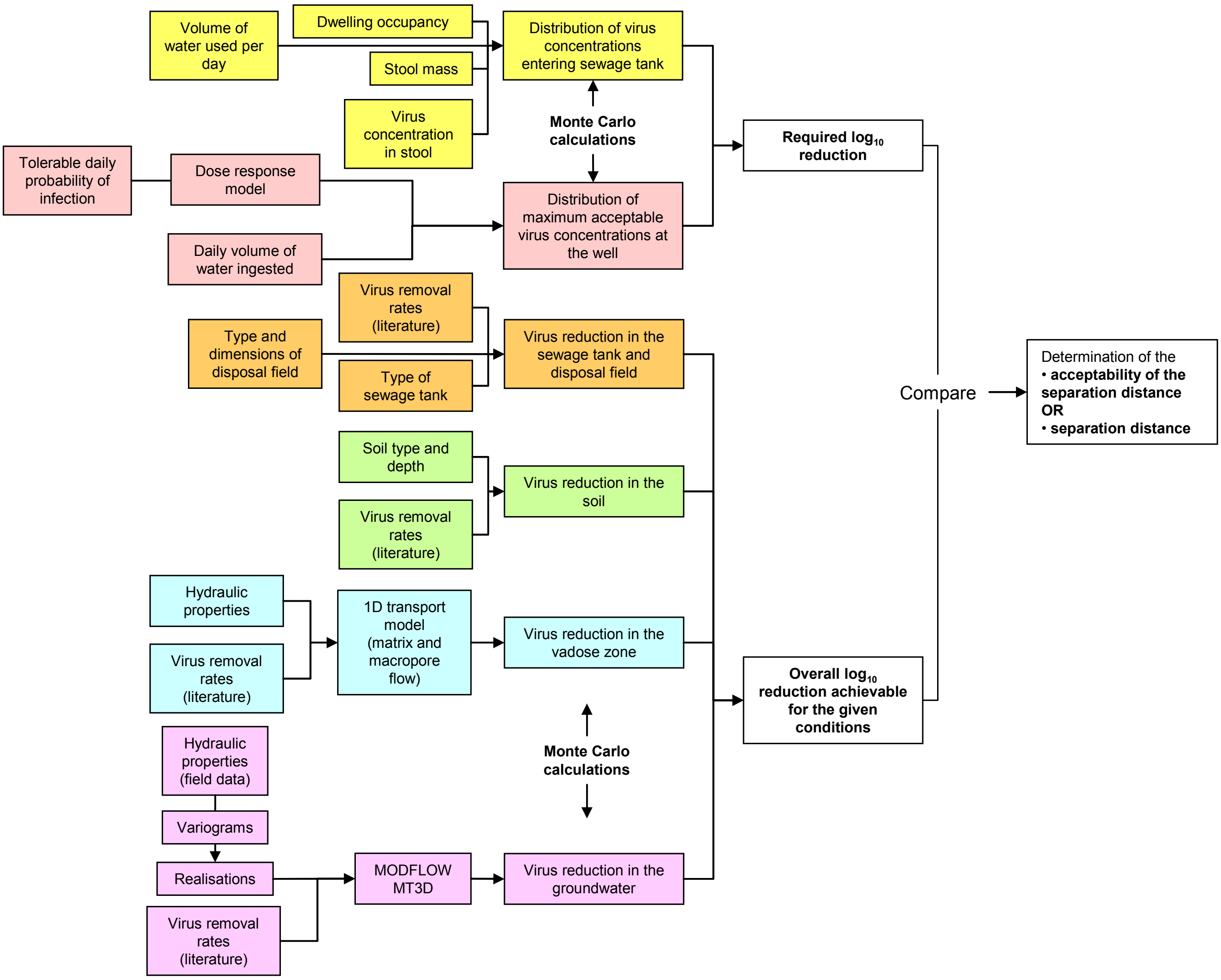


Fig. A1 **Overview of components required to determine the separation distances and primary data requirements**

Text boxes, identifying "key points" from each section, are incorporated into Part 3 to assist in understanding the approach taken to the modelling.

A1.2 Uncertainty and confidence levels

Uncertainty is an intrinsic feature of the modelling undertaken in this work. Sometimes uncertainty arises from the stochastic nature of the parameter being modelled, for example groundwater flow through heterogeneous aquifer materials or the amount of faecal material excreted daily by an individual. Uncertainty also arises from simply not knowing the exact value of an input parameter that is required for the model. Consequently, the parameter can have any value within a range of values. In this work, the form of the probability distribution for such parameter values was known (or it could be approximated) in some cases, while in others it was not.

Uncertainty was included in the models by using Monte Carlo techniques (which allow parameters to be represented as distributions of possible values rather than as a single value). The output from these models was a range of values, rather than a single result, as shown in Fig. A2. From the output distribution, an appropriate percentile value was selected that provided a result with a specified level of certainty.

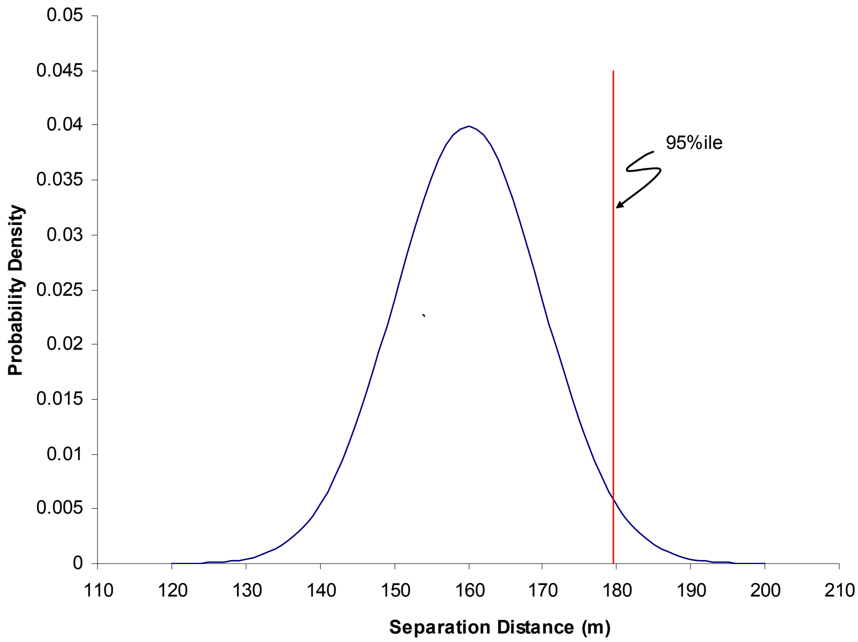


Fig. A2 Idealised model output distribution showing the 95th percentile (see example below)

> *Example: Suppose a calculated separation distance to achieve a required 5 log_{10} reduction in virus concentration ranges from 120–200 m, and the 95% percentile of the distribution is 180 m (see* Fig. A2*), by specifying 180 m as the guideline, the user can be 95% certain that by maintaining this separation, at least a 5 log_{10} reduction in viruses will be achieved. Viewed another way, this separation distance will ensure that 95% of the time virus concentrations will have been reduced by 5 log_{10} – this means that 5% of the time the separation required to reduce the virus concentration by 5 log_{10} would have to be more than 180 m.*

A level of 95% confidence is used widely in the DWSNZ (MoH, 2008), and it is the basis for the calculations supporting many of the required monitoring frequencies. The Guidelines document is designed to protect the quality of water that may be used for human consumption, so the output values from this work are specified to the same level of confidence.

The Monte Carlo approach adopted in this work was supported by the use of the spreadsheet-based @RISK® software, and by the use of batch files (when undertaking the stochastic groundwater transport component of this work).

To assess the separation distance at a confidence level of 95%, the various calculation input distributions need to be combined. This can be done using either (i) a full "parent" Monte Carlo assessment or (ii) the use of probability axioms. The second method was chosen to facilitate the worksheet format in Part 2 of the guidelines (refer to Probability of Union calculations in standard statistical texts). This method requires an assumption of the various levels of confidence that will be accepted to form a combined 95% confidence level. For simplicity, we assumed that each component of the sewage discharge-to-well system was equally uncertain. The particular individual probability was chosen on the basis that the combined probabilities from all the components formed a 95% confidence interval for the separation distances.

Key points

- Uncertainty is an intrinsic feature of the modelling for this work.
- Monte Carlo techniques were used to take account of the uncertainty.
- The Monte Carlo approach allows the separation distances between the disposal field and well to be provided with a 95% level of confidence.

A1.3 Sensitivity analysis

This section examines the sensitivity of the model outputs to the various model inputs. The analysis is portrayed using tornado graphs. A tornado graph is a bar chart that can be used as a sensitivity analysis tool, where the change in output as a result of a change in input is displayed. In this case the tornado graph depicts the change in output from a plus one standard deviation change in input. The longer the bar, the more sensitive is the model output to the model input.

The sensitivity analysis assesses the relative importance of the calculated output to the three major groups of components involved in the removal of viruses in sewerage discharges, namely, the processes in the septic/tank disposal system (including transport through soil), transport through the vadose zone, and transport through the saturated zone. It requires calculating a simple ratio of the $\log_{10}$ of the input concentrations to the combined $\log_{10}$ reduction that is achieved in the vadose and saturated strata, and examining the sensitivity of this ratio to the various inputs (in effect this is a simplified but appropriately representative version of the calculation involved in the worksheets in this report).

The relative importance of each of these three components differs depending on the combination of components. For example, when simply examining combinations of an alluvial gravel vadose and saturated zone, the following is observed.

For the most conservative case, i.e., for very shallow water tables, the model outputs are dominated by variability in the saturated transport. As the water table deepens, the model outputs become increasingly affected by the characteristics of the vadose zone. Changes to the sewerage system input values are the least significant in terms of the variation they cause in the model output. This is illustrated in Fig. A3, Fig. A4 and Fig. A5 where three combinations of an alluvial gravel vadose zone thickness and a saturated zone horizontal separation distance are selected. These results were applicable across the other geological settings modelled.

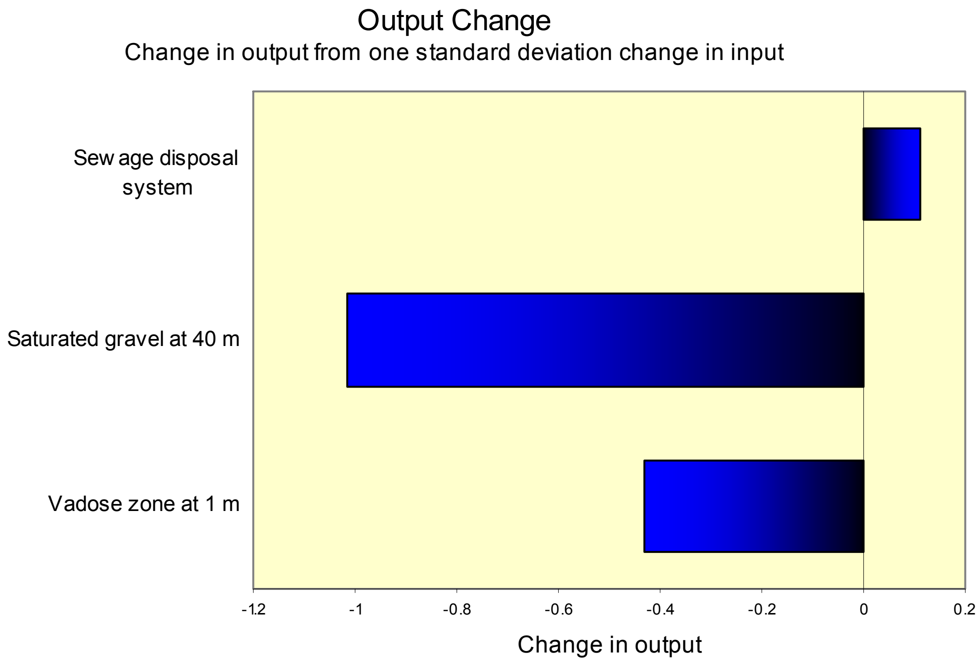


Fig. A3 Tornado graph for saturated gravel with 1m vadose zone thickness and a separation distance of 40 m

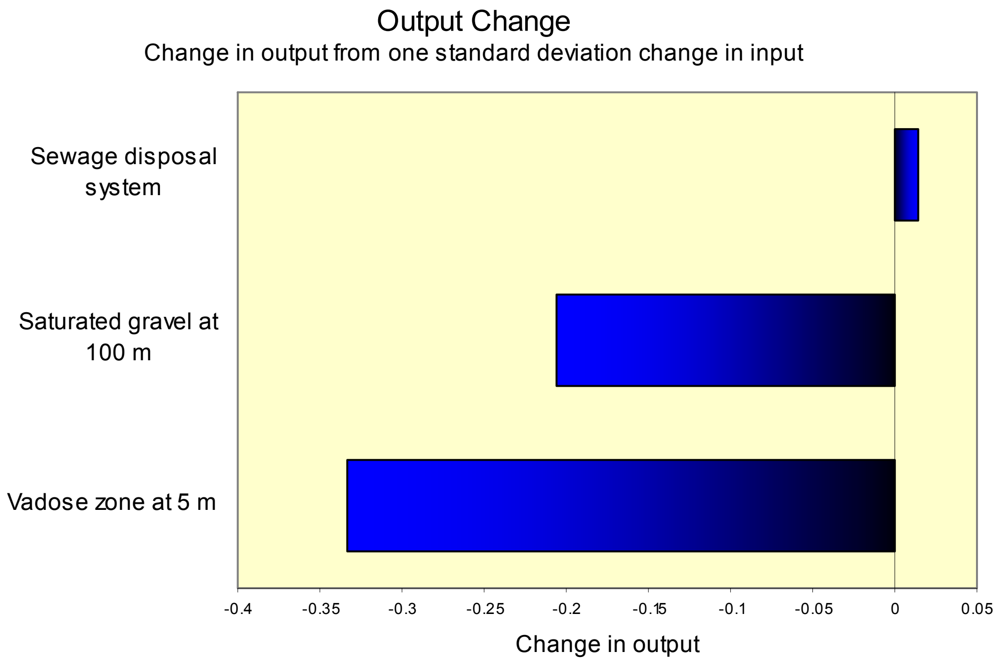


Fig. A4 Tornado graph for saturated gravel with 5 m vadose zone thickness and a separation distance of 100 m

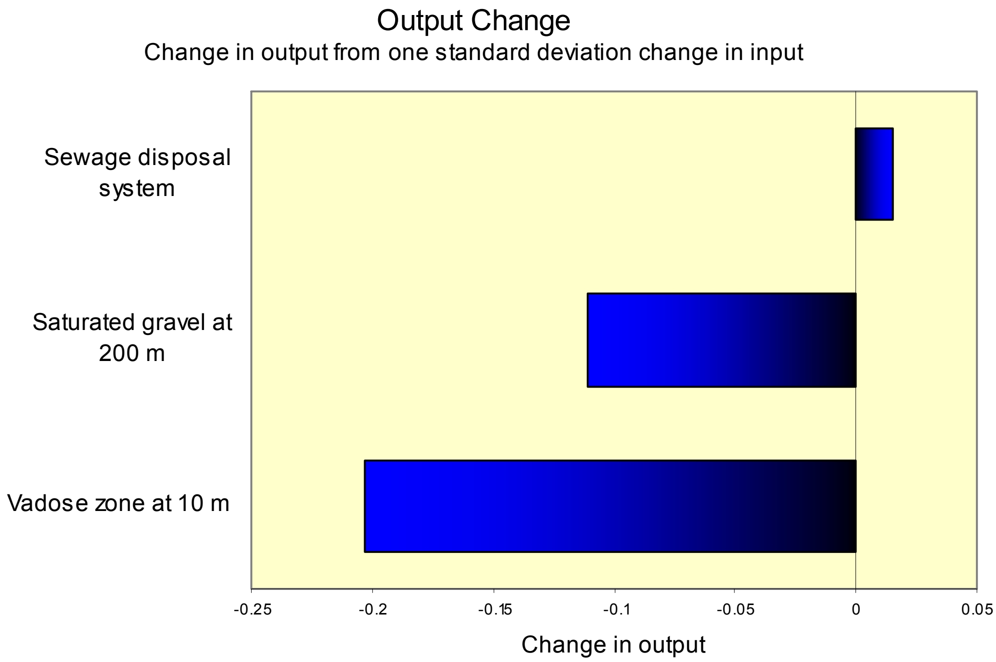


Fig. A5 Tornado graph for saturated gravel with 10 m vadose zone thickness and a separation distance of 200 m

In Fig. A3, the results for the shallowest water table modelled (at a depth of 1 m) combined with a horizontal separation distance of 40 m, indicate that the most significant change in model output for an increase in the input parameter of 1 standard deviation, is made by the variability of the transport within the alluvial gravel aquifer. The output variability is next most sensitive to the variability of the transport through the vadose zone, and least influenced by the variability in the virus concentration entering the vadose zone from the sewage disposal system.

In Fig. A4, where the water table is deeper at 5 m, and the horizontal separation is 100 m, vadose zone transport is the most significant in terms of model output uncertainty, next the saturated zone transport, and finally, the model output uncertainty is least sensitive to the input concentration variability or uncertainty in the sewage disposal system.

Finally in Fig. A5, where the water table is simulated to occur at 10 m, and the horizontal separation is 200 m, vadose zone transport remains the most significant in terms of propagating model output uncertainty, followed by the saturated zone transport, and finally the input concentrations.

The sensitivity of the individual vadose zone and the saturated zone models was explored in the same fashion, employing tornado graphs to depict the results of the analyses. Fig. A6 shows the results for one case of the vadose zone model testing the relative importance of removal rate and transport porosity. Fig. A7 shows the results for one case of the saturated zone model, testing the relative importance of removal rate and dispersion. Both figures indicate that the output concentration reduction is most dependent on the removal rate parameter, and in comparison the importance of transport processes is significantly less. Once again, the sensitivity results depicted by these two cases were found in all the model outputs.

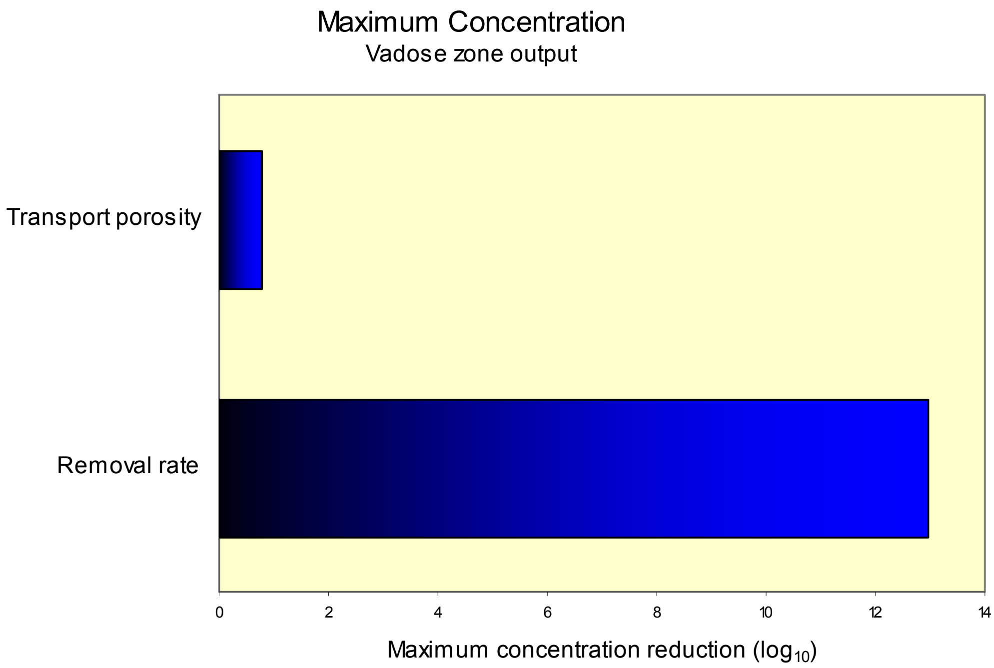


Fig. A6 Tornado graph showing the relative importance of removal rate and transport porosity in determining the model output for the vadose zone

Key points

- Three major components determine the removal viruses in sewage: processes in the septic/tank disposal system (including transport through soil), transport through the vadose zone, and transport through the saturated zone.
- At shallow depths, transport through the saturated zone is the most important, but as the groundwater depth increases, the characteristics of the vadose zone become more important.
- The modelling results are most sensitive to the removal rates. Transport processes play a less significant role in determining the calculated virus removal.

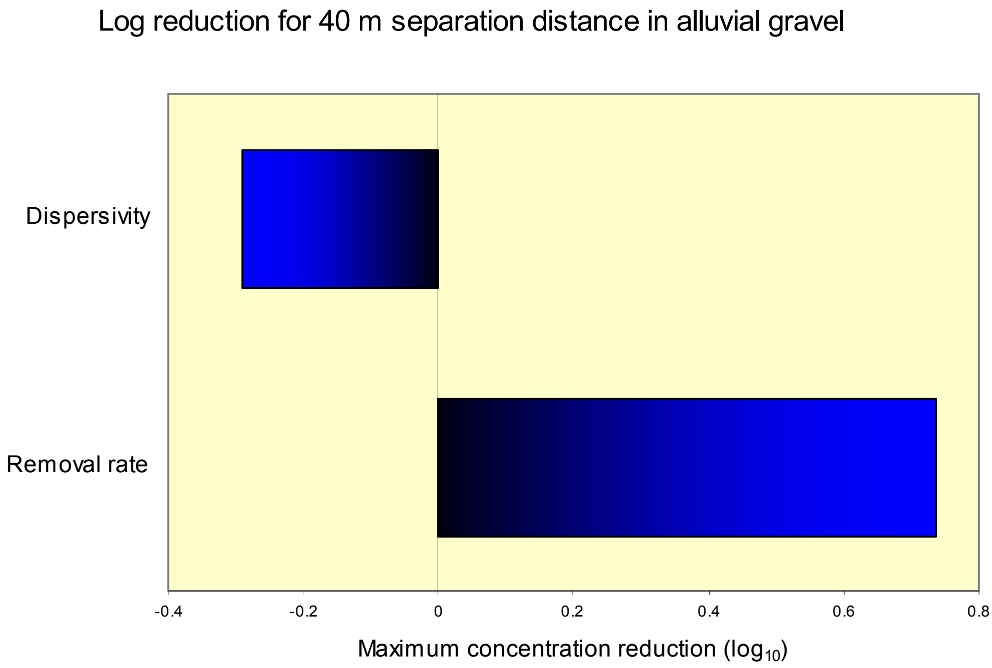


Fig. A7 Tornado graph showing the relative importance of removal rate and dispersion in determining the model output for the saturated zone

A1.4 Viruses used as the basis for the Guidelines

Part 1 discussed the types of viruses that could be of concern in drinking water. Guideline calculations have not been performed for all of these pathogens, as there are typically no data available for pathogenic species to allow them to be specifically modelled. "Generic virus" data were used by selecting the most appropriate data available, whether they were derived from studies of pathogenic species or bacteriophage (viruses that infect bacteria). When the value a parameter should take was uncertain (e.g. as the result of a small dataset), the value chosen was guided by the precautionary principle, i.e. value ranges were selected that were more likely to overestimate separation distances.

Species-specific information for the pathogens was used in determining the $\log_{10}$ reductions required to provide a tolerable probability of infection (Section A2). To make the guidelines more manageable, calculations are presented for only two of the five virus groups considered, rotavirus and hepatitis A virus.

These viruses were selected because they represent two extreme cases, and the data needed for the calculations tended to be most readily available for them. Rotavirus was selected because it has the greatest probability of infection. This is due to two factors: when infected, individuals shed rotavirus at concentrations in their faeces that are, on average, higher than any other virus; and the infectivity of rotavirus (along with norovirus) is the highest of the five virus groups considered.

Hepatitis A virus was selected because the consequences of infection are potentially the most severe, provided children infected by any of the other viruses receive adequate treatment.

The guidelines offer the user flexibility in setting the requirements for their jurisdiction by providing the necessary $\log_{10}$ reduction in concentration required for both viruses. Separation distances based on rotavirus will provide adequate protection for all the viruses noted in Part 1, but this comes with the price of an extended separation distance. A user may decide that a greater likelihood of infection is acceptable to achieve shorter separation distances. Working to the hepatitis A virus reduction requirements will protect against this virus with its more severe consequences of infection. In this circumstance, the probability of infection by rotavirus and some of the other pathogens will be greater than the target tolerable infection probability.

Key points

- Data for pathogenic viruses are scarce. Generic virus data (pathogenic and bacteriophage data, where available) were used in many places in the modelling.
- Probability of infection calculations were undertaken for rotavirus and hepatitis A virus. Rotavirus is shed in high concentrations and is highly infectious. Infection by hepatitis A virus has potentially serious consequences.
- Data specific to rotavirus and hepatitis A virus were available for calculating the likely concentrations of the viruses entering the sewage tank, and the maximum acceptable concentrations in the well water.
- Separation distance calculations based on rotavirus should provide adequate protection against all the pathogenic viruses considered in Part 1.

A1.5 Removal rates

The rate at which viruses are removed from the water can be expressed as a function of time or the distance travelled by the water as shown by Pang (2009). Pang used a number of simplifying assumptions, and knowledge of the average velocity of water, to express time-dependent processes (decay rates) as distance-dependent processes (spatial removal rate). She assumed that the removal of microbes in both saturated and unsaturated zones can be considered a first-order irreversible process, and that microbial transport is at a steady-state and predominantly occurs along one-dimensional preferential flow paths with negligible dispersion.

The spatial removal rates derived by Pang (2009) from previously published results for a range of hydrogeological settings are the basis for the removal rates used in this modelling for both the vadose and saturated zones. The explanation of her derivation of an expression for a spatial removal rate from a temporal removal rate is given below.

In conventional transport models, microbial removal is considered to be a first-order process:

$$\frac{dC}{dt} = -k\,C \qquad (1)$$

where C is the microbial concentration in solution, k is the first-order temporal removal rate, and t is the time.

For a constant velocity $\frac{dx}{dt} = V$ along the flow direction, where x is the distance travelled and V is the average pore-water velocity of microbes, Equation 1 becomes

$$\frac{dC}{dt} = \frac{dC}{dx}\frac{dx}{dt} = \frac{dC}{dx}V = -k\,C \qquad (2)$$

Replacing $\lambda = \frac{k}{V}$ (3)

Equation 2 becomes

$$\frac{dC}{dx} = -\lambda\,C \qquad (4)$$

where λ is the spatial removal rate of microbes. Equation 4 implies that microbial concentration decreases exponentially with travel distance as a first-order process.

Under steady-state conditions, the solution of Equation 4 for a continuous solution input is given by (Matthess et al., 1988)

$$\lambda = -\frac{\ln\left(\frac{C_p}{C_o}\right)}{x} = -2.30\frac{\log_{10}\left(\frac{C_p}{C_o}\right)}{x} \qquad (5)$$

in which C_p is the effluent concentration at the plateau (i.e. peak) of the breakthrough curve, and C_0 is the influent concentration. Therefore, the λ value can be interpreted from the slope of a $\log_{10}$ (C_p/C_0) vs. x plot or concentration reduction measured at a single distance x.

The spatial removal rates reported by Pang account for the range of processes contributing to both spatial and temporal removal rates. These composite spatial removal rates given by Pang are the removal rates used in this modelling. The use of these removal rates avoids the need for separate entry of the decay rate. For this approach to be valid, the infiltration rate used in the model should approximate the infiltration rates used in the field when the empirical values listed by Pang were determined.

Key points

- Time-dependent processes that reduce virus concentrations can be expressed as a function of travel distance.
- The removal rates reported by Pang (2009), which are used in this study, are expressed as spatial removal rates (distance-dependent) and account for removal processes that are both distance- and time- dependent.

A2 Required $\log_{10}$ reduction calculations

A2.1 Introduction

To determine the necessary $\log_{10}$ reduction in virus concentration between the sewage tank and the point of abstraction, the following are needed:

i) an estimate of the virus concentration in wastewater entering the sewage tank

ii) the maximum acceptable concentration of viruses at the point of abstraction.

This section describes these calculations and from them, the $\log_{10}$ reductions required for rotavirus and hepatitis A virus.

A2.2 Input virus concentration calculation

A2.2.1 Introduction

Virus concentrations in the wastewater entering the sewage tank could be determined by any one of three methods. Each of these approaches has shortcomings, which are explained below, together with the rationale for selecting the method used.

i) Direct measurement of virus concentrations in municipal sewage

This approach is unsatisfactory because based on an average household, the viral concentrations in reticulated sewage collected at a wastewater treatment plant will be less than those in the wastewater from a single dwelling with infected occupants. This occurs because in a community situation, the number of infected individuals at any time is a small percentage of the total population (in the absence of an outbreak). Consequently, viruses that do enter the sewerage system are diluted by discharges from dwellings without disinfected individuals and from other non-residential sources of wastewater.

ii) Direct measurement of virus concentrations in on-site wastewater systems

Measurement of virus concentrations in sewage-tank effluent would require sampling at a time when the inhabitants are infected and shedding the virus. To identify an infected household to enable virus sampling would be impracticable.

iii) Calculation of the virus concentration

Expected concentrations of virus from an infected household can be calculated from data in the literature. The uncertainty in some of these values is substantial, but we judged that despite these uncertainties, this approach was preferable to the inherent inaccuracies of method i) or the practical difficulties of method ii).

Four types of data are needed for this calculation:

- the number of people in the dwelling
- the human shedding rate of viruses (the number of viruses per gramme of faeces)

- the weight of faeces daily excreted by humans
- the volume of wastewater daily discharged per person.

Fig. A8 shows the input parameters required to calculate the virus concentration in the wastewater entering the septic tank, and how they are incorporated into the calculation.

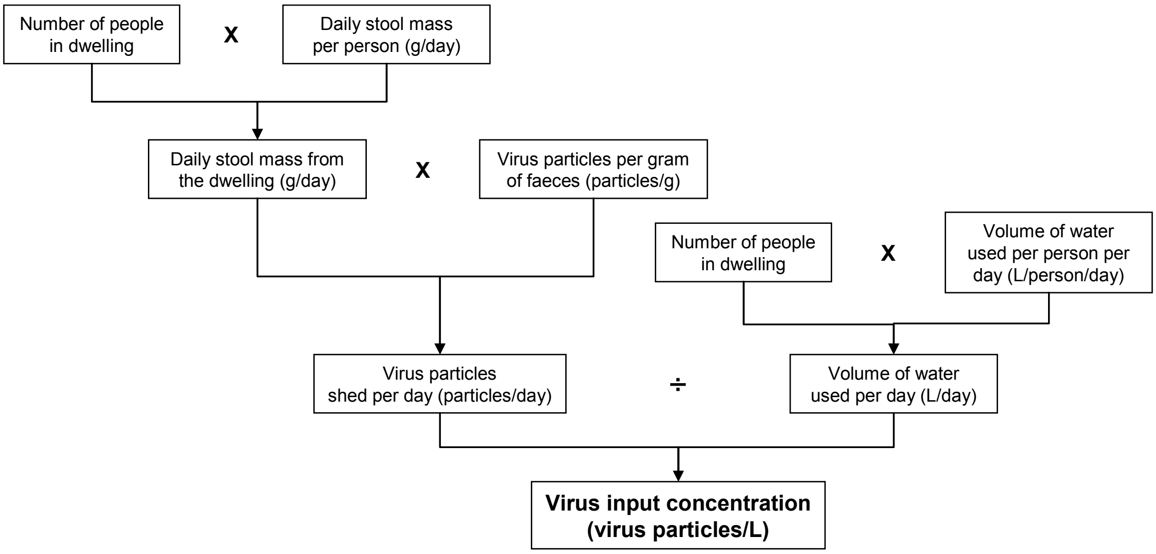


Fig. A8 Algorithm showing the data requirements and their relationship in the calculation of the virus concentration entering a sewage tank from an infected household

A2.2.2 Dwelling occupancy

Dwelling occupancy statistics for New Zealand were obtained from the 2006 census (Statistics New Zealand, 2007). The "Quickstats" document provides information about the number of households with varying numbers of occupants, as set out in Table A1.

Table A1 Dwelling occupancy statistics for the 1996, 2001 and 2006 censuses

Number of usual residents	Numbers of households		
	Year		
	1996	**2001**	**2006**
One Usual Resident	264,360	307,935	328,314
Two Usual Residents	420,027	452,580	494,043
Three Usual Residents	215,670	221,883	240,291
Four Usual Residents	201,951	200,994	221,667
Five Usual Residents	102,408	99,402	102,714
Six Usual Residents	38,889	37,359	39,261
Seven Usual Residents	13,776	13,029	14,766
Eight or More Usual Residents	11,010	11,079	13,122
Total	**1,268,094**	**1,344,267**	**1,454,175**

The 2006 dataset (corrected in July 2007) was used for the modelling.

To develop generic guidelines, a distribution of possible occupancies was used. The form of the input distribution for dwelling occupancy for @Risk® was specified using the *RiskDiscrete* function. By entering the numbers from the census, this function allowed the exact distribution to be used.

Situations may arise in which the number of occupants of the dwelling *is* known. The use of a distribution, rather than the single value, as the model input is still appropriate. Use of a distribution extends the protection of the guideline to cover occupancy changes.

A2.2.3 Daily stool mass per person

Data for this parameter were obtained from the literature. The review was not exhaustive, but did show a very wide range of daily stool masses that varied among individuals, and for the same individual. The dataset used to establish the form of the distribution for this parameter is contained in Appendix 1.

None of the studies provided an indication of the nature of the distribution of stool masses. Although factors, such as dietary fibre intake, might influence results between individuals, variability in colonic functioning within the same individual also contributed to the spread of results (Wyman, 1978).

To develop a generic guideline, the gender, age and dietary habits of the occupants of a dwelling are not required. Therefore, all data contained within Appendix 1 have been included in the calculation of the median value of the means. The mean of the means is almost the same value, indicating that the distribution is not skewed.

The @RISK® input distribution was determined by using the *Fit Distribution* capability of the software. With the lower limit fixed at zero and the upper limit set as "Unsure", the software ranked an inverse Gaussian fit as best by all three statistics used for assessing goodness of fit. The @RISK® input function used for these data was *RiskInvgauss*.

A2.2.4 Shedding rate

The shedding rate is the number of viruses per gramme of faeces. Table A2 summarises the shedding data obtained from a literature search. Appendix 2 provides the data obtained from individual sources for each virus species.

Table A2 Virus shedding data

Virus	Shedding rate (virus particles/g faeces)	Range of shedding of typical shedding periods (days)
Adenovirus	10^{6}–10^{11}	1–14
Enterovirus	10^{3}–10^{10}	30, 49
Hepatitis A	10^{4}–10^{10}	13–30[1]
Norovirus	10^{4}–10^{10}	3–44
Rotavirus	10^{7}–10^{12}	1–39

[1] Up to 6 months has been reported for children (Chin, 2000)

Viral shedding data are scarce, and reported viral concentrations range over 5–7 orders of magnitude, depending on the virus. Rotavirus is shed at the highest concentrations.

As explained in Section A1.4, rotavirus and hepatitis A virus are the viruses for which guidelines have been calculated. The risk assessments undertaken by Schönning et al. (2007) include calculations for rotavirus and hepatitis A virus. In their calculations they assumed that the concentrations vary log-normally about the median concentrations. The values used by Schönning et al. are given in Table A3 and were used as the basis for the calculations for these viruses in the Guidelines.

Table A3 Shedding parameters for rotavirus and hepatitis A virus used by Schönning et al. (2007) for risk modelling of these viruses

Virus	Median concentration	$\log_e$(median concentration)	$\log_e$(standard deviation)
Rotavirus	9.8×10^8	20.7	2.3
Hepatitis A virus	9.9×10^4	11.5	1.2

The @RISK® functions used in the modelling are *EXP(RiskLognorm(20.7, 2.3)* and *EXP(RiskLognorm(11.5, 1.2)*, for rotavirus and hepatitis A virus, respectively.

A2.2.5 Water usage per person per day

This parameter is the estimate of the volume of water used daily by each person in a dwelling that contributes to the flow into a sewage tank. It can be determined from wastewater or water flow information. With the latter, care is needed to avoid counting water uses external to the dwelling that will not contribute to the wastewater flow. Two sources of information on the daily volumes of wastewater discharge/water usage from New Zealand dwellings were used.

The Building Research Association of New Zealand (BRANZ) studied water usage in houses (Heinrich, 2007). Data were collected over summer and winter and the study was restricted to 12 houses in the Kapiti District. A summary of data from the study is contained in Table A4. The distribution is skewed towards higher usage values.

Table A4 Data obtained from the BRANZ study in Kapiti District in 2007

Season	Total Usage			Indoor usage
	Average (L/person/day)	Standard deviation (L/person/day)	Median (L/person/day)	Average (L/person/day)
Winter	168.1	169.6	129.7	147.1
Summer	203.9	233.5	150.5	151.3

The second source of information was Auckland Regional Council's Technical Publication TP58 (ARC, 2004) that presents estimated daily wastewater flows considered to be typical for a standard household. It accounts for different facilities that can influence water usage and the nature of the water source (See Table A5).

Table A5 Wastewater flow data from TP58

Source	Typical wastewater Flow allowance (L/person/day)	
	On-site roof water Tank supply	Reticulated community or well water supply
A. Up-market with extra wastewater producing fixtures – including garbage grinders; dishwashers, modern shower or bath facilities or other comparable fixtures	220	220
B. Households with standard fixtures – including 1 litre flush water cisterns; automatic washing machine and dishwasher.	180-200	200
C. Households with 11/5.5 or 6/3 flush toilets and standard fixtures – low water use dishwasher and NO garbage grinder	160	180
D. Households with 6/3 flush toilets and standard water reduction fixtures – and NO garbage grinder	145	165

The average indoor usage of water in Kapiti in both summer and winter is similar to the 145 L/person/day given by TP58 for a D source using rainwater. This flow figure is the lowest in Table A5 and its use in defining the distribution of values for this input parameter ensures a greater virus concentration in the water entering the tank than any of the other figures in Table A5. A high input virus concentration is consistent with the precautionary approach, and will provide protection for all other situations described in Table A5.

The frequency distribution of wastewater flows is unknown. For the @RISK® calculation a *RiskTriang* function was selected[36]. The most likely value was set at 145 L/person/day. Based on the Kapiti data set, the minimum and maximum values for the input function were selected as 50 and 400 L/person/day.

A2.2.6 Input virus concentrations

The distribution of possible virus concentrations entering a septic tank was determined following the calculation tree in Fig. A8. The 95th percentile virus concentrations calculated through @Risk® for rotavirus and hepatitis A virus are given in Table A6. These values are 95% confidence limits, i.e. the virus concentration in the effluent is expected to exceed these concentrations on 1 in 20 occasions during an outbreak (note that if no outbreak is occurring, viruses are unlikely to be present).

[36] A simple function, such as a triangular function, is best used when the distribution function of an input parameter is unknown.

Table A6 95th percentile concentrations of rotavirus and hepatitis A virus entering a septic tank

Virus	Virus concentration entering the septic tank (95th percentile) (virus particles/L)
Rotavirus	4.4×10^{10}
Hepatitis A virus	7.3×10^{5}

As will be seen in Section A2.4, these concentrations are not used directly to calculate the required $\log_{10}$ reduction. Instead, the full distribution of calculated virus concentrations is combined with other virus reduction components in a Monte Carlo calculation of the $\log_{10}$ reduction.

Key points

- @RISK® software was used to calculate the virus input concentrations, using the algorithm shown in Fig. A8. Input data were obtained from the following sources:
  - dwelling occupancy – 2006 census data
  - daily stool mass – scientific literature. All data gathered were used in the calculation irrespective of gender, age and dietary habits
  - shedding rate – studies from the literature. Rates ranged from 10^3–10^{12} virus particles/g depending on the virus
  - water usage per person – based on estimated values from the Auckland Regional Council technical publication, TP58, and data from a BRANZ study in Kapiti District.

A2.3 Maximum acceptable virus concentration

A2.3.1 Introduction

As noted in Section 7.1.2, the DWSNZ 2005 (Revised 2008) does not contain MAVs for viruses that could provide a basis for the separation distance calculations. Instead, the maximum acceptable virus concentration had to be calculated.

To calculate the maximum acceptable virus concentration in the groundwater at the point of abstraction, three pieces of information are required:

- the tolerable probability of infection
- the dose-response function for the virus being considered
- the volume of water ingested daily by an individual.

Each of these factors is discussed in this section. Fig. A9 shows how they are brought together to calculate the maximum acceptable virus concentration in the well.

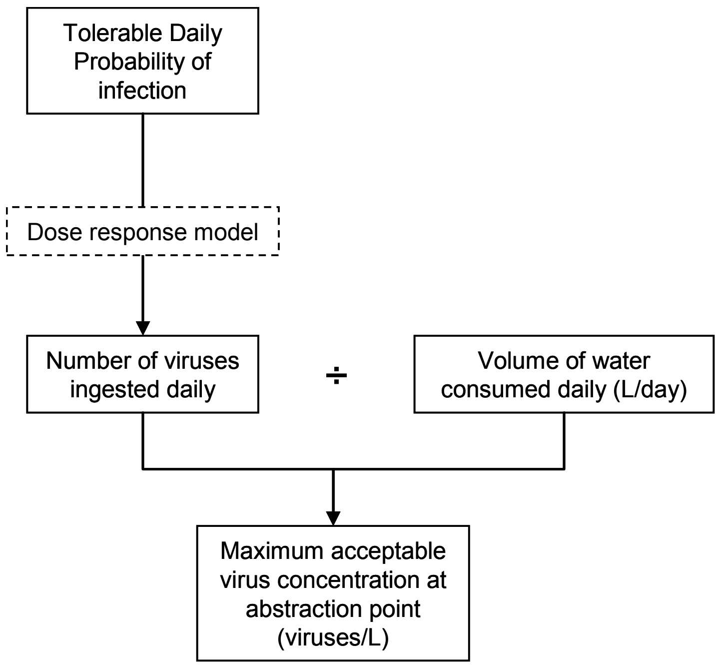


Fig. A9 Algorithm for calculating the tolerable virus concentration in water in a well

A2.3.2 Tolerable probability of infection

In 1989, the USEPA (USEPA, 1989) set requirements for the removal of *Giardia* by water treatment plants to meet a tolerable probability of infection of 1 in 10^4 per year, i.e., no more than one person in a population of 10,000 becoming infected from waterborne pathogens per year. This target was based on an analysis of waterborne disease outbreak data gathered to that time. The data showed that in each reported outbreak of giardiasis, at least 0.5% (i.e. 50 in 10,000 people) were infected. The EPA stated:

> *"EPA believes that public water supplies should provide much greater protection than simply that necessary to avoid this level of risk from waterborne disease. EPA believes that providing treatment to ensure less than one case of microbiologically caused illness per year per 10,000 people is a reasonable goal."*

Note that this statement refers to *illness*, but it is the probability of *infection* that the EPA finally used to determine the treatment requirements. The distinction is important because not everyone infected becomes ill. As a result, a target based on infection probability is more protective than one based on the probability of illness.

Haas (1996) noted that the EPA's estimation of acceptable risk was based on infection, rather than illness, as the endpoint because it compensated for:

- some cases not being reported (underreporting);
- certain segments of the population being more susceptible than others.

Haas has argued that the tolerable risk of infection of 1 x 10^{-4}/person/year needs to be reconsidered, and that even a risk of infection of 1 x 10^{-3}/person/year may be unnecessarily low. This is because the total burden of waterborne illness associated with water supplies in the USA in 1989 was probably underestimated in the initial assessment. It was more likely to have been as high as several million cases per year, translating into an annual illness rate of 1 x 10^{-2}.

Despite the concern that the tolerable infection probability of 1 in 10^4 is too conservative, this probability limit has been widely adopted as the yard stick when evaluating tolerable pathogen loadings in drinking water. For example, it is the limit for infection probability stated in Dutch legislation (Schijven et al., 2006). Although originally derived from giardiasis statistics, this probability is used for pathogen infection in general.

New Zealand's Ministry of Health, although considering the inclusion of viruses in the next edition of the DWSNZ, has not yet made a decision on the tolerable probability of infection on which virus requirements might be based. At the time of preparing the Guidelines there is no reason to believe that the Ministry will select a different tolerable probability.

For these reasons, this probability of infection has been used as the *tolerable probability of infection* in the development of the Guidelines.

Although the primary calculations in the Guidelines are based around the tolerable probability of infection of 1 x 10^{-4}/person/year, two other auxiliary calculations have been undertaken. These use probabilities of infection of 1 x 10^{-3} and a 1 x 10^{-5} /person/year. The purpose of these additional calculations is to enable users to recalculate separation distances (or treatment requirements) if the user wishes to employ a different tolerable probability of infection. This could occur if later editions of the DWSNZ do not use the 1 x 10^{-4} infection probability anticipated.

A2.3.3 Dose-response functions

Dose-response functions in the context of the Guidelines, are the mathematical relationship between the dose of pathogen ingested (usually expressed as the number of organisms) and the consequent probability of the person who ingested the organisms becoming infected.

There are two common mathematical forms of dose-response functions. The exponential model takes the form:

$$P_d = 1 - e^{-\left(\frac{1}{k}\right)N} \qquad (6)$$

where P_d is the probability of infection per day, N is the number of virus particles ingested daily, and $1/k$ is the probability of one organism initiating an infection.

The second form, the simplified beta-Poisson model[37], can be expressed in two ways:

$$P_d = 1 - \left[1 + \frac{N}{N_{50}}\left(2^{\frac{1}{\alpha}} - 1\right)\right]^{-\alpha} \qquad (7)$$

where N_{50} is the median infective dose, and α is a shape parameter for the beta distribution. The alternative form is

[37] A rigorous derivation of this model gives: $P_d = 1 - {}_1F_1(\alpha, \alpha + \beta, -N)$, where ${}_1F_1$ is Kummer confluent hypergeometric function. The approximation becomes poorer at large N (Haas, et al., 1999).

$$P_d = 1 - \left[1 + \left(\frac{N}{\beta}\right)\right]^{-\alpha} \qquad (8)$$

where β is a second shape parameter that characterises the dose-response curve.

Parameter values that define the dose-response functions for the viruses are given in Appendix 3. Schönning et al. (2007) used beta-Poisson models to model both rotavirus and hepatitis A virus. There are few hepatitis A virus fitting parameters available against which to compare the values used by Schönning and co-workers, but their parameter values are similar to the values used in other studies (see Appendix 3). The parameter values given by Schönning et al. (2007) for both rotavirus and hepatitis A virus were used for these calculations (Table A7).

Table A7 Dose-response parameter values used for calculating the maximum acceptable virus concentration

Virus	$\log_e(N_{50})$	$\log_e$(Standard deviation of N_{50})	α
Rotavirus	1.7	1.2	0.265
Hepatitis A virus	3.4	1.2	0.2

Data are provided in Appendix 3 for all viruses to allow recalculation of the maximum acceptable virus concentration for a different virus from those suggested here, if needed.

A2.3.4 Volume of water ingested daily

Water consumption data from New Zealand surveys have been collected by Andrew Ball, ESR, to allow a distribution to be derived for use with quantitative microbial risk assessment of New Zealand drinking water.

Ball collected data from the following surveys:

1. 1977 survey by Birkbeck (1979) (National Heart Foundation of New Zealand Diet Survey) which included 1,960 participants (raw data are unavailable but the distribution is reported to have been normal).
2. 1983 survey by Gillies and Paulin (1983) of 109 South Island adults.
3. 1997 National Nutrition Survey (NNS) by Russell at al (1999) in which 4,636 adults (aged 15 years and above) participated. It collected data on volumes of unboiled water consumed from a 24-hour recall interview.
4. 2002 National Children's Nutrition Survey (NCNS) by Parnell et al. (2003) which is similar to than by Russell et al. (1999) except that the participants were children of 5–14 years. There were 3,275 participants.

Data from the 1977 and 1983 surveys were not included in analysis of the data for this work because the 1977 survey was old and possibly no longer representative of the volumes of water consumed, and the 1983 survey had only a small number of participants.

Table A8 Summary statistics for the NNS and NCNS

Age Group	5–14 years	≥ 15 years
Median	420 mL/day	600 mL/day
Geometric mean	522 mL/day	827 mL/day
95th percentile	1,189 mL/day	2,100 mL/day

Using a "bootstrapping" technique[38], Ball resampled the datasets of the 1997 and 2002 surveys to obtain a distribution for the water consumption by all ages for a typical New Zealander. Each of the NNS and NCNS datasets was re-sampled in proportion to the number of adults and children in the New Zealand population (as determined by the 2006 Census). Sixty-five thousand re-sampling iterations were run for the model.

Using the distribution assessment functions within @RISK® Ball decided that lognormal fits were suitable for both the NNS and NCNS data sets. A lognormal fit was also found most suitable for the age-combined dataset, and was defined by:

RiskLognorm (α =796.31, β = 868.47)

This is the input distribution function used for this work.

A2.3.5 Calculation of the maximum acceptable virus concentration

The maximum acceptable virus concentration is the concentration expected to result in the tolerable annual infection probability. This requires assumptions about the volume of water consumed daily and the number of days over which the water is consumed.

Daily infection probabilities were obtained from the dose-response function given by using the parameter values in Table A7. The tolerable probability of infection of 1 x 10^{-4} is an *annual* probability. The annual infection probability can be calculated from the daily probability by

$$P_{ann} = 1 - (1 - P_d)^{365} \tag{9}$$

where P_{ann} is the annual probability of infection (Haas et al., 1999). This equation assumes that exposure to the pathogen is the same throughout the year. However, in the case of infection in the residents of a single dwelling, the shedding of viruses occurs for only a fraction of the year. For this work, the pathogen is assumed to be shed for a period of 50 days. Reported shedding periods are variable even for the same organism (Table A2). The 50-day period covers the periods reported for rotavirus and for the great majority of hepatitis A virus cases. For the 50-day calculation period, Equation 9 is modified by replacing the 365 index with 50, i.e.,

$$P_{ann} = 1 - (1 - P_d)^{50} \tag{10}$$

Although the calculation is for 50 days only, the resulting probability is expressed as an annual figure.

For rotavirus and hepatitis A virus, Equation 7 or 8 in conjunction with Equation 10 can be used to calculate the annual infection probability given a specified dose of the

[38] Bootstrapping is a method for developing a sample distribution from a set of data by resampling the data and recomputing the statistics of the resampled data (Hass et al., 1999).

pathogen. For this work, the reverse calculation is required – the maximum acceptable virus dose must be calculated from a required infection probability. Rearrangement of Equations 10 and 7 to Equations 11 and 12, respectively, allowed the calculation

$$P_d = 1 - \left[\sqrt[1/50]{(1 - P_{ann})} \right] \tag{11}$$

$$N = \frac{\left[\sqrt[-1/\alpha]{(1 - P_d)} - 1 \right] N_{50}}{(2^{1/\alpha} - 1)} \tag{12}$$

In the @RISK® modelling, the shape parameter, α, is given a single value (i.e. no distribution), but the lognormal distributions given by Schönning et al. (2007) were used for the median infective dose, N_{50}, for both viruses rotavirus, *RiskLognorm*(1.7,1.2) and hepatitis A virus *RiskLognorm*(3.4, 12.).

The dose, N, is expressed as the number of virus particles ingested. This is converted to a concentration by dividing by the volume of water ingested daily (see the input distribution function in Section A2.3.4).

Maximum acceptable concentrations for both viruses (at the 95th percentile), determined from the Monte Carlo calculations, are given in Table A9.

Table A9 Maximum acceptable concentrations of rotavirus and hepatitis A virus (95% confidence level)

Virus	Concentration giving rise to a probability of infection of 1 x 10^{-4} /person/year (virus particles/L)
Rotavirus	7.9 x 10^{-7}
Hepatitis A Virus	2.0 x 10^{-6}

A2.4 Log_{10} reduction requirements

An *estimate* of the required $\log_{10}$ reduction in virus concentration could be obtained from the data in Table A8 and Table A9. However, to properly account for the uncertainties in the datasets, a full Monte Carlo calculation is required. These calculations for annual infection probabilities of 1 x 10^{-3}, 1 x 10^{-4} and 1 x 10^{-5} are given in Table A10.

Table A10 Log$_{10}$ reductions in rotavirus and hepatitis A virus required to achieve annual probabilities of infection of 1 x 10^{-3}, 1 x 10^{-4} and 1 x 10^{-5}

	Log$_{10}$ reduction requirements		
	Annual Probability of infection		
Virus	**1 x 10^{-3}**	**1 x 10^{-4}**	**1 x 10^{-5}**
Rotavirus	15.2	16.2	17.2
Hepatitis A virus	10.1	11.1	12.1

Key points

- @RISK® calculated the maximum acceptable virus concentration, following the algorithm shown in Fig. A9. The input data used were:
  - o the USEPA tolerable annual probability of infection of 1 x 10^{-4} (1 in 10,000)
  - o dose-response functions for rotavirus and hepatitis A virus from the literature
  - o a probability distribution function for the daily volume of unboiled water ingested derived from two New Zealand studies, a National Nutrition Survey (1997) and a National Children's Nutrition Survey (2002)
  - o a shedding period of 50 days, based on clinical references.
- Log$_{10}$ reductions in virus concentration between the sewage tank and the well were calculated from the input virus concentration and the maximum acceptable virus concentration in the well. Although the primary focus is on a tolerable annual probability of infection of 1 x 10^{-4}, log$_{10}$ reduction calculations were also undertaken for probabilities of 1 x 10^{-3} and 1 x 10^{-5}.

A3 Virus reduction in the sewage tank and disposal field

A3.1 Introduction

The first part of the system where virus concentrations may be reduced is in the sewage tank. Three types of septic system have been identified by the Ministry for the Environment in their draft of the *National Environmental Standard for On-site Disposal Systems* (MfE, 2008).

Primary systems

These systems involve separating bulk solids, grease and grit from the main liquid stream. Septic tanks are a well-known traditional example of on-site primary systems. Typical primary systems are either one- or two- chamber septic tanks.

Secondary systems

These systems involve biological processes to biodegrade the organic contaminants in the wastewater. Secondary treatment processes can include wastewater aeration, such as aerated wastewater treatment systems (AWTS), treatment and filtering media, disinfection and other technologies. These systems are typically designed, operated and maintained by specialist companies. The disposal field often includes dripper lines and evapo-transpiration beds. Advanced systems are generally used in more 'difficult' sites, such as in poorly drained soils, those in close proximity to surface waters, or where there is limited room for the disposal field.

Tertiary systems

The treatment process following secondary treatment can involve the use of sand filters to further improve the removal of organic matter (fine solids) from biological secondary treatment, and the use of disinfection units to remove human intestinal bacteria before treated effluent discharge. Disinfection can be achieved for on-site treatment units via tablet chlorination or ultraviolet light units.

Data on which to base an estimation of virus removal for these systems are scarce. Some guidance is provided in the following sections on the $\log_{10}$ reduction that can be incorporated into the virus reduction calculations. There is a growing trend for local authorities to require the installation of the more sophisticated treatment systems. Field measurements of the effectiveness of these systems in removing viruses are needed for a more accurate estimation of their performance in New Zealand. Such measurements are beyond the scope of this work.

A3.2 Virus reduction in primary systems

Studies of virus removal within septic tanks are few. The primary mechanism by which viruses are removed from water in septic tanks is considered to be sedimentation. This is the result of association of viruses with particulates within the wastewater. Further guidance concerning the extent of virus removal in septic tanks can therefore be gained from the findings of studies of sedimentation processes in wastewater treatment plants.

Rao et al. (1981) studied the effect of primary sedimentation in sewage treatment over several seasons. In the full-scale plant studied, the average removal of viruses was 63% (range: 41–83%) over autumn, winter and summer. During the monsoon months of June and July, the removal efficacy dropped to 29%.

Morris (1984) studied the removal of enteroviruses in two wastewater treatment facilities and determined that sedimentation had no significant effect on virus concentrations.

Payment et al. (1986) found a mean reduction of 75% in virus concentrations following settling at a wastewater treatment plant. This finding was based on measurement of poliovirus, echovirus, coxsackievirus B and reovirus.

Higgins et al. (2000) report a study[39] of MS2 coliphage in standard septic tank systems. They determined a 74% reduction in the concentration of MS2 phage between the input and exit of the tank (i.e. prior to the disposal field).

The Australian Cooperative Research Centre for Water Quality and Treatment has published key results of its research programmes as fact sheets (CRC, 2004). One of these covers the movement of pathogens in catchments and groundwaters. This document states that septic tanks reduce virus concentrations by 75% (0.6 $\log_{10}$ reduction).

Further confirmation that sedimentation achieves relatively low reductions in virus concentrations is provided by influent and effluent measurements at wastewater treatment facilities that show low overall $\log_{10}$ reductions, as noted in the two following studies.

Lodder and de Roda Husman (2005) studied noroviruses and other enteric viruses at a wastewater treatment plant in the Netherlands. The calculated $\log_{10}$ removal values between raw and treated water are tabulated in Table A11. The treatment train consisted of: primary settling, activated sludge treatment and phosphorus removal, hence the reduction values given in Table A11 include removal by processes other than sedimentation. They provide an upper-limit of extent of virus reduction in a full scale treatment plant.

Using molecular techniques Morsy El-Senousy et al. (2007) looked at genogroups A and B of human astrovirus in wastewater treatment operations in Egypt. Their methods determined reductions in levels of RNA and infectivity. For both genogroups A and B, sedimentation reduced infectivity by 1 $\log_{10}$. Levels of RNA of genogroup A were reduced by 2.7 $\log_{10}$, and of genogroup B by 0.9 $\log_{10}$. The authors considered that the best estimate of astrovirus removal was provided by the RNA measurements.

Taken together, these studies indicate that sedimentation alone achieves limited virus removal. A reduction in virus concentration of *ca.* 1 $\log_{10}$, or less, appears typical. The value suggested for use in these calculations is 0.6 $\log_{10}$, as it is representative of the values typically reported for septic tanks or the sedimentation process alone.

[39] Papers in this publication did not undergo peer-review.

Table A11 Log$_{10}$ reduction in virus concentration between raw and treated water at a wastewater treatment plant in the Netherlands (Lodder and de Roda-Husman, 2005)

Sampling occasion	Somatic phage	F-Specific phage	Enterovirus	Reovirus	Norovirus	Rotavirus
1	1.0	1.6	0.7	1.4	0.9	0.9
2	1.4	2.0	1.6	1.4	1.9	-0.1
3	0.8	1.3	1.5	0.9	2.1	1.1
4	1.4	1.8	1.5	1.3	1.0	0.03
5	1.4	1.8	1.8	1.1	0.2	-1.8
Mean	**1.1**	**1.6**	**1.4**	**1.3**	**1.8**	**0.2**

A3.3 Virus reduction in secondary systems

The only reference found that provides a figure for virus removal by AWTS is the CRC fact sheet (CRC, 2004). The fact sheet indicates a 90% reduction (1 log$_{10}$) in viruses by AWTS in the absence of any additional disinfection.

A3.4 Virus reduction by disinfection

The CRC factsheet (CRC, 2004) indicates that a further 90–98% (1.0-1.7 log$_{10}$) reduction in virus concentration can be achieved by disinfection using chlorine or UV irradiation following the AWTS. The reduction resulting from these processes is likely to be species-dependent, but at this time such distinctions cannot be made.

A3.5 Virus reduction in the disposal field

A3.5.1 Introduction

Four disposal systems are considered in the guidelines to demonstrate the varying degrees to which the design of the disposal field can contribute to reducing virus concentrations:

- Boulder pit
- Conventional trench
- Shallow dripper system
- Mound disposal system.

TP58 (ARC, 2004) is widely used as the basis for regulations concerning on-site waste disposal systems. Therefore, it was used here as the basis for calculating the reduction in virus concentrations achieved by the last three systems in the above list.

In situations in which the disposal field design does not fit into any of these categories, the removal achieved should be assumed to be equal to that calculated for a conventional trench.

A3.5.2 Boulder pit

Boulder pits were assumed to extend through the top soil. As a result, as a disposal field they make no contribution to a reduction in virus concentration. Moreover, they eliminate any contribution to removal that might be made by the soil.

A3.5.3 Conventional trench

Two possible aggregates for backfilling the trench are considered. The $\log_{10}$ reduction/m assumed for each medium is listed in Table A12. These are estimated values for saturated media (pers. comm., L Pang, ESR) which is a reasonable approximation for an operational on-site disposal system.

Table A12 $\mathbf{Log_{10}}$ reduction values for trench aggregates

Medium	$\mathbf{Log_{10}/m}$
Sand	0.49
Pea gravel	0.36

Fig. A10 provides a cross-sectional view of a conventional trench. The aggregate for a trench is specified as 20–40mm in TP58 (although builders "premix" (12 mm) is often used – *pers. comm*. M Leonard, ESR). The virus reduction achieved by this material is assumed to be equal to the pea gravel in Table A12. Virus reduction in the soil is discussed in Section A4. The contribution of the disposal system to virus reduction is determined by multiplying the depth of aggregate the effluent has to pass through, i.e., d_2-d_3 (expressed in metres), by the $\log_{10}$/m value for the appropriate medium from Table A12.

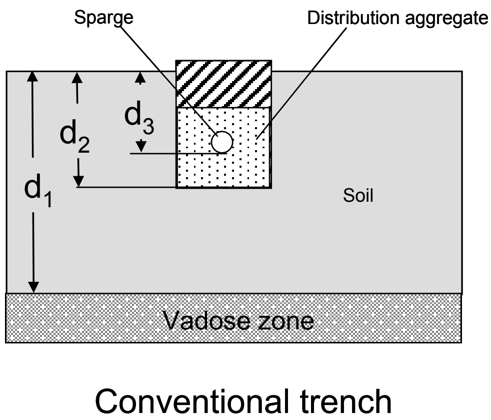


Fig. A10 Cross section of a conventional trench showing depths required for the calculations

A3.5.4 Shallow dripper system

Fig. A11 gives a cross-sectional view of a dripper disposal system.

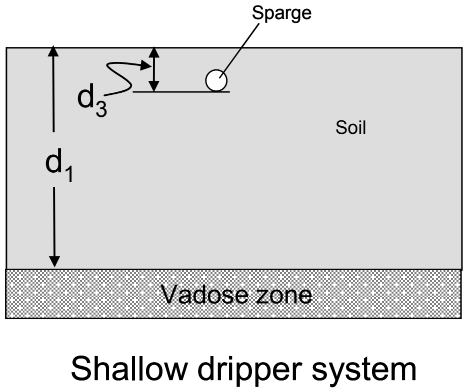


Fig. A11 Cross section of a dripper disposal system showing depths required for the calculations

The specifications for pressure compensating shallow dripper systems from TP58 were used. TP58 states that d_3 should be 0.05–0.2 m[40]. Because the sparge lines of the dripper system are buried in the soil, the only removal that has to be calculated in these systems is that occurring in the passage of the effluent through the distance d_1-d_3 in the soil. This is described in Section A4.

A3.5.5 Mound disposal system

Fig. A12 gives a cross-sectional view of a mound disposal system.

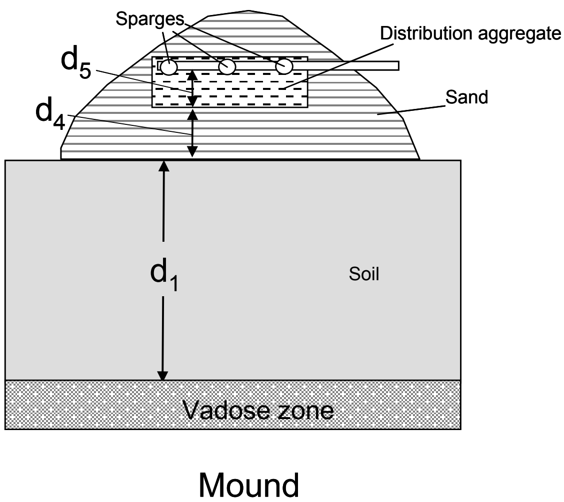


Fig. A12 Cross section of a mound disposal system showing depths required for the calculations

There are two zones of removal in the mound system prior to any removal achieved by passage through the soil. The first is passage through distribution aggregate, which

[40] The widely used "Oasis" aerated systems use a 0.1m burial depth for their dripper lines.

is specified in TP58 to be 20–60 mm gravel. The removal is calculated by multiplying d_5 by the log_{10}/m value for pea gravel from Table A12.

Passage through the gravel is followed by passage through the mound of sand. The removal is calculated by multiplying d_4 by the log_{10}/m value for sand from Table A12.

Removal during passage through the soil is covered in Section A4.

A3.6 Summary

The overall reduction in viruses by components of the system before the effluent passes through the soil, is achieved in the sewage tank and any gravel or sand in which the disposal lines are set.

The recommended virus log_{10} reduction values to use in the virus reduction calculations until such times as field data from New Zealand become available are given in Table A13.

Table A13 Summary of recommended log_{10} removal values in the on-site treatment system (i.e. prior for the disposal field)

	Septic Tank (Primary system)	AWTS (Secondary system) without disinfection	Disinfection by UV or chlorine (following AWTS)[1]
Reduction in virus concentration (Log_{10})	0.6	1.0	1.0

[1] This log_{10} reduction value is additional to log_{10} reductions achieved by other parts of the process. Although the CRC fact sheet indicated a range of 1.0-1.7 log_{10} reduction, the Guidelines cannot give guidance on the conditions likely to lead to the higher removals, therefore only the conservative figure of 1.0 is retained.

Removal by the aggregate material in which the disposal lines are set depends on the depths of material used.

Points to note.

a) Too few data are available to provide values for each virus species. The values in Table A12 and Table A13 are consequently generic.

b) Viruses can be retained on the gravel or sand used in the construction of the disposal system. Rain events or prolonged peak flows from disposal systems, may boost virus concentrations in the water by releasing these retained entities. The separation distance calculations take no account of increases in virus concentrations due to such effects. However, because of the precautionary approach taken in selecting values for input parameters for the modelling, such events are unlikely to lead to unsafe virus concentrations reaching the point of abstraction if the separation distance is based on the calculations in the Guidelines.

c) In some situations, virus concentrations increase as clumps of organic matter (containing viruses) that have settled in the tank are broken up. The comment on the precautionary approach in b) also applies in this instance.

Key points

- Very little information is available about the level of virus reduction within sewage tanks.
- Conservative values for reduction in primary systems (septic tanks) and secondary systems (AWTS) were obtained from an Australian Cooperative Research Centre for Water Quality and Treatment publication. Log_{10} reduction values were taken as 0.6 and 1.0, for primary and secondary systems, respectively.
- The reduction achieved by either chlorine, or UV irradiation, was conservatively taken to be 1 log_{10}.
- Three types of disposal field are considered: conventional trench, shallow dripper and mound.
- Virus reduction in the disposal field is determined from the log_{10}/m reduction achievable in the distribution aggregate (pea gravel or sand – see Fig. A10 and Fig. A12), multiplied by the depth of the aggregate. The log_{10}/m reductions in pea gravel and sand are taken to be 0.36 and 0.49, respectively.
- Spikes in virus numbers entering the ground can arise through:
  - viruses retained on gravel or sand washing off during rain or prolonged peak flows
  - clumps of organic matter breaking free of the settled mass in the sewage tank.
- The modelling cannot account for spikes in virus concentrations. However, the conservative assumptions made in the modelling will help in ensuring that calculated separation distances provide adequate protection for well-water quality.

A4 Soil virus removal calculations

A4.1 Introduction

The extent to which soil horizons can reduce the microbial loading of wastewater percolating through them depends on such factors as their composition, structure and depth. For the calculations for the Guidelines, the reduction in virus concentrations occurring in the soil is considered separately from reduction occurring in the vadose zone (Section A5).

A4.2 Virus removal in soils

Pang et al. (2008) determined values of virus removal for nine New Zealand soils using *Salmonella* bacteriophage. As data for the removal of pathogenic viruses in New Zealand soils are unavailable, the bacteriophage data were used as the basis for the development of the Guidelines.

The nine soils studied by Pang and co-workers do not give full geographical coverage of New Zealand. To extend the coverage for the Guidelines, work by McLeod et al. (2008) was also used. McLeod et al. (2008) ranked the soils into classes of “high”, “medium” and “low” with respect to the potential for microbial by-pass flow (BPF), based on the removal of faecal coliforms and *Salmonella* bacteriophage in a range of soils occurring commonly in dairy farming regions of New Zealand. The BPF ranking is an indicator of the extent to which microbial contaminants are likely to be carried in flow that does not pass through the soil matrix – the greater the BPF the poorer the soil’s ability to remove microbes.

From the characteristics of the soil parent materials and the soil morphology of the selected soils, McLeod and co-workers extrapolated the BPF rankings from the soils studied to other soils throughout New Zealand. From this extrapolation, the virus removal data from Pang et al. (2008), and the assumption that the BPF rating can be used as an indicator of virus removal, it is possible to assign an estimate for the reduction in virus concentration per metre for soils of different BPF ratings.

The soils studied by Pang et al. (2008), their New Zealand Soil Classification (NZSC) order, the average (of three values) $\log_{10}$ removal value, and the microbial BPF rating given by McLeod et al. (2008), are provided in Table A14.

From Table A15 the BPF ratings are associated with the following ranges of $\log_{10}$ reduction in virus concentration per metre:

High BPF	1.0–1.8
Medium BPF	2.0–2.3
Low BPF	2.5–20.

Table A15 is based on the extrapolation to a wide range of New Zealand soils by McLeod et al. (2008). It takes the NZSC description and BPF ratings given by McLeod’s group and assigns to each a virus removal value. These removal estimates are the lower bound of each of the removal ranges listed above, giving a conservative estimate of virus removal, except for the two soil types that show greatly increased removal.

Table A14 Virus reduction data from Pang et al. (2008) and microbial by-pass flow ratings for these soils from McLeod et al. (2008)

Soil identification	NZSC[1] order	Microbial bypass flow rating	Average $\log_{10}$ removal/m
Netherton Clayey soil	Gley	High	1.0
Hamilton Clay	Granular	High	1.8
Lismore shallow silt loam over gravels	Brown	Medium	2.0
Templeton silt loam	Pallic	Medium	2.0
Waikiwi silt loam	Brown	Medium	2.3
Waikoikoi silt loam	Pallic	Medium	2.3
Waitarere sandy recent soil	Recent	Low	2.5
Manawatu fine sandy loam	Recent	Low	3.0
Atiamuri pumice soil	Pumice	Low	16.6
Waihou silty allophanic soil[2]	Allophanic	Low	-

[1] NZSC: New Zealand soil classification ; [2] Complete removal, no $\log_{10}$ removal rate given

Where a separation guideline is being determined for a situation in which the soil is listed in Table A14, the virus reduction value listed in that table should be used. When direct measurements of a soil are unavailable, the conservative removal rates in Table A15 should be used. When the type of soil is unknown, a default reduction of 1 $\log_{10}$/m should be applied in the calculation.

Table A15 Microbial bypass flow rating assignments based on McLeod et al. (2008)

NZSC Feature	Microbial bypass flow Rating	Virus removal $\log_{10}$/m
Organic soils	High	1.0
Ultic soils	High	1.0
Granular soils	High	1.0
Melanic soils	High	1.0
Podzol soils	High	1.0
Gley soils	High	1.0
Brown soils	Medium	2.0
Pallic soils	Medium	2.0
Oxidic soils	Medium	2.0
Raw & Recent soils	Low	2.5
Semi-arid soils	Low	2.5
Pumice soils	Low	16
Allophanic soils	Low	20[1]

[1] This is an arbitrary conservative estimate to allow calculations.

A4.3 Calculation of virus removal

Monte Carlo modelling is not used in calculating the contribution of soils to the removal of viruses. The $\log_{10}$ reduction in the virus concentration in the effluent as it percolates through the soil is calculated by multiplying the $\log_{10}$ reduction/m obtained from Table A14 or Table A15 by the depth of soil through which the effluent passes.

Identifying the boundary between soil[41] and the vadose zone[42] is not straightforward. Pang et al. (2008) have assumed that all soils have a 1 m depth. When the soil depth is known, the known value should be used in the calculation. However, where the soil depth is unknown or uncertain, the default assumption of a 1 m depth should be used.

This assumption will overestimate the soil depth in some New Zealand locations, thereby overestimating the degree of virus removal. Because the $\log_{10}$ reduction/m for most soil types is between 1 and 3, the assumption of a 1 m depth will not greatly overestimate the removal, and the conservative nature of other estimates made in the modelling will compensate to some degree for it.

Whether the soil depth is known or the default 1 m depth is used, this is not necessarily the depth of soil through which the effluent passes. The nature of the disposal system affects this. Only with the mound disposal system does the soil depth equate to the depth of soil available for reducing virus concentrations. The outlets for the conventional trench and dripper systems are both below ground level so the available soil depth will be less than the actual soil depth. In both instances, if the disposal depth is greater than the soil depth, as with boulder pits, the removal achieved by the soil must be set to zero.

Key points

- Very few data for the removal of viruses in New Zealand soils are available.
- The $\log_{10}$/m reductions for New Zealand soils used in the modelling were obtained from two New Zealand studies (Pang et al., (2008); McLeod et al., 2008)). These papers measured removal of bacteriophage.
- Using the data from these studies, it was possible to assign to a range of soils (described using the New Zealand Soil Classification) a $\log_{10}$/m reduction value. The soils were assigned to one of three generic groups according to their estimated ability to remove viruses. The groups were based on the microbial bypass flow rating assigned to each soil order by McLeod et al.
- The $\log_{10}$ reduction achieved in the soil at a site is determined by multiplying the soil thickness by the assigned generic $\log_{10}$/m for the soil.

[41] The unconsolidated minerals and organic materials on the immediate surface of the earth.
[42] The unsaturated zone between the soil and water table.

A5 Vadose zone modelling

A5.1 Introduction and modelling approach

The modelling of one-dimensional solute transport through the vadose zone for this work was based on the model described by Bidwell (2000). Two advective-dispersive mixing cell models were run in parallel for these calculations: the first described matrix flow, and the second flow through macropores.

Bidwell's model was run in conjunction with @RISK® (providing Monte Carlo calculation capability) to allow some input parameters to take a range of values. Value ranges were required when there was natural variability in the parameter that could result from differences in the characteristics of vadose zone material, or when there was uncertainty over the value the parameter should take because of a scarcity of experimental data on which to base an estimate. From the Monte Carlo calculations a distribution of possible $\log_{10}$ reductions predicted to be achieved within the vadose zone was obtained.

For each observation depth the model was run for 5,000 iterations. Trials showed there was no significant change in the results by increasing the number of iterations to 10,000.

The input parameters required for the model, the values, or value distributions, assigned to the parameters, and the model outputs are discussed in this section. A summary of all parameter values used in the modelling is given in Table A16. Each parameter is discussed in the following subsections.

A5.2 Infiltration rate

The infiltration rate used for the modelling was based on the maximum rates that the TP58 (ARC, 2004) recommends for a conventional trench system and the nature of the vadose zone material. Maximum loading rates recommended in TP58 were used to provide a conservative estimate of virus removal in the vadose zone. In general, when it was unclear from TP58 which infiltration rate should be used for a particular vadose zone material, a value of 0.020 m/day was used on the assumption that a lower infiltration rate would be more suitable for the less porous materials. The values used are tabulated in Table A16.

A5.3 Flow split between the matrix and macropores

The model requires an estimate of the percentage split between matrix and macropore flow. Estimations based on field observations indicate that the fraction of the flow passing through macropores ranges from 25–50% in gravel (Dann et al., 2010). In alluvial sand, the development of macropores is much reduced and the percentage of flow through them is estimated to be between 1–10%.

No experimental data are available to provide guidance on the split for the other hydrogeological settings. Macropore flow was not considered to make any contribution to the flow through pumice sand, coastal (fine) sand, sandstone/non-karstic limestone, and peat. Macropore flow is the predominant contributor to flow in fractured rock and cracked clay systems, and a small contribution was assumed for silts and ash.

As there are no data available to indicate whether any value within the estimated ranges is more likely than any other, the @Risk® *Uniform* input distribution, bounded by the values given in Table A16 was selected for modelling this parameter for all hydrogeological settings.

The influence of macropores on groundwater flow is expected to decrease with depth for some settings. Field measurements down to 7 m in gravel support the estimate of 25–50% of the flow passing through macropores to this depth. Below this, the contribution will decrease, although the rate of decrease with depth is unknown. No data are available to assess the depth to which the 1–10% range is valid for alluvial sand. For this modelling, the contribution of macropores to flow in gravel and alluvial sand is linearly dropped to zero over the depth interval of 7–12 m.

The contribution from macropore flow in fractured rock systems was assumed to be independent of depth. No data were available on which to base a depth-dependence for the macropore flow contribution in cracked clay, silt and ash. For the modelling they were assumed to undergo a 5% loss in their macropore flow contribution with each metre of depth (pers. comm. R Dann, ESR).

A5.4 Transport porosity or water content of the medium during flow (Θ)

The transport porosity is the fraction of the pore volume occupied by water. The values for the transport porosity in alluvial gravel and sand matrices, and in the macropores of alluvial gravels, estimated from field measurements (Dann et al., 2010) are given in Table A16. Experimental values for Θ are not available for the other settings, and are based on expert opinion (pers. comm. R Dann, ESR).

A uniform input distribution function was used in @Risk® for modelling the porosity, either because of the randomness of size distributions of the media (alluvial gravels and sand), which determine porosity, or the absence of experimental data on which the estimates were based.

A5.5 Péclet number (Pe)

The Péclet number relates the rate of diffusion to the rate of advection. In the model, it is used to calculate the dispersion value:

Dispersion = Observation Depth/Péclet number

Dispersion for solutes generally varies from 5–10% of the distance travelled (i.e. the observation depth) in gravels, which equates to a Péclet number ranging from 10–20. However, the dispersion of viruses will tend to be lower than that of solutes as viruses sorb to colloidal material. Dispersion data for viruses in the vadose zone are unavailable, but examination of the data for soils in Pang et al. (2008) shows an average dispersion of approximately 5% of the travel distance. Consequently, a Péclet number of 20 was used for both alluvial gravel and alluvial sand (pers. comm., L. Pang, ESR).

For the remaining hydrogeological settings, Péclet numbers ranging from 7–20 were used, and a uniform input distribution function. Where some contribution from matrix flow is expected, a Péclet number of 80 was used (except for alluvial gravels), corresponding to the low dispersion expected for these conditions.

Table A16 Input parameter values used for vadose zone modelling[1]

Hydrogeological setting	Infiltration rate (m)	Macropore flow contribution to total flow	Transport porosity Θ		Péclet Number		Longitudinal dispersion[2]		Retardation factor	Removal Rate (log_e/m)	
			Matrix flow	Macropore flow	Matrix flow	Macropore flow	Matrix flow	Macropore flow		Matrix flow	Macropore flow
Alluvial gravel	0.050	25–50%[3]	0.1–0.2	0.005–0.015	20	20	5%	5%	1	0.12–1.4	0.12–1.4
Alluvial sand (coarse)	0.035	1–10%[3]	0.35–0.40	0.01–0.05	20	80	5%	1%	1	0.35–3.5 1.7[4]	0.35–3.5 1.7[4]
Pumice sand	0.030	0%	0.25–0.36		7–20		5–15%		1	3.1–9.2	
Coastal sand (fine)	0.030	0%	0.35–0.40		7–20		5–15%		1	1.0-4.8	
Sandstone – non-karstic limestone	0.020	0%	0.01–0.03		7–20		5-15%		1	0.033– 0.10	
Fractured rock and karstic geology	0.050	50–70%	0.01–0.03	1	7–20	80	5–15%	1%	1	9.2×10^{-4}– 28×10^{-4}	9.2×10^{-4}– 28×10^{-4}
Clay (cracking)	0.010	85–95%	0.45–0.65	0.015–0.035	7–20	80	5–15%	1%	1	1.8–5.5	1.8–5.5
Silts	0.020	0.5–2%	0.15–0.25	0.0025-0.0075	7–20	80	5–15%	1%	1	1.0–3.0	1.0–3.0
Peat	0.020	0%	0.35–0.55		7–20		5–15%		1	1.2–3.5	
Ash	0.020	0.5–2%	0.05–0.15	0.0025-0.0075	7–20	80	5–15%	1%	1	1.0–3.0	1.0–3.0

Notes:
1 The @RISK distributions used are “uniform” for all parameters except those for alluvial sand for which a “triangular” distribution was assumed.
2 Dispersion values are calculated from the Péclet Number and observation depth.
3 Linearly decreased to 0% between 7 and 12 m.
4 “Most likely value” for @RISK “triangular” distribution.

Table A17 Basis of virus removal rates used in vadose zone modelling

Hydrogeological setting	Reference	Table in Pang (2009)	Microbe	Infiltration Rate (mday^{-1})	Mean Removal Rate (log_{10}/m)	Mean Removal Rate (log_e/m)	Removal Rate Range (log_{10}/m)	Removal Rate Range (log_e/m)
Alluvial gravel	Gerba et al (1991)	11	MS2 phage	0.92-1.53	0.53	1.2	0.05 – 0.59	0.12-1.4
			PRD-1 phage	"	0.52			
	Powelson et al (1993)		MS2 phage	"	0.05 (min)			
			PRD-1 phage	"	0.59 (max)			
Alluvial sand (Coarse)	Jansons et al (1989)	11	Echovirus type 11	0.3-9	0.37	0.85	0.15-1.52	0.35-3.5
			Echovirus type 24	"	1.08	2.5		
			Poliovirus type 2	"	0.95	2.2		
			Enterovirus	"	0.26	0.60		
			Coxsackievirus B4	"	0.48	1.1		
			Coxsackievirus B5	"	0.95	2.2		
	Ho et al (1992)		Coliphage	0.1	0.15	0.35		
	Anders and Chrysikopoulos (2005)		MS2 phage	-	0.95	2.2		
			PRD-1 phage	-	1.52	3.5		
Pumice sand	Pang et al (2008)	11	Faecal coliforms[43]	0.15	2.66	6.1	1.33-3.99	3.1-9.2

[43] FRNA phage data are available from this study, but the faecal coliform data were used because: 1) there were too few data to provide a reliable estimation 2) the faecal coliform data provided a more conservative rate.

Table A17 Basis of virus removal rates used in vadose zone modelling – cont'd

Hydrogeological setting	Study	Table in Pang (2009)	Microbe	Infiltration Rate (mday^{-1})	Mean Removal Rate (log_{10}/m)	Mean Removal Rate (log_e/m)	Removal Rate Range (log_{10}/m)	Removal Rate Range (log_e/m)
Coastal fine sand	Carre and Dufils (1991)	11	Faecal streptococcus				0.45-2.1	1.0-4.8
	Anders and Chrysikopoulos (2005)		MS2 phage					
			PRD1 phage					
Sandstone/non-karstic limestone	Krapac et al (2002)	14	Faecal streptococcus	-	0.0413	0.067	0.0145-0.0435	0.033-0.10
			Faecal streptococcus	-	0.016			
	Mid-point between the two values from Table 14			-	0.029			
Fractured rock[44]	Masciopinto et al (2008)	14	Range of bacteria and somatic phage	10-250			0.0004-0.0010	0.00092-0.0028
Clay (fractured)	McKay et al (1999)	11	PRD-1 phage	0.03-0.25	1.59		0.80-2.3	1.8-5.5
Silt	Krapac et al (2002)	11	Faecal streptococcus	-	0.88		0.44-1.3	1.0-3.0[45]
Peat	pers comm. Pang (ESR)				1		0.5-1.5	1.2-3.5

[44] Fractured limestone data.
[45] Removal rate in macropore flow assumed to be half that in matrix flow.

A5.6 Retardation factor (R)

This factor indicates whether the viruses are travelling faster (R <1) or slower (R >1) than the average water flow. The sorption of viruses to particles can produce size-exclusion effects that favour passage through large pores and result in viruses travelling faster than the average groundwater flow. Balancing this phenomenon is the possibility of reversible sorption processes retarding virus transport. The balance between these phenomena has not been determined, therefore R was set to unity for this modelling.

A5.7 Longitudinal dispersion

A contaminant entering a groundwater undergoes dispersion as the water travels through the aquifer. Longitudinal dispersion is the dispersion occurring in the same direction as groundwater flow. See the discussion on the Péclet number (Section A5.5).

A5.8 Observation depth

This is the depth at which the calculation is carried out, i.e. it is the vertical distance travelled by the viruses through the vadose zone.

A5.9 Decay rate

The model allows for the input of a value for the inactivation rate of the viruses. This covers thermal inactivation, predation, and other process that are time-dependent but do not result from the movement of water through the media of the vadose zone or being in contact with these media.

The temporal removal rate can be expressed as a spatial removal rate, if the temporal removal rate is assumed to be first order and the average pore-water velocity is constant (see Section A1.5). In this modelling, the time-dependent removal of viruses was accounted for through a spatial removal rate, with the decay (temporal removal) rate being set to zero.

A5.10 Removal rate

The use of the spatial removal rates derived by Pang (2009) was discussed in Section A1.5. The use of spatial removal rates avoids the need for separate entry of the decay rate. For this approach to be valid, the infiltration rate used in the model should approximate the infiltration rates used in the field when the empirical values listed by Pang were determined.

The ranges of removal rates used in the modelling of each hydrogeological setting are listed in the right-most column of Table A16, and the detailed origin of the rates in Table A17. Empirical studies cannot distinguish between the contributions to virus removal during matrix and macropore flow, and the rate given is an overall rate. Consequently, the same removal rate is used here for both matrix and macropore flow.

Table A17 identifies the table in Pang's review (2009) and the original papers from which she derived the removal rates. Where infiltration rate information was provided in the original studies, these are tabulated, together with the removal rate information derived from the study. In most cases the removal rates are mean values, where they are not, this is stated.

The removal rates tabulated by Pang (2009) are in $\log_{10}$/m units. These were converted to $\log_e$/m for input into the model. An @RISK® uniform input distribution function was used in all cases, except that of alluvial sand when it was judged that sufficient data were available to allow the use of the @RISK® triangular function. Where there were too few data to define minimum and maximum values for the range, the range was taken to be the mean ±50% of the mean.

For some hydrogeological settings data for viruses were unavailable, and experimental removal rates for bacteria were used as the basis for the estimate. While not ideal, this approach is expected to provide a reasonable basis for estimating virus removal.

The reasons for the selection of the removal rates chosen from Pang (2009) are given below. The tables referred to are those in Pang's paper.

Alluvial Gravel	Pang derived removal rates for MS2 and PRD-1 phages in gravel from two studies. Only values derived from the lower infiltration rates from Gerba et al. (1991) were considered because they are closer to those assumed for the model. These removal rates fall within the range derived from the study by Powelson et al. (1993). The minimum and maximum values from Powelson et al. were taken to define the range.
Alluvial sand (coarse)	Pang derived removal rates for a number of viruses in sand, based on data from three studies, covering pathogenic and indicator viruses. There is no evidence for a systematic difference between removal rates of pathogenic and indicator viruses, consequently all data were considered in determining rate constants for the modelling to provide a larger dataset. The mid-point is the mean of the means reported, and the minimum and maximum values are those reported by Pang.
Coastal sand (fine)	The only data for fine sand in the vadose zone are those derived from the paper by Carre and Dufils (1991) (Table 11). These are for bacteria (faecal coliforms and faecal streptococci) and only minimum removal rates are quoted. Moreover, these removal rates were obtained at high infiltration rates. Therefore, the Carre and Dufils data were not used. To estimate the range of removal values that might be expected in coastal sand, phage removal rates derived from the study of fine-coarse sand by Anders and Chrysikopoulos (2005) were used. The minimum rate for MS2 phage (0.46) from Andrew and Chrysikopoulos is similar to the minimum value derived from the Carre and Dufils work. The maximum removal value is the maximum value Pang estimated for PRD-1 phage (2.09) from the Anders and Chrysikopoulos work.

Pumice sand	Data for New Zealand pumice sand is recorded in Table 11. Mean values are given for F-RNA phage and faecal coliforms. The minimum-maximum interval is estimated from the mean ±50%.
Sandstone/non-karstic limestone	The literature does not provide suitable studies from the vadose zone for this hydrogeological setting. However, in Table 14, removal rates are derived from a paper by Krapac et al (2002) for faecal streptococci removal in limestone (mid-point = 0.016) and sandstone (0.0413). These are the best available data on which the vadose zone modelling can be based. The mid-point between these two values (0.029) was taken to be the mid-point of the range for this work, with the minimum and maximum values set at the mid-point ±50%.
Fractured rock	No vadose zone studies in fractured rock are recorded by Pang, but saturated zone removal values for fractured limestone are derived by Pang (Table 14) for a number of bacteria and somatic phages from a study by Masciopinto et al. (2008). The mean of these values ±50% defined the range for this work.
Clay (fractured)	One study (McKay et al., 1999) recorded in Table 11 provided data from which removal rates for this setting could be derived. Pang derived a mean removal rate for PRD-1 phages. The range was taken to be this value ±50%.
Silt	A single mean removal value in the vadose zone for silt is derived by Pang (Table 11). The range was taken to be this value ±50%.
Ash	No studies are reported in the literature from which removal values for this hydrogeological setting can be derived. To allow modelling, virus removal in an ash vadose zone was assumed to be similar to that in silt.
Peat	No studies are reported in the literature from which removal values for this hydrogeological setting can be derived. The rate values used in the modelling were recommended by Pang (pers. comm.)

A5.11 Modelling output

@RISK® was used to identify the best fit to the output distributions from the model. The output distributions at each observation depth for all hydrogeological settings were saved for further Monte Carlo processing with the distributions from the groundwater model.

Key points

- A one–dimensional transport model, developed by Bidwell (2000), was the basis for modelling the transport of viruses in the vadose zone (the region between the soil and the water table).
- Two advective-dispersive mixing cell models were run in parallel: one for flow through the matrix material, and the second for flow through macropores.
- The values used for the input parameters to the model, for a range of hydrogeological settings, are listed in Table A16.
- Experimentally determined values were available for only a few of the input parameters in Table A16. Where experimentally determined values were unavailable, expert opinion was sought to establish a likely value range.
- To take account of the uncertainties in the input parameter values Monte Carlo techniques were incorporated into the modelling using @Risk®. This required input parameters to be entered into the model as distributions of values.
- For each hydrogeological setting, the log reduction in virus concentration was calculated for each of a series of vadose zone depths. The model output at each depth was a distribution of values. A fit describing the distribution was obtained from @Risk®.

A6 Groundwater modelling

A6.1 Introduction

Modelling virus transport through a particular type of aquifer can be undertaken using stochastic methods to allow estimates of uncertainties in the results to be made. When sufficient field data are available the method can be refined to take account of these data with the outcome that uncertainties in the results are reduced. If field data are absent, the analysis relies on literature-reported hydraulic property value ranges. The collection of pump-test results from regional councils throughout the country has shown a general paucity of data. As a result, refinements in the approach were limited to the modelling of virus transport in alluvial gravels and sands.

This section sets out the methodology used for all aquifer types, including the details of the refinements to the method where data have permitted. The section starts with an explanation of some of the concepts involved in the stochastic determination of uncertainties. The details of the modelling of virus transport are then given.

The many uncertainties that can contribute to the uncertainty of a virus transport prediction, mean that the modelling problem becomes intractable if comprehensive account is to be taken of all these uncertainties. Some studies have assumed hydraulic property homogeneity and then assessed predictive uncertainty in terms of the likely distribution of such homogeneous parameters. However, aquifer contaminant transport studies indicate that it is the heterogeneity of aquifers that is particularly responsible for most of the uncertainty in contaminant transport predictions (e.g. Eaton (2006); Hassan et al., (2008)). Consequently, the modelling philosophy adopted in this project has been to describe the heterogeneity-based uncertainty with rigour, and to adopt typical values for parameters with relatively insignificant impacts on the uncertainty of the predictions.

A diagrammatic overview of the approach taken, when field data are available to allow the refinements in uncertainty calculations, is given in . In this work, the one exception to the heterogeneity-based approach detailed in was the analysis undertaken for karst and fractured rock aquifers. This would have required the heterogeneity of the discrete fracture networks within the karst or fractured rock to be defined in a probabilistic sense (e.g., generation of stochastic realisations of the fracture networks). This work is currently being developed as part of a research project in ESR; however, it was beyond the budget and scope of this current guideline project. In the interim, a conservative approach was adopted where the spatial removal rate distributions were simply applied to a range of distances, as described in Section A6.6.1.6, using Equation 5 (Section A1.5).

A6.2 Supporting concepts

A6.2.1 Aquifer heterogeneity

The nature of an aquifer's materials (composition, size distribution, and flow path disposition) affect the way water passes through the aquifer. Large gravels with large pore-spaces readily allow the flow of water. Similarly, karstic limestone or fractured rock aquifers have large interconnected spaces through which water can be transported with little resistance. In contrast, groundwater flow through sand is much reduced because of the smaller pore-spaces. The spatial distribution of hydraulic

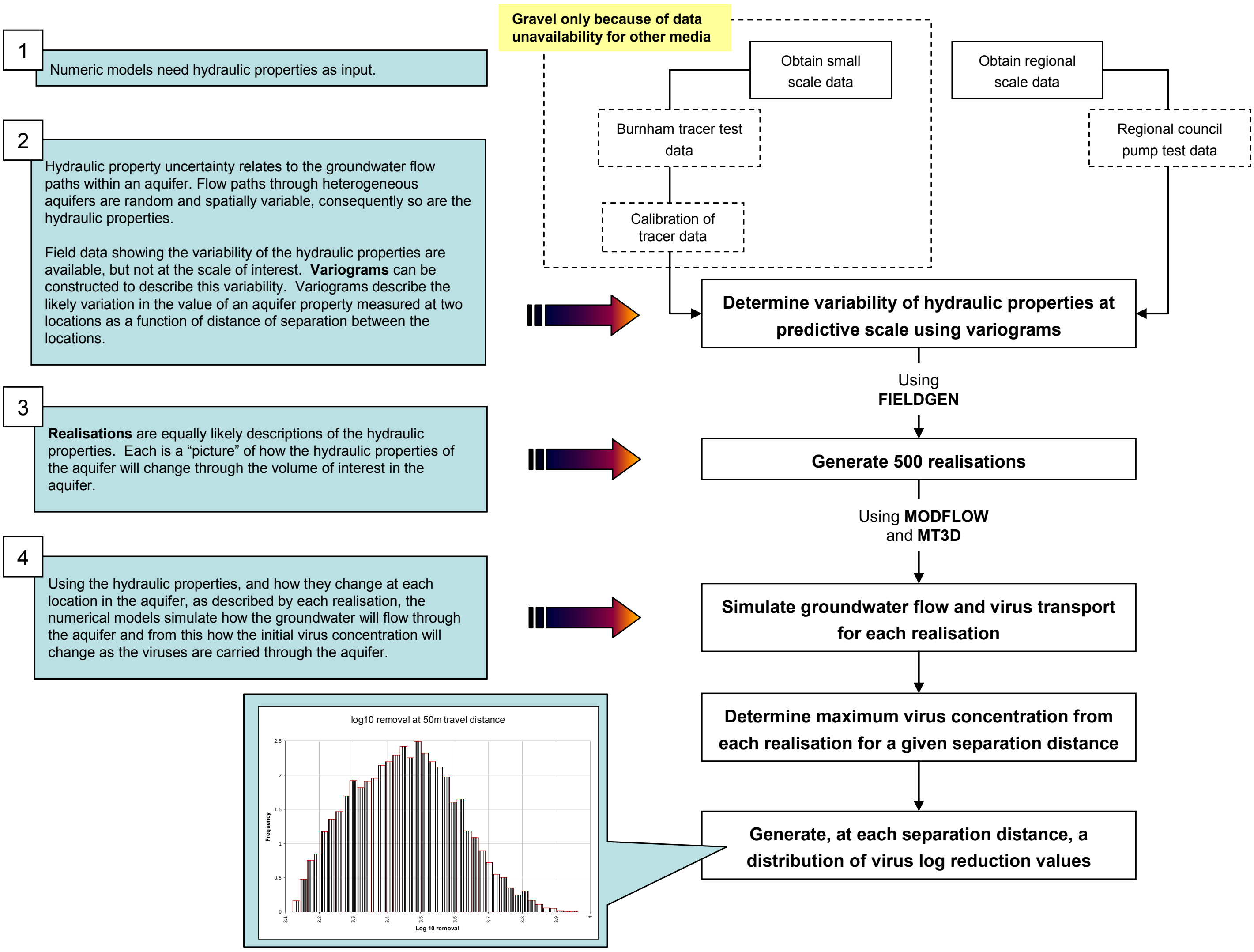


Fig. A13 Overview of the saturated zone modelling

properties (e.g., hydraulic conductivity and porosity) that are determined by the groundwater flow paths of the aquifer are of particular interest for virus transport modelling. Modelling contaminant transport through aquifers consisting of homogeneous materials is straightforward. However, most aquifers contain materials with a wide range of sizes, i.e., they are heterogeneous. This creates a much greater challenge for modelling.

A description of the exact disposition of hydraulic properties cannot be calculated in detail because the hydraulic properties of a heterogeneous aquifer vary spatially. Too few field data are available to allow aquifer heterogeneity to be precisely described. The accepted approach to overcoming this difficulty is to determine the variability in the aquifer's hydraulic properties and use this as the basis of a statistical model of the aquifer. This allows aquifer properties to be simulated at every unsampled point. These simulated aquifer properties cannot be determined uniquely (only the variability description itself can be uniquely determined), consequently multiple, equally-likely realisations of the simulated aquifer properties are explored. The probability of potential reductions in contaminant concentrations can then be determined based on exploration.

Aquifer heterogeneity (particularly in terms of hydraulic conductivities) is the principal source of uncertainty in modelling the transport of contaminants in groundwater. Heterogeneity effects on contaminant transport are most extreme in fast-moving groundwater systems because advection transport mechanisms (e.g., mixing and associated filtration), which are controlled by hydraulic conductivity, are very fast compared with other contaminant transport mechanisms, such as diffusion.

A6.2.2 Semi-variograms

To be able to model the likely changes in hydraulic property values from point to point within an aquifer, field information about the variability of the properties within the aquifer is needed.

Typically, the variability (or differences) in aquifer properties is greater when considering two locations with considerable distance between them, and is less when two locations are near each other. This fact can be expressed mathematically in a semi-*variogram* (also referred to as "variogram" herein). Variograms describe the structure of the spatial variability of a property (defined as semivariance), and also allow the interpolation of a property between observations to locations at which no observations were made.

Semivariance is a measure of the dissimilarity in the values of a property measured at two different locations. It is given by:

$$\gamma(s_i,s_j) = \mathrm{var}(Z(s_i) - Z(s_j))/2$$

where var is variance and $Z(s_i)$and $Z(s_j)$ are the values of a property at two locations s_i and s_j. The semivariance increases with separation distance, and is not a function of the absolute location of the points. The plot of the semivariance as a function of the distance between two locations, is a *semi-variogram*. It is the semi-variogram that is used in this work. Fig. A14 shows the characteristics of a generic semi-variogram.

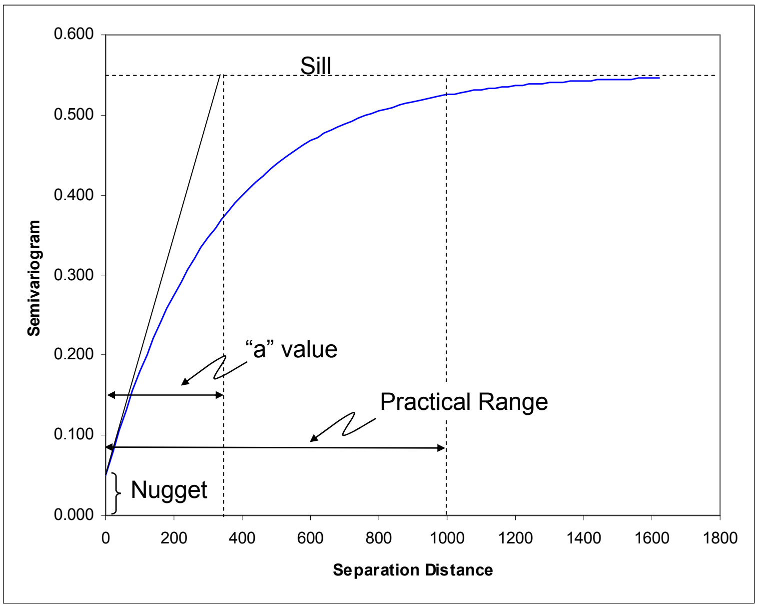


Fig. A14 Generic semi-variogram with features labelled

The *sill* is the maximum value the semi-variogram reaches as the distance between observations increases. The *nugget* is the semi-variogram value at zero separation distance. The nugget results from experimental error and microscale variation. The separation distance at which the semi-variogram levels off to the sill is the *practical range*. Within the range there is spatial correlation of the aquifer property, and beyond the range there is no correlation, i.e., the semi-variance is independent of separation distance. The *a* value is defined as the distance at which the tangent line to the curve at zero separation intersects the sill.

For the sake of stochastic simulation, a semi-variogram model is needed; it is the means of capturing the shape of the semi-variogram mathematically. Semi-variograms may take several forms. The one used for modelling the field data in this study was the exponential model which is of the form:

$$g(h) = c\left(1 - \exp\left(-\frac{3h}{r}\right)\right)$$

Where *c* is the sill, *h* is the separation distance (also termed *lag*) and *r* is the practical range. In exponential semi-variograms, the sill is approached, but not reached, and at a separation distance of 3*a* the model reaches ca. 95% of the sill (i.e. *a* is approximately one third of *r*). These parameters need to be determined from empirical data to define the semi-variogram.

The hydraulic properties of an aquifer are usually anisotropic, i.e., they depend on direction. Where necessary, anisotropy was incorporated into semi-variograms used in this work. The anisotropic ratio (direction of groundwater flow: transverse direction) depends on the aquifer material.

One of the factors influencing a semi-variogram's properties is the *sampling area* or *support*. In field measurements, this is the area of the aquifer that may affect the measurement. For instance, the results of a pump test may be influenced by the nature of the aquifer for a distance of, say, 500 m from the test bore. In contrast, when data for the semi-variogram have been obtained from a calibrated model, the support is simply the size of the grid dimensions (cell size) used in the model.

The variogram range is typically of the same order as the dimension of the largest physical features creating the heterogeneity (e.g. continuous high conductivity channels).

A6.2.3 Change of support

If the empirical data on which a semi-variogram is based have not been obtained at a scale (or sampling area) that matches the required predictive scale (the scale at which the final modelling is to be undertaken) an adjustment to the variogram description needs to be made to account for this difference in scale. The adjustment is described as a "change of support". By increasing the support the semi-variogram sill value reduces. Conversely, a decrease in the support increases the sill value.

It is relatively straightforward to develop a large-scale semi-variogram from a small-scale semi-variogram, e.g., Journel and Huijbregts (1978), but much more difficult to work the other way.

In working from a large scale to a smaller scale, the same increase in sill could be obtained from a number of combinations of range and support (area of the aquifer sampled in the pump test). Consequently, in this second case, a number of semi-variograms and associated sampling volumes have to be hypothesised to give the apparent average semi-variogram.

A6.2.4 Realisations

Predictive modelling requires input values of the aquifer's hydraulic properties throughout the aquifer. It is impracticable to make measurements of these properties at such a fine level of detail, therefore values for these properties have to be generated stochastically (i.e., randomly on the basis of what is known about the mean value and the distribution about this mean). The use of semi-variograms allows the distributions of hydraulic property values to be determined and used in the generation of the stochastic fields.

A *realisation*[46] is one of a number of possible descriptions of the hydraulic properties of the aquifer and is based on the average property value and a description of property variability (as encapsulated in the variogram). Each realisation contains a randomly generated hydraulic property value at each point within the aquifer. The hydraulic property values obtained from the realisation are then used as the input for the groundwater flow and contaminant transport modelling software. Because realisations are randomly generated, each realisation is a different, though equally probable, description of the distribution of hydraulic field properties within the aquifer.

By generating a large number of realisations, and obtaining a modelling prediction for each, a distribution of the likely predictions of (in this case) virus concentrations at different locations and times within an aquifer can be obtained. The characteristics of the distribution allow the uncertainty in the modelling predictions to be determined.

A6.3 Hydraulic property values and their variability adopted for this modelling work

A6.3.1 Data sources

Information about the variability of the hydraulic properties of aquifers was requested from regional councils and unitary authorities from throughout New Zealand. These data provided some guidance as to typical "average" parameter values which should be used in the modelling. The data also allowed the construction of semi-variograms, which could then be used in the generation of aquifer property realisations.

Most of the data available were relevant to gravel and sand aquifers, at regional scales larger than the predictive scale needed for the modelling. This resulted in the need for change of support adjustments to the variogram to the predictive scale. Variability information was based on pump-test data (or specific capacity data if pump-test data were unavailable). Data were also obtained from two other sources: a URS report (URS, 2001) (Pauanui, Waikato) and a Landfill report (Burwood, Canterbury). The data from the Environment Canterbury pump-test database had already been obtained for the preparation of a report for Environment Canterbury (Moore, 2008).

In addition, one small-scale hydraulic property variability description was also available in an alluvial gravel aquifer, from chloride and rhodamine-WT tracer experiments undertaken at ESR's experimental site at Burnham in 1995 (Pang et al., 1998). Use of these data is discussed in A6.3.3.

[46] Realisation and stochastic field are equivalent terms.

A6.3.2 Generation of larger scale semi-variograms

The nature of the information contained within the datasets provided by territorial authorities varied from region to region, but all of the data were representative of larger scale heterogeneities only. Some regional councils provided calculated estimates of hydraulic properties derived from pump-test or specific capacity data, others provided raw data from which the properties of interest were calculated. The minimum dataset, from which hydraulic conductivity could be calculated if not already provided, needed to contain:

- Grid references for each pumping site to allow spatial separation to be determined
- Maximum pump rates
- Maximum drawdowns
- Aquifer thicknesses or screen lengths.

When the aquifer thickness was not available, the thickness was assumed to be equal to the screen length, unless other information suggested a different assumption was more appropriate. When the screen length was unavailable, a default thickness of 6 m was assumed.

If not provided by the council, the hydraulic conductivity was calculated using the following set of equations:

$$Specific\ Capacity\,(SC) = \frac{Pumping\ Rate}{Drawdown}$$

$$Log_{10}(Transmissivity) = 0.9619 Log_{10}(SC) + 0.611$$ [47]

$$Hydraulic\ Conductivity = \frac{Transmissivity}{Aquifer\ thickness}$$

No data from which porosity could be determined were obtained.

The first step in processing the data was to group bores into areas likely to be related to the same aquifer system. This was sometimes done by the councils before they provided the data. When this had not been done, groupings were made using a combination of:

- information the regional council had provided
- the geographical locations of the bores
- examination of topographical (based on geographical features such as river valleys) and geological maps
- knowledge of the area held by ESR staff.

Once a preliminary grouping of bores was completed, bores were rejected from the group if the bore depth, or other data about the bore, did not match well the data from other bores in the group. In some instances, regional councils commented on the accuracy of bore data.

[47] This equation for gravel aquifers was reported by Bal (1996).

Distances between bores were bracketed (e.g., 1000–1200 m) to contribute a larger number of data pairs to the variogram for a given average separation, because of the paucity of data.

Semi-variograms were generated using the geostatistical software package, Surfer®[48]. Input files for Surfer® contained the grid reference of the bore, and the logarithm of the hydraulic conductivity measured at the bore. Parameter values that described the best-fit exponential semi-variogram were output from Surfer®.

Table A18 contains a listing, by region and sub-region, of the aquifer types for which data were processed by Surfer®. The table also indicates whether there were sufficient data to allow a semi-variogram to be constructed, and the quality of the fit of the semi-variograms that were produced from the data. Data for gravel aquifers from Canterbury had been previously generated in a project for Environment Canterbury (Moore, 2008).

As can be seen from Table A18, the only aquifer types for which semi-variograms could be produced were alluvial gravels and alluvial sands, with the exception of one set of data for a basalt aquifer.

Table A19 summarises the minimum, mean and maximum of the reported hydraulic conductivity values that were used to compile the regional variograms.

[48] Golden Software Inc., 809 14th Street, Golden, Colorado 80401-1866, USA.

Table A18 Summary of semi-variograms produced from regional aquifer types

Region	Sub-region	Aquifer Type	Semi-variogram quality*
ARC	Kaawa	Sand - Shell/gravel	Few data/Poor fit
	Basalt	Basalt	Few data/satisfactory fit
	Waitemata	Sandstone	Too few data
EW	Waikato River	Alluvial coarse sand	Satisfactory fit
	Hamilton	Alluvial coarse sand	Satisfactory fit
	Pauanui	Coastal fine sand	Too few data
	Matamata	Sand	Too few data
	Wairakei	?	Few data/Poor fit
	Whitianga	Coastal fine sand	Too few data
HBRC	Ruataniwha Plains	Alluvial gravel	Satisfactory fit
	Heretaunga Plains	Alluvial gravel	Satisfactory fit
TRC	Patea	Sandstone	Too few data
	Waverley	Sandstone	Too few data
	Deer Park	Sandstone	Too few data
GWRC	Wairarapa	Alluvial gravel	Satisfactory fit
	Paraparaumu	Coastal Sand	Too few data
MDC	Wairau Aquifer	Alluvial gravel	Satisfactory fit
	Rarangi	Coarse sand	Too few data
TDC	Motueka	Alluvial gravel	Satisfactory fit
	Takaka-Pupu springs	Karst	Too few data
	Well 6535	Alluvial gravel	Too few data
	Appleby	Alluvial gravel	Too few data
ECan	Burwood	Coastal fine sand	Too few data
	Canterbury Plains	Alluvial Gravel	Satisfactory fit
ORC	Alexandra	Highly variable clay bound gravel to alluvial gravel	Poor fit
	Clinton	Clydevale-Clutha outwash alluvial gravel	Satisfactory fit
	Cromwell-Tarras	Alluvial gravel	Satisfactory fit
	Pomohaka Basin	Alluvial gravel	Few data/Poor fit
	Lake Hawea-Luggate	Alluvial gravel	Satisfactory fit
	Wakatipu Basin	Post glacial sandy gravels	Satisfactory fit
	Roxborough	Clutha outwash alluvial gravel	Few data/Poor fit
ES	Riversdale-Gore	Alluvial gravel	Satisfactory fit
	Edendale	Alluvial gravel	Too few data
	Mossburn	Alluvial gravel	Too few data

* *Too few data* – no attempt to generate semi-variogram; *Few data* – small number of data but semi-variogram generated all the same; *Poor fit* – semi-variogram generated but fit of model to data was poor; *Satisfactory fit* – semi-variogram generated which fitted data satisfactorily.

Table A19 Summary of hydraulic conductivity data from regional aquifer types

Region	Sub-region	Mean	Min	Max
ARC	Kaawa	148	13	2026
	Basalt	136	20	1416
	Waitemata	1.2	0.12	33
EW	Waikato River	67	0.2	2237
	Hamilton	57	0.091	1400
	Pauanui	4.3	-	-
	Matamata	155	1.3	1622
	Wairakei	121	1.12	1685
	Whitianga	5.5	0.195	94
HBRC	Ruataniwha Plains	2847	34	3129
	Heretaunga Plains	379	4.7	42200
TRC	Patea	1.5	-	-
	Waverley	4.8	-	-
	Deer Park	0.031	-	-
GWRC	Wairarapa	898	5	17270
	Paraparaumu	119	24	2400
MDC	Wairau Aquifer	2215	16.7	21450
	Rarangi	402	282	648
TDC	Motueka	5369	132	92928
	Takaka-Pupu springs	-	-	-
	Well 6535	58212	-	-
	Appleby	11965	3217	22000
ECan	Burwood	10	-	-
	Canterbury Plains	1300	10	7200
ORC	Alexandra	139	1.03	2172
	Clinton	79	2.14	2384
	Cromwell-Tarras	2043	13.3	45723
	Pomohaka Basin	37	3.7	3204
	Lake Hawea-Luggate	1010	0.7	43440
	Wakatipu Basin	281	5.2	18938
	Roxborough	1156	461	4992
ES	Riversdale-Gore	1505	-	-
	Edendale	1596	-	-
	Mossburn	1174	-	-

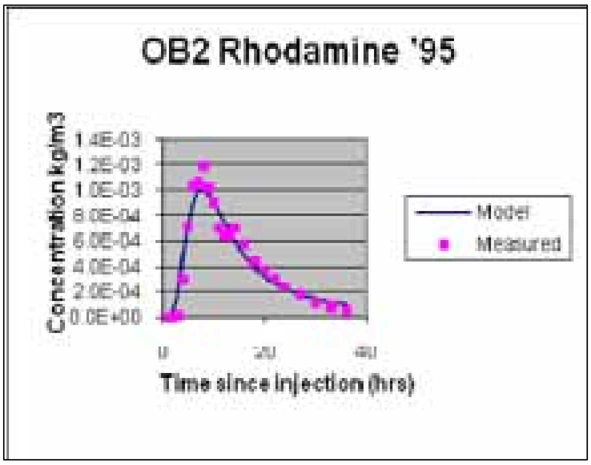
Note that where there are too few data no range of values has been reported. The test analyses used to derive these values have been summarised based on the data supplied to ESR, but have not been independently verified as part of this project.

A6.3.3 Small-scale semi-variograms

A small-scale variogram was derived for gravels from estimating fine-scale hydraulic property variability on the basis of calibrating a flow and contaminant transport model to water levels and conservative tracer data from ESR's Burnham field experimental site. This work is described in detail in Moore (2008). It was hoped that more fine scale tracer test data would have been available for other aquifer types for use in this project, but the Burnham dataset contained the only data at a fine enough scale to be useful.

The model grid contained 150 rows and 250 columns (1 m x 1 m cells). The very fine grid was chosen to allow any spatial heterogeneity indicated from the tracer test bore data to be included in the calibrated fields.

The calibration process resulted in a good match between the model predictions and the measured concentration, as can be seen in the match to the breakthrough curves for two selected bores in Fig. A15 (refer to Moore 2008 for the full reporting on this analysis).



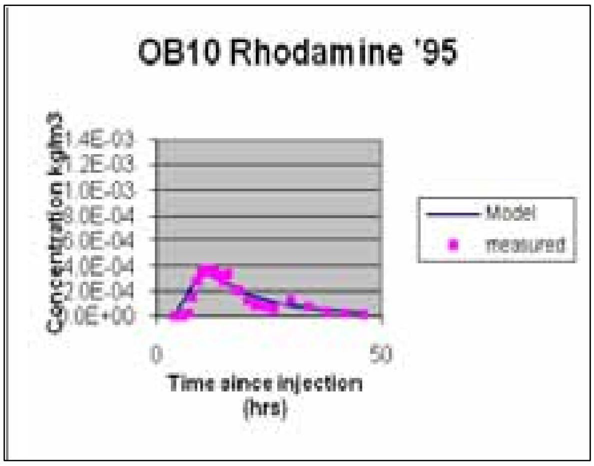


Fig. A15 Measured and model output concentrations resulting from calibration to Burnham conservative tracer test data for two selected bores

The spatial average conductivity in the vicinity of the observation wells was approximately 1300 m/day. The range of the hydraulic property values calculated for the Burnham site could be used to generate a small-scale semi-variogram for the site. The semi-variogram obtained from the Burnham data is shown in Fig. A16. Because of the spread in the calibrated hydraulic conductivities, logarithms ($base_{10}$) of these values are used in the semi-variogram.

The theoretical semi-variogram inferred from the calibrated hydraulic conductivity values has a sill of 0.6 ($log_{10}(m/day)^2$) and an *a* value of 15 m, implying a range of approximately 45 m. Changes of support calculations for this small-scale variogram were undertaken and were used to constrain the range of possibilities for the regional scale variogram change of support calculation for the alluvial gravel aquifer type.

The calibrated porosity field was much more homogenous, ranging over one order of magnitude and consequently a variogram was not constructed for this property.

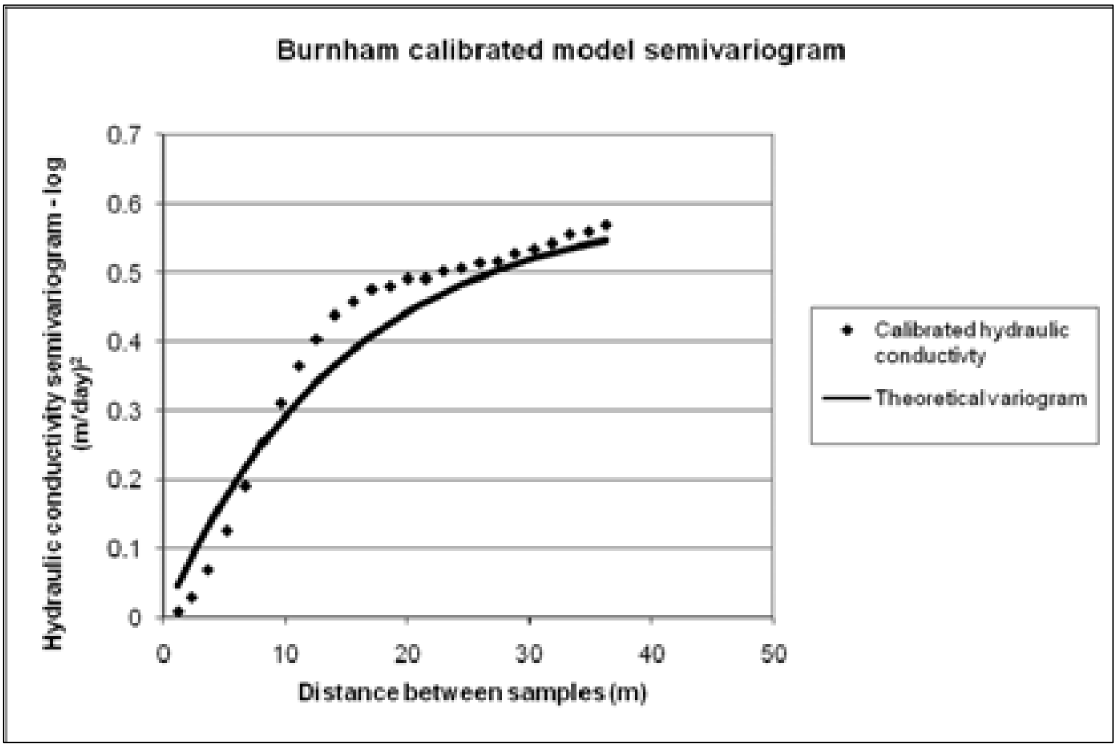


Fig. A16 Burnham semi-variogram for hydraulic conductivity derived from tracer experiments

A6.4.5 Property values adopted for modelling

Analysis of the pump test- and slug test- derived data from councils supported estimates of typical hydraulic property values and their likely variability for alluvial gravel and sand aquifers. Where there were few data, average values of hydraulic properties and their variability were conservatively selected. A summary of the aquifer parameters and their variability descriptions used in this modelling work are given in Table A20 and Table A21.

A6.4.5.1 Aquifer properties

For most of the aquifer types, average aquifer property values were informed by the literature and experience. However, for the alluvial gravel and sand geologies, the data supplied by the councils were used, as discussed below. Parameter values were considered on the basis of the reported reliability of the data and the extent of the dataset. A summary of the average aquifer properties used in the groundwater modelling work supporting the guidelines is given in Table A20.

Alluvial gravel aquifer

Data for gravel alluvial aquifers were obtained from the Canterbury, Marlborough, Hawkes Bay, greater Wellington and Tasman regions. Average hydraulic conductivities for this hydrogeological setting range from 379–5369 m/day (although exceptionally high single localised values of 58,000 and 93,000 m/day were reported in the Tasman region). Given this range of data, it was difficult to select a representative average hydraulic conductivity value for all alluvial gravel regions. In response to this difficulty the largest alluvial gravel data set from Environment

Canterbury was used, and hence an average value of 1300 m/day was used for the hydraulic conductivity in alluvial aquifers. This was derived from both the tracer test data in alluvial gravel strata together with the regional pump-test data. While this value is at the lower end of the reported average hydraulic conductivity values for alluvial gravel, it is based on the largest dataset, and therefore is more likely to accurately represent an "average" for this setting.

The average porosity estimate was based on field experiments outlined by Dann et al. (2010) who estimated a transport porosity value in alluvial gravels of 0.0032. This value is very low. However, given that it is based on actual measurements in this hydrogeological setting, it represents a more robust 'average' than reported literature values from different geological contexts outside New Zealand.

Alluvial sand aquifer

Data for alluvial sand aquifers were available for the Waikato and Otago regions. The pump-test data from councils indicated an average hydraulic conductivity value the alluvial sand setting of 57–120 m/day (1.76–2.08 $\log_{10}$) with a standard deviation of 0.74–0.95 ($\log_{10}$). An average of 80 m/day was selected, with a standard deviation of 1 ($\log_{10}$), being used to represent the likely variability.

The average porosity estimates for alluvial sand were based on literature values and general experience.

Pumice sand aquifer

As already discussed, there were insufficient data available to allow a variogram assessment for pumice sand aquifers. However, work undertaken by ESR staff in these aquifers in the Rotorua and Taupo region allowed an estimate of the likely range of transport porosity and hydraulic conductivity properties for pumice sand aquifers. An average hydraulic conductivity value of 80 m/day is indicated by this work, but with an estimated range from 50–100 m/day. In this analysis we assumed that this range was responsible for approximately 95% of the likely full parameter range (and that this property was log-normally distributed), which is approximately equivalent to assuming a standard deviation for this property of $\log_{10}$ 0.01.

The reported estimates of transport porosity were from 0.25–0.36 with a mean of 0.3. Once again it was assumed that this range related to approximately 95% of the parameter range in a log-normal distribution, such that the standard deviation for this property was $\log_{10}$ 0.002.

Coastal sand aquifer

Coastal sand data were obtained from the Waikato, greater Wellington, and Canterbury regions. As with pumice sand, data for coastal sand aquifers were scarce. Data from the few ESR studies undertaken in this setting were used to guide likely parameter averages and ranges. A hydraulic conductivity range of 0.1–20 m/day with an average of 10 m/day, and a transport porosity range of 0.1–0.3 with an average of 0.2, were considered reasonable on the basis of these previous studies. As with pumice sand it was assumed that these estimated ranges equated to approximately 95% of the possible parameter ranges in this setting. This results in calculated standard deviations for hydraulic conductivity and porosity of $\log_{10}$ 0.58 and $\log_{10}$ 0.014, respectively.

Sandstone and non-karstic limestone

The average hydraulic properties adopted for sandstone and non-karstic limestone were based on the literature (Freeze and Cherry, 1979; Domenico and Schwartz, 1990) and a few measurements from Taranaki Regional Council (as reported in table A20), which ranged from 0.03–5 m/day. On the basis of these data, an average hydraulic conductivity of 0.01 m/day and a transport porosity of 0.1 were used in the modelling. Ninety-five percent of the hydraulic conductivity range was estimated to lie between 1×10^{-4} and 1, with a variance in the $\log_{10}$ domain of 0.44. Ninety-five percent of the porosity values were estimated to lie between 0.05 and 0.15, with a variance of 0.0142.

Karstic and fractured rock

As discussed in section A6.1, the physically-based modelling approach used for the other geological settings was abandoned for karstic and fractured rock. As a surrogate for this, the application of a distribution of removal rates in Equation 5, was applied. However, it is noted that while there are few data in the literature, what is reported indicates very high values of hydraulic conductivity can occur in this setting (up to 1000 m/day), associated with flow within the fractures.

Table A20 Summary of average or typical aquifer properties adopted in the modelling work

Aquifer Type	Transport Porosity	Hydraulic conductivity (m/day)
Alluvial gravel	0.0032	1300
Alluvial (coarse) sand	0.2	80
Pumice sand	0.3	80
Coastal sand	0.2	10
Sandstone and non-karstic limestone	0.1	0.01
Karstic and fractured rock (e.g. basalt and schist)	0.1 and 1 for matrix and fractures respectively	1000

A6.4.5.2 Aquifer property variability

As with the average property values there is much uncertainty regarding the variability descriptors themselves for all of the aquifer types except alluvial gravel and sand. The information base for alluvial gravel and sand aquifers is discussed below. Where there are no data, the correct approach is to account for this additional uncertainty (e.g., full Bayesian stochastic analysis discussed in Woodbury (2000)). A simple way to do this is to adopt the most conservative of variogram descriptors for an aquifer type and this approach was used here. A summary of the variogram parameters adopted for the groundwater modelling work supporting these guidelines is given in Table A21.

Alluvial gravel

A sill of 0.6 (log_{10}) was adopted for the semi-variogram of the log_{10} hydraulic conductivity parameter. The semi-variogram sill gives an indication of the sample variance, and its square root an indication of the standard deviation. Combining mean and standard deviations, regional hydraulic conductivity can be considered to vary approximately between 40 m/day and 4,000 m/day for one standard deviation either side of the mean, and between 4 m/day and 40,000 m/day for two standard deviations either side of the mean. The range for the semi-variogram was determined on the basis that the "true" range in a semi-variogram is often close to the size of the physical anomalies. In alluvial gravel aquifers, connected high conductivity paths could possibly extend up to 1500 m. For this reason a range of 1500 m was assumed, and an *a* value of 500 m.

There are insufficient measurements of regional porosity for variogram analyses. However, the following approach was adopted. Dann et al. (2010) estimated transport porosity value in alluvial gravels of 0.0032 and this was used as the mean value, and the range was taken to extend one standard deviation either side of the mean (0.01 to 0.001). Stochastic porosity representations were generated from these values. The estimate of 0.0032 is slightly lower than generally considered reasonable in gravel strata, but in the absence of any other regional indication of an appropriate mean, this conservatively low value was chosen, which will tend to create longer separation distances.

Microbial transport occurs through the high hydraulic conductivity zones of gravel aquifers. This is expected to be the case for all gravel aquifers (pers. comm., M. Close, ESR).

Alluvial sand

In alluvial sand aquifers, connected high conductivity paths are not expected to extend as far as in gravels. For this reason a range of 500 m was assumed, and an *a* value of 170 m. The sill used is 1 (log_{10}), and is based on the standard deviation of reported values from councils.

As with gravel aquifers, there are insufficient measurements of regional porosity for semi-variogram analyses for sandy alluvial aquifers. A semi-variogram sill of 0.0025 of the log_{10} of porosity was used with an average porosity of 0.2. This is equivalent to a parameter range (at three standard deviations either side of the mean) from 0.15–0.25. Note that these are much higher porosity values than used for the alluvial gravel hydrogeological setting.

Pumice and coastal sand, sandstone and non-karstic limestone aquifers

Data to support variogram analysis were not available for these aquifer types. Therefore, the following approach was adopted for these aquifer types. The variogram sill was based on the estimated standard deviations discussed in the section above, where the sill is assumed to be equivalent to the hydraulic property variance. The spatial dependence relationship was described by an isotropic exponential variogram with an "a" value of 100 m.

Table A21 Summary of the exponential semi-variogram properties for hydraulic conductivity used to represent the selected aquifer types in this study – sill values in $\log_{10}$

Aquifer Type	Sill for $\log_{10}$ hydraulic conductivity	Sill for porosity	*a* value (1/3 Range)	Anisotropy
Alluvial gravel[49]	0.6	0.25	500	10:1
Alluvial (coarse) sand	1.2	0.0025	170	2:1
Pumice sand	0.01	0.002	100	1:1
Coastal sand	0.33	0.014	100	1:1
Sandstone and non-karstic limestone	0.44	0.014	100	1:1
Karstic and fractured rock (e.g. basalt and schist)	None assumed			

A typical example of the type of variograms derived from the pump-test analysis is depicted in Fig. A17. Also shown in this figure is the small-scale variogram derived from the tracer test, and the combined variogram calculated for the predictive support scale.

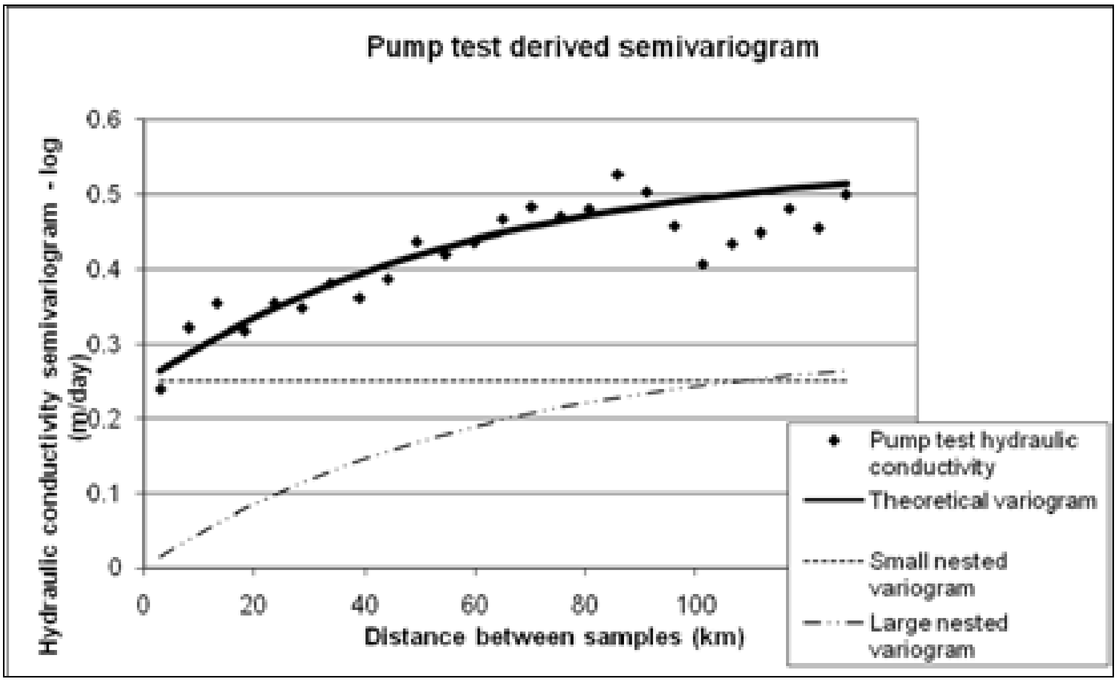


Fig. A17 Regional semi-variogram for hydraulic conductivity derived from the Environment Canterbury pump-test data

[49] Both the small-scale tracer test and the Environment Canterbury pump-test data were used as the basis for the alluvial gravel modelling, the change of support methodology is discussed in Moore (2008).

A6.5 Realisation generation

On the basis of the mean hydraulic property values and their semi-variograms, the PEST (Doherty, 2009) utility FIELDGEN (a geostatistical field generator) was used to generate stochastic hydraulic conductivity and porosity fields (realisations). FIELDGEN is based on multigaussian field generation routines presented in GSLIB (http://www.gslib.com).

Approximately 500 hydraulic conductivity realisations and 500 porosity realisations were generated for each aquifer type. For this work, hydraulic conductivity and porosity were assumed to be uncorrelated (as the calculations required by the assumption of correlation were beyond the project's scope). Given the small range of porosity values, the effects of this assumption are negligible when compared with the effect of the hydraulic conductivity variability.

A6.6 Transport modelling

Groundwater flow and transport were simulated using the MODFLOW (Harbaugh et al., 2000) and MT3D (Zheng and Wang, 2006) modelling packages, respectively. MODFLOW is a physically-based, three-dimensional, finite-difference groundwater flow model. MT3D is the accompanying solute transport software package for MODFLOW.

The domain used for the models was 5 km (in the direction of groundwater flow) x 1 km (in the transverse direction). The model grid cells were 10 m x 10 m in area and 5 m in depth, and the domain was one layer of cells thick. Representation of the contaminated portion of the aquifer as a single 5 m thick model layer was selected such that it was commensurate with the minimum aquifer thickness that would be expected to contribute to a domestic pumping well with a 2 m well screen length. This represents a conservative modelling assumption, as greater vertical mixing could be expected as the contaminant moves farther from the source, and where the well screen is far below the water table. The initial dilution of effluent as it mixes with the groundwater occurs within the area of the effluent disposal field, and this was assumed to occur within a single 10 m x 10 m cell.

The boundaries for the model were defined as constant head cells on the up- and down- gradient boundaries. The other model boundaries were defined by zero-flow conditions.

To determine the reduction in virus concentration expected to occur by a specified separation distance, a source of virus contamination was located in the up-gradient area of the model domain. Discharge from the virus source was specified to be occurring continuously over a 50-day period. Comparison between the initial concentration introduced into the model and the predicted concentration then allowed the $\log_{10}$ reduction in concentration to be determined.

Five hundred model simulations were undertaken, each selecting one of each of the 500 hydraulic conductivity realisations and the 500 porosity realisations. This allowed a Monte Carlo determination of the distribution of virus concentrations at each separation distance.

Pumping of the bores, and the associated cones of depression, were not taken into account in the model. Pumping will increase groundwater velocities, but the low pumping rate of domestic bores was considered to be minor compared with the variability in concentrations created by the aquifer heterogeneity over the predictive scale.

A6.6.1 Additional model input parameter values

A6.6.1.1 Cell dimensions

The cell area was determined on the basis of the volume of effluent that might typically be discharged per day. A dwelling with four people, each using approximately 250 L of water/day, will discharge approximately 1 m^3 of effluent/day. The design of disposal fields in TP58 (ARC, 2004), allows application rates to range from 5–50 mm/day. For a discharge of 1 m^3/day to be applied at 5 mm/day requires an application area of 14.1 m x 14.1 m (assuming a square area). At the other extreme a 50 mm/day application rate would require an area of 4.5 m x 4.5 m. The 10 m x 10 m area was selected as a compromise between these two extremes.

The 5 m depth (thickness) of the cell was chosen because of the thickness of the aquifer from which the average domestic bore will draw (assuming a 2 m well screen). This cell thickness is a very conservative assumption because it implies that any plume will be completely intercepted by the well screen when in fact this may not occur. Further, it is conservatively assumed that water is abstracted at the water table. In situations where a well is screened substantially below the water table, contaminants introduced at the top of the saturated zone will be greatly diluted by the time they reach the screen depth.

A6.6.1.2 Hydraulic gradient

The difference in head at the two boundaries of the model domain was specified to produce an hydraulic gradient of 0.001 as this value was considered typical of New Zealand aquifers. Gradients of between 0.01 and 0.0001 are expected to occur in aquifers throughout the country. The uncertainties in velocity estimates and concentration reduction relating to the choice of 0.001 are minor compared with the variability associated within the hydraulic conductivity fields, as is demonstrated in the sensitivity analysis section.

A6.6.1.3 Flux

Simulations for virus transport were run to represent a 50-day virus shedding period.

A6.6.1.6 Removal rates

As discussed in Section A1.5, the removal rates used in the groundwater modelling are defined as the spatial removal rate of viruses as they are transported through an aquifer. These removal rates were obtained from the review by Pang (2009).

The removal values in Pang's review lump together dispersion, decay, and filtration type processes (in fact any concentration reduction process) and are reported as distance-based lumped parameters. For the groundwater modelling work it was necessary that these removal rates were decomposed into dispersion and other distance based processes, because dispersion was handled separately in the physically based modelling (MODFLOW and MT3D) via movement through the heterogeneous aquifers. The removal rates (adjusted so that they do not include dispersion) were applied to the model outputs on a distance specific basis, providing the groundwater virus concentration estimate distributions used in the separation distance considerations.

The rate of virus removal depends on the state of contamination of the aquifer. Removal rates are reduced in contaminated systems. The rates used in this modelling were those determined in contaminated aquifers because prolonged disposal of effluent from an on-site system will contaminate the aquifer. A distribution of removal rates was based on the relevant reported removal rates in Pang (2009). These distributions are listed in Table A22.

For the gravel aquifers 64% of the removal rate was assumed to be unrelated to dispersion processes. This was based on a comparison of breakthrough curves for reactive and non-reactive tracers obtained from the Burnham site. For sandy aquifers, expert opinion (pers. comm., L Pang, ESR) is that dispersion will make a much smaller contribution to removal than is the case in gravels. In line with this opinion, 90% of the overall removal rate is assumed to result from non-dispersive processes.

Similar assumptions regarding the removal rates and what percentage of the rate is attributable to dispersion were made for the full suite of aquifer types examined and these are summarised in Table A22. For karstic and fractured rock there were insufficient data available to support the physically-based stochastic modelling approach. Instead the removal rate distribution specified in Table A22 was applied simply using Equation 5 (Section A1.5). This simple approach tends to inflate the calculated separation distances required, but this conservatism is appropriate in the face of scarce data.

Table A22 Summary of virus removal rates and assumptions of the likely dispersion contributions to these rates that were adopted in the modelling work

Aquifer Type	Removal rate range average (log_{10}/m)	Removal rate distribution adopted	Contribution from dispersion
Alluvial gravel	0.0139	*RiskInvgauss*(0.013139,0.0029229, *RiskShift*(0.00089314))	36%
Alluvial (coarse) sand	0.07 (average)	*RiskNormalAlt*(0.1,0.0103,0.5,0.07, risktruncate(0))	10%
Pumice sand	1.655 (average)	RiskNormalAlt(0.05,1.46,0.95,1.85)	2%
Coastal sand	0.085 (average)	RiskNormalAlt(0.01,0.0142,0.5,0.085)	5%
Sandstone and non-karstic limestone	0.49 (average)	Risknormal(0.5,0.46,risktruncate(0))	2%
Karstic and fractured rock (e.g. basalt and schist)	0.0153 (average)	Risknormal(0.0153,0.0245)	NA

A6.6.3 Model outputs and post-processing

The MT3D outputs include a file which contains concentration arrays for each specified model reporting time. Processing of the arrays in this file is undertaken to define the maximum concentrations at any given distance for all the model reporting times collectively. This allows the maximum concentration for any particular distance to be determined and collated with the outputs resulting from running the model with alternate parameter realisations. The end result of this collation process is a distribution of concentrations (and concentration reductions) for specified distances down-gradient of the contaminant source.

This analysis was undertaken with the help of two utility programs specifically written for this post processing. MODFLOW, MT3D and these two utility programs were called from a batch file which automated the stochastic process.

As was done for the vadose zone model outputs, @RISK® was used to identify the best fit to the model output distributions. Typically these were either a normal, log-normal or log-logistic distribution.

The log_{10} reduction distributions simulated as a function of separation distance for each hydrogeological setting for the saturated zone are not provided here, but are available.

Key points

- To model the transport of contaminants through the saturated zone, information about the hydraulic properties (hydraulic conductivity and porosity) of the aquifer is required.
- Most aquifers contain materials with a wide range of sizes, i.e. they are heterogeneous. The hydraulic properties vary spatially within these aquifers.
- Contaminant transport within aquifers can be modelled statistically from knowledge of the spatial variability of the hydraulic properties.
- Field data are needed to determine the variability of the hydraulic properties within the aquifer. Pump-test- and slug-test- data were obtained from regional councils, although in general there was a paucity of data.
- The variability of hydraulic properties measured at two different locations within an aquifer increases with the separation distance of the locations. The relationship between the hydraulic property variability and the separation distance is described mathematically by a variogram.
- For hydrogeological settings for which there were adequate pump-test data (alluvial gravel and alluvial sand aquifers), variograms were used to determine the variability in hydraulic properties at the predictive scale from the regional scale of the pump-test data. For the remaining hydrogeological settings, average/typical hydraulic property values, and their variability, were obtained from the literature and experience.
- Aquifer parameters and their variability descriptions are given in Table A20 and Table A21.
- Using the geostatistical field generator FIELDGEN (a utility within the PEST software package), a set of 500 realisations were generated from the information about the variation in the hydraulic properties of the aquifer.
- A realisation contains a randomly-generated value for a hydraulic property at each point within the aquifer. The 500 realisations are equally probable descriptions of the spatial distribution of property values within the aquifer.
- From each realisation a simulation of groundwater flow and virus transport was determined using the modelling software MODFLOW and MT3D.
- The domain used for the modelling was 5 km (in the direction of groundwater flow) x 1 km (in the transverse direction). Model grid cells were 10 m x 10 m in area and 5 m in depth, and the domain was one layer of cells thick.
- Virus reduction was determined by introducing a source of virus contamination up-gradient in the domain, and comparing this concentration with the concentration predicted by the model to be present at the well. Five hundred simulations were carried out, and each produced a value for the $\log_{10}$ reduction predicted to occur.
- From the $\log_{10}$ reductions obtained from the 500 realisations, a Monte Carlo determination of the distribution of virus concentrations at each separation distance was possible.
- Coupling the description of the output distribution of $\log_{10}$ reductions obtained from @Risk® in the saturated zone, with the distributions of $\log_{10}$ reductions in the vadose zone, an overall distribution of virus reduction due to transport through the vadose zone, an overall distribution of virus reduction due to transport through the vadose and saturated zones combined was determined. From this distribution the $\log_{10}$ reduction at the required percentile was obtained.

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Appendices and Tables

Appendices and Tables

FIGURES

PART 1

Appendices and Tables

Appendix 1 Stool mass data (daily)

Study	Gender	Dietary Gp	Age Group	Number of participants	Stool mass (g)		
					Mean	Min	Max
Cann et al. (1983)	Male	-	-	27	166		
	Female				112		
Davies et al. (1986)	-	Omnivore	-		153	54	415
	-	Vegetarian	-		168	81	265
	-	Vegan	-		225	129	499
Wyman et al. (1978)	Female			10	125.8	65	233
	Male			10	131.1		
Alles et al. (1996)	Male		19–28 years	24	272		
Forsum et al. (1990)		High cereal fibre	5 years		288		
		High vegetable and fruit fibre	5 years		179		
		High vegetable and fruit fibre	5 years		108		
		Low fibre	6 years		74		
Stephen et al. (1986)	Male			19	162		
	Female			11	83		
Silk et al. (2001)			26–45 years	10	166		
Kelly et al. (1998)			Average 36 years	76	91.7		
Eastwood et al. (1984)	Male		18–80 years	33	83	46	278
	Female			28	73	19	170
Ciba-Geigy (1981)	Male	Balance European		115	124	35	224
			2months–6 years	44		6.6	54.1
		High fibre	Children	500	275	150	350
			Vegetarians	24	225	71	488
		Mixed diet	Children	500	165	120	260
			Adults	13	155		
		European diet	Children	9	110	71	142
			Adults	15	104	39	223

Appendix 2 Supporting virus data

Virus	Faecal concentration (virus particles/g faeces)	Shedding period (days)	Comments	References
Rotavirus	Up to 10^{10}	Up to 29	The faecal concentration is based on a estimate by Flewett (1982). Flewett made his estimates from electron microscope grids from adenovirus cases.	Gerba et al. (1996)
	10^{10}–10^{12}	Up to 30 days		Guardabassi et al., 2003,
	10^{7}–10^{11}	1-39	The values contained in Westrell (2004) are quoted by the WHO (2006).	Westrell, 2004
	Median 9.8 x 10^{8} (Log$_e$ normal distribution: mean = 20.7; std dev = 2.3)	Median 5 (Log$_e$ normal distribution: mean = 1.6; std dev = 1.25)		Schönning et al., 2007
		8	Most vulnerable population is children under about 5 years, although adult outbreaks have been reported.	Chin, 2000 (APHA)
	Median 10^{8}		This paper modelled health impacts of pathogens. Modelling parameters are based on empirical data reported by Flewett (1982). Concentrations $\leq 10^{7}$ and $\geq 10^{9}$ assumed to occur less than 1% of the time. Concentrations assumed to vary log-normally about the median.	Anderson et al.., 1998

Virus	Faecal concentration (virus particles/g faeces)	Shedding period (days)	Comments	References
	$>10^{12}$		Review document.	Bishop, 1996
	10^{10}-10^{11}	10	Maximum concentrations are found during the first 3–4 days of the infection. Shedding period is an average value.	Schwartzbrod, 2000
Norovirus	10^{4}–10^{6}	Up to 14		Guardabassi et al., 2003
	10^{5}–10^{9}	5–22	The values contained in Westrell (2004) are quoted by the WHO (2006). Rockx et al. (2002) indicate that in 78% of cases there was shedding from day 1 after the on-set of the illness; in 26% of cases viruses were shed up to 22 days, and in 10% of cases virus could be detected from day 8-22, but not at day 1. Percentage of patients shedding decreased with time after the onset of illness. Okhuysen et al. (1995) (basis of the shedding duration value) reported that ca. 50% of the volunteers were not shedding after about 5 days.	Westrell, 2004
	$>10^{6}$	3	Shedding period is an average value	Schwartzbrod, 2000
	1.1×10^{8} $\pm 3.3 \times 10^{8}$	13.5–44.5 Median = 28.5, mean = 28.7	Faecal concentration is an average of the GII genogroup from day 0 to 7. PCR results were expressed as RNA copies/g and a 1:1 correspondence between RNA copies and virus particles has been assumed.	Tu et al., 2008

Virus	Faecal concentration (virus particles/g faeces)	Shedding period (days)	Comments	References
	2.0×10^{10} particles 1.1×10^{9} particles 6.3×10^{10} particles 1.1×10^{10} particles		Data from a number of outbreaks. Results in the reference are expressed as RNA copies/g and a 1:1 correspondence between RNA copies and virus particles has been assumed.	Kageyama et al., 2003
	4.3×10^{4}–7×10^{9}		Results in the reference are based on GII genogroup quantification and are expressed as RNA copies/g and a 1:1 correspondence between RNA copies and virus particles has been assumed.	Pang et al., 2004
		Up to 2 days after diarrhoea stops	It is unclear how long the diarrhoea lasts.	Chin, 2000 (APHA)
Hepatitis A	Up to 10^{10}	At least 30 days from onset of disease and possibly up to 3 months		Guardabassi et al., 2003,
	10^{4}–10^{6}	13–30	The values contained in Westrell (2004) are quoted by the WHO (2006).	Westrell, 2004
	Median 9.9×10^{4} particles (Log_e normal distribution: mean = 11.5; std dev = 1.2)	Median 20 (Log_e normal distribution: mean = (3.0; std dev = 0.25)		Schönning et al., 2007

Virus	Faecal concentration (virus particles/g faeces)	Shedding period (days)	Comments	References
	10^{9}	21	Shedding period is an average value.	Schwartzbrod, 2000
		21, up to 6 months has been reported for children and infants	A value for the shedding period is not specifically given: peak concentrations in faeces are noted from the week or two before the onset of symptoms. Most cases are non-infectious after the first week of jaundice. Overall therefore about three weeks (21 days).	Chin, 2000 (APHA)
Enterovirus	10^{8}–10^{10}	49	Shedding period is an average value.	Guardabassi et al., 2003,
	10^{3}–10^{6}	30	Shedding period is an average value, but excretion may last several months.	Schwartzbrod, 2000
Adenovirus	10^{11}	1–14	The values contained in Westrell (2004) are quoted by the WHO (2006)*,* although the WHO does not quote the faecal concentration given in Westrell's thesis.	Westrell, 2004
	10^{6}–10^{7}	10	Duration period is an average value.	Schwartzbrod, 2000
	$< 10^{11}$			Crabtree et al., 1997

Appendix 3 Dose-response functions

Virus	Model details (probability of infection)	Reference (Source of raw data)	Comment
Rotavirus	Beta-Poisson $Log_e(N_{50}) \approx N(1.7;1.2)$ $\alpha = 0.265$ Notation: N(median; std deviation)	Schönning et al., 2007	Work by Ward et al., (1986) appears to have been the basis for parameter values derived or quoted in other studies: Regli et al. (1991), Mara et al., (2007), Haas et al. (1999) , Schönning et al. (2007).
	Beta-Poisson $\alpha = 0.232$ $\beta = 0.247$	Rose and Gerba, 1991	
	Beta-Poisson $\alpha = 0.26$ $\beta = 0.42$	Regli et al., 1991	
	Beta-Poisson $\alpha = 0.253$ $N_{50} = 6.17$	Mara et al., 2007	
	Beta-Poisson $\alpha = 0.265$ $N_{50} = 5.597$	Haas et al., 1999	
Hepatitis A	Beta-Poisson $Log_e(N_{50}) \approx N(3.4;1.2)$ $\alpha = 0.2$	Schönning et al. (2007), and Westrell (2004)	These studies based their work on data from Shuval et al. (1997).
Norovirus	Beta-Poisson (non-simplified) Without aggregation $\alpha = 0.111$ $\beta = 32.81$ With aggregation $\alpha = 5.35 \times 10^{-3}$ $\beta = 2.51 \times 10^{-3}$	Teunis et al., 2008	Teunis et al.,(2008) contains an extended discussion on the influence on aggregation of virus particles and its effect on infectivity.

Virus	Model details (probability of infection)	Reference (Source of raw data)	Comment
Enterovirus			
Echovirus 12	Beta-Poisson $\alpha = 0.374$ $\beta = 186.69$	Regli et al., (1991)	Parameters based on those from Schiff et al. (1984).
Echovirus 12	Exponential k = 78.3	Haas et al. (1999)	Parameters based on those from Akin (1981).
Poliovirus III	Beta-Poisson $\alpha = 0.409$ $\beta = 0.788$	Rose at al (2006) and Regli et al. (1991)	Both Rose et al. (2006) and Regli et al. (1991) based their work on data from Katz and Plotkin (1967). Rose et al. (2006) selected Poliovirus III as the representative member of the Enterovirus family because it would provide a conservative risk assessment.
Coxsackievirus B4	Exponential k = 129	Mena et al.,(2003)	Mena et al. (2003) based their work on data from Suptel (1963). Mena et al. also noted that shedding may occur for as long as 3 months. Original study was of mice.
Adenovirus			
Adenovirus 4	Exponential k = 2.397	Crabtree et al. (1997), Westrell, (2004).and Haas et al., (1999).	The parameter value used by Crabtree et al. and quoted by Westrell and Haas et al., was obtained from Couch et al. (1966) which was a study of airborne infection.