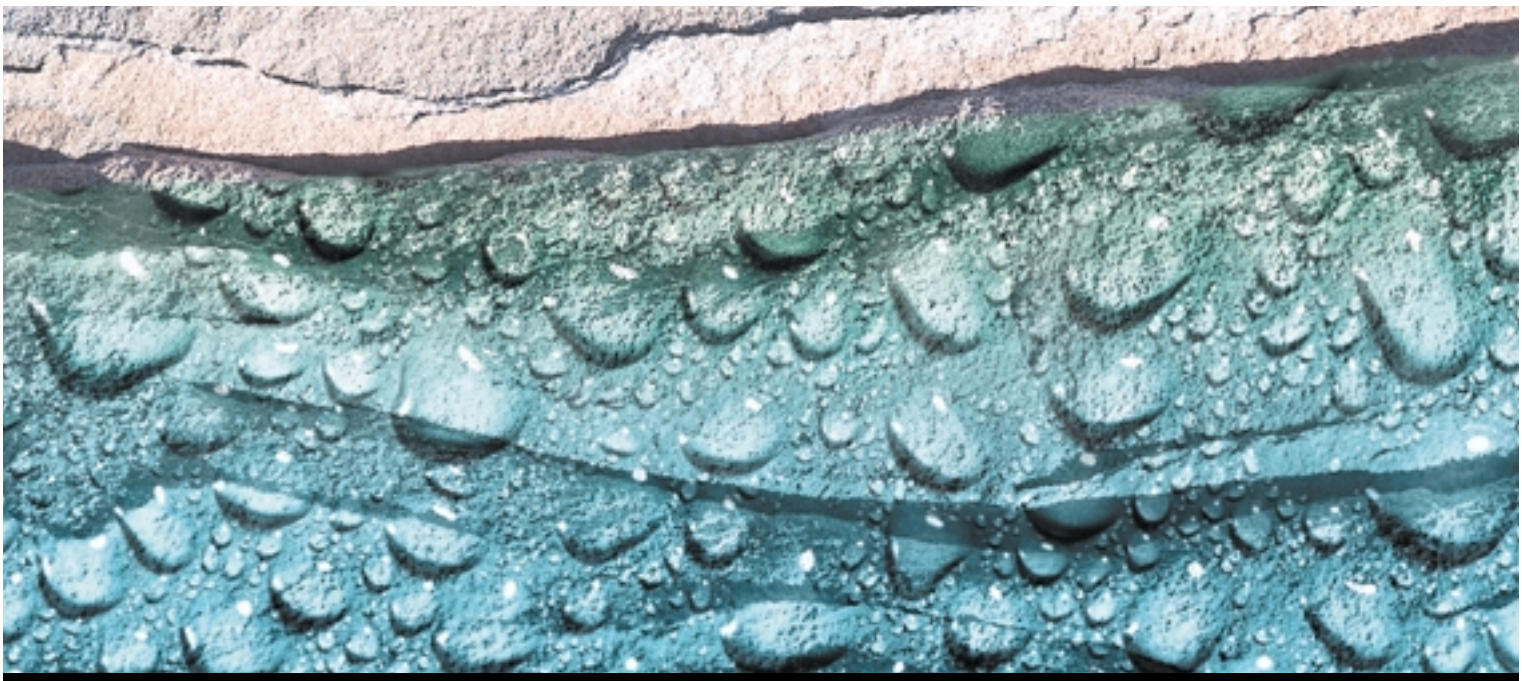

GUIDELINES FOR

Assessing the **Risk** to **Groundwater** from **On-Site Sanitation**

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

DFID Department for International Development

BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/01/142

Guidelines for Assessing the Risk to Groundwater from On-Site Sanitation

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Foreword

There has been encouraging progress with access to safe drinking water and sanitation in both rural and urban areas since the United Nations Water Decade of the 1980s. However, more than 1 billion people around the world still lack access to safe water supplies and more than 2.4 billion are without adequate sanitation. A substantial majority of these people live in Asia where the lack of sanitation provision is particularly acute. In Africa, over one third of the population still remains without access to safe water and sanitation, and many of these can only be served by groundwater. The need for renewed efforts to improve the situation is recognised in DFID's recently published water strategy paper – "Addressing the Water Crisis - Healthier and More Productive Lives for Poor People".

The health benefits of safe water supply are only properly realised when programmes combine safe water supply with sanitation and the promotion of safe hygiene practice. With increasing population, the pressure on land in all cities is becoming intense. High levels of pollution are increasing the risk to groundwater from sanitation and drainage facilities.

These guidelines are an important contribution to risk assessment and the avoidance of the contamination of groundwater supplies from on-site sanitation. They have been developed as part of a project funded by DFID through the water component of the Infrastructure and Urban Development Division's Knowledge and Research Programme.

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1 Overview

Purpose

Many people in developing countries rely upon untreated groundwater supplies for their drinking water. These supplies are obtained from drilled boreholes or tubewells, dugwells and springs. Such sources are usually of good quality and much better than some traditional sources of supply, for example ponds and streams. However, groundwater can become contaminated and there is special concern that the introduction of on-site sanitation systems may in certain circumstances contribute to contamination of drinking water supplies.

The purpose of this manual is to provide guidance on how to assess and reduce the risk of contamination of groundwater supplies from on-site sanitation systems and is aimed at those responsible for planning low cost water supply and sanitation schemes. Specific objectives include providing:

- guidance where water supply and/or sanitation systems are planned;
- confidence that existing groundwater supplies are properly constructed (pollution risk is assessed as low and monitoring confirms good quality water);
- help to identify the likely source(s) and pathway(s) of pollution where pollution is observed;
- guidance on the planning of monitoring programmes.

The need for such a manual is apparent given the importance of groundwater for water supply and the lack of any existing decision making guidelines. The manual does not seek to provide a set of prescriptive rules but instead to provide the framework for arriving at a decision based on an evaluation of the risks posed by on-site sanitation systems to groundwater drinking water supplies in different settings or environments. However, the risk needs to be balanced by the requirements of the user community, the cost of design, and the quality of supply. Decisions on what risks are acceptable will vary with location and situation.

The guidelines developed needed to meet certain criteria:

- only easily available or known data are required when making a risk-based evaluation;
- the tables and figures provided to aid the decision-making process are easy to use and require only basic understanding of geology/hydrogeology;
- the approach is rational and transparent.

It is anticipated that the readership for this manual will include both those with good technical knowledge of the problem (e.g. water and sanitation engineers) and those who are less familiar with the scientific and technical arguments. This manual aims to be accessible to everyone with a role in the planning of water supply and sanitation at programme level.

An overview of the manual

The manual can be conveniently subdivided into two parts:

Part 1: the background to the problem which provides the rationale for the guidelines in Part 2

Chapter 2: Water supply and sanitation choices. Water supply and sanitation is set within the context of other measures that can be taken to reduce the incidence and prevalence of infectious disease caused by pathogenic micro-organisms. In relation to water quality, the role and value of indicator bacteria is discussed (it is not feasible to test for all pathogens in water so water quality monitoring is based on the occurrence of bacteria that indicate the presence of faecal contamination). The advantages and disadvantages of a range of sanitation types are presented, including both off-site and on-site sanitation. The main groundwater

supply types are described.

Chapter 3: Technical background

The role of groundwater and basic hydrogeological terms used in the manual are defined. Contamination from on-site sanitation can reach groundwater supplies by a range of pathways. In the manual these are grouped into pathways through the main body of the aquifer and pathways created by the design and construction of the groundwater supply (localised pathways). In relation to the aquifer pathway, the concept of aquifer pollution vulnerability is presented. This represents the intrinsic characteristics of the aquifer, which determine whether it is likely to be affected by a contaminant load. The vulnerability is assessed based on travel time for water to move from the ground surface to the water-table. The greater the travel time the greater the opportunity for contaminant attenuation.

The broad range of hydrogeological environments are described in terms of this vulnerability.

A brief overview of sources of faecal contamination is given. The contaminants associated with on-site sanitation are discussed, i.e. microbiological and chemical, primarily nitrate. Their persistence, mobility and effect on health are described. The attenuation processes that control the numbers or concentration of the contaminants is key to understanding the risks from on-site sanitation. The discussion of microbiological contaminant attenuation leads on to a definition of categories of risk, **significant, low** and **very low.** These are defined in terms of travel time in the subsurface from the contaminant source to the groundwater supply. They relate to levels in confidence that abstracted groundwater for drinking will meet the WHO guidelines for indicator bacteria. It is emphasized that the lack of indicator bacteria does not necessarily mean that more persistent pathogens will have been removed from water entering the supply.

As well as following a pathway through the aquifer from source to supply, contamination of groundwater supplies can also occur via pathways introduced by the design and construction of the borehole, dugwell or spring. Key issues are highlighted both for the design and construction of groundwater installations and for sanitary protection measures at the headworks. Maintenance of the headworks and the surrounding area over time is also of prime importance if the measures that have been put in place are not to deteriorate. This issue is addressed here and in Chapter 5 of the guidelines.

Part 2: the guidelines with explanatory notes

Chapter 4: First-step risk assessments

Three risk assessments are presented based on combinations of contaminant type and pathway.

Assessing the risk of microbiological contamination of groundwater supplies via aquifer pathways.

The assessment is made in 4 steps.

- Background data are collected on the basic geology, the depth to water-table and the sanitation system used or planned to be used;
- likely attenuation in the unsaturated zone is assessed;
- if this is not considered sufficient for the risk to be acceptable, an assessment is made for boreholes as to whether it is possible to place the screen section of the borehole at sufficient depth such that the travel time is increased to the point where the risk is acceptable;

- for dugwells and springs, and boreholes where vertical separation is not appropriate, assessment is made as to whether it is feasible to laterally separate the potential pollution sources and supply so that the risk is acceptable.

Where there is a residual risk, options are suggested.

Assessing the risk of nitrate contamination of groundwater supplies as a result of widespread aquifer contamination.

Estimating nitrate leaching is at best approximate. This risk assessment seeks to indicate only whether or not a potential risk is likely. A critical element in assessing risk of widespread nitrate contamination of an aquifer is to consider the short and long-term water supply and sanitation plan. Generally nitrate does not degrade in shallow aquifers. In some cases the use of shallow groundwater may be viewed as a short-term intervention, the long-term aim being to develop a piped distribution network based on surface water or distant groundwater sources. In this situation concerns over nitrate in groundwater may be relatively limited and the potential benefits of improved sanitation may outweigh the risks. In other situations, however, long-term water supply may be based on continued use of groundwater. The risk assessment provides simple tools for estimating nitrate leachate concentrations and discusses the sustainability of groundwater usage within a range of environments.

Assessing the risk of microbiological contamination due to pathways created by construction of the groundwater supply

Reducing the risk of contamination via localised pathways is achieved firstly by keeping potential pollution sources away from the immediate vicinity of the water supply and secondly by minimising the pathways created by the design or construction of the supply. The assessment is divided into two steps, the first assessing the sanitary conditions of the headworks and the second the sanitary provisions below ground surface.

Chapter 5: Ongoing assessment of risk through monitoring

Risk assessment does not end with the construction of the groundwater supply and/or the sanitation facility. Monitoring is a key element of any water supply and sanitation programme.

Why monitor

This section reviews the objectives of water quality monitoring covering four different types of monitoring:

- providing confidence in the design of water and sanitation programmes as a means of verifying the decisions made on the basis of the first-step risk assessment;
- establishing the cause of contamination when this has been found, as a means of determining a remedial action;
- health-based surveillance to ensure that water quality meet health-based standards and guidelines;
- evaluating trends in water quality and risk over time so that changes can be identified and actions taken.

How to monitor

This section discusses the ways in which monitoring programmes can be designed and how data can be collected. It provides information concerning:

- the selection of water quality parameters and the facilities and equipment that are required.
- the advantages and disadvantages of field and laboratory approaches and the cost implications of each approach.

- how to perform a sanitary inspection and the use of sanitary inspections in monitoring.

When and where to monitor

This section discusses the numbers, frequency and location of sampling points. These decisions are influenced by a number of factors:

- the objectives of the monitoring and the resources available;
- it is often not possible to test all water supplies and a sample of water supplies is selected for the monitoring programme. These should be representative of the different environments and water supplies in the country;
- water quality often deteriorates during the wet seasons and this should be taken into account when planning sampling programmes;
- chemical quality often varies less significantly than microbiological quality and so need less frequent testing.

Data analysis and interpretation

This section provides guidance on how data can be analysed, interpreted and used:

- whether contamination is localised or widespread and the indicators that help interpreting the scale of the contamination;
- how to investigate the causes of widespread contamination in aquifers and to interpret water quality data in relation to flow rates;
- how to investigate the cause of localised contamination and how to carry out analysis of water quality and sanitary inspection data in order to identify which factors are most likely to be influencing water quality;
- how to use the data and initiate follow-up actions to improve water quality;
- how communities can be involved in monitoring, what roles they can play and how they may use the data.

The manual as a tool for planning water supply and sanitation programmes

The manual is designed to help those people who are involved in the planning and design of water and sanitation programmes. This may include technical staff such as engineers and hydrogeologists, but will also include programme managers and others making management decisions.

Reading the manual

The structure of the manual allows readers with different levels of understanding of hydrogeology and water and sanitation to use the manual in different ways. For those readers who have very little knowledge about groundwater, it is useful to read Part 1 (Chapters 2 and 3) before using the guidelines in Part 2. Part 1 of the manual provides some useful background information. All readers should make sure that they understand the health impacts of poor water supply, sanitation and hygiene contained in Chapters 2 and 3 as this is critical to making decisions about planning water and sanitation facilities. It is also important that all readers understand the different severity of risk posed by different types of contaminant and the potential for reducing these risks through separating on-site sanitation and water supplies.

Readers who already have a good understanding of the health, groundwater and water supply and sanitation options may not need to read Chapters 2 and 3 in detail and may wish to go straight to the guidelines contained in Part 2 (Chapters 4 and 5). When using the guidelines, two approaches are presented: first-step risk assessments using simple hydrogeological and engineering information to make decisions about locating on-site sanitation and water supplies; and, ongoing risk assessment through monitoring. These approaches are complementary and even where

the first-step risk assessment has been undertaken, ongoing risk assessment through monitoring is recommended to ensure that changes over time can be identified and remedial actions taken. Where the first-step risk assessment is difficult to perform, perhaps because of limited data, then planning can be based on the outputs of monitoring. However, it is recommended that even in such cases, the data needed for the first-step risk assessment is collected and the risk assessment procedure followed.

Using the guidelines in planning

It is important that when planning water supply and sanitation programmes that an integrated approach is taken to the design, construction and location of the two elements. Planning of water supply and sanitation facilities often requires sound technical competence. However, it is now widely accepted that communities and users of facilities must be actively involved in water and sanitation programmes from the design stage, as in many cases, communities will undertake management of the water and sanitation facilities. These guidelines are supportive of such a process as they use a flexible approach to managing risk that allows compromises to be made between the level of risk accepted in drinking water and the health consequences of poor sanitation. Therefore, it is expected that these guidelines should help water and sanitation programmes to provide more information to communities to help them make better informed decisions about technologies and risks to their health.

The principal components of the major water supply and sanitation technologies are described in the guidelines, however, readers are encouraged to consult other documents on the design of different technologies and the implementation of water and sanitation programmes, to help make decisions about how risks can be managed. Some suggested texts are provided in the Reference section at the end of the document. It may be necessary when addressing elements of the decision-making process within the guidelines to refer to organisations with expertise in the relevant topic.

These guidelines are based on the best available scientific evidence. However, research on the movement and attenuation of pathogens in the subsurface is not at all extensive, in particular there have been few well-documented studies from developing countries. Nevertheless, this manual fulfils an important role given the pressing need for guidelines that address the design, construction and relative siting of groundwater supplies and sanitation. These guidelines should be seen as a first step only and as more data and research become available the manual will need to be updated and revised.

Using the guidelines at a national level

These guidelines provide a clear and easy to follow approach to assessing risks to groundwater, however, it has been prepared as a document with broad application in developing countries and therefore cannot provide detailed information on every hydrogeological environment. Furthermore the guidelines present a process of risk assessment. By following this process, specific guidance in terms of lateral separation distances, technologies used and design criteria may be developed in each country and for different hydrogeological regimes within each country.

At a national level, it is likely to be useful for the guidelines to be used to define a set of design and planning criteria for water and sanitation programmes that are specific to local conditions. The guidelines provide the basis for this approach

and allow the user to define more precise limits acceptable to local populations.

Links to other documents on groundwater

This manual is designed as a document to help decision-making in programmes. The approach presented is underpinned by proven scientific evidence and fieldwork. However, as a document designed for use in planning, the manual does not present all the scientific arguments and evidence as this would make the document much larger and would be less user-friendly for routine consultation.

Much fuller and complete discussion of the scientific principles and evidence drawn on in the manual is available in two other related documents. There is a scientific review/case study report that is a companion to this manual and is available from the ARGOSS project. This document provides the key arguments for the approach presented and provides detailed descriptions of case studies undertaken by the ARGOSS project in Uganda and Bangladesh, as well as related case studies from other countries. It is recommended that readers consult these case studies for more information about data analysis.

In addition, there is also a WHO monograph in preparation (Protecting groundwater for health: a guide to managing drinking water sources) that also contains useful material on the health impacts of contamination of groundwater. As members of the ARGOSS team have been actively involved in the preparation of this document, it provides a useful background to many of the principles used within the ARGOSS project.

Part 1:

Background and rationale

2 Water supply and sanitation choices

The provision of water and sanitation facilities are important public health measures that contribute significantly to the reduction in the disease burden of populations. The provision of such facilities is also critical to socio-economic development and has important equity implications as increasing numbers of international protocols and national policies emphasise the 'rights-based' approach to development.

Whilst the absence of water and sanitation facilities is associated with high rates of disease incidence and prevalence and high infant mortality rates, it is important that the improvement of water and sanitation should be integrated and properly planned. One of the outcomes of poorly planned water and sanitation programmes may be the contamination of drinking water by faecal matter derived from on-site sanitation.

This chapter provides an overview of the water supply and sanitation choices available, discusses the possible contamination of groundwater supplies in the context of infectious disease transmission and assesses the value of present methods for indicating faecal contamination of groundwater.

2.1 Health implications

The improvement of water and sanitation in developing countries is largely driven by the need to reduce the incidence and prevalence of infectious disease caused by pathogenic micro-organisms. The majority of pathogens that affect humans are derived from faeces and transmitted by the faecal-oral route. Pathogen transmission may occur through a variety of routes including food, water, poor personal hygiene and flies, see Figure 2.1. Thus in order to reduce the health burden caused by infectious disease, interventions are required in excreta disposal (to remove faeces from the environment), water supply (to prevent consumption of water containing pathogens) and hygiene education (to prevent transmission from contaminated hands into food or water).

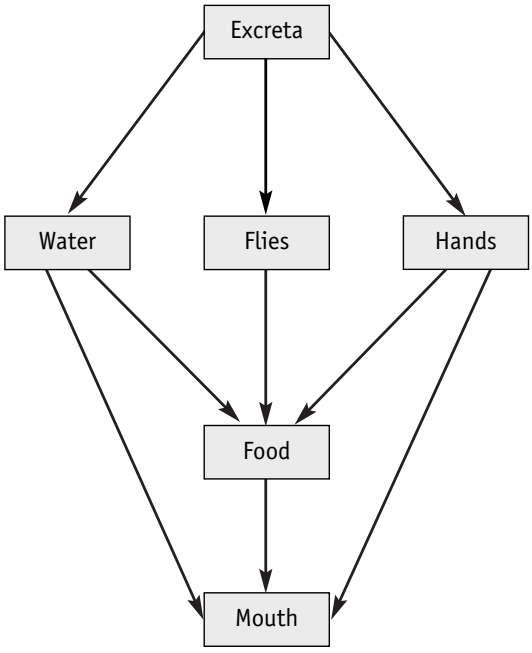


Figure 2.1. *Principal elements of faecal–oral disease transmission*

These guidelines are designed to protect public health by ensuring that the quality of water from groundwater supplies is adequate. However, it should be understood from the outset that risks can be reduced or managed, but not eliminated – some risk, however small, will always remain.

When planning and developing a water and sanitation programme a balance must be maintained between several different competing risks to health. Decisions designed to reduce one health risk, for instance by reducing contamination of drinking water, should not increase health risks due to a lack of sanitation. The control of risks to groundwater from on-site

sanitation only addresses one set of pathways in Figure 2.1. It is essential that all routes of disease transmission are addressed to improve public health.

It may be necessary to accept water of lower quality if it means that sanitation can be provided that is acceptable and affordable to the community. Low levels of contamination may represent a very limited risk to health in situations when there is no excreta disposal or hygiene is very poor. In addition to the presence of pathogens, disease may be influenced by a range of factors in different individuals such as immune status, nutritional status and concurrent disease burden. When setting a level of risk to health that is acceptable, it may not be possible to reduce the risks to the whole population. To produce water supplies of little risk to very vulnerable groups may be very costly and it might be more cost effective to promote household water treatment for these groups.

Various epidemiological studies have been undertaken to review the importance of different components of water and sanitation in order to establish where improvements may give the greatest benefits. The impact of different aspects of water and sanitation appears to be largely dependent on the conditions within a particular community and existing access to other components of water and sanitation as well as other factors. However, there is significant evidence that integrated approaches yield the greatest benefits.

There may be a number of reasons why source water quality improvements have only a limited impact. Whilst source water quality may be good, evidence from many countries indicates that subsequent re-contamination during transport and storage is common. This affects both people utilising communal sources and those utilising piped water subject to frequent, unpredictable or extended periods of interruption. Thus, great attention is often paid to the promotion of safe handling practices and treatment of water within the home.

However, there is evidence that the improvement of source water quality may be more important than is sometimes considered for two reasons:

- source water quality may be critical to prevent the introduction of an exotic pathogen into the community, which may lead to an unexpected explosive outbreak. Water quality has been consistently shown to be important in epidemic control;
- if source water quality is poor, then treatment of water within the home will be necessary. This is generally expensive and represents an additional burden on the rural and urban poor. Where source water quality is good, health education can focus on lower-cost interventions such as safe handling and storage practices that require little additional household expenditure.

However, the need for improvements in sanitation is well recognised world-wide and current rates of access to improved sanitation lag far behind those for drinking-water supply.

2.2 Water quality problems and contamination indicators

There is a wide range of pathogens that may be found in drinking water including bacteria, viruses, protozoa and helminths. Infective doses vary enormously but may be as little as a single virion or cyst. Different people may be more susceptible to disease depending on their immune status, prior exposure and nutritional status. Therefore the basis of most guidelines and standards for drinking water is an absence of pathogens within drinking water.

In many cases analytical methods for

pathogens do not exist or are expensive and time consuming. As a result current approaches to water quality control are usually based on the absence of bacteria that indicate the presence of faecal contamination within samples taken from the water supply (principally *E.coli* or thermotolerant (faecal) coliforms). Absence of such indicator bacteria within samples is often then taken to define the water supply as 'safe'.

It is increasingly recognised that the current indicators have significant limitations and there is evidence world-wide of pathogen presence in water which meets current guidelines and standards, resulting in disease outbreaks. In particular, indicator bacteria are of limited use in predicting the presence of protozoa and viruses both of which may be significantly more resistant to disinfection and may survive longer in the environment. In the case of protozoa, sanitary completion measures usually provide sufficient security for groundwater supplies. In the case of viruses, control is more problematic as viruses may survive for substantially longer in water than faecal coliform bacteria and may undergo only temporary retardation. This can result in later release of viruses into the water in an infective state. Furthermore, there is increasing evidence from research that many pathogens undergo rapid changes in virulence due to genetic mutation outside the human body, thus making identification of pathogens more difficult. Further problems result from the ability of some indicators to multiply within contaminated water in warmer climates.

However, despite these well-recognised limitations, the limited number and scale of outbreaks of infectious water-related diseases, where water supplies have in general met the standards set for indicator bacteria, implies that they provide a reliable estimate of health risk. However, the meaning of the presence or absence of indicators should be clearly understood and the analysis of indicator bacteria should be supported by risk assessment and source protection. The presence of indicator bacteria indicates that there has been recent gross contamination, largely derived from sources of faeces within the environment. An absence of indicators does not mean a total absence of pathogens, however, the absence of faecal indicators can be taken as an indication that water is relatively *low risk*.

In addition to microbiological contamination, chemical contaminants may also cause ill health, although in most cases this is related to chronic as opposed to acute effects. There are exceptions to this and nitrate, fluoride and arsenic are all substances that can lead to a short-term health impact. In the context of the impact of on-site sanitation, the principal contaminant of concern is nitrate, which has been linked to methaemaglobinamenia or infantile cyanosis.

Nitrate is the most stable form of nitrogen in environments where abundant oxygen is available. This is the usual condition of shallow groundwater where hand pumps and protected springs are most often used. Generally nitrate does not degrade in shallow groundwater and dilution is the principal mechanism for reducing concentrations. Nitrate contamination problems may not become obvious immediately. However, the potential long-term impact of nitrate contamination should be borne in mind when planning sanitation programmes as remedial action is difficult and blending with low nitrate waters may be the only viable option. As nitrate may be derived from other sources, it is important to evaluate both the relative contribution of different sources and the total nitrate load. Nitrate concentration is relatively cheap and simple to determine and does not require an indicator.

2.3 Types of sanitation and their potential impacts

Sanitation facilities may be water-borne or dry. There are many different forms of sanitation ranging from conventional and modified sewerage, to water-borne on-site systems such as septic tanks, aquaprivies and pour-flush latrines to dry systems which are generally different forms of pit latrines, some of which may include urine separation (Figure 2.2). The choice of sanitation system is based partly on availability of water, but also on cultural reasons and anal cleansing methods. Sanitation systems can be divided into two principal categories:

1. Off-site methods—these are different forms of sewerage where faecal and household wastes are carried away from the household. No treatment occurs at the household and the waste must be taken to a treatment plant before discharge into the environment.
2. On-site methods—including septic tanks and all forms of pit latrines. In these systems the wastes are stored at the point of disposal and usually undergo some degree of decomposition on site. On-site systems either require periodic emptying or construction of new facilities once they fill up.

Off-site methods

Off-site methods are often found in urban areas where space constraints limit the potential for on-site facilities. They often, but not always, provide a greater degree of convenience than on-site methods and ultimate responsibility for the treatment and disposal of waste usually lies with a utility or local authority. Conventional sewerage is very expensive and requires an in-house level of water supply to function properly. However, cost analyses have shown that modified sewerage becomes cheaper than on-site methods at higher population densities.

Whilst sewerage is often viewed as the most desirable form of sanitation, it has several drawbacks. There is evidence from Europe that leaking sewers may significantly contribute to microbiological and nitrate contamination of groundwater and therefore may represent a significant risk where groundwater is exploited for domestic supply. Furthermore, sewage requires treatment and this is often poorly operated and managed leading to the discharge of inadequately treated wastes into the environment. In most cases this will be into surface water bodies although groundwater may become contaminated subsequently where it is in hydraulic connection

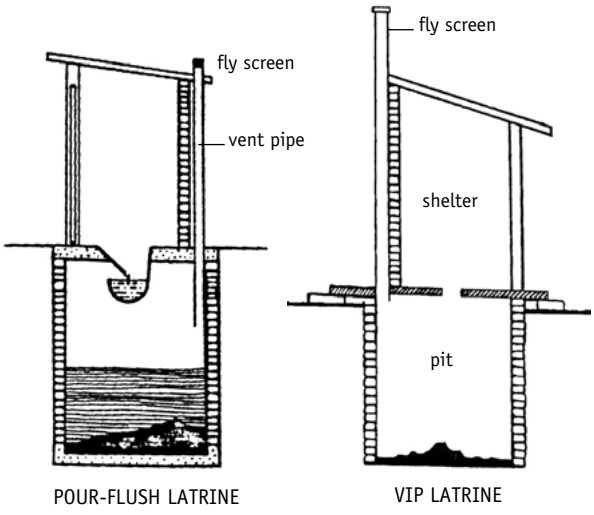


Figure 2.2. *Examples of on-site sanitation design*

Table 2.1. *Advantages and disadvantages of different sanitation systems (adapted from Franceys* et al*, 1992)*

Sanitation system	Water requirements	Advantages	Disadvantages
On-site			
Simple pit latrines & sanplat	dry	Cheap builds on existing experience limited expertise needed for construction	significant fly and odour problems concerns by users over safety
VIP latrine	dry	fly and odour problem is reduced lower-cost than water-borne systems limited construction expertise required	cost significantly higher than simple latrines siting requires careful consideration semi-dark interior may be disliked by users
Pour-flush latrines	wet with low volume water use	Low-volume water use appropriate in cultures where water used for anal cleansing fly and odour problem controlled convenience for users easily upgraded	costs increased reliable supply of water must be assured cannot be used where bulky materials used for anal cleansing
Composting latrine	dry	useful humus produced as fertiliser/ soil conditioner	requires careful operation sludge needs careful handling some systems require urine separation ash and vegetable matter must be added regularly
Soak Trenches	dry	cheap limited expertise needed for construction shallower than pits, greater thickness of unsaturated zone	significant fly and odour problems difficult to protect covers large area, difficult to find space in urban areas
Urine separation	dry with urine collected separately	provides useful humus for fertiliser urine can be used as fertiliser low-cost systems available reduces hydraulic load	desludging requires careful handling pathogens may not be inactivated in sludge pile user education on use of system required significant time spent in O&M
Septic tanks	wet with high volume water use	convenience same as conventional sewerage limited fly or odour problems wastes removed rapidly	high cost in-house piped water generally required large space requirement regular desludging required permeable soil required
Aqua privies	wet with medium volume water use	in-house piped water not required less expensive than septic tank	reliable supply of water required close to the home more expensive than pour-flush fly and odour problems may still exist regular desludging required permeable soil needed for effluent disposal
Off-site			
Modified sewerage (small-bore and shallow)	wet with low volume water use	convenience to user similar to conventional sewerage can be maintained by communities costs reduce at higher population densities shallow sewers have very limited space requirements	small-bore systems require solids tank and periodic emptying—not appropriate in areas with space constraints shallow systems needs relatively large number of users to ensure stagnation does not occur wastes require treatment
Conventional sewerage	wet with high volume water use	user convenience limited fly or odour problems wastes removed rapidly	needs large volumes of water piped into the home very expensive treatment required leakage common

with surface water. Some forms of treatment plant, such as waste stabilisation ponds, may be prone to leaching of both microbiological and chemical contaminants. Thus when considering the use of sewerage, attention must be paid to the potential for groundwater contamination, ensuring that systems are operated and designed with groundwater protection needs in mind.

On-site methods

On-site methods include both expensive systems such as septic tanks that provide the same degree of convenience as a sewer, and cheaper pit latrines. On-site systems often represent a significant hazard to groundwater because faecal matter accumulates in one place and leaching of contaminants into the subsurface environment may occur. Septic tanks typically hold the solid component of wastes in a sealed tank where the matter decomposes anaerobically. Liquid effluent is usually discharged into a soakaway pit. In well-designed septic tanks, the solid matter does not represent a significant hazard, but the soakaway pits may cause both microbiological and chemical contamination. The liquid part of the waste in a pit latrine that infiltrates into the soil is called the hydraulic load. Where hydraulic loads are high and exceed natural attenuation potential in the sub-surface this may lead to direct contamination of groundwater supplies.

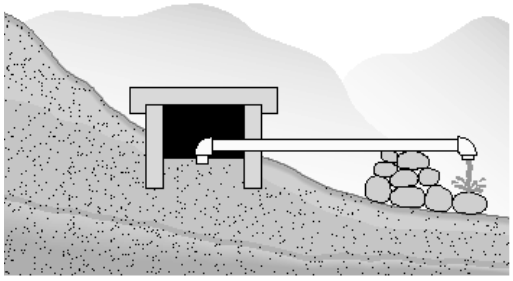
Pit latrines are usually not sealed, although sealed pits may be used in urban areas or in areas of high water-table. In general pit latrines are only appropriate where the level of water supply is low (communal or yard) and are not appropriate when large volumes of wastewater are generated. In most pit latrine designs, the liquid part of the waste is allowed to infiltrate into the soil, although some pour-flush latrine designs provide a soakaway. This infiltration of wastes (often containing micro-organisms and nitrogen, the latter may be oxidised to nitrate) represents an additional hazard to groundwater, particularly as this frequently occurs at some depth in the subsurface and thus by-passes the soil. The soil is the most biologically active layer and is where contaminant attenuation is greatest. However, biological communities also typically develop around the active parts of the pit and contain predatory micro-organisms capable of removing pathogens. This may help limit the risk of contaminant movement to deeper layers to some degree.

The choice of sanitation technology depends on many economic, technical and social issues and each type of technology has advantages and disadvantages as noted in Table 2.1.

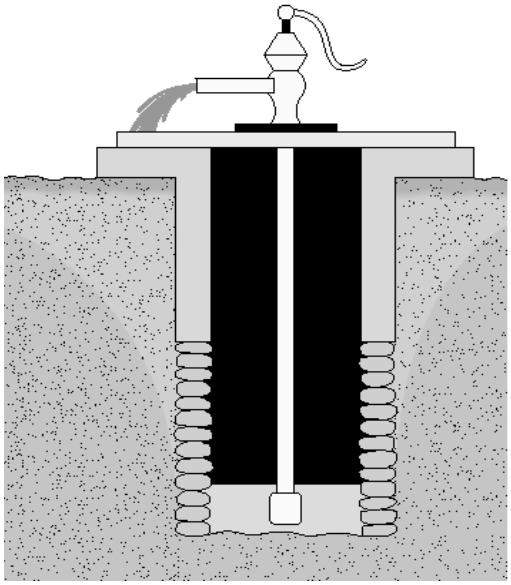
Pit latrines are in general the cheapest form of sanitation and can be easily constructed at a household level. In rural areas, they often represent the only viable sanitation option given the low-level of water supply service. In many peri-urban areas pit latrines may also be commonly used and may represent a greater hazard as the numbers and densities of pit latrines increase the potential for groundwater pollution. Pit latrine designs can be improved to reduce such risks.

2.4 Groundwater supplies

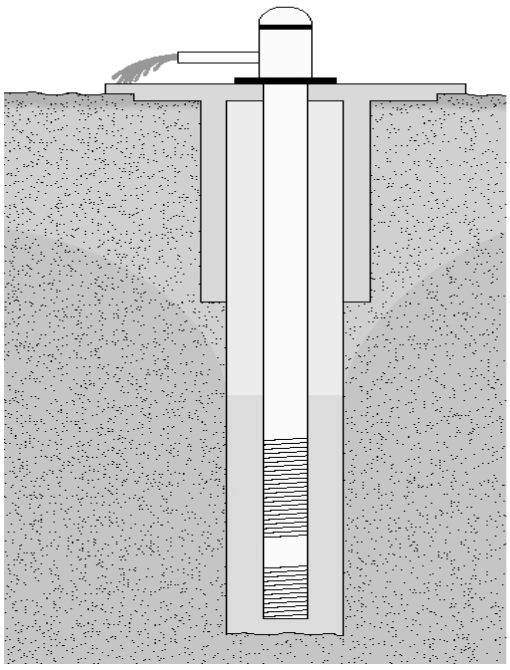
In its natural state, groundwater is usually of good microbiological quality and as a result is often the preferred source of drinking water supply as treatment is limited to disinfection. In the case of rural and peri-urban supplies, groundwater supplies are usually untreated. However, the construction of groundwater supplies may provide a direct route for contamination of groundwater and therefore need to be properly designed and constructed.



protected spring



protected dugwell



borehole or tubewell

Figure 2.3. *Typical groundwater supply designs*

The principal forms of groundwater supply used for drinking water are shown in Figure 2.3 and are briefly discussed below:

Boreholes (also known as tube wells)—These are narrow-diameter, drilled holes that can be shallow or deep, and use a handpump or motorised or electric submersible pump to abstract water. A variety of methods may be used to construct boreholes, including simple hand-drilling methods and some of these may increase the risks of contamination. Boreholes are often easier to protect from pollution than other groundwater supplies.

Dug wells—these are usually dug by hand and are typically of large diameter and of relatively shallow depth. These may be fitted with a hand pump or some other form of improved water collection or buckets and ropes utilised. Dug wells are susceptible to contamination, especially where shallow and/or uncovered.

Springs—these may occur where groundwater discharges at the surface. They are generally protected by constructing a spring box around the eye of the spring and may feed piped systems by gravity. Springs can be susceptible to contamination and great care needs to be taken to protect the supply. Where groundwater forms a seep line, an infiltration gallery may be used.

2.5 Risk: source-pathway-receptor

The risk of contamination of groundwater supplies by on-site sanitation uses the concept of source-pathway-receptor, as shown in Figure 2.4. For a risk to a receptor (in this case a groundwater supply) to exist both a source of contamination and a pathway must be present (the pathway provides the means or route for contamination to reach the receptor).

In the natural environment, sources of contamination are always present and usually widespread, including on-site sanitation. Pathways that allow water to move from these sources to the receptor can be subdivided into (Figure 2.5):

- pathways that occur naturally in the subsurface due to openings and cracks in the soil and rock **(aquifer pathway)**
- man-made pathways that occur as a consequence of the design and construction of the receptor **(localised pathway)**

Fortunately, many contaminants, especially micro-organisms, can be rendered harmless or reduced to low numbers/concentrations by natural processes provided there is sufficient time. Chapter 3 discusses these processes as well as the sources of contamination and the pathways. Reducing the risk (to the receptor) can be achieved by:

- removing the source of contamination or reducing the levels of contaminants that are produced;
- increasing the time for water to travel from the source to the receptor; and
- minimising man-made pathways

The assessment of risk and identification of options to reduce it are discussed in detail in Chapters 4 and 5.

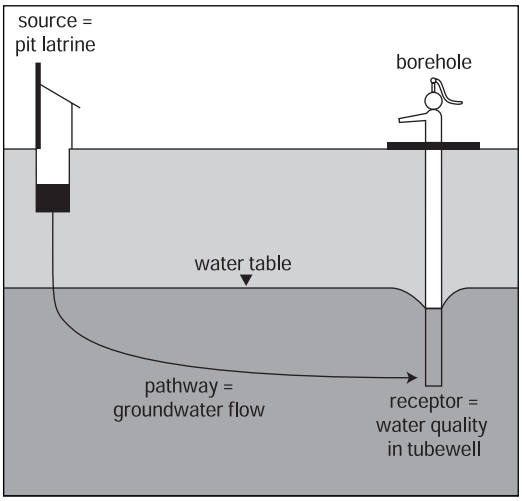


Figure 2.4. *The source—pathway—receptor concept. An example using the aquifer pathway for contamination from pit latrine to borehole*

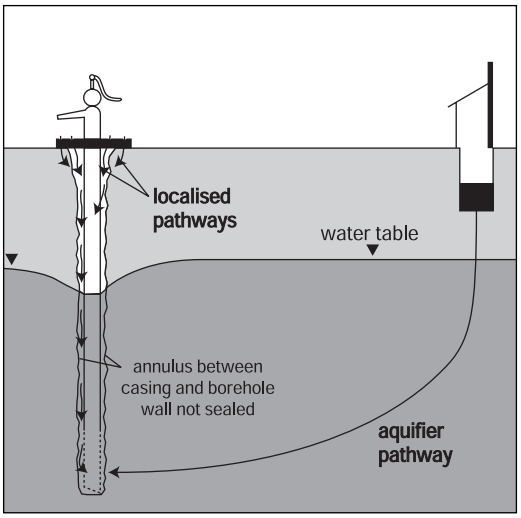


Figure 2.5. *Natural and man-made pollution pathways to groundwater supplies*

Summary of key points from Chapter 2

- The majority of pathogens that affect humans are derived from faeces and transmitted by the faecal-oral route through a variety of ways including food, water, poor personal hygiene and flies. Therefore to reduce the health burden caused by infectious disease, interventions are required in excreta disposal, water supply and hygiene education.
- The quality of water supplied is of crucial importance; firstly to prevent the introduction of an exotic pathogen into the community, which may lead to an unexpected explosive outbreak and secondly, because treatment (which may be necessary if water quality is poor) is often expensive and represents an additional burden on the rural and urban poor. Where the quality of the water supplied is good, hygiene education can focus on safe handling and storage practices.
- On-site systems often represent a significant hazard to groundwater because faecal matter accumulates in one place and leaching of associated microbiological and chemical contaminants into the sub-surface environment may occur.
- Infective doses of microbiological contaminants vary enormously but may be as little as a single virion or cyst.
- Although it is increasingly recognised that current faecal indicator bacteria have significant limitations, they still provide a reasonable estimate of risk of pathogen presence.
- The principal chemical contaminant of concern is nitrate, the potential long-term impact of this contamination should be borne in mind when planning sanitation programmes as remedial action is difficult.
- The construction of groundwater supplies may provide a direct route for contamination of groundwater and therefore need to be properly designed and constructed.

3 Technical background

3.1 Importance of groundwater

Groundwater constitutes some 97% of all freshwater that is potentially available for human use. Groundwater is therefore of fundamental importance to human life.

When rain falls, a part infiltrates the soil. While a proportion of this moisture will be taken up by plants or evaporate back into the atmosphere, some will infiltrate more deeply, eventually accumulating as an underground water body or reservoir. Where this underground reservoir permits significant quantities of water to be abstracted it is known as an aquifer. The ground above the aquifer through which the infiltration percolated is referred to as the unsaturated zone. The level to which the ground is fully saturated is known as the water-table (Figure 3.1).

An aquifer's productivity depends on the fundamental characteristics of being able to both store and transmit water. But all aquifers are not the same. Unconsolidated granular sediments such as sands contain pore spaces between the grains. The proportion of pore spaces to the total volume of sediments is known as the porosity, for example, the porosity of a sand can exceed 30%. However, where these sediments become buried, they are transformed, over millions of years, to harder more compact consolidated rocks such as sandstones and limestones. One consequence is that the porosity is reduced. In consolidated rocks, cracks or fractures may form; these fractures also store and transmit groundwater although the percentage of the rock taken-up by fractures (that is the fracture porosity) rarely exceeds 1%. However, these fractures can play an important role in groundwater flow as is discussed below. Other rocks which can be useful aquifers, where they are fractured or weathered, include volcanic lavas and crystalline basement.

Aquifers need to transmit water, as well as store water. The water-transmitting characteristic

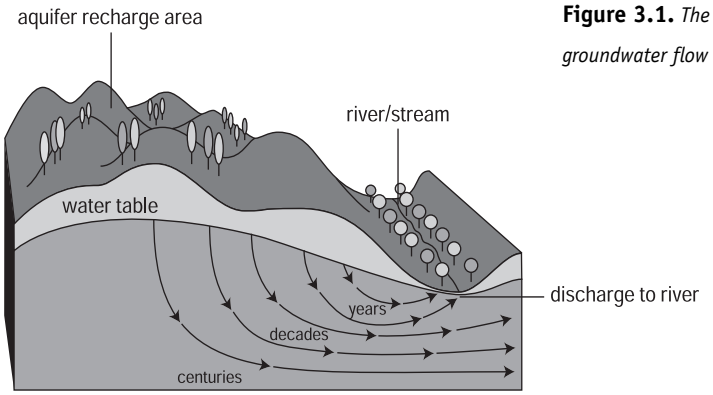


Figure 3.1. *The groundwater flow system*

of an aquifer is known as its permeability. This is a measure of the ease with which water can flow through the rock. Permeability will be greater in rocks with larger pores that are well connected with each other or in rocks with wider and connected fractures. Therefore sands and gravels, which have large, well-connected pore spaces between the grains, make good aquifers. Clays, however, which have high porosity but very little connection between the pores, transmit water only very poorly. Fractures in rocks are able to transmit water very easily and rapidly, indeed fractured aquifers (e.g. limestones) can produce the most permeable aquifers. The unit of measurement of permeability is the same as that for velocity (e.g. m/day). Typical permeability values for various rock types are given in Table 3.1.

All aquifers have a source of recharge water. This is normally rainfall but can be seepage from rivers, lakes or canals. The water-table rises in response to recharge and declines due to outflow from the system. Water leaves the aquifer where the water-table reaches the land surface, for example as a spring or seepage or as flow into a stream, or river (Figure 3.1). Groundwater systems are therefore dynamic with groundwater continuously in slow motion from zones of recharge to areas of discharge. Since flow rates do not normally exceed a few metres per day and can be as low as 1 metre per year, the passage of water

Table 3.1. *Typical permeability values for various rock types.*

Lithology	Range of likely permeability (m/d)
Silt	0.01–0.1
Fine silty sand	0.1–10
Weathered basement (not fractured)	0.01–10
Medium sand	10–100
Gravel	100–1000
Fractured rocks	difficult to generalise, velocities of tens or hundreds of m/d possible

through this subterranean part of the hydrological cycle may take tens, hundreds or even thousands of years.

3.2 Aquifer vulnerability to pollution and risks to groundwater supplies

As water moves through the ground, natural processes reduce (or attenuate) the concentration of many contaminants including harmful microorganisms. These processes will be discussed in more detail later in Section 3.6. The degree to which attenuation occurs is dependent on the type of soil and rock, the types of contaminant and the associated activity.

The term aquifer pollution vulnerability is used to represent the intrinsic characteristics of the aquifer which determine whether it is likely to be affected by an imposed contaminant load. Vulnerability assessment is based on the likely travel time for water to move from the ground surface to the water-table – the greater the travel time the greater the opportunity for contaminant attenuation. Aquifer vulnerability can be subdivided into four broad classes which are defined in Table 3.2; extreme vulnerabilities are associated with highly fractured aquifers of shallow water-table which offer little chance for contaminant attenuation.

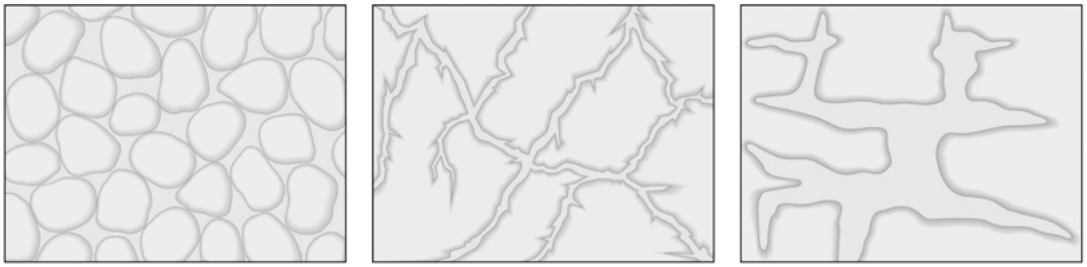
Significance of unsaturated zone

The unsaturated zone is of special importance since it represents the first line of natural defence against groundwater pollution. It is, therefore, essential that the unsaturated zone be fully considered in the evaluation of risks to groundwater supplies. Should it be ignored, evaluations will be excessively conservative. However, the role of the unsaturated zone can be complex and its ability to attenuate contaminants difficult to predict.

While natural flow rates in the unsaturated zone of almost all formations do not generally exceed 0.2 m/d in the short term, and less when averaged over longer periods, water flow and pollutant penetration rates in fractured formations may be more than an order-of-magnitude higher, given high rates of infiltration (for example from septic tanks). Thus rock type, and especially the grade of consolidation and whether there are fractures, will be key factors in the assessment of aquifer pollution vulnerability (Figure 3.2), especially in relation to microbial pathogens.

Table 3.2. *Aquifer vulnerability subdivided into four broad classes*

Vulnerability class	Definition
extreme	vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
high	vulnerable to many pollutants except those highly absorbed and/or readily transformed
low	only vulnerable to most persistent pollutants in the very long-term
negligible	confining beds present with no significant groundwater flow



pores fractures karst

Figure 3.2. *Illustration of types of voids within rocks: pores - spaces between sediment grains; fractures - cracks in hard rock; karst - enlargement of fractures in calcareous rocks due to dissoluton by infiltrating water that is slightly acidic*

Significance of saturated zone

Contaminant removal processes will, in the main, continue below in the saturated zone of the aquifer but generally at much lower rates because groundwater moves more rapidly. Within the saturated zone, dispersion and dilution (spreading out of the contaminant plume) will play an important role in reducing contaminant concentrations although it is not a reliable reduction mechanism for highly toxic contaminants.

Nevertheless, for low yielding boreholes (e.g. those fitted with a handpump) in porous aquifers the travel time for water to move downward from the water-table to the intake of the borehole can be considerable even for quite small vertical distances. Such travel times, whilst they would only delay the arrival of persistent contaminants, will substantially reduce the risk of less persistent contaminants including many microorganisms.

3.3 Hydrogeological environments

The previous section shows that the vulnerability of groundwater to pollution is dependent on the nature of the subsurface and depth to the water-table. Although there are many types of rocks, these can be summarised into a number of broad groups (described below) that takes into account not only the rock type but also the environment in which the rocks were formed. The likely vulnerability of aquifers in each of these environments is suggested. Those hydrogeological environments where the aquifers are consolidated (and therefore potentially fractured) are indicated because they are likely to be especially vulnerable to pollution. The broad classification of aquifer vulnerabilities for the major hydrogeological environments is summarised in Table 3.3.

3.3.1 Unconsolidated aquifers

Thick sediments associated with rivers and coastal regions

These unconsolidated sediments form the most important aquifers of the world in terms of volumes of water pumped. Many of the world's largest cities are supplied by groundwater from these rocks, including Bangkok, Calcutta and Dhaka.

These aquifers are rarely simple systems, they are typically layered, with permeable layers of sands and gravel separated by less permeable layers of clay or silt, producing complex groundwater flow patterns (Figure 3.3). The porosity of these rocks are typically high (in the range 15–35%) which means greater potential for dilution of contaminants. Groundwater flow velocities are low, so that deeper groundwaters may be derived from recharge that occurred several thousand years ago.

Groundwaters in these aquifers are naturally of excellent microbiological quality; natural filtration produces clear, colourless water, free from microbial contamination and thus requiring minimal treatment. However, this may not be the case at shallow depths and especially where the

Table 3.3. *Principal hydrogeological environments and their associated pollution vulnerability.*

Hydrogeological environment		natural travel time to saturated zone	attenuation potential	pollution vulnerability
Thick sediments associated with rivers and coastal regions	shallow layers deep layers	weeks-months years-decades	low-high high	high low
Mountain valley sediments	shallow layers deep layers	months-years years-decades	low-high low-high	low-high low-high
Minor sediments associated with rivers		days-weeks	low-high	extreme
Windblown deposits	shallow layers deep layers	weeks-months years-decades	low-high high	high low
Consolidated sedimentary aquifers	sandstones karstic limestones	months-years days-weeks	low-high low	low-high extreme
Weathered basement	thick weathered layer *(>20 m)* thin weathered layer *(<20 m)*	weeks-months days-weeks	high low-high	low high

aquifer underlies urban areas where the contaminant load is high.

A consequence of the slow travel times and the long contact time with the sediment, is that groundwater in deeper aquifers often contains significant quantities of minerals in solution (solutes), some of which may be harmful to health. The solute content of groundwater is very variable and depends on the residence time of water in the aquifer and the mineral composition of the aquifer itself.

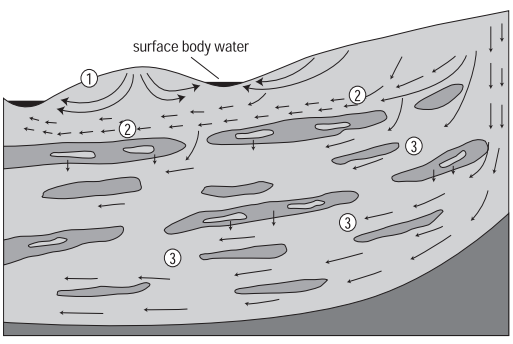


Figure 3.3. *Thick sediments associated with rivers and coastal regions*

Mountain valley sediments and volcanic systems

Aquifers in this environment result from the rapid infilling of basins within mountain regions which produce thick accumulations of sediment (Figure 3.4). Inter-layering of volcanic lavas may also occur. Aquifer permeabilities and porosities are generally high although variable, producing a complex groundwater system similar to the previous hydrogeological environment. When combined with high rainfall, typical of this environment, this results in valuable aquifers capable of substantial well yields. Examples include the aquifers present beneath Mexico city and Kathmandu.

Minor sediments associated with rivers

Groundwater can occur in thin river sands and gravels that may be of limited lateral extent and depth (Figure 3.5). These permeable sands and gravels may rest on relatively impermeable hard rock and therefore may represent the only significant groundwater resource available. Whilst the rivers may flow for only quite short periods of the year, sufficient water usually remains stored within the

deposits during the dry season to meet the demands for village water supply. Traditional means of obtaining water are usually through shallow excavations; these are highly susceptible to pollution.

Windblown deposits

Fine windblown deposits, called loess, form an important aquifer in China and South America. The deposits are generally extensive but of low permeability and the presence of ancient soils may produce a layered aquifer. Groundwater in loess deposits can represent a key source of domestic water.

3.3.2 Consolidated sedimentary aquifers

Consolidated sediments

Younger sandstones usually retain a primary porosity (the porosity between grains) and are typically of low-moderate permeability. In older, more-cemented formations, the primary porosity is virtually absent and it is the secondary (fracture) porosity which provides the aquifer permeability and storage.

The vulnerability to pollution of consolidated sedimentary aquifers is greatly increased by the development of secondary permeability, especially in the karst limestones where particularly rapid water movement along fractures is possible.

Recent coastal limestones

These formations can form important aquifers. Their permeability is often dominated by fracturing and is, as a consequence, high, producing rapid groundwater movement with velocities frequently in excess of 100m/d. The high infiltration capacity of these rocks often eliminates surface runoff and very often groundwater is the only available source of water supply in these environments.

These characteristics have important implications for groundwater quality. Water movement from the soil to the water-table is often via fractures and is so rapid that even filtration and removal of micro-organisms within the unsaturated zone is not effective. Consequently these formations are extremely vulnerable to widespread pollution. In addition, as these coastal aquifers are usually underlain by seawater often at shallow depths, excessive abstraction, may induce seawater upconing and contamination of fresh water.

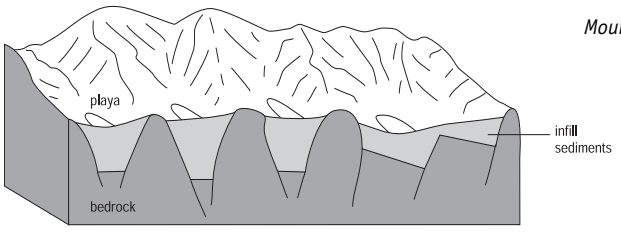


Figure 3.4.
Mountain valley sediments

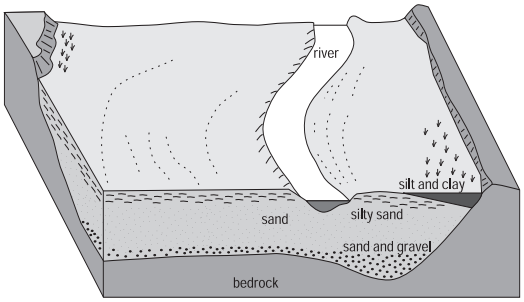


Figure 3.5.
Minor sediments associated with rivers

3.3.3 Weathered basement aquifers

Over large areas of Africa and parts of Asia, groundwater occurs in basement rock aquifers. These aquifers are often ancient crystalline rocks with little or no primary porosity e.g. granite. Groundwater is present within the weathered and fractured layers (Figure 3.6). In some cases the basement rock is covered by an extensive and relatively deep weathered clayey layer of low permeability. Below this the rock becomes progressively harder until fresh fractured basement rock is reached. Where the deeply weathered low permeability layer is both extensive and deep, the aquifer can be considered to have relatively low pollution vulnerability. Such

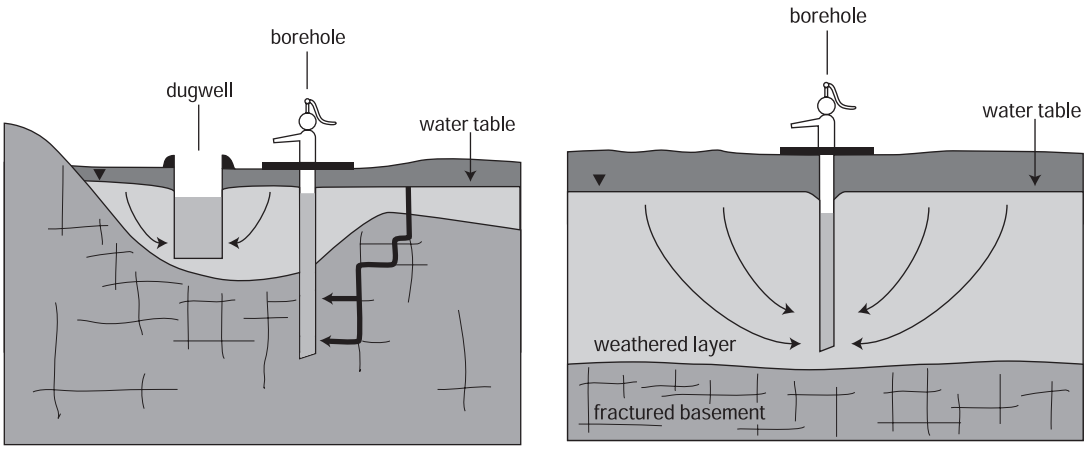


Figure 3.6. *Weathered bedrock aquifers. Basement aquifer with thin weathered layer (left)—the travel time from contamination source to the inlet of the groundwater supply may be fast due to the shorter distances to travel within the low permeability weathered material and the potential for fractures to extend to close to the surface. Basement aquifer with thick weathered layer (right)—the travel time from contamination source to the inlet of the groundwater supply will be greater due to the greater distances to travel within the low permeability weathered material.*

environments are characterised by low relief and absence of rock outcrops.

However, there are other areas where the weathered layer is of variable thickness and basement rock can occur at the ground surface. Such aquifer environments are more vulnerable to pollution because of the likelihood of fractures extending close to ground surface. These areas can be recognised by the presence of more variable relief and by records from drilling boreholes or digging wells which confirm a thin or variable weathered layer.

3.4 Sources of contamination

In most developing countries, faecal matter is widespread in the environment and poses a risk to untreated groundwater supplies. In addition to on-site sanitation, sources of faecal matter include other forms of sanitation, solid waste dumps and refuse pits, household sullage and stormwater drains as well as animals. Which sources occur will depend on the type of settlement, population density, sanitation arrangements and sanitation behaviour.

3.4.1 Sanitation

As discussed in Chapter 2, all forms of sanitation represent a potential source of faecal pollution (Figure 3.7). In urban areas, leaking sewers may contribute significant microbiological and nitrate loads to shallow aquifers that may affect groundwater supplies used for drinking water supply.

In rural areas and low-income urban settlements, on-site sanitation facilities may be a significant source of contamination. As all these systems accumulate and retain faecal matter in one place, they represent a major potential source of faecal pollution. The contamination derived from on-site sanitation in most rural areas will only impact groundwater supplies in the immediate area but in larger villages and within urban settlements, where there may be many installations within a small area, there may be widespread contamination of the aquifer.

Other hazards relating specifically to excreta disposal facilities will include treatment works such as waste stabilisation ponds. These may cause either localised or widespread contamination depending on the degree to which leaching occurs and the location of works in relation to the water-table and groundwater flow regimes.

3.4.2 Other sources of faecal contamination

Whilst this manual is written specifically to consider the hazard posed to groundwater by on-site sanitation, it is important to be aware that

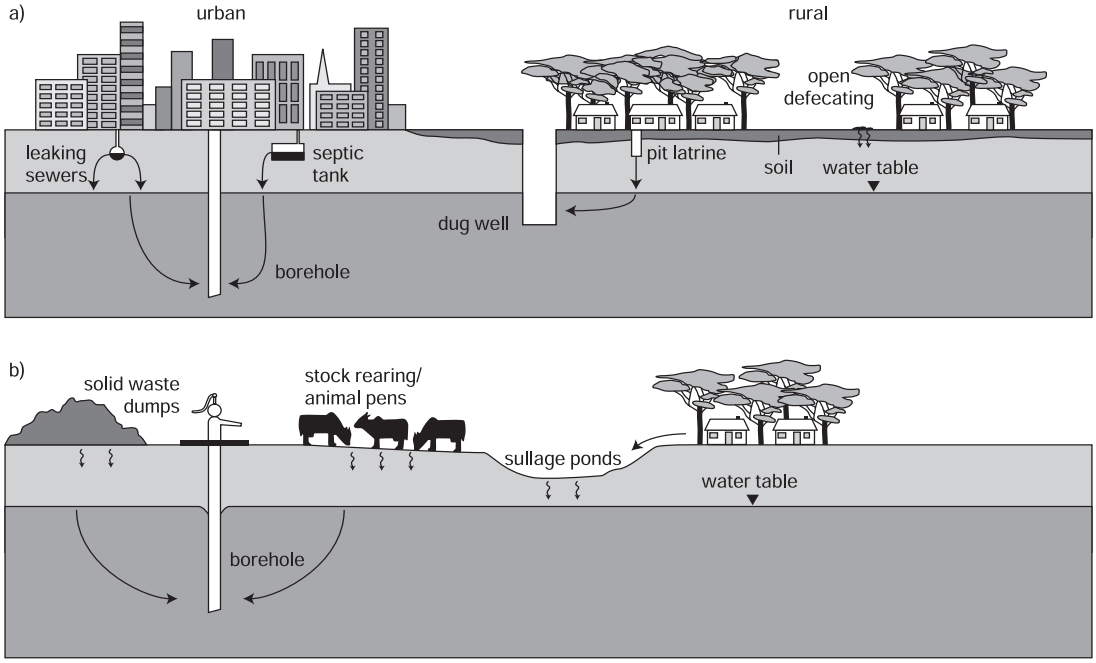


Figure 3.7. *Sources of faecal pollution within urban and rural settings from: a) sanitation (top); and b) other sources (bottom)*

there are other hazards within the environment that may contain faecal material (Figure 3.7). These include solid waste dumps, household sullage, stagnant surface water, and animal enclosures and free range animals. These sources are discussed below to make the reader aware that on-site sanitation is not the only source of contamination. These sources may in some settings represent a significantly greater hazard than on-site sanitation.

Solid waste

Where excreta disposal facilities are absent or insufficient to meet the needs of the population, faeces are often disposed of into the general environment and commonly end up on solid waste dumps, refuse pits and drainage channels. This is likely to be more common in high-density urban settlements than rural areas. Where this form of excreta disposal occurs, the risks to general health will be high, but the risk to groundwater sources will depend on whether the faeces are located up-gradient of the water supply and whether under rainfall events they can enter the supply directly due to poor sanitary completion. It should be noted that even where sanitation facilities are available, the disposal of children's faeces in particular may remain unhygienic given cultural beliefs about the nature of their faeces.

The impact of solid waste sources of faecal contamination on the microbiological quality of groundwater is likely to be more localised than widespread, unless an entire urban area lacks any form of improved sanitation. Poorly managed solid waste may, however, represent a significant source of nitrate as in many developing countries much of the solid waste generated is organic. The control of unrestricted dumping of solid waste may help to reduce nitrate contamination.

Sullage and surface water

Domestic waste derived from washing, cooking etc, is often discharged into open ditches or channels. This sullage is known to often contain large numbers of faecal indicator bacteria and may also contain pathogens. Whilst of lower risk in terms of concentration of microbiological contamination, the amount of sullage produced

(over 90% of all domestic water) may represent a significant source of microbiological contamination if it is not disposed of properly. No significant nitrate load would be expected to derive from sullage.

Stagnant surface water may also represent a significant contamination risk, particularly if excreta disposal facilities are inadequate, sullage is disposed of indiscriminately and free-range animals are in the area. Stagnant water pools may end up collecting much of the faecal matter and may directly contaminate groundwater though infiltration or inundation of the source when rainfall occurs.

Animals

A further hazard is likely to be animal faeces within the environment, whether as a result of organised husbandry or where animals are allowed to roam in the environment. However, in general, animal faeces represent a lower infectious disease risk than human faeces, although some pathogens (for instance protozoa and *E.coli* O157:H7) have an animal host.

Animal enclosures represent a significant source of faecal contamination as a relatively large volume of faeces may be produced and manure may be allowed to build up over a long period of time. Where animals are free-range, their faeces will be likely to be found throughout the environment and may collect in stagnant surface water or be washed directly into a poorly maintained water supply.

Organised animal husbandry may have a significant impact on nitrate contamination. Where significant numbers of animal enclosures are found, this may contribute significantly to a more widespread aquifer contamination. In Botswana, high nitrate concentrations in some drinking water wells have been linked to the proximity to large numbers of cattle at nearby stock watering points.

3.5 Contaminants associated with on-site sanitation

3.5.1 Microbiological

Many types of pathogens transmit infectious diseases. These have differing impacts on health and transmission routes may vary. These should be understood in order to predict the health consequences of different pathogen types and levels of contamination.

The pathogens that cause infectious diarrhoeal diseases that can be transmitted through contaminated water are grouped into three principal types of organisms: bacteria, viruses and protozoa (or cysts). All these pathogens may be transmitted by other routes, including via contaminated hands, flies and animals. Helminths (or worms) are not included as their size makes them unlikely to be present in groundwater supplies unless there is a direct entry for surface water, in which case pathogens of other types will also be present and are likely to represent a greater risk to health. Table 3.4 lists the major viral, bacterial and protozoan pathogens, the source of these pathogens and the associated diseases.

Bacterial pathogens cause some of the best known and most feared infectious diseases, such as cholera, typhoid and dysentery, which still cause massive outbreaks (or epidemics) of diarrhoeal disease and contribute to ongoing infections. Bacterial pathogens tend to have high infectious doses – i.e. a large number must be consumed in order to cause an infection. However, the symptoms tend to be severe and the control of such pathogens was the original target of the pioneers in sanitary improvements. Their control in drinking water remains critical in all countries worldwide.

Bacteria tend to be very susceptible to the natural processes which reduce their numbers (attenuation), which are described in Section

3.6.1. Therefore, reducing bacterial pathogens loads through simple protection measures is relatively simple and should be a major target of the planners of water and sanitation programmes.

Viruses are much smaller organisms and cause a range of diarrhoeal diseases. Some viral diseases, for instance polio, are most effectively controlled through vaccination rather than measures to safeguard water quality. Epidemics of viral diseases have been recorded, although in general viral infections tend to lead to milder and self-limiting infections. Viruses are often spread

Table 3.4. *Illnesses acquired by ingestion of faecally contaminated water.*

Pathogen	Source	Disease
Viruses		
Hepatitis A virus	Human faeces	Infectious hepatitis
Polioviruses	Human faeces	Poliomyelitis (best controlled through vaccination)
Astrovirus, Calcivirus, Rotaviruses, Norwalk-type viruses	Human faeces	Diarrhoeal diseases
Coxsackieviruses and Echoviruses	Human faeces	Diarrhoeal diseases
Bacteria		
Campylobacter jejuni	Human and animal faeces	Diarrhoeal diseases
Enterohaemorrhagic *E. coli* 0157	Human and animal faeces	Hemorrhagic colitis
Enteroinvasive *E. coli*	Human faeces	Diarrhoeal diseases
Enteropathogenic *E. coli*	Human faeces	Diarrhoeal diseases
Enterotoxigenic *E. coli*	Human faeces	Diarrhoeal diseases
Salmonella typhi	Human faeces and urine	Typhoid fever
Shigellae spp.	Human faeces	Dysentery
Vibrio cholerae 01	Human faeces	Cholera
Protozoan parasites		
Cryptosporidium spp.	Human and animal faeces	Diarrhoea
Giardia lamblia	Human and animal faeces	Diarrhoea

through poor hygiene and drinking water is often not the principal route of transmission.

The severity of viral infections also depends significantly on when first exposure to the pathogen occurs. When first exposure occurs in childhood, the symptoms are often relatively mild and a degree of lifelong immunity is acquired. When first exposure is in adulthood, the effects tend to be more severe. In most developing countries, exposure to viruses through water and other routes during childhood is likely to be significant and therefore it can be expected that the overall risk of severe symptoms is relatively low.

Infectious doses of viruses tend to be very low and viruses are often less likely to be attenuated. Therefore, reducing the risks from viruses in drinking water is difficult without disinfection of the water supply. Protection measures may greatly reduce the numbers of pathogens in the water and therefore reduce the risks of infection, but controlling sources of viruses (for instance on-site sanitation) alone is unlikely to reduce the risk to an acceptable level.

Protozoa are relatively large organisms and include *Cryptosporidium* and *Giardia.* Protozoan pathogens cause diarrhoea, although in most cases this is relatively mild and self-limiting. In most developing countries, exposure to protozoan pathogens occurs through direct contact with animals, poor hygiene and contaminated food. Drinking water is unlikely to be the major route of transmission. Although infectious doses of many protozoa are very low, attenuation is often easy given the large size of the organisms. Therefore, control of protozoan pathogens in groundwater is relatively easy because of the size of the cysts and should be an easily achievable target, even though the actual health risk is relatively limited.

3.5.2 Chemical

The chemical contaminants of principal importance that are derived from on-site sanitation are nitrate and chloride. Each person excretes in the region of 4kg of nitrogen per year and under aerobic conditions it can be expected that a significant percentage of this nitrogen will be oxidised to form nitrate. The nitrogen loading from on-site sanitation in densely populated areas can be very large indeed. In one urban slum area of Dhaka as much as 1500 kg of nitrogen per hectare is deposited each year through on-site sanitation systems. Chloride is also abundant in human wastes (the ratio of chloride to nitrogen in human waste is approximately 1:2). Each person on averages loses approximately 4g of chloride per day through urine (90–95%), faeces (4–8%) and sweat (2%). However, the chloride content can be very variable and depends in part on its concentration in drinking water.

Nitrate is a health concern and WHO have set a Guideline Value of 50mg/l as the safe level of nitrate where the likelihood of methaemaglobinamenia will be low. Chloride is of less concern for health, but affects the acceptability of the water and thus may result in use of alternative more microbiologically contaminated water. In both cases, environmental protection concerns also need to be addressed, as remediation of contamination is difficult. Nitrate and chloride are generally stable, especially in aerobic environments and therefore contamination is likely to build-up and persist in the longer term. In anaerobic environments ammonium is the stable form of nitrogen and it may represent a health hazard. Remediation of the aquifer or treatment of the water supply are expensive and difficult to achieve. Conversely, where groundwater is anaerobic any nitrate will be reduced to nitrogen gas. For example, in some peri-urban areas of Dhaka, Bangladesh, it has been noted that groundwater nitrate concentrations are low despite heavy nitrogen loadings from on-site sanitation.

When assessing the potential risk of widespread contamination of groundwater by nitrate or chloride from on-site sanitation, the other possible sources should also be considered. Whilst quantifying the relative contribution from each source is likely to prove difficult, where potentially high nitrogen loadings are indicated, it would probably be worthwhile monitoring for nitrate in groundwater.

Both nitrate and chloride may show significant seasonal fluctuations in shallow groundwater, although concentrations are expected to be more stable in deeper groundwater. Therefore, when assessing the risk of widespread nitrate or chloride contamination, it is important to recognise the possibility of seasonal peaks. Where such information is not available, it may be necessary to set-up a monitoring network (see Chapter 5).

In general the likely level of nitrate contamination of groundwater will depend on the:

- quantity of recharge, which controls the degree of dilution (the higher the rainfall, the lower the nitrate content for a given population density);
- population density, which relates to the contaminant load;
- type of on-site sanitation system, which determines the proportion of nitrogen leaching;
- other sources of nitrate in the environment, for example large concentrations of livestock animals may contribute a significant nitrate load;
- the nature of the sub-surface and the hydrogeological environment including the potential for denitrification.

3.6 Attenuation of contaminants in the subsurface

Pathways will nearly always exist in the subsurface that provide a link between the sources of contamination and the receptor (groundwater supply). The pathways are a result of the normal porosity and the permeability of the rocks. However, natural (attenuation) processes in the subsurface can remove or significantly reduce contaminant concentrations. A brief description of these processes is given here.

Attenuation is generally most effective in the unsaturated zone and in particular in the upper soil layers where biological activity is greatest. The soil layer represents the greatest opportunity for attenuation as both microbiological, and to a lesser extent key chemical contaminants, are removed, retarded or transformed as a result of biological activity. At deeper layers in the unsaturated zone, attenuation still occurs, although the processes tend to be less effective as biological activity decreases. Once the saturated zone is reached, attenuation usually becomes far more limited and natural die-off and dilution predominate (Figure 3.8).

3.6.1 Attenuation of microbiological contaminants

The key processes in the attenuation of microbiological contaminants are:

- die-off and predation
- filtration
- dilution/dispersion
- adsorption

Micro-organisms, like all life forms, have a limited life span. Die-off rates vary enormously from a few hours up to several months. In groundwater, some viruses are known to survive for up to 150 days. In the case of indicator bacteria, an estimated half-life (i.e. the time taken for a 50% reduction in numbers) in temperate groundwater has been noted as being as high as 10–12 days, with survival of high numbers up to 32 days. Some pathogenic bacteria (for instance Salmonella species) have been shown to persist for up to 42 days.

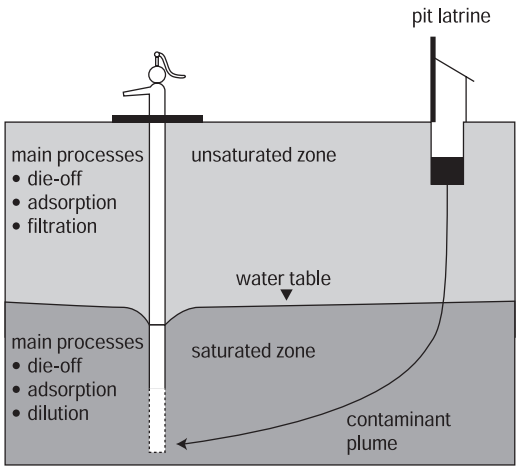


Figure 3.8. *Attenuation processes within the unsaturated and saturated zones*

The removal of micro-organisms through predation by other micro-organisms may occur readily in biologically active layers that develop around the filled sections of pit latrines and these may represent the most effective barrier to breakthrough. It is difficult to predict how rapidly this layer will take to develop, as this depends in part on the soil type and the hydraulic and pollutant load applied, but the establishment of such communities is likely to take several weeks to reach maturity. However, the benefits of a biologically-active layer may be limited in time as the layer becomes more developed, pores may become clogged and greatly reduce effluent infiltration lower in the pit, encouraging greater infiltration at higher layers.

Other key processes in microbiological attenuation are adsorption and filtration. In the first case, micro-organisms become attached to particles in the sub-surface, thus effectively removing them from water infiltrating into the soil. The ability of micro-organisms to be adsorbed depends on the nature of the organism, the pH of the water and the type of unsaturated zone material. Some micro-organisms, particularly viruses, carry an electrical charge and thus may be easily adsorbed in the unsaturated zone, particularly when reactive clay minerals are present. However, the charge that a virus carries can change with pH, thus the adsorption potential will also be dependent on the pH of water and the charge on the minerals within the soil. Viruses can be de-sorbed (or eluted) when flow rates change and pH alters, especially during recharge periods.

Mechanical filtration is more effective for larger organisms such as protozoan cysts and helminths but will also help to attenuate bacteria and is dependent on the pore size of the rock (Figure 3.9). Filtration can be effective in removing larger micro-organisms, but it should be noted that this does not inactivate these organisms, but merely retards them. Filtration may be especially important close to the base of the pit latrine where clogging may reduce the effective pore openings in the aquifer.

Dispersion, caused by the tortuous route taken by water flowing through the rock material, has the effect of spreading contaminant plumes and in effect diluting the 'concentration' at any point and increasing the range of time that contaminants take to flow from source to groundwater supply. The effect of dispersion/dilution on micro-organisms is less easy to quantify than for chemicals, given the discrete nature of microbes in water and the observed phenomenon that micro-organisms are often found to clump together.

3.6.2 Definition of risk categories for microbiological contamination via aquifer pathways

The mechanisms controlling the attenuation of micro-organisms are clearly complex and what evidence there is suggests survival and breakthrough is variable, being dependent on local conditions. This variability is also season-dependent with increased breakthrough following rainfall widely recorded. Such variability makes it difficult to have complete confidence in any realistic separation between contaminant source and groundwater supply.

The guidelines presented in Part 2 of this

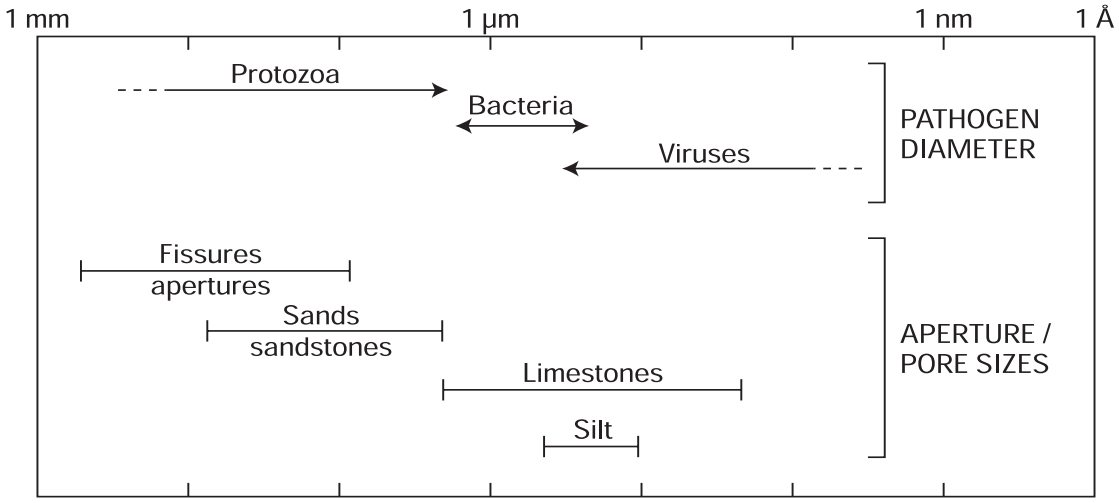


Figure 3.9. *Pathogen diameters compared with aquifer matrix apertures*

manual, rather than being prescriptive, promote a risk-based approach, acknowledging that in some circumstances it may be necessary to accept some level of risk. The risk of microbiological contamination relates to the potential for pathogens to reach the groundwater supply. The risk is defined in terms of the travel time of contaminated water from source to the supply. Empirical evidence is used in making the definition. Although there are significant uncertanties in identifying travel times, the authors believe that such an approach is the most practical option.

Empirical evidence from a limited number of field studies has shown that a separation between the pollution source and the water supply equivalent to 25 days travel time is usually sufficient to reduce concentrations of faecal indicator bacteria to levels where detection within most samples is unlikely. However, the studies did not analyse for other pathogens such as viruses that are expected to survive for longer travel times in the subsurface. The generally accepted minimum separation for contaminant source and groundwater supply in western Europe, which aims to bring water quality within WHO guidelines or national standards, is that equivalent to 50 days travel time. This 50 day travel time is based on survival times of viruses from laboratory and field experiments. However, this travel time is likely to result in prohibitive distances of separation in the developing world context under certain circumstances. Therefore, within the ARGOSS guidelines three levels of risk are defined:

- **significant risk - less than 25 day travel time**
- **low risk - between 25 and 50 day travel time**
- **very low risk - greater than 50 day travel time**

The 'low risk' category provides confidence, but no guarantee, that the travel time between contaminant source and groundwater supply would result in levels of micro-organisms which are unlikely to represent a major risk to health. The 'very low risk' category provides a further margin of safety and therefore greater confidence that the water will meet WHO guidelines and that more persistent pathogens will be removed from water entering the supply. However, since routine monitoring rarely analyses for individual pathogens, it is not normally possible to confirm this.

It is important to differentiate between the

'survival time' for micro-organisms, which can be many days, months or even years, and is a measure of the rate of die-off, and the ***travel time within the groundwater system necessary to reduce the numbers of micro-organisms to levels unlikely to represent a risk to health***. The latter incorporates all the attenuation processes discussed above.

In this manual we suggest that a water supply is 'acceptable' where the risk assessment is considered low or very low and the monitored water quality meets the guideline value.

3.6.3 Attenuation of chemical contaminants

Biological uptake of nitrate occurs within the soil (through plants etc). However, this may be easily overwhelmed during recharge periods, when rapid leaching of nitrate held in the soil may occur. In the case of nitrate sources such as on-site sanitation and solid waste dumps, leaching is expected, partly because there is limited ability for uptake of nitrate either because plants are not present or their roots do not normally extend to the base of the latrine. Once in the deeper unsaturated zone, there is normally little attenuation of nitrate as it is largely unreactive and not retarded. Under aerobic conditions nitrate is mobile and not retarded. In the saturated zone and where groundwater conditions are anaerobic, denitrification can occur. Denitrification is a microbiological process in which bacteria consume nitrate (in the absence of oxygen) for their metabolic needs, producing nitrogen gas. This process is thought to be responsible for the low nitrate concentrations found in groundwater beneath Dhaka. In the saturated zone, dilution is the other attenuation process that that can reduce nitrate concentration. However, this will not be particularly effective where the nitrate load is high and derived from a large number of point sources over an extensive area (equivalent to widespread diffuse leaching of nitrate). In many cases, a nitrate front is developed that slowly migrates downwards from the surface through the groundwater. **Once high levels of nitrate are present in groundwater, concentrations will not decrease rapidly, even if the load is reduced or removed.**

3.7 Pathways for localised contamination

Contamination of groundwater supplies may result either from contaminants moving through the body of the aquifer or via pathways resulting from the design and construction of the supply or its deterioration with time (localised contamination). The former was addressed in Section 3.2. Localised contamination is a very common means for the decline in the quality of groundwater supplies. In this section we identify the local pathways for contamination to get into groundwater supplies (Figure 3.10) and provide general advice on programme-wide measures.

Localised contamination can occur either

- where contaminated water is in direct contact with the headworks of boreholes, wells and springs and where pathways exist that allow this to mix with the water supplied; or
- where contaminated water that has infiltrated into the sub-surface in the close vicinity of a borehole, well or spring moves along fast horizontal pathways to the supply.

Localised contamination will result where:

1. potential contaminating activities are not excluded from the vicinity of the headworks;
2. sanitary protection measures employed in the headworks are insufficient; or
3. the design and construction of a groundwater supply is inadequate.

The general measures required to avoid localised contamination of groundwater supplies are summarised here.

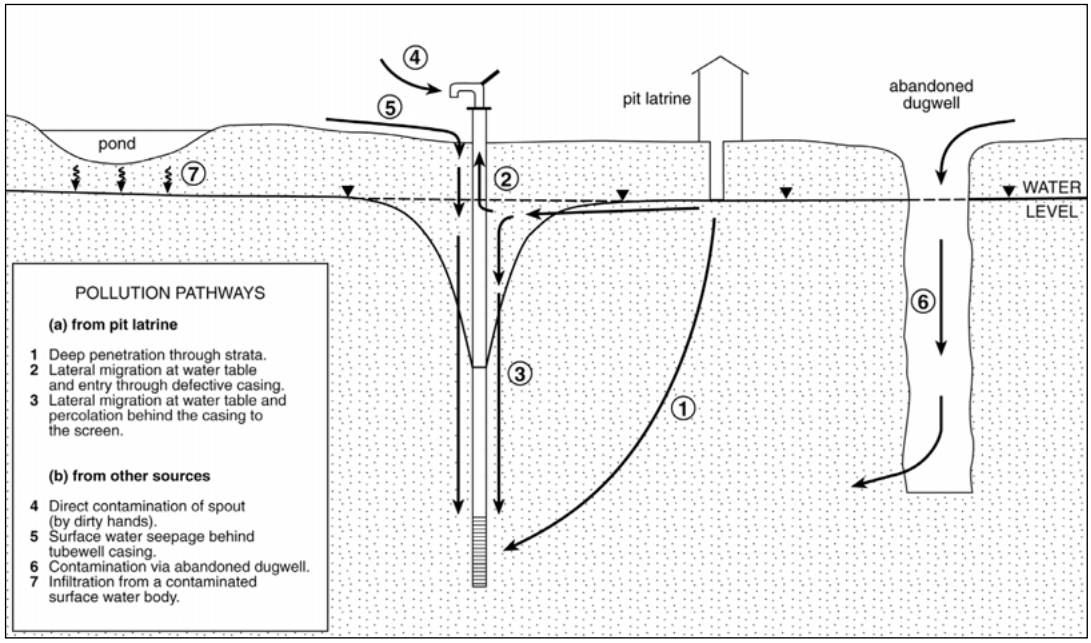


Figure 3.10. *Pathways for contamination into groundwater supplies*

3.7.1 Design and construction of groundwater supplies

The good design and construction of groundwater supplies is critical to the prevention of contamination. In addition to the actual designs utilised and construction practices followed, the ongoing maintenance of the infrastructure and protection measures is critical to ensure that the risk of contamination remains low. It is not the purpose of this manual to review in detail design and construction methods for groundwater sources.

The brief sections below describe the basic or essential components for design and construction that are required to limit the risk of contamination.

Boreholes

To avoid localised contamination of groundwater supplies it is preferable in all cases to include a sound cement seal (at least 5cm thick) around the casing to the top of the intake screen. The cement seal is especially important where the formation is stable and thus does not collapse around the casing, as this will produce a pathway capable of transmitting contaminated water very rapidly to the screen, either from the wellhead or through fast pathways in the sub-surface. Even where the formation is likely to collapse, this does not guarantee that a pathway will not exist and so the seal should still be constructed.

However, it is accepted that this is not always practical. Where this is not achievable the seal should be as deep as possible and at least 2-3m below the ground surface.

It is acknowledged that in some countries hand-drilling methods that are cheap and widely available are the only practical solutions to constructing water supply wells. The method makes the inclusion of a cement seal problematic and other measures need to be accepted to reduce risk. These include:

- the use of good quality casing materials;
- screw thread joints in preference to glued joints;
- the provision of a cement seal to beyond the first joint where wear and tear will be greatest;
- placing the screen as deep as possible, increasing the likelihood that the formation

will collapse around sufficient length of the casing;

- ensuring there is a non-return valve at the base of the rising ain of the pump to avoid contamination from water used in priming.

Recommendations for the design of boreholes in terms of the depth of screen may result from the widespread microbiological assessment guidelines in Section 4.2.

Protected springs

Springs should be protected against direct contamination. Usually a spring box or retaining wall is built with an outlet pipe some distance from the 'eye' of the spring. The area between is filled with gravel, sand and overlain with grass (Figure 3.11). This backfilled area is often at greatest risk of contamination as this area has been excavated and unless well designed and maintained may allow contaminated surface water to enter the spring.

The filter media is laid from the base of the excavation to the expected highest level of wet season water-table rise. The filter media laid should be sufficiently fine to provide reasonable filtration and attenuation, whilst not unduly retarding the flow. This will help remove any contaminants that have already entered the groundwater. However, further protection is needed to prevent direct contamination from surface water that inundates the backfill area during rainfall or from sullage. The filter should be overlain by a clay layer to reduce infiltration by surface water, with above this a sand layer to remove cysts and finally a soil layer. The backfill should have a full grass cover and be protected by a fence and diversion ditch to ensure that contaminated surface water cannot flood the spring during wet periods.

The maintenance requirements for springs are often low, but it is essential that the ditches, grass cover on the backfill area and fencing are all kept in good condition and are not allowed to fall into disrepair. The concrete and other construction work should also be maintained in good condition to prevent direct entry of contaminated surface water.

Dug wells

Hand dug wells are one of the lower-cost forms of water supply and as a result are popular technologies. Hand-dug wells in particular offer great potential for participation of communities in the planning and construction phases and unlike boreholes still provide water when a handpump has broken down.

However, dug wells are particularly vulnerable to contamination as it is often difficult to ensure that the lining of the top layers is impermeable and so it may be easy for contamination to enter the well. A cement seal between the top one or two rings and the dug ground helps prevent contamination through the joints between well rings. Ensuring that a strong or medium cement mix is used for the lining (1:2:4 or 1:3:6) will help to provide structural stability and it is advisable to provide a plaster seal on the lining wall to prevent ingress of water in the lining column. The lining should extend at least 0.3m above the level of the ground as a headwall and preferrably a cover slab should be fitted with a handpump or windlass used to withdraw the water. As with boreholes, it is essential that the handpump has a non-return valve to prevent contamination from priming water.

One method of constructing a dug well below the water-table is to sink a column of 'caissons'. These are concrete rings of smaller diameter than the lining and are designed to provide water security during dry periods. Usually the base of the caisson has a 'cutting edge' of greater diameter than the caissons. The annulus between the

outside edge of the caisson and the cutting edge should be filled with gravel and sand to provide a filter pack and the base of the well should include either a 0.2–0.3m filter pack of sand and gravel or a permeable concrete slab. Further protection can be provided by constructing an intake box at the base of the well which can be filled with sand and gravel.

3.7.2 Sanitary protection measures at headworks

Sanitary protection measures at the headworks of a groundwater supply aim to prevent both sources and pathways of contamination occurring. The critical measures required are summarised in Table 3.5 and illustrated in Figure 3.11.

By maintaining the critical sanitary protection works noted above, the potential for direct contamination by surface water can be greatly reduced. However, whilst these may prevent the most direct forms of contamination, other controls may be required in the vicinity of the source to reduce the potential for contamination.

The failure in key sanitary protection measures often results from the poor maintenance of basic infrastructure that allows pollutant pathways to develop. For instance, the absence of a fence around a spring allows animals and people greater access to the immediate backfill area and this may lead to erosion of the catchment. Equally, the failure of diversion ditches often increases the potential for erosion around protection works and thus often allows direct pathways for pollutants to develop. Table 3.6 summarises the interaction between pollutant pathways and indirect factors.

In many cases, contamination may occur when a surface hazard exists uphill combined with poor sanitary protection measures and development of a direct pathway into the supply. It should be noted that these factors are highly inter-related and direct ingress is unlikely to occur

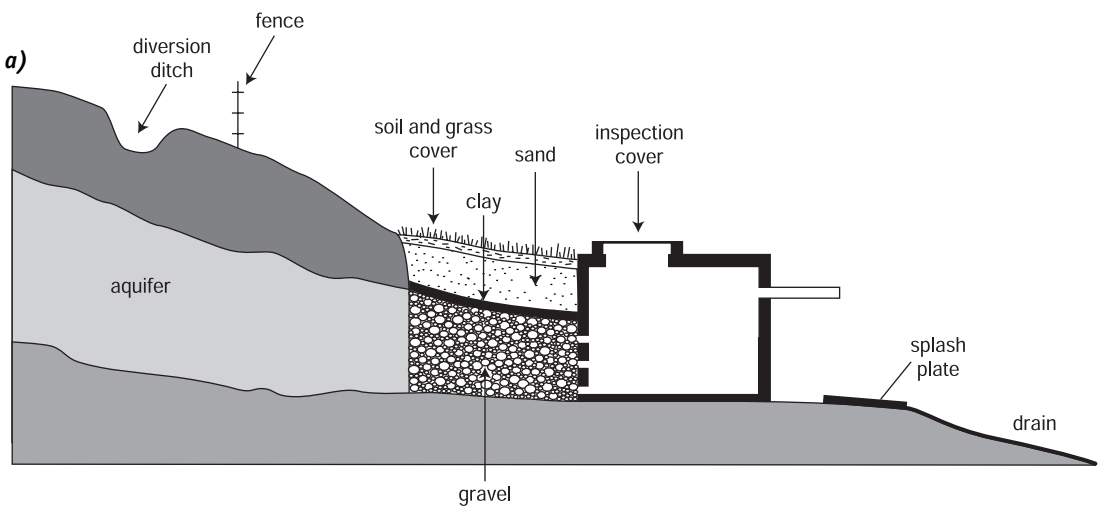


Figure 3.11. *Sanitary protection measures for* ***a)*** *springs and* ***b)*** *boreholes*

Table 3.5. *Sanitary protection measures required for different sources*

Source type	General sanitary completion measures	Specific sanitary completion measures
Borehole	Wellhead protection to prevent direct contamination	apron extends at least 1.5m from casing/lining no cracks in apron no ponding of water on the apron the join between apron and the casing/lining is sound the floor is sloped away from the wellhead drainage for wastewater away from the well head
	Immediate area managed properly	fencing excludes animals from the wellhead diversion ditches direct run-off away from the wellhead ponding of surface water close to borehole does not occur
Protected spring	Local protection works to prevent direct contamination	backfill area behind a spring box or retaining wall is protected and retains grass cover retaining wall and other protection works kept in good order
	Immediate area managed properly	fencing excludes animals from the backfill area diversion ditches direct run-off away from the backfill area good drainage of wastewater from spring ponding of surface water uphill and close to spring does not occur
Dug well	Wellhead protection to prevent direct contamination	apron around wellhead extends at least 1.5m wellhead raised by at least 0.3m and covered by slab no cracks in apron no ponding of water on the apron join between apron and the casing/lining is sound floor is sloped away from the wellhead handpump or windlass used to withdraw water
	Immediate area managed properly	fencing excludes animals from the wellhead diversion ditches direct run-off away from the wellhead ponding of surface water close to well does not occur drainage for wastewater away from the well head

when one element is not present.

In order to assess the risks of contamination of groundwater, it is important to evaluate all the potential hazards, pathways and indirect factors that may influence the potential for contamination. The role of each factor in causing localised contamination is investigated through the use of sanitary inspection. A range of risk factors are evaluated at a groundwater supply and the likelihood of each factor contributing to contamination assessed. This is used within the assessment procedure presented in Chapter 5 and is discussed further there.

In addition to maintenance of key sanitary protection measures, is the control of other activities in the immediate area of the groundwater supply. These include:

- Abandoned wells—these should be properly capped or backfilled;
- Shallow pits which provide means for contaminated water to by-pass surface sanitary measures and reach the supply via shallow pathways that allow rapid movement of the contaminated water. Good design and

Table 3.6. *Pathways and indirect factors influencing contamination of groundwater sources*

Source type	Pathway factor	Contributing factors to contamination
Protected spring	Eroded backfill or loss of vegetation cover	Lack of uphill diversion ditch Lack of fence Animal access close to the spring
	Faulty masonry	Lack of uphill diversion ditch Lack of fence Animal access close to the spring
Borehole	Gap between riser pipe and apron	Lack of diversion ditch Lack of wastewater drain Animal access to borehole
	Damaged apron	Lack of diversion ditch Lack of wastewater drain Animal access to borehole
Dug well	Lack of headwall	Lack of diversion ditch Lack of wastewater drain Animal access to dugwell
	Lack of cover	Animal access to dugwell Uncontrolled use
	Use of bucket and rope	
	Gap between apron and well lining	Lack of diversion ditch Lack of wastewater drain Animal access to dugwell
	Damaged apron	Lack of diversion ditch Lack of wastewater drain Animal access to dugwell

construction may reduce the likelihood of this occurring, for instance by ensuring there is a satisfactory cement seal at the upper levels in a borehole;

- Flooding of the water supply - In low-lying areas this may be largely unavoidable. Where the flooding is a result of rising groundwater levels, entry into the groundwater supply will be limited as the water levels in the supply are likely to be equal to those outside. In areas where flooding from surface waters is a problem, sanitary completion measures should be designed to address this. Raising the ground at the wellhead is an option although attention must be given to ensuring that this does not introduce additional pathways for the entry of contaminants into the supply.

The aim in all water and sanitation programmes should be to limit all risks, rather than concentrate on simply the potential for contamination from one hazard. There is little benefit in reducing the risk of contamination from on-site sanitation if other hazards and pathways result in microbiological or chemical contamination. Mitigating measures will involve good siting of latrines and groundwater supplies, but should also address construction and design of supplies and sanitation facilities and sustained maintenance of sanitary protection measures. This is likely to require training of community operators.

The methodologies for assessing risks of

widespread and localised contamination, and the mitigating measures that may be put in place, are covered in Part 2 of this manual. It should also be stressed that there are no hard and fast rules in contamination prevention and conditions at each site should be assessed whenever planning new water and sanitation programmes or investigating contamination risks of existing facilities.

Summary of key points from Chapter 3

- The degree to which contaminant attenuation occurs in the sub-surface is dependent on the type of soil and rock, the types of contaminant and the associated activity. The term aquifer pollution vulnerability is used to represent the intrinsic characteristics of the aquifer which determines whether it will be adversely affected by an imposed contaminant load
- Attenuation of contaminants is generally most effective in the unsaturated zone and in particular in the upper soil layers where biological activity is greatest. Microbiological, and to a lesser extent key chemical contaminants, are removed, retarded or transformed as a result of this biological activity. At deeper layers in the unsaturated zone, attenuation still occurs although the processes tend to be less effective as biological activity decreases. Once the saturated zone is reached, attenuation usually becomes far more limited and natural die-off and dilution predominate
- Three levels of risk of microbiological contamination are defined in this manual:
  - significant risk: less than 25 day travel time
  - low risk: between 25 and 50 day travel time
  - very low risk: greater than 50 day travel time

  The 'low risk' category provides confidence, but no guarantee, that the wet season travel time between contaminant source and groundwater supply would result in water meeting WHO guidelines. The 'very low risk' category provides a further margin of safety and therefore greater confidence that the water will meet WHO guidelines and that more persistent pathogens will be removed from water entering the supply.
- Once high concerntrations of nitrate are present in groundwater, they will not decrease rapidly even if the load is reduced or removed
- Contamination of groundwater supplies may result either from contaminants moving through the body of the aquifer or via pathways resulting from the design and construction of the supply or it's deterioration in time (localised contamination).
- The aim in all water and sanitation programmes should be to limit all risks rather than concentrate on simply the potential for contamination from one hazard. There is little benefit in reducing the risk of contamination from on-site sanitation if other hazards and pathways result in microbiological or chemical contamination. Mitigating measures will involve good siting of latrines and groundwater supplies but should also address construction and design of supplies and sanitation facilities and sustained maintenance of sanitary protection measures. This is likely to require training of community operators.

Part 2:

The guidelines

Overview

The guidelines of this manual are designed to help those planning water supply and sanitation schemes to select design options that will minimise the risk of contamination of the water supply. These guidelines also stress the importance of follow-up monitoring as an integral part of the design for water supply and sanitation schemes. In this manual a water supply is considered acceptable when the initial risk assessment is low or very low and the monitored water quality meets the national standards or guidelines. However, it is recognised that it may not always be possible to have a low or very low risk design; under these circumstances it may be appropriate to accept a higher risk but instigate a programme of enhanced monitoring to confirm that water quality is still acceptable.

Chapter 4 of the manual takes the reader through the initial risk assessment.The initial risk assessment covers three aspects (or components):-

- microbiological contamination of the water supply via aquifer pathways
- nitrate contamination of the water supply via aquifer pathways
- microbiological contamination of the water supply via pathways created by the construction of the water supply

A flow chart, for each of these risk components, helps the reader through the decision-making process and allows appropriate design options to be identified. Chapter 5 discusses monitoring and helps the reader to select the most appropriate types of monitoring, the key parameters and frequency. Chapter 5 also provides advice on data analysis and interpretation.

4 First-step risk assessment

4.1 Introduction

There are two principal routes by which boreholes, wells and springs may become contaminated by on-site sanitation systems:

- the first relates to the natural vulnerability of the aquifer to pollution. This pathway exists naturally because the subsurface is permeable and water and contaminants can percolate from on-site sanitation systems to the water-table and from there migrate into the groundwater supply. This route can potentially produce widespread contamination of the shallow groundwater;
- the second route is where a pathway is created by the poor design or construction of the groundwater supply. This will produce only localised contamination of the supply (where a large number of groundwater supplies are installed as part of a water supply and sanitation programme, many may be contaminated because of a repeated fault in the design or the construction).

It is important to assess the risk of contamination of the groundwater supply via both pathways. The main concern is microbiological contamination, however nitrate contamination can also be a problem, especially where the population density is high and/or rainfall recharge is low. This is discussed in Section 4.3.

Thus when assessing the risk posed by on-site sanitation to a water supply it is necessary to consider three aspects:-

(1) microbiological contamination of the groundwater supply via aquifer pathways;
(2) nitrate contamination of groundwater supplies via aquifer pathways;
(3) microbiological contamination via pathways created by construction of the groundwater supply.

The risk assessment methodology presented here uses three categories to describe the level of risk. These are defined as follows:

Significant risk: water quality is highly unlikely to meet WHO guidelines because the travel time for water to move from contaminant source to groundwater supply either via aquifer pathways or localised pathways which exist due to the design/construction of supply is less than 25 days.

Low risk: confidence, but no guarantee, water will meet WHO guidelines because travel time exceeds 25 days.

Very low risk: greater confidence that the water will meet WHO guidelines and that more persistent pathogens will be removed from water entering the supply because the travel time is greater than 50 days, providing a further margin of safety.

Note, this definition of risk applies to microbiological contaminants only. See Section 4.3 for a discussion of the risks associated with nitrate contamination.

A staged approach is adopted for each of these assessments, summarised by a flow chart. These three assessments are described in sections 4.2, 4.3 and 4.4. This manual will, for each assessment, provide one or more options for the design of the water supply (or on-site sanitation system). A number of worked examples are provided in Appendix A that apply the assessment procedures presented in this section.

In this manual a water supply is considered as acceptable when all three risk assessments are judged to be low or very low risk and monitored

water quality meets the guideline value. Whilst wherever possible the design should meet these criteria, it is recognised that this may not always be feasible. Thus under some circumstances, it may be necessary to accept an option that carries a significant risk (but one minimised as far as is practical) provided that an increased level of monitoring is also instigated. Guidance on monitoring is given in Chapter 5.

Whilst these guidelines focus on contamination caused by on-site sanitation, it is important to recognise that there are other sources of contamination, especially in urban areas.

4.2 Assessing the risk of microbiological contamination of groundwater supplies via aquifer pathways

Two circumstances may arise when undertaking this assessment:

1. groundwater supplies are being installed, either in combination with the construction of on-site sanitation systems or where on-site sanitation already exists. In this circumstance there is some control over the design and construction of the groundwater supply;
2. on-site sanitation is being installed where groundwater supplies already exist. Here there is no control over the design or construction of the groundwater supply (although the design of on-site sanitation and its location can be altered).

These two circumstances will be addressed separately in this section although there is some overlap.

4.2.1 Installation of groundwater supplies where on-site sanitation already exists, or in combination with the installation of on-site sanitation

Figure 4.1 (p 46) is a flow chart summarising the steps within the assessment.

STEP 1: collect background information

first identifying the hydrogeological environment (Table 4.1 p 47)

- determine a typical minimum depth to water-table (by measuring water-levels in open wells, using local knowledge or from water level records held by the government agency).
- collect information on the types of sanitation system used, or likely to be used, and their hydraulic loading (Table 4.2 p 48).

  If necessary, seek specialist advice at a local university, national geological survey or other agency.

STEP 2: assess attenuation in the unsaturated zone

In this step we need to assess whether attenuation within the unsaturated zone (Figure 4.2 p 47) is likely to stop pathogens reaching the water-table or reduces numbers to acceptable concentrations.

Hydraulic loading

A conservative approach is to assume that where the hydraulic loading is high (greater than 50 mm/day) the risk of pathogens reaching the water-table is considered significant. This is because the unsaturated zone beneath the on-site sanitation will be sufficiently wetted that travel time will be low and the attenuation capacity reduced. Table 4.2 uses a simple approach to estimating the hydraulic loading based on sanitation design.

Nature of unsaturated zone

Even if the hydraulic loading is less than 50 mm/day there still may be significant risk that pathogens will reach the water-table. Whilst previous studies have suggested that as little as 2 m of fine unsaturated sand can provide sufficient attenuation of faecal indicator bacteria, this may not be true for all pathogens. Table 4.3 (p49)

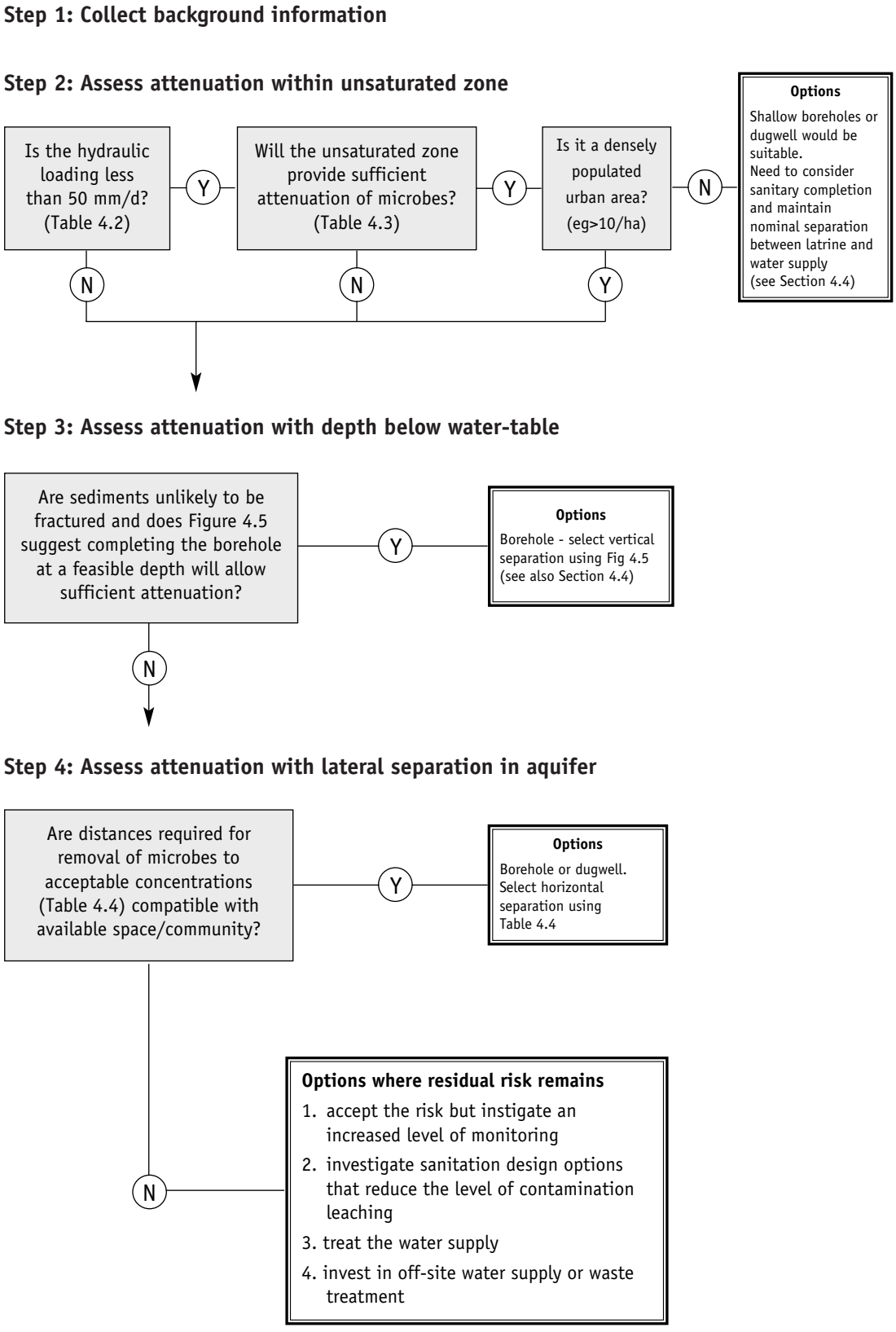


Figure 4.1. *Flowchart for assessing the risk of microbiological contamination of groundwater supplies via aquifer pathways. Installation of groundwater supplies where on-site sanitation already exists, or where this is done in combination with the installation of on-site sanitation*

identifies the risk of contamination reaching the water-table based on the rock type and the thickness of the unsaturated zone (a chart is provided which may help to identify the rock type based on grain size, Figure 4.3 p 48). A safety factor is incorporated into the table to allow for uncertainty both in classifying the rock type and in estimating minimum depth to water-table. The depth to the water-table is measured from the base of the pit.

For highly permeable unconsolidated sediments or where fractures are suspected, attenuation within the unsaturated zone cannot be relied upon and it is necessary to proceed to Step 3.

In densely populated urban areas it is probably safer to assume that groundwater is contaminated at the water-table because locally it is possible that:

(i) relatively large volumes of sullage/domestic water may be disposed of, wetting the unsaturated zone and producing rapid flow to the water-table (saturated rock is more permeable than unsaturated rock); and

(ii) various structures (e.g. abandoned wells/boreholes) may exist which provide contaminant pathways that short-circuit the unsaturated zone.

If Step 2 indicates that the risk of microbiological contamination reaching the water-table is low to very low, then a shallow borehole (screened at the water-table) or a dug well are appropriate options. However, it is important that the risk of localised contamination is minimised. This requires a

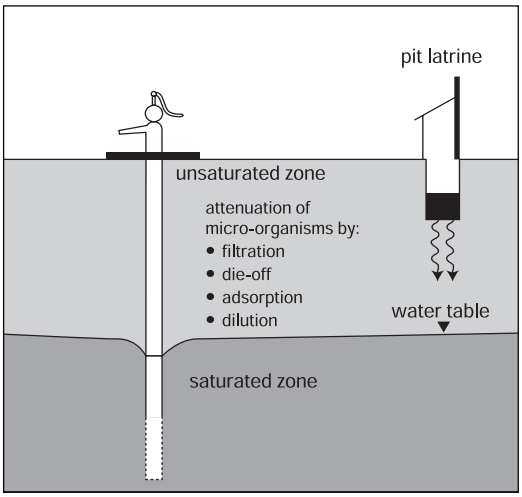


Figure 4.2. *Attenuation mechanisms within unsaturated zone*

Hydrogeological environments (see Table 3.3)	Typical rock types	Potential for aquifers to exist at depth (>30 m)
thick sediments associated with rivers and coastal regions	clay, silt, sand and gravel	high
mountain valley sediments	clay, sand, gravel and some interbedded lavas	high
minor sediments associated with rivers	clay, silt sand and gravel	low
windblown deposits	silt/sand	moderate
consolidated sedimentary aquifers	sandstones, limestones (potentially fractured)	moderate-high
Weathered basement	thick weathered layer underlain by fractured rock	low-moderate
	thin weathered layer underlain by fractured rock	moderate

Table 4.1. *Characteristics of hydrogeological environments relevant to risk assessment*

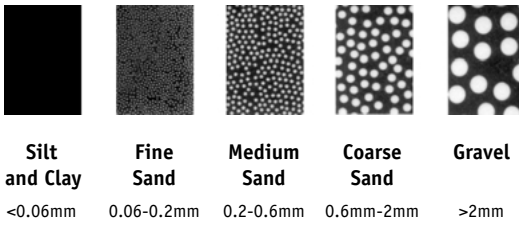


Figure 4.3. *Grain sizes of a range of sediment types.*

nominal or minimum separation between the water supply and the sanitation system (see Section 4.4).

STEP 3: assess attenuation with depth below the water-table

Putting the screen section of the borehole at greater depth will increase the travel time for contaminated water from the pit latrine. This may be sufficient to reduce the risk of contamination to low or very low (Figure 4.4). Even quite small increases in the depth of the screen can increase the travel time by many tens or even hundreds of days. This is applicable to unconsolidated sediments only, since in consolidated rocks, near-vertical fractures may be present which could provide a rapid pathway from the water-table to deeper aquifer zones.

The vertical separation necessary for the required travel time can be calculated from Figure 4.5 (p 50) using appropriate graphs for the rock type in question (Table 4.4, p 54 may help). (Larger versions of the graphs in Figure 4.5 can be found in Appendix B). The likely pumping rate of the borehole is important as the greater the rate, the faster water, and any associated contaminants, will move towards the borehole. A typical pumping rate for a handpump is 0.2 l/s (averaged over a day).

The option of increasing the depth to the borehole screen is attractive because:

- the incremental cost of constructing deeper boreholes is often relatively small;
- many aquifers are layered or stratified so that travel times for groundwater to penetrate to depth are likely to be long, providing an additional safety factor;
- using vertical separation allows the horizontal separation between borehole and pollution source to be reduced to a nominal value. As a consequence the borehole can be conveniently located close to users which may be especially valuable in urban areas where space is limited. However, reducing the separation between the borehole and the pit latrine may increase the risk of localised contamination that short circuits the natural subsurface profile (see Section 4.4).

However for aquifers which are not sufficiently thick, vertical separation may not be a feasible option; in this case it is necessary to proceed to Step 4.

Table 4.2. *Hydraulic loading associated with on-site sanitation types*

	Sanitation type	
	dry on-site sanitation	*wet on-site sanitation*
low hydraulic loading (< 50 mm/d)	simple VIP composting urine separation	pour-flush (low usage <10 people)
high hydraulic loading (> 50 mm/d)		septic tanks aqua privies

STEP 4: assess attenuation due to lateral groundwater movement

In Step 4, an assessment is made as to whether it is feasible to provide sufficient lateral separation between the pollution source and the groundwater supply so that the risk can be considered low or very low (Figure 4.6 p 51).

The horizontal separation required is the distance that groundwater would travel (horizontally) in a time interval of 25 or 50 days. Although each rock type will have a large range of permeabilities covering several orders of magnitude, permeabilities will fall within a narrower band of more likely values (Table 4.4, p 54). Whilst this narrower band of values will provide the basis for more realistic groundwater velocities, higher velocities are of course possible. A horizontal separation based on Table 4.4 (p 54) is therefore subject to some uncertainty and careful monitoring is required to provide confidence in the design criteria.

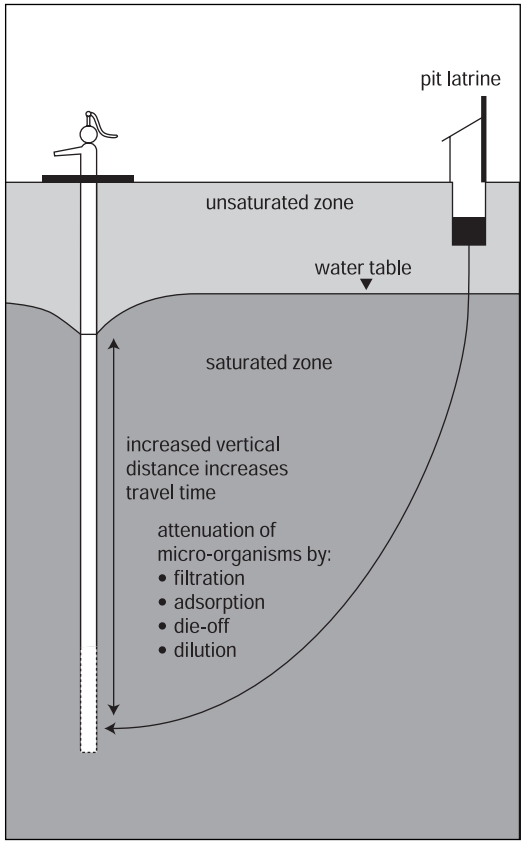


Figure 4.4. *Attenuation with depth below water-table*

Rock types in unsaturated zone	Depth to water-table (minimum depth) (metres below base of pit)		
	<5	5–10	>10
fine sand, silt and clay	■	▒	▒
weathered basement[1]	■	■	▒
medium sand	■	■	▒
coarse sand and gravels	■	■	■
sandstones/limestones fractured rock	■	■	■

[1] where the weathered material is soft and easily dug. Where weathered rock is competent and therefore potentially fractured it should be considered as fracured rock

■ significant risk that micro-organisms may reach water-table at unacceptable levels

▒ low to very low risk that micro-organisms may reach water-table at unacceptable levels i.e. travel time through the unsaturated zone greater than 25 days

Table 4.3. *Assessment of risk following attenuation of micro-organisms within the unsaturated zone*

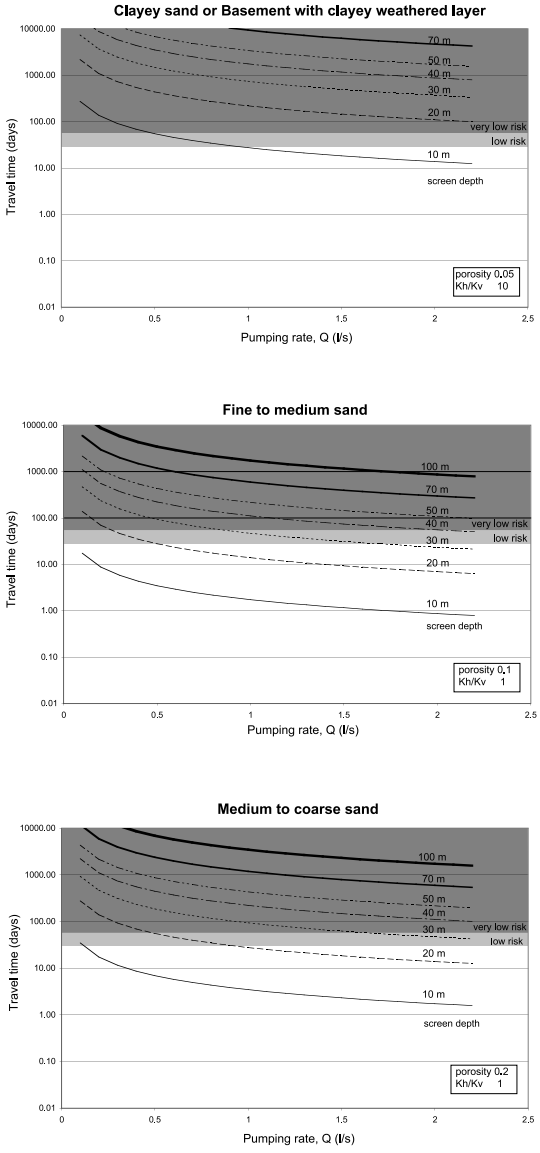


Figure 4.5. *Travel time for the flow to a borehole screen for the water-table for a range of pumping rates and screen depths, and a series of aquifer porosities and Kh:Kv ratios. Kh:Kv ratio is the ratio of hydraulic conductivity in the horizontal and vertical directions. (Full page versions available in Appendix B).*

The horizontal separation is calculated by the following simple equation:

separation = velocity x time
(t = 25 or 50 days)

where $velocity = \frac{Ki}{\varphi}$

K = hydraulic conductivity (permeability) m/d
i = hydraulic gradient (assume 1/100)
φ = porosity

Values for the parameters can be obtained from Table 4.4. Use the maximum permeability and the minimum porosity suggested to give the most conservative estimate of lateral separation.

There are two major areas of concern when relying on horizontal separation between the contaminant source and groundwater supply to provide sufficient attenuation:

- thin highly permeable normally horizontal layers may occur within the aquifer that provide a more rapid pathway than would be anticipated by the broad-scale lithology of the aquifer and an assumed average permeability (Figure 4.6). For this reason, especially in layered aquifers and where permeable sand layers are suspected, great care needs to be taken in choosing appropriate lateral separation; and
- the horizontal separation required may be incompatible with available space.

Where it is feasible to install a water supply at a sufficient lateral separation to provide a low or very low risk, then options could include a shallow borehole, dug well or spring.

Options where residual risk remains

Where providing a sufficient horizontal separation between contaminant source and groundwater supply is not a feasible option because of a) lack of space, b) the aquifer is fractured or c) the aquifer is thin and highly permeable, then there will be a significant residual risk of contaminated groundwater entering the supply. Options at this stage include:

- accept the risk but instigate an increased level of monitoring (see Chapter 5). This is likely to be most acceptable where attenuation in the unsaturated and saturated zones, although individually not sufficient, may together provide significant attenuation;

- where appropriate, investigate sanitation design options that reduce the level of contamination leaching;
- treat the water supply – probably most appropriate for fractured aquifers;
- invest in off-site water supply or waste treatment.

4.2.2 Installing on-site sanitation alone, where groundwater supplies already exist

Figure 4.7 (p 52) is a flow chart summarising the steps within the assessment.

STEP 1: collect background information

Collect information as in Step 1 of Section 4.2.1. In addition collect information on the design and construction of groundwater supplies in the area in which sanitation is to be installed.

STEP 2: assess attenuation in the unsaturated zone

If the existing water supplies are obtained from dug wells or boreholes screened at the water-table it is necessary to assess whether the unsaturated zone can provide sufficient attenuation of pathogens using Table 4.3 (p 49). If the risk is low or very low the option is for any dry-type latrine. However, one will need to consider latrine separation to avoid localised contamination. This is discussed in Section 4.4.

STEP 3: assess attenuation with depth below water-table

This assessment is similar to that in Step 3 of Section 4.2.1 but approaches the question from the opposite direction. Given the details that are available on the design of the groundwater supply, are the screened sections of the borehole sufficiently deep to allow the required attenuation of microbiological contaminants? If uncertain of design go to Step 4. Dug wells will not allow sufficient attenuation as water will always be able to enter at shallow depths. Use Figure 4.5 as in Section 4.2.1.

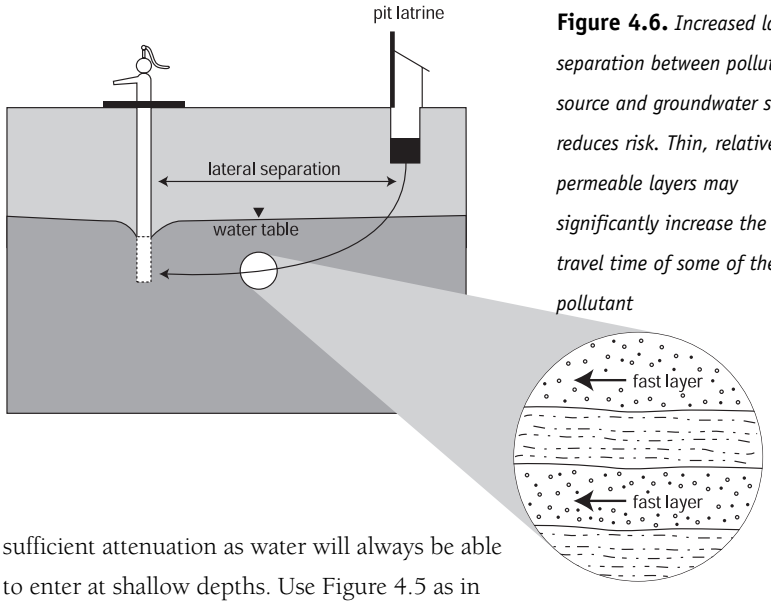


Figure 4.6. *Increased lateral separation between pollution source and groundwater supply reduces risk. Thin, relatively permeable layers may significantly increase the travel time of some of the pollutant*

STEP 4: assess attenuation due to lateral groundwater movement

Undertake this assessment as in Step 4 of Section 4.2.1. If risk is low (Table 4.4 p 54) any latrine type can be installed. However, it is important to consider a minimum separation between latrine and the water supply to reduce the risk of localised contamination. This is discussed in Section 4.4.

Where a residual risk remains, various options can be considered. These include: (1) investigate special sanitation design options that reduce risk; (2) examine appropriateness of installing new (deeper) water supply; (3) treat water supply; (4) invest in off-site waste treatment; (5) accept risk but instigate an increased level of monitoring.

4.3 Assessing the risk of nitrate contamination of groundwater supplies as a result of widespread aquifer contamination

A critical element in assessing the risk of widespread nitrate contamination of an aquifer is to consider the short and long-term water supply

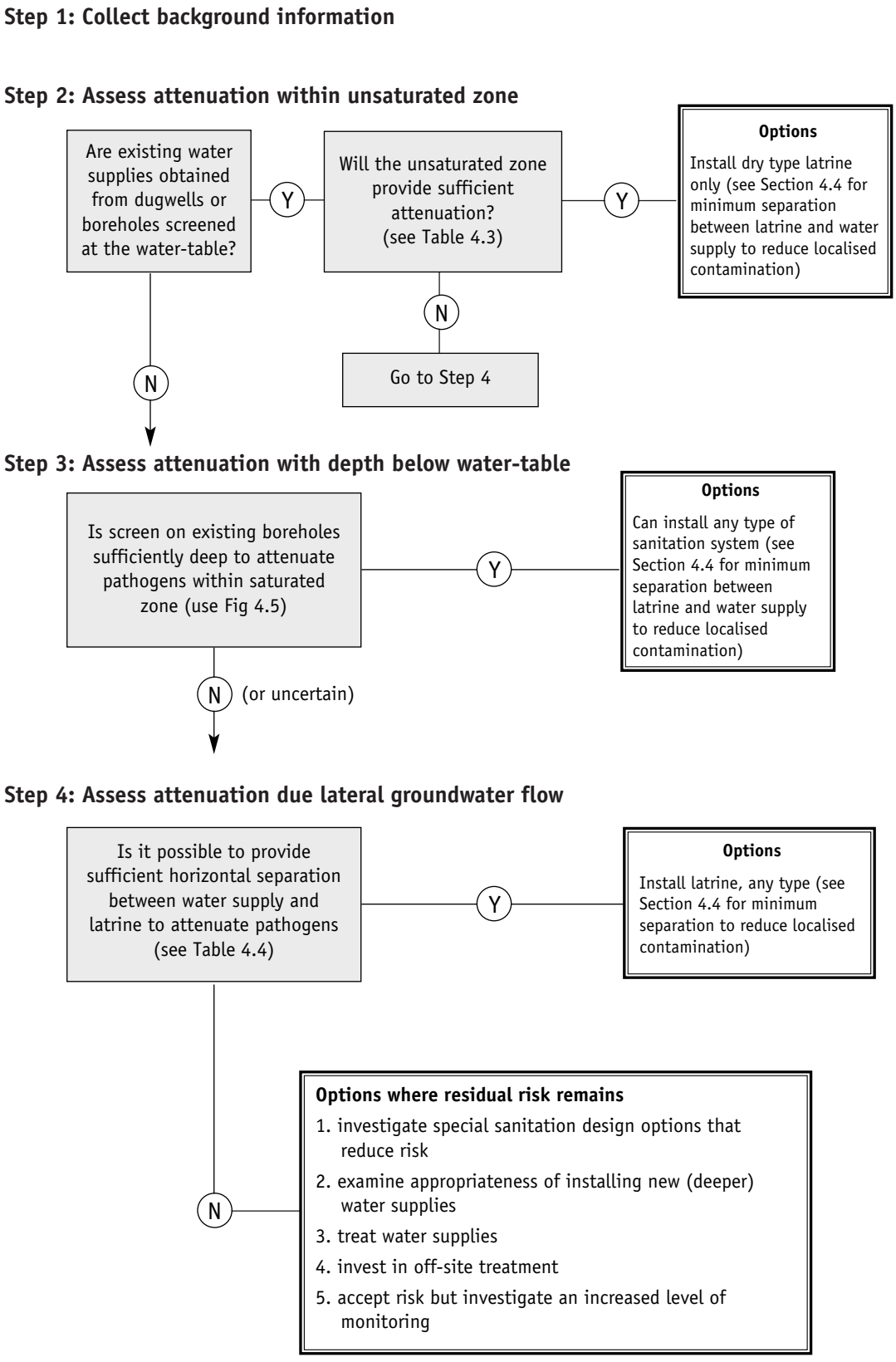


Figure 4.7. *Flow chart for assessing the risk of microbiological contamination of groundwater supplies via aquifer pathways where groundwater supplies exist and only on-site sanitation is being installed.*

and sanitation plans, i.e. the type of groundwater supplies available and the long-term need to protect groundwater. In some cases, the use of shallow groundwater, which is more susceptible to nitrate contamination, may be viewed as a short-term intervention, the long-term aim being to develop a piped distribution network based on surface water or more distant deep groundwater sources. In this situation, concerns over nitrate in groundwater may be relatively limited and restricted to the immediate health concerns. The potential benefits of improved sanitation are likely to significantly outweigh these risks.
In other situations, however, long-term water supply strategies will be based on the continued use of groundwater for domestic supply. Even when such plans indicate abstraction of deeper groundwater in the future, the control of nitrate contamination will become critical, as in many situations there is hydraulic continuity between shallow and deep groundwater. As a consequence, fronts of high nitrate water may migrate from shallow to deep groundwater and this potentially places the resource at long-term risk.

A staged approach is adopted and is summarised by a flow chart in Figure 4.8 (p 55). It must be emphasised that estimating nitrate leaching is at best approximate. This risk assessment therefore seeks to indicate only whether or not a potential risk is likely due to on-site sanitation alone. It should be noted that other sources of nitrate may exist which, on their own or in combination with nitrate from on-site sanitation, cause nitrate concentrations in groundwater to be unacceptable.

STEP 1: Collect background information
Background information is collected which is required to estimate the likely nitrate concentration in groundwater recharge derived from on-site sanitation systems. The following data/information is required;

- a typical minimum depth to water-table;
- an estimate of the average annual recharge (mm). If necessary this can be based on a knowledge of average annual rainfall using Figure 4.9;
- population density;
- identification of the hydrogeological environment.

STEP 2: Estimate nitrate concentration in recharge
Using the information collected in Step 1 and Figure 4.10 (p 57), the potential nitrate concentration in the recharge can be estimated. This assumes that all organic nitrogen deposited in the pit latrine is oxidised and leached to groundwater. However, in many cases the percentage oxidised and leached will be less than 100% (Table 4.5, p 58). Multiplying the potential nitrate concentration leached by the fraction corresponding to the hydrogeological environment gives an estimate of the nitrate concentration in the recharge. These figures for fractions of total nitrate leached are uncertain and are used to indicate only the approximate magnitude of the nitrate concentration that can be anticipated. For groundwaters with low dissolved oxygen, denitrification can occur producing very low nitrate concentrations within the aquifer.

If the estimated nitrate concentration is low, then on-site sanitation is likely to be acceptable. However, it is still advisable to monitor because other sources of nitrate may be present which alone, or in combination with the nitrate from on-site sanitation, result in the total nitrate concentration exceeding the guideline value. Where the estimated nitrate concentration exceeds

the drinking water guideline value then it is useful to consider the time delay and dilution in Step 3.

STEP 3: Consider time-delay and whether short term option

So far the nitrate concentration in recharge from a settlement has been estimated. However, the nitrate concentration in the groundwater should be lower because of mixing and dilution within the aquifer (Table 4.6, p 58). If all the recharge to groundwater is derived from the settled area, then this dilution within the aquifer will only delay the onset of predicted nitrate concentrations. Nevertheless this delay may be important and allow other measures (different source of water or sewered sanitation) to be installed in the longer term.

In smaller settlements (rural areas), recharge to the deeper groundwaters may be derived in part from outside the settled area (see Figure 4.11 p 57) and the recharge will accordingly be of lower nitrate concentration. In this case nitrate concentrations may remain low in the longer term and on-site sanitation is likely to be an acceptable option. However, it is important even in rural areas that groundwater nitrate concentrations are monitored.

In urban areas, recharge for deeper aquifers is likely to be derived from an urban/settled environment and therefore nitrate concentrations are likely to be high. Significant delay can be anticipated where the screened interval of the borehole is deep (>30 m) and the aquifer possesses considerable porosity (e.g. unconsolidated). Thus on-site sanitation may be acceptable as a short term measure but may be problematic in the longer term. It is essential to monitor nitrate.

Where on-site sanitation may cause nitrate contamination even in the short term (e.g. aquifer

Table 4.4. *Typical aquifer properties for a range of rock types and feasibility of using horizontal separation*

Rock types	Typical porosity	Typical Kh:Kv ratio#	Range of likely permeability (m/d)	Feasibility of using horizontal separation	Lateral separation to reduce pathogen arrival at water supply to low risk
Silt	0.1–0.2	10	0.01–0.1	Yes	up to several metres*
Fine silty sand	0.1–0.2	10	0.1–10	Yes, should be generally acceptable*	up to several metres*
Weathered basement (not fractured)	0.05–0.2	1-10	0.01–10	Yes	up to several metres*
Medium sand	0.2–0.3	1	10–100	uncertain, will need site specific testing and monitoring	Tens–hundreds of metres
Gravel	0.2–0.3	1	100–1000	not feasible	up to hundreds of metres
Fractured rocks	0.01	1	difficult to generalise,velocities of tens or hundreds of m/d possible	not feasible	up to hundreds of metres

this is the ratio of horizontal permeability and vertical permeability – greater in fine-grained sedimentary rocks
* need to select a minimum separation to avoid localised contamination (see Section 4.4)

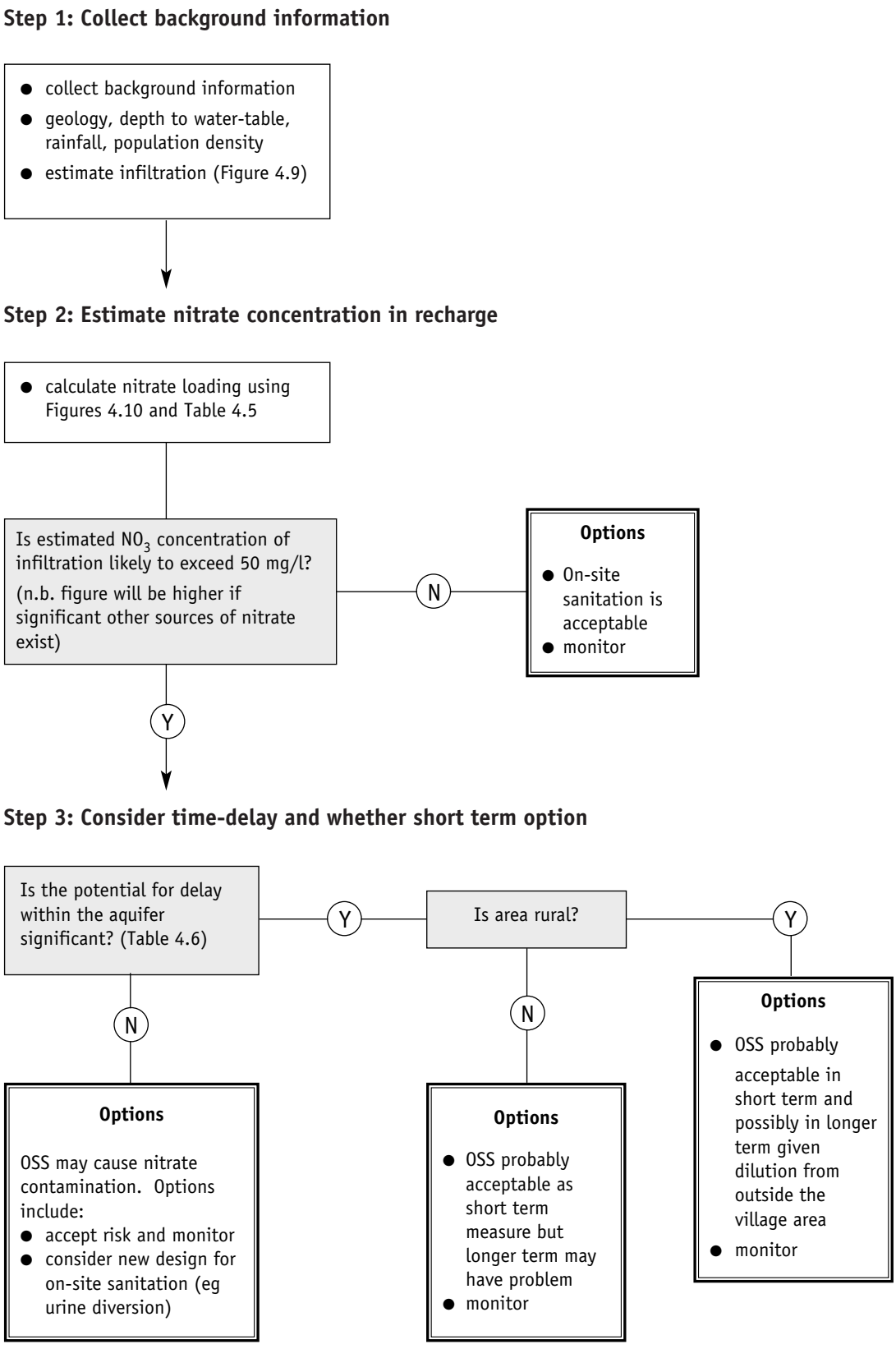


Figure 4.8. *Flow chart for assessing the risk of nitrate contamination of groundwater supplies as a result of widespread aquifer contamination*

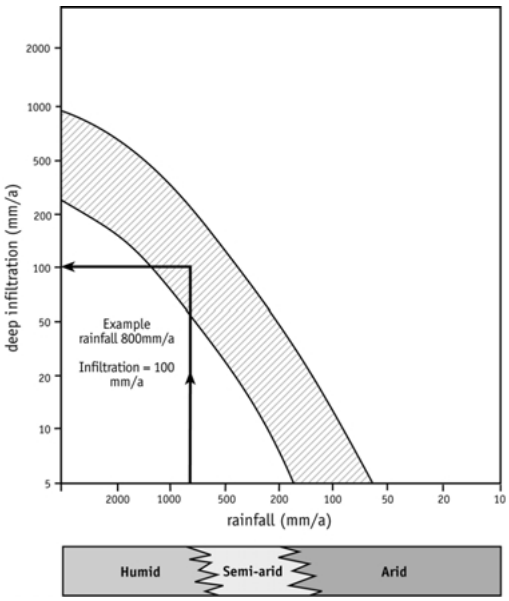


Figure 4.9. *Simplified relationship between average annual rainfall and groundwater recharge. Used in Step 2 of risk assessment due to nitrate.*

provides limited potential for delay - see Table 4.6, p 58). Two options are possible:

i) accept risk and monitor; actual nitrate concentration may be less than estimate. May need to consider alternative water supplies if nitrate concentrations are excessive;

ii) consider changes in on-site sanitation design (e.g. urine diversion – see Section 3.4).

This process has restricted the analysis of nitrate loading to that originating from on-site sanitation. If it is thought that other sources of nitrogen loading are significant in comparison with that from on-site sanitation (see Section 3.4), expert advice should be sought to quantify this. Monitoring data will be important in this circumstance and in general when assessing the risk to groundwater supplies from nitrate contamination.

4.4 Assessing the risk of microbiological contamination due to pathways created by construction of the groundwater supply

Reducing the risk of contamination of the water supply via localised pathways is achieved by firstly keeping potential pollution sources away from the immediate vicinity of the water supply and secondly, by minimising pathways created by the design or construction of the supply. This assessment is sub-divided into two steps, the first assessing the sanitary conditions of the headworks and the second, the sanitary provisions below ground surface. The assessment is summarised in Figure 4.12 (p60).

STEP 1: Assessment of sanitary condition of the headworks

The measures required to ensure adequate sanitary protection at the headworks when constructing a groundwater supply were discussed briefly in Section 3.7. Table 4.7 (p59) lists key criteria for headworks design. Those listed in Table 4.7a are relatively cheap and easy to implement and should be complied with, without exception. The criteria listed in Table 4.7b should, where possible, be included in the design although it is accepted that this may not always be possible. Thus it may be necessary to accept the limitations and the corresponding residual risk.

Some example sanitary inspection forms are provided in Appendix C. Further, detailed advice on 'best-practice' approaches to sanitary completion measures are presented in the WHO Guidelines for Drinking-Water Quality Volume 3 and in a range of manuals on urban water supply surveillance (see the WEDC web page http://www.lboro.ac.uk/watermark for information). Where a groundwater supply is already in existence, sanitary survey forms provide a means to assess the risk to the supply from inadequate headworks and inappropriate activities in the vicinity. Efforts or measures to address problems highlighted in the survey will reduce the risk to the supply. This is discussed further in the next chapter.

STEP 2: Assessment of sanitary provisions below ground surface within the supply design

Boreholes

If a sanitary seal exists and has been properly installed then the borehole/well is acceptable for the purposes of this assessment. If no sanitary seal is present or cannot be installed as a result of the drilling method, an alternative drilling method should be sought which allows insertion of a cement seal. If this is not possible (because costs are prohibitive) a borehole design without a sanitary seal may be considered under some circumstances, accepting that the residual risk is significant and that more frequent monitoring is essential. These circumstances would include where:

- aquifer is unconsolidated and not coarse-grained; and
- depth to screen exceeds 30 m.

However, the risk of contamination will be increased where (i) environment is urban, (ii) the water-table is shallow and (iii) the separation between the on-site sanitation and the water supply is less than the nominal 10 m.

The risk of contamination can be decreased by reducing the likelihood of leakage through the casing by:

- using screw-threaded casing joints rather than glued-joint casing
- avoid using suction-lift pumps that create a pressure differential between inside and outside of casing at the water-table. Such a pressure differential would increase the risk of contaminated water at the water-table being

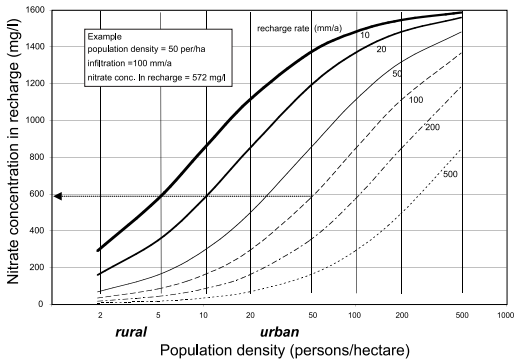


Figure 4.10. *Estimated nitrate concentration in groundwater recharge based on population density and average annual recharge (full page version available in Appendix B).*

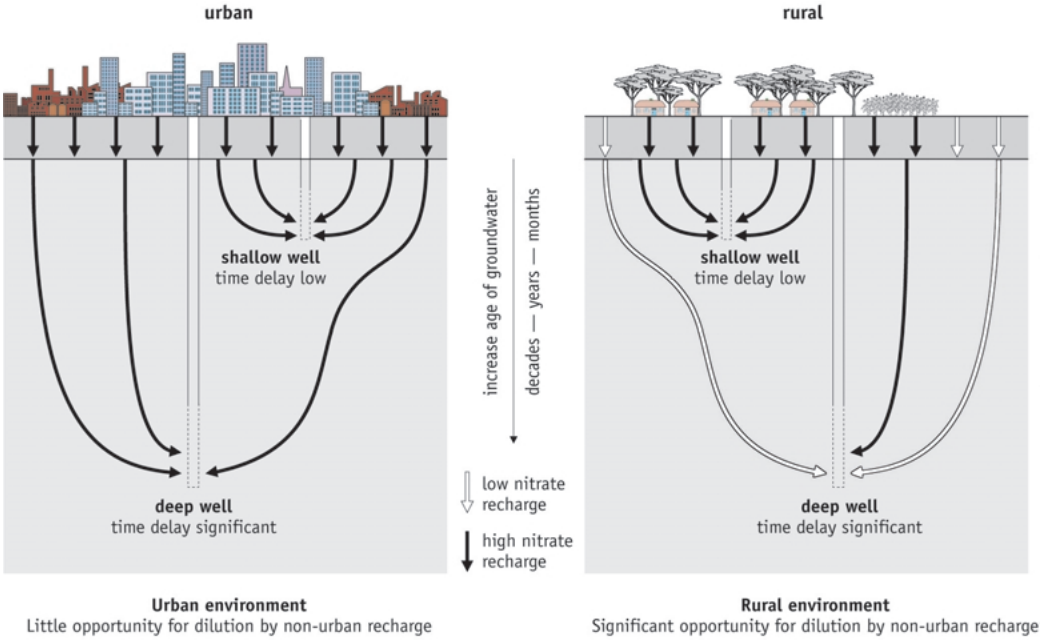


Figure 4.11. *Where boreholes are deep, the onset of high nitrate concentrations will be significantly delayed due to the time taken for the front of high nitrate waters to reach the borehole inlet. In smaller 'rural' settlements deep boreholes may tap lower nitrate waters derived from outside the settled area, which is less likely in an urban environment.*

Table 4.5. *Percentage of potential nitrate in groundwater recharge likely to leach from a pit latrine to the water-table in a range of hydrogeological environments*

Hydrogeological environment	**Fraction of nitrate likely to be leached**
(1) Unconsolidated sedimentary aquifer	
a) Clay, silt, fine sand	Up to 0.3 could be very low especially where water-table is shallow and sediments clayey
b) Fine-medium sand	c. 0.3
c) Medium sands and gravels	0.3–0.5
(2) Weathered basement aquifer	
a) Thick weathered layer	Up to 0.3 but could be very low especially where water-table is shallow and weathered material clayey
b) Thin and/or highly permeable weathered layer	0.3–0.5
(3) Fractured consolidated sedimentary aquifer	Up to 1.0

Table 4.6. *Potential for time-delay in the onset of nitrate problems*

Hydrogeological environment	**Delay potential**	**Urban (limited dilution) Likely to be:**	**Rural (significant dilution) Likely to be:**
(1) Unconsolidated sedimentary aquifer			
(a) <30 m depth	low-moderate	Problematic in short term Unsustainable in long term*	Problematic in short and long term
(b) >30 m depth	high	Sustainable in short term, problematic in long term	Sustainable in short term and probably in long term
(2) Weathered basement aquifer			
(a) thick weathered layer	low-moderate	Problematic in short term Unsustainable in long term*	Problematic in short and long term
(b) thin weathered layer	low	Problematic in short term Unsustainable in long term	Problematic in short and long term
(3) Fractured consolidated sedimentary aquifer			
	low	Problematic in short term Unsustainable in long term	Problematic in short and long term

*Unless fraction of nitrate leached is low due to denitrification

sucked in through a defective casing joint. Where the formation is not unconsolidated or the depth does not exceed 30 m, it is necessary to seek specialist advice. For consolidated formations a sanitary seal is essential.

Springs

If the design of the protected spring has included a backfill media of pea gravel and sand which is overlain by protective sand, clay and grass layers with adequate diversion ditches and fences, then design problems are unlikely to be a significant cause of failure in water quality. However, what is crucial is for these protective measures to be maintained properly to ensure ongoing protection. As already discussed, if these measures are allowed to deteriorate, then contamination may well result.

a) Factors that should be included in design

Boreholes and wells:

- apron extends more than 1.5 m from well
- cement floor is sound with no cracks and slopes away from borehole or well
- drainage channel in good working order (not cracked, broken or blocked)
- handpump firmly attached to apron
- protective fence is in sound condition

Springs:

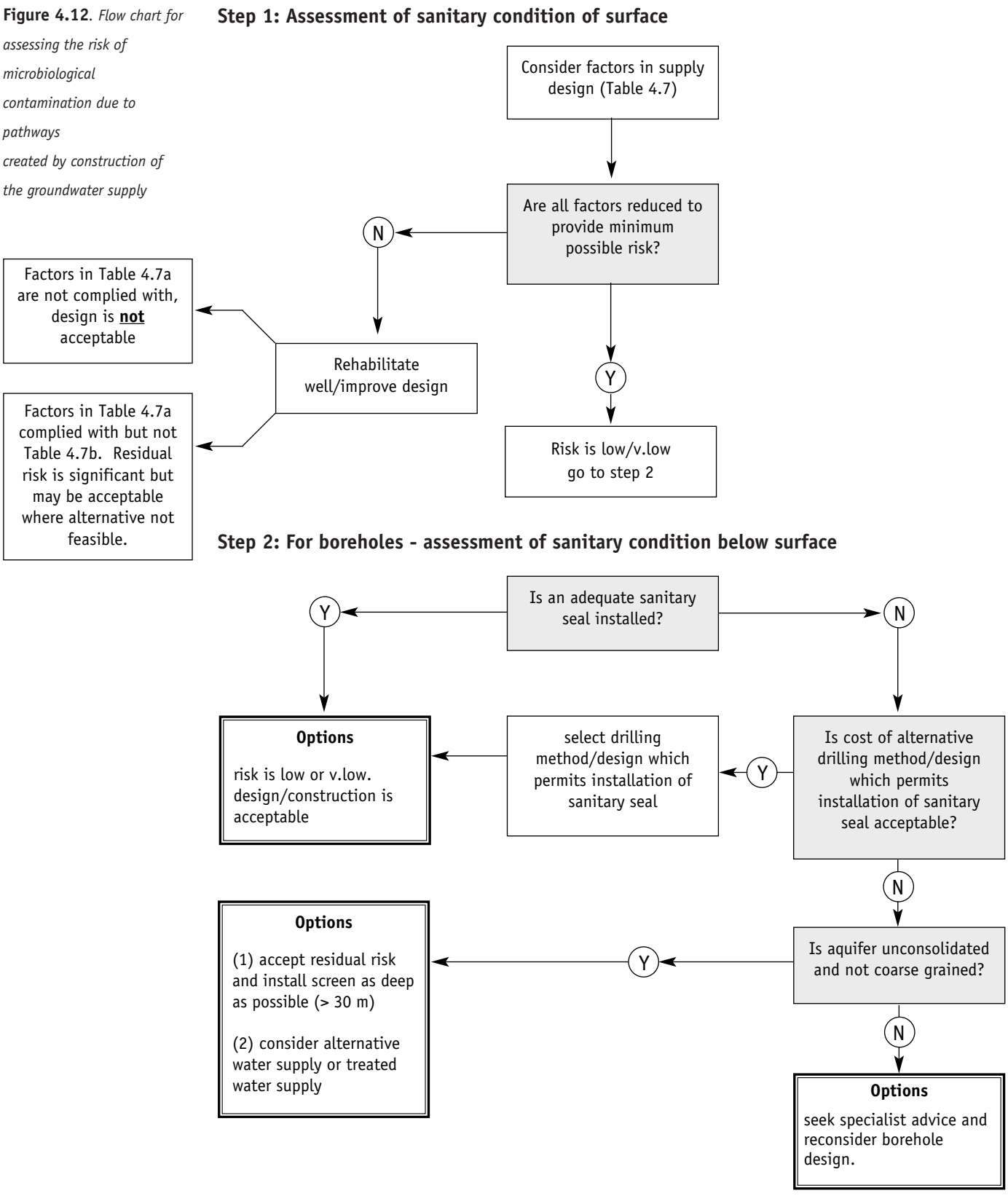
- protection of the spring
- backfill area behind a spring box or retaining wall protected and has grass cover
- backfill media used is fine gravel or sand
- retaining wall and other protection works in good condition and without cracks
- fencing excludes animals from the backfill area
- diversion ditches direct run-off away from the backfill area
- drainage of wastewater from spring

b) General: factors that should be included in design, where possible

- sources of pollution such as surface water sources kept as far away as possible (at least 30m)
- solid waste is removed from immediate area
- animals should be kept at least 10m away from the supply

Table 4.7. *Key criteria for headworks design*

Figure 4.12. *Flow chart for assessing the risk of microbiological contamination due to pathways created by construction of the groundwater supply*



5 Ongoing assessment of risk through monitoring

5.1 Introduction

Monitoring is an integral part of the design, construction and maintenance of water supply and sanitation schemes. Monitoring serves several objectives, to:

- provide confidence/confirmation that the design of the water supply scheme is adequate, in particular where a significant residual risk is identified during the design/planning stage;
- help to identify the cause of contamination, where it exists, so that follow-up remedial work can be undertaken as appropriate;
- evaluate changes in both water quality and near well-head environment over time, and identify remedial maintenance required;
- check that water quality is fit for consumption (health-based surveillance).

Monitoring involves both the determination of chemical and microbiological quality of the water and a survey of the sanitary conditions of the water supply and its immediate environs. This data needs to be analysed and interpreted to address the objectives above.

However, collecting and analysing the data is not an end in itself. The benefits of monitoring can only be gained if the interpretation is fed back to those planning the schemes and carrying out operation and maintenance and that any recommendations are acted upon. Recommendations might include that the design of the water supply is modified or that maintenance of a water supply needs to be carried out.

This chapter will provide answers to the following:

- why monitor?
- how to monitor – how are samples collected, which parameters should be analysed and how are sanitary inspections carried out?
- when and where to monitor (e.g. numbers of samples, numbers of water supplies, frequency of sampling, influence of seasons)?
- how to analyse the data and how it can be fed back to the water supply and sanitation programme?

5.2 Why monitor?

There are several reasons why it is important to monitor water supplies, these are discussed in detail below. Monitoring should be seen as an essential part of the water supply and sanitation programme providing valuable data on the reliability, security and sustainability of the schemes. Monitoring can also help by recognising problems at an early stage and may help avoid costly failures. A flow chart that maps the decision-making process for monitoring is presented in Figure 5.1.

5.2.1 Monitoring to provide confidence in design

Monitoring can be used to help confirm that the design and construction methods for groundwater supplies and/or selection of sanitation system type is adequate to prevent contamination. This information can be fed back to those planning the water supply and sanitation programme. Where the results confirm water quality is acceptable then this provides confidence to programme managers, regulators and to the users of the water supplies. This is essential to ensure that effective measures to protect water quality are highlighted and replicated.

Assessments of existing water supply designs may be used to select designs and planning for water and sanitation projects in other areas and this is often a sensible way of assessing risks when data for the first-step risk assessment outlined in Chapter 4 is not available. However, if this approach is followed, it is essential that the area used in the assessment is similar to the area where the water and sanitation programme is to be

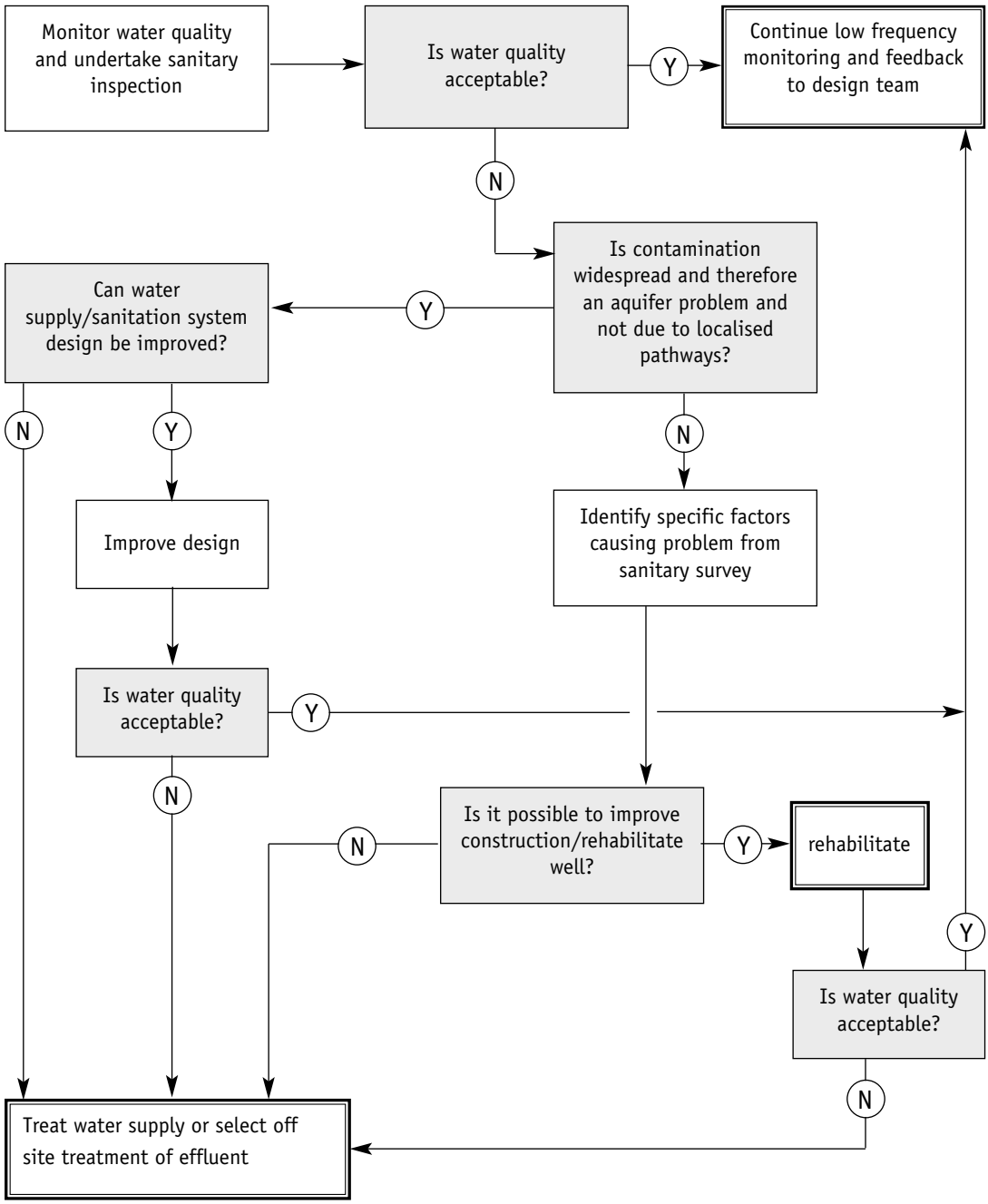


Figure 5.1. *Flow chart for monitoring of groundwater supplies*

initiated. For example, it may not be possible to project the results of assessments of water quality of shallow groundwater sources in small towns or rural areas to large urban areas with high-density populations.

Monitoring is very important in circumstances where a significant residual risk was identified in the planning stage (Chapter 4) or where an assessment of existing water supplies suggests the residual risk is high. For example, where hand-drilling methods are used to construct boreholes that preclude the use of a sanitary cement seal around the casing, a significant residual risk can be anticipated which is difficult to quantify. The difference in borehole construction costs between conventional drilling methods and hand-operated techniques is very considerable and therefore before abandoning the cheaper hand-drilled technique, it is important to assess whether the residual risk is acceptable. This could be tested by monitoring the water supplies constructed using hand-drilling methods to see whether contamination has occurred at concentrations exceeding those that are acceptable.

Even when risks identified during planning are low, it is always valuable to undertake at least some monitoring (perhaps of a small number of water supplies constructed) in order to verify whether water quality is acceptable. Should contamination be found, the causes need to be investigated further as these may relate to a number of different factors, of which on-site sanitation is only one problem. This is discussed further in Section 5.5.

5.2.2 Monitoring to establish cause of contamination

Monitoring can be used to identify the causes of contamination and to establish whether the problem is general (aquifer wide) or restricted to individual water supplies (localised problem). Understanding the extent and nature of pollution is critical to be able to plan and implement remedial actions. Where the problem is aquifer wide, then consideration should be given to whether it is possible to change the design of the water supply. This could involve using a deeper tubewell with the contaminated shallow aquifer sealed-off, or by adding treatment to the source, for instance through chlorination of a shallow well. Alternatively, the sanitation system could be changed with a design that is less prone to leaching contaminants into the groundwater or by ensuring that latrine pits are never dug into the water-table. Where a change in design or construction is not possible, an alternative means of water supply (for instance through piped water) could be considered or a household water treatment system promoted.

Where the problem is 'localised' it is necessary to identify the factor(s) causing the contamination, which will help identify how the problem might be rectified. This relies on using both sanitary inspection and water quality data and, unless both are available, it will be difficult to do this analysis. In many cases, the problem may be relatively easy to overcome through improved operation and maintenance and limited investment in repair works. If it is not possible to improve the construction or rehabilitate the supply, then consideration should be given to either treating the water supply or by promoting the use of household water treatment technologies.

5.2.3 Health-based surveillance

One reason for monitoring is to ensure that the water supplied meets the appropriate drinking water guideline or standard. Priority is always given to microbiological water quality. In the context of on-site sanitation, the key parameters will include faecal coliforms and nitrate.

However, other quality parameters that affect health or cause consumers to reject the water, for example turbidity, fluoride, arsenic and iron, should be considered under this type of monitoring. For further information please consult the WHO Guidelines for Drinking-water quality Volume 1 (Recommendations) and Volume 3 (Surveillance and control of community water supplies) and the manuals on water supply surveillance in urban areas of low-income countries (available at www.lboro.ac.uk/watermark).

Where the design and the construction method for the supply are considered to present a low risk (see Chapter 4) it is probable that the water quality will meet the relevant guideline or standard, but this should be verified for at least some of the water supplies. Where water quality does not meet the guideline or standard, monitoring should be used to establish the cause of contamination (see Sections 5.2.2 and 5.5). It is also useful to try to link the water quality data to health surveillance data (if this exists) to see if the contamination of the water supply is leading to definite adverse health effects. If health data show an impact and the water quality cannot be improved at the source, it is important that hygiene education programmes are undertaken in the affected communities and household water treatment is promoted.

5.2.4 Monitoring to evaluate trends in water quality and risks

Whilst the good design and planning of water and sanitation systems often greatly reduces the risk of

Table 5.1. *Parameters to monitor, equipment needed and requirements for sampling*

Determinand	**Purpose**	**Field analysis**	**Laboratory analysis**	**Sampling requirements**
Microbiological				
Thermotolerant coliform *E.coli* Faecal streptococci	indicate a faecal source of pollution and increased risk of pathogen presence	field kits available for faecal coliforms and faecal streptococci.	not all laboratories have facilities for carrying-out microbiological analyses but where they do, faecal coliforms and E.coli are standard parameters; faecal streptococci analysis may not be available.	sterilise sampling equipment, bottles and spout. Keep cool, dark and analyse within 6 hours
Chemical				
Nitrate Ammonium	major chemical contaminant associated with sanitation pollution (see Section 3.5)	spectrophotometer photometer meter and ion specific electrodes possible	spectrophotometer standard method	keep cool prior to analysis – undertake analysis within a few days
Chloride	major chemical contaminant associated with sanitation pollution (see Section 3.5)	spectrophotometer photometer meter and ion specific electrodes or titration	standard method	keep cool prior to analysis
Dissolved oxygen	availability of oxygen to oxidise nitrogen into nitrate	meter and electrode	not applicable	use flow cell to avoid water contact with air
Electrical conductivity	measures total dissolved solids which can be an indicator of pollution	meter and electrode	standard method standard parameter	best measured in field

Field analysis	Laboratory analysis
Advantages	*Advantages*
• cheap equipment	• able to handle large numbers of samples more efficiently and cost-effectively
• easy to measure	• wider range of analyses
• immediate results can be obtained and checked	• more complex analyses
• can be analysed within short distance/time of field site	• better quality control possible
• essential for dissolved oxygen and often for microbiological parameters	
• greater participation of communities in surveillance and improvement of water supply	
Disadvantages	*Disadvantages*
• large number of samples take long time	• expensive for small numbers of samples
• limited range of analyses	• may require long time in transit if laboratory far from field area
• diverts investment from laboratories	• analyst does not 'see' sites
• poor quality control	

Table 5.2. *A comparison of field and laboratory analysis of samples*

groundwater contamination from on-site sanitation, it should be recognised that this is unlikely to ensure that there is no increase in risks with time. As communities develop, there is increasing pressure for land and thus encroachment into areas where sanitation is controlled may occur over time, unless the community and support agencies have plans to counter-act this. In addition, risks of contamination will increase when basic protective measures are not well-maintained.

In order to keep the risks of contamination to an acceptable level, it is important that there is ongoing monitoring of groundwater supplies to assess whether conditions at the supplies are changing and whether these are leading to increasing risks. This helps to determine whether major changes are needed in design, construction or planning of water and sanitation programmes.

5.3 How to monitor

This section discusses the means by which monitoring data are collected, for discussion of when and where data are collected please see the next section. When planning a monitoring programme a number of issues are of importance:

- parameters to measure and sampling methods;
- facilities required to analyse samples;
- costs incurred; and
- conducting sanitary inspections.

Table 5.1 lists the standard parameters that a monitoring programme should include when addressing contamination from sanitation sources. Some basic information on sampling is provided that relates to the type of equipment necessary and sampling methods.

A key issue to address in the planning of a monitoring programme are the analytical facilities. Analysis can be undertaken in the field or in laboratories although commonly a combination of both are used. The choice will depend principally on:

- number of samples to be routinely analysed;
- availability of a laboratory that can analyse for the required parameters;
- availability and reliability of field equipment that can analyse for the required parameters;
- distance of field sites from the laboratory;
- availability of personnel to collect samples and availability of equipment for analysis in the field;

- the degree of community participation desired.

Field equipment may be used for the analysis of microbiological and chemical parameters where the number of samples is relatively small and community involvement in surveillance and improvement of water supply is desired. Alternatively, samples can be analysed in a laboratory, which will allow a greater range of tests to be carried out and greater number of samples to be analysed. Consumables costs for both laboratory and field equipment can be relatively high.

Field analysis is essential for some parameters, for instance electrical conductivity or dissolved oxygen, where transport back to a laboratory may cause deterioration of the sample and potentially inaccurate results. Field analysis for such parameters normally relies on meters and chemical analysis may use ion-selective electrodes. These generally provide sufficiently accurate results but are time-consuming when large numbers of analyses are required. Field photometers and spectrophotomers can also be used to analyse nitrate and other chemicals, although it may be easier to perform these analyses in an office or laboratory.

Laboratories are able to handle large numbers of samples more easily and will be able to perform a wider range of analysis and undertake more complex analysis. However, the main disadvantage is the distance of the laboratory from the field and the potential for the condition of the sample to change during transport from the field site. Samples for bacteriological analysis must be kept below 4°C and analysed within 4-6 hours of taking the sample in order for the results to be reliable.

The comparison of field and laboratory analyses is made in Table 5.2.

It is difficult to generalise about costs. However, the main components are likely to be:

- staff time involved and field expenses;
- purchase, running costs (including maintenance) of transportation;
- capital and running costs of field equipment; and
- laboratory costs.

As monitoring is essential when undertaking a water and sanitation programme, the costs and the logistics of taking and analysing samples should be incorporated at an early stage. Further information on establishing field and laboratory based programmes is provided in 'Water quality monitoring' by Bartram and Ballance, which is listed in the References.

Sanitary inspection

Whenever a sample is taken, a sanitary inspection should be carried out. This is an assessment of the potential sources of faeces (hazards) that may affect the water supply and the state of the infrastructure and protection works. These relate to the pathways and indirect factors that can lead to contamination as discussed in Section 3. WHO and other organisations recommend that a systematic approach is taken to sanitary inspection, using standardised formats. Examples of sanitary inspection forms are included in Appendix C. However, these should only act as a guide as the different risks may be relevant in different areas.

In this type of sanitary inspection, there are a limited number of questions. Each question has a yes/no answer. When the answer to a question is 'yes' this means a sanitary risk is presented and when the answer is 'no' it means that the risk is not present. Where the answer is yes, then one point is awarded and where the answer is no, zero points are awarded. The total score can then be

Table 5.3 *Broad guidance on the frequency of monitoring*

Type of monitoring	Purpose	Type	Parameters	Assessment	Undertake
Provide confidence in design and construction	To provide feedback to the team that design & construction are acceptable	Microbiological Chemical	Indicator bacteria Nitrate Chloride	All water supplies tested on commissioning	Rolling programme based on year grouping if all supplies are to be visited. Sample of water supplies taken (using cluster sampling) which reflect different environments. Testing once per year in wet season.
Monitoring of residual risks	Where risk assessment indicates that the design/construction of the supply may lead to a significant residual risk, then more frequent monitoring is required both for confidence in design/construction and public health protection	Microbiological Chemical	Indicator bacteria Nitrate Chloride	All water supplies tested on commissioning	Where possible include all supplies with a residual risk. If this is not feasible, select a sample of supplies that represent the range of environments found (usually 10-30% of all supplies selected in clusters for ease of sampling) for a study of microbiological quality over 12 months, with samples taken monthly. If testing shows no water quality problems revert to programme above or health-based surveillance. Chemicals less likely to vary and testing can be kept to programme above.
To establish cause of contamination	To identify the principal pathway(s) of contamination when this is observed	Microbiological Chemical	Indicator bacteria Nitrate Chloride Dissolved oxygen Conductivity	All water supplies tested on commissioning	Select a sample of water supplies using a cluster sampling approach made up of between 10 and 30% of the water supplies. Water supplies must reflect the range of environments found. Test microbiological quality over 12 months, with samples taken monthly. If testing shows no or limited water quality problems revert to health based surveillance programme.
Health-based Surveillance	To confirm that water quality meets drinking water guidelines or standards surveillance Assess changes in water quality that occur due to changes in the local environment or poor maintenance	Microbiological Chemical	Indicator bacteria Nitrate	All water supplies tested on commissioning	a) Rolling programme of all water supplies based on 'year' groupings for visits by public health team, with community monitoring. Testing undertaken every 2-5 years in wet season. b) Select a samples of water supplies using a cluster sampling technique (usually 10-30% of water supplies) and undertaken microbiological testing and sanitary inspection twice per year and chemical testing once per year.
To assess seasonal influences or trends in water quality	To asesss whether water quality varies with rainfall or deteriorates over time.	Microbiological Chemical	Indicator bacteria Nitrate Chloride	All water supplies tested on commissioning	Select a sample of sources (usually 10-30%) using a cluster sampling approach and undertake seasonal sampling. Sample selected should reflect the range of environments in the country.

calculated to provide a measure of overall vulnerability to contamination and of operation and maintenance performance. However, it may also be useful to analyse each factor in relation to contamination to identify which are the most important factors that influence contamination.

5.4 When and where to monitor

It is not possible to be too prescriptive about when or how frequently to sample as this will depend on the situation, the objectives of the monitoring and the resources available. Often, the monitoring of small water supplies varies between no monitoring at all (or only on commissioning) to attempting to visit all supplies every year. It is desirable to develop an ongoing routine programme of health-based surveillance of water quality for public health reasons, but this may not be feasible in all cases and alternative strategies may need to be developed.

One approach which has been successfully implemented in Latin America and Africa is to develop a 'rolling' programme of visits to water supplies to collect information for management needs. In this situation all the water supplies are assigned to a 'year group' which means that they will only be visited during that year. Different 'year group' supplies are visited each year. A sample of water supplies is selected from each 'year group' which may be as low as 100 water supplies. This approach is designed for collecting general management information, but can also be used to determine the major causes of contamination when this is found. This approach will provide information that may be of use in evaluating overall design and construction quality or operation and maintenance performance. However, it is most effective when communities also regularly inspect their water supply and act on the findings.

In order to undertake a specific assessment of the problems related to on-site sanitation or to evaluate a range of risk factors on water quality, monitoring can be restricted to a small number of water supplies. These should be selected to ensure that they are representative of the supplies found in the area of interest or in the country as a whole. This selection can be done by first selecting an area and undertaking a rapid assessment of all or at least the majority of water supplies. This should usually be done under 'worst case' conditions when contamination is

Table 5.4. *Elements to check when re-evaluating the 'first-step risk assessment'*

Attenuation Mechanism	Check[1]
Unsaturated zone	is hydraulic loading from sanitation systems higher than originally suspected?
	is depth to minimum water-table estimate correct?
	is permeability of shallow sediments more than assumed in original risk assessment?
	is unsaturated zone potentially fractured?
Vertical separation (between water-table and screen) within saturated zone	are figures used for aquifer type, pumping rate etc correct? is aquifer potentially fractured?
Horizontal separation between pit latrine and borehole	are permeable layers potentially present which were not taken into account in the initial risk assessment?
	is aquifer potentially fractured?

[1] expert advice may be necessary

Hydrogeological environment	Depth to water-table	Arrival time for chemical contaminants[1] at water-table	at borehole screen[2]
Thick unconsolidated sediments associated with rivers and coastal regions	shallow < 10 m deep > 10 m	weeks – years years – decades	months – decades years – decades
Unconsolidated mountain valley sediments	shallow < 10 m deep > 10 m	weeks – years years – decades	months – decades years – decades
Minor unconsolidated sediments associated with rivers	shallow < 10 m deep > 10 m	weeks – years years – decades	months – decades years – decades
Windblown deposits	shallow < 10 m deep > 10 m	weeks – years years – decades	months – decades years – decades
Consolidated sedimentary aquifers	shallow < 10 m deep > 10 m	days – years weeks – decades	weeks – decades months – decades
Weathered basement thick weathered layer	shallow < 10 m deep > 10 m	weeks – years years – decades	months – decades years – decades
Weathered basement thin weathered layer	shallow < 10 m deep > 10 m	days – years weeks – years	weeks – years months – years

Table 5.5. *Approximate travel times in various aquifer systems to indicate likely times before onset of chemical contamination*

[1] This is the broad range of time that is aniticpated for the bulk of recharge to arrive, some rapid by-pass flow may arrive earlier but is unlikely to significantly modify chemical water quality. The actual time will depend on porosity/permeability of the aquifer and the climate type.

[2] Depends on depth of screen

most likely to occur (for instance during the wet season).

When the assessment has been completed, look at the data and see whether you can group the data into categories – e.g. <10 FC/100ml, 10-50FC/1ml, 50-100FC/ml, 100-150 FC/100ml, 150-200 FC/100ml, >200FC/100ml. Then look at how many water supplies fall into each category and select a sample from each category for inclusion in a monitoring programme. The monitoring programme would then focus on a small number of water supplies that are visited on a regular basis. In rural areas this may only need to be once per season as the major influence on quality is likely to be recharge through rainfall. In urban or peri-urban areas, visits may be needed on a monthly basis, as there are many more potential sources of recharge that could cause contamination.

It is difficult to be prescriptive about the numbers of sources that should be included as this should by preference be based on a statistical analysis of the assessment data. Where there are very large numbers of supplies (e.g. several hundred or thousand) a relatively low proportion of the supplies can be included in the sample provided this ensures that differences in hydrogeological regime are taken into account. In most cases, a sample of 10 to 20% of supplies will be adequate and for very large numbers of supplies (e.g. several tens of thousands) the sample size may be reduced further to say 5%. With a smaller total number of supplies (e.g. below 50), a larger proportion should be taken, for instance 20–30%. Where a specific study is being undertaken related to residual risks or research into the causes of contamination, a larger sample may be advisable to provide an adequate database. Some broad guidance on monitoring is provided in Table 5.3 and further

general principles include:

- where distinct wet and dry seasons occur it is advisable to collect samples in each season;
- where residual risk is high or where water quality shows that some microbiological contamination occurs albeit within acceptable limits, then the sampling frequency needs to be high;
- as chemical quality of water generally changes in a more subdued manner than microbiological quality, the frequency of monitoring for chemical parameters may be lower;
- where chemical quality is good, the frequency of monitoring may be reduced but it is useful to check for trends in quality with time;
- where residual risk is low and where monitoring data show water quality is within national standards or guidelines, then the frequency of sampling can be reduced.

5.5 Data analysis and interpretation

5.5.1 Localised versus widespread contamination

Once contamination of groundwater supplies has been detected the first priority is to make a decision as to whether short-term action is needed in respect of those water supplies that do not meet the drinking water guidelines. This might involve the closure of the supply or treatment of the abstracted water. Alternatively it may involve using household water treatment units to protect public health.

The next priority is to establish whether the source of contamination is likely to be localised (due to poor design or construction of the water supply) or more widespread (leaching from pit latrines to the water-table and then into the water supply). There are a number of indicators that provide evidence to help establish whether the source of contamination is localised or widespread:

Localised indicators

- patchy (or isolated) distribution of poor quality water;
- assessment (Chapter 4) indicates risk of widespread contamination is low;
- localised risk judged to be significant (from initial assessment, Chapter 4);
- water quality is associated with occurrence of localised risk factors;
- in an outbreak, disease cases cluster in certain areas close to particular sources.

Widespread indicators

- assessment (Chapter 4) indicates risk of widespread, contamination is significant;
- poor association between water quality observed and localised risk factors;
- poor quality water is associated with areas where risk factors for widespread contamination are considered more significant (e.g. shallow depth to water-table or near surface rocks are more permeable);
- in a disease outbreak, cases do not cluster around particular sources but can be linked to water.

5.5.2 Widespread microbiological contamination

Where widespread contamination by aquifer pathways is suspected, it is necessary to re-evaluate the risk assessment (Chapter 4) to identify possible specific causes (see Table 5.4).

In general, the vertical separation is likely to be the most reliable mechanism for attenuating microbial contaminants because pathways that provide rapid vertical transport are less likely to be present in most areas. Horizontal separation is less reliable because thin highly permeable layers may be present, which could provide a rapid pathway for water (and microbial) transport. These may be difficult to identify when making the initial risk assessment.

Where the assessment shows that widespread contamination by aquifer pathways is probably not the cause, an assessment should be made to determine how localised contamination is occurring (see 5.5.4 below).

5.5.3 Widespread chemical contamination

The main chemical water quality concern with respect to on-site sanitation is nitrate. Interpretation of the monitoring data needs to focus on the questions:

(i) is current water quality acceptable and if so how long is it likely to remain so?

(ii) what is the source or origin of the nitrate?

Chemical quality does not normally change as rapidly as the microbiological water quality except possibly in fractured groundwater systems characterised by very rapid flow. Interpretation of the monitoring data needs to consider the following:

- current water quality (nitrate, ammonium, chloride) and indication of the source or origin of the nitrate;
- likely time scale for modern recharge to reach the monitoring borehole (see Table 5.5);
- observed trends in water quality with time;
- processes which are likely to control water quality in the longer term (e.g. denitrification).

Whilst the risk assessment may indicate that on-site sanitation represents a potential groundwater nitrate problem, current water quality may have relatively low nitrate concentrations and meet national standards or guideline values.

The ratio of nitrate to chloride may help to indicate the origin of the nitrate and the percentage of organic nitrogen, derived from on-site sanitation, that is oxidised and leached to the water-table. Where the nitrate:chloride ratio is between 1:1 and 8:1, then it is likely that the nitrate is primarily from a faecal source. With higher nitrate:chloride ratios, the proportion of the nitrate derived from other, non-faecal sources (for instance inorganic fertilisers) is likely to be greater, although some may still be derived from faecal matter. This is illustrated by Figure 5.2.

Assuming all the nitrate and chloride is derived from on-site sanitation, then the percentage of nitrogen oxidised and leached can be determined. This allows the future long-term nitrate concentration in groundwater to be estimated (see Chapter 4).

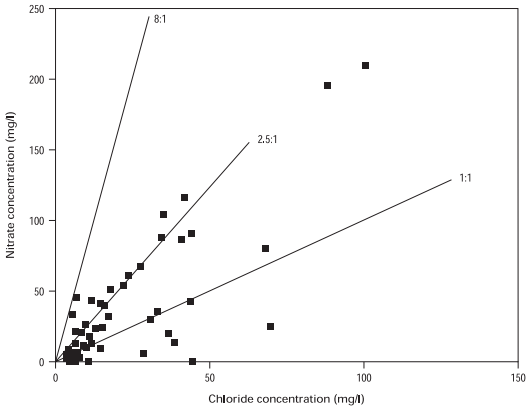


Figure 5.2.
Correlation of nitrate and chloride concentrations in groundwater beneath Santa Cruz, Bolivia. The nitrate: chloride ratio (~ 2.5:1) indicates nitrate is primarily from a faecal source.

A useful check can be made by comparing the time since on-site sanitation has been installed (or when the settlement developed) and the likely arrival time of the bulk of the recharge (Table 5.5). Where the travel time for recharge to reach the borehole screen is significantly less than the time since installation of on-site sanitation, then groundwater nitrate observed should reflect the impact of the on-site sanitation. Under these circumstances, low groundwater nitrate could be due to natural processes in the aquifer, for example, in groundwaters which are anaerobic (low or no dissolved oxygen), nitrate can be transformed by naturally occurring bacteria to nitrogen gas. However, nitrogen may also be present in such environments as ammonium.

Where the travel time for recharge to reach the borehole is much longer than the development of

the settlement and/or installation of on-site sanitation then groundwater nitrate concentrations may be low because the 'front' of the high nitrate groundwaters has not yet reached the borehole screen. In these cases, continued background monitoring is important to check whether there is an increasing trend in nitrate concentrations.

5.5.4 Localised microbiological contamination

When microbiological contamination is believed to be primarily due to localised problems related to poor sanitary completion of the water supply or sources of contaminants close to the supply, then it is useful to assess the importance of different factors in causing the contamination. This will aid in selecting and planning appropriate remedial or preventative actions. In order to do this, the results of sanitary inspections and water quality results are analysed together.

The first step in making an assessment of the risk of localised microbiological contamination is to review the frequency of reporting of different risks with varying degrees of recorded microbiological quality (usually expressed in faecal coliforms per 100ml). This will provide an indication of the relative importance of different factors. In this case, it is essential to be clear what exactly you are attempting to evaluate – the prevalence of any contamination in the supply or the severity of contamination. Where records suggest that a significant number of a supply type do not show contamination and when contamination is found, it is generally low, the first approach may be used. However, where the data suggest that contamination is common and a wide range of actual values of contamination are noted, it may be important to also look at influences on severity of contamination.

In order to analyse the data, simple frequency analysis of sanitary inspection risk data often provides sufficient information to inform action. Statistical analysis can be performed to measure the strengths of identified associations and in many cases carrying out such analysis is recommended.

As the interaction between risk factors and water quality is the principal purpose of this assessment, it will be necessary to define key water quality objectives. Examples of water quality objectives could include:

Table 5.6. *Percent frequency of reporting from an assessment of springs in a town in south-west Uganda*

Risk factor	Frequency % (of samples in each category)		Difference %
	≤10 FC/100ml	>10FC/100ml	
Masonry defective	8	17	+9
Backfill eroded	29	67	+38
Collection area flooded	79	83	+4
Fence faulty	83	100	+17
Animal access <10 m	79	100	+21
Latrine less than 30 m uphill	4	0	-4
Surface water uphill	46	100	+54
Diversion ditch faulty	79	100	+21
Other pollution uphill	46	83	+37

Risk factor	Town A – frequency			Town B - frequency		
	≤1FC/100ml	>1FC/100ml	Diff %	≤1 FC/100ml	>1FC/100ml	Diff%
Latrine <10m	40	56	+16	12	41	+29
Latrine uphill	0	59	+59	18	45	+27
Other pollution <10m	40	41	+1	13	41	+28
Ponding <2m	20	26	+6	19	23	+4
Drainage cracked/blocked/dirty	20	6	-14	68	0	-68
Fence missing/faulty	80	88	+8	93	86	-7
Apron <1m	0	0	0	2	0	-2
Water collects on apron	20	21	+1	14	18	+4
Apron cracked/damaged	20	12	-8	19	9	-10
Handpump loose	0	6	+6	1	0	-1

Table 5.7. *Percent frequency of reporting of sanitary risk factors against water quality categories from boreholes in two towns in Uganda*

- <1FC/100ml – often used as a national standard and indicating very low contamination;
- ≤10FC/100ml – a relaxation suggested by WHO in 1993 as being acceptable in untreated supplies.

To assess the importance of each risk, use the data collected from a number of samples and then categorise them into those that meet the water quality objective and those that failed the water quality objective. Record the total number of samples in each category. Count the number of times each individual risk factor was reported from sample sites where the water quality met the objective and then the number of times each risk factor was reported at samples sites where the water quality exceeded the objective target. Using the total number of samples in the category, calculate the percent of samples in each category when the risk factor was reported to be present.

If the frequency of reporting of a particular risk is higher for samples that exceed the water quality objective than for those that meet the objective, this is evidence of a positive association between the risk factor and water quality. This indicates that water quality is likely to be worse when the risk factor is present. The size of the difference between the two groups of samples is likely to reflect the strength of the association.

If the frequency of reporting for the risk is the same between the two groups, or lower for the group which exceeds the water quality objective, it is unlikely that there is a strong positive association between the risk factor and water quality. However, the factor may contribute to overall poor management or be associated with the formation of other risk factors.

Table 5.6 illustrates the results of analysis of sanitary risk and microbiological data from a town in Uganda where the primary interest is to identify the factors that appear to be most associated with increasing contamination of protected springs. In this case, a water quality objective of 10 FC/100ml was selected as being a reasonable target to meet, based on wet season assessment data.
The data were based on a wet season sampling round of the springs. Contamination here appears to be most associated with increasing presence of surface water uphill of the spring (+54%), eroded backfill area (+38%) and other pollution uphill (+37%). Several other factors also show a marked increase in reporting, such as faulty diversion ditch (+21%) and animal access (+21%). The

other factors seem less strongly associated with increasing contamination and latrines presence appears to have no impact on contamination as the relationship is negative (-4%).

We can conclude that when there is contamination of springs in this town, the principal problems relate to the presence of the factors that show the greatest increase in reporting. Therefore to prevent contamination in this case, it would be important to ensure that the environment uphill of the spring is kept clean, that surface water is drained away from the spring and that the erosion of backfill is prevented and diversion ditches are maintained.

A second example from Uganda that identifies latrines as a likely cause of contamination, is given in Table 5.7. Here the water quality objective is 1 FC/100 ml based on long-term monitoring as part of a routine surveillance programme.

These data show that latrines appear to exert the most important influence on water quality failure in boreholes in both towns. In the case of Town A, this is clearly due to the presence of a latrine uphill. In Town B, there are three factors that seem to have a similar influence: the influence of a latrine within 10m (+29%), the presence of latrine uphill (+27%) and the presence of other pollution within 10m (+28%). The other factors appear to have much weaker associations with contamination and we would probably not carry out further statistical analysis on this data as firm conclusions about the importance of latrine hazards is obvious.

The above methods of assessing the risks of localised contamination provide a simple framework for assessment. Where possible, some statistical analysis is usually advisable in order to test the associations between risks and contamination and between different risk factors. This could include tests of association such as chi-squared tests; or more sophisticated techniques such as logistic regression.

In general, in environments with a greater number of contaminated supplies and where there may be a greater degree of interaction between different risks, the use of statistical analysis is strongly recommended. This would be likely to be more important in urban as opposed to rural environments. However, where this is not possible, simple evaluation of frequencies may provide all the information required. The flow-chart in Figure 5.3 summarises the decision-making process and is an aid to identifying the appropriate response.

5.6 Follow-up action

For monitoring to be of any use, some follow-up action is necessary once the data has been analysed. Where the monitoring results are favourable, this should be forwarded to those planning water supply and sanitation schemes to provide confidence/assurance on the design and construction. Clearly, if evidence emerges of contamination and risks, action should be taken. This may require action in areas with existing facilities and in the planning of new water and sanitation programmes.

The specific cause of the contamination needs to be identified and recommendations for modification of the design or construction of the water supply (or of the on-site sanitation system) made. Where widespread contamination has been identified and it is clear that modifications to the design and construction are necessary, then follow-up monitoring is required to confirm an improvement in water quality. The results of this 'follow-up' monitoring data will also need to be fed back to those planning water supply schemes. Attention must still be paid to ensuring that the sanitary protection measures around water supplies are maintained.

Where monitoring has identified that

contamination is localised it is necessary to assess which factors are most important in causing the contamination and recommendations made regarding improvements required. Where latrine proximity or siting is a major risk then attempts must be made to either improve designs to reduce the potential for contamination (for instance drilling to greater depths) or to improve latrine design. The addition of treatment at the supply or in the home may also be required. Where the impact of latrines is likely to be highly significant and no alternative to sanitation arrangements is feasible, then an alternative water supply should be considered. Where the localised contamination can be linked with the maintenance of the wellhead or activities allowed within the vicinity of the wellhead, this information should be reported to the users of the supply and to those responsible for operation and maintenance (if appropriate). This information may also provide useful feedback into the design of the headworks and sanitary protection measures.

5.7 Community participation in monitoring

It is now widely accepted that communities must be actively involved in the planning, design and management of water supplies and sanitation. In order to sustain water and sanitation systems, community participation and management is essential. In addition to the role in managing water and sanitation, communities can be actively involved in monitoring of their water supply. In many ways, ensuring that communities can operate and maintain their water supply is in part dependent upon their ability to monitor their supply.

Most communities already informally monitor their water supply through observations about colour, taste and odour. This information can be very useful when water supplies are being monitored by local Government, NGOs or other organisations. Very often, major problems (for instance colour changes after heavy rainfall) are only detected by the regular users of the supply unless sampling is undertaken immediately after such a rainfall event.

It is unlikely that in many cases communities will be able to undertake water quality analysis. The equipment required is in most cases too expensive for communities to sustain and it may be difficult to find adequately trained people within a community. Some projects have developed 'community water testing kits'. However, in most cases, these kits test for total coliforms and therefore they have limited value in water supplies that are not chlorinated. As discussed in Chapter 2, the majority of the total coliform bacteria are derived from environmental sources and do not represent a risk of faecal contamination.

Although communities may not be able to undertake water quality testing themselves, they still have an important role. Community members, as the users of the water supply, have a right to know the quality of their water and should be supported in demanding that water supplies are periodically tested and that they are informed of the results. The results of the testing should be provided to communities in a format that is understandable and which provides them with information on actions they can take to improve their water supply and water quality. This may be achieved through community meetings or by providing reports to community leaders. For more information, please consult the manuals on water surveillance at: www.lboro.ac.uk/watermark.

Communities can undertake sanitary inspections and they should be encouraged to perform these on a regular basis. The sanitary inspection forms shown in Appendix C can also be provided in a pictorial form. Inspection forms have been developed that are more closely linked

to actions required and these may be found at the web site noted above. It is important that community sanitary inspections are always closely linked to actions to be taken, to ensure the water supply remains at low risk, as otherwise they become less useful and relevant to communities.

However, community members will require training in the use of sanitary inspection forms, how the information should be interpreted and how actions can be identified from the form. Such training should focus on identifying factors that both the community and the monitoring agency recognise as being important. There is little point in trying to force communities to monitor risks unless they understand and accept that they are a problem. It is important for instance that the community understands the need to ensure that when lateral separation distances have been defined for a water supply that these are maintained and encroachment is not allowed. The trainer therefore should ensure that they allocate enough time to ensure that these issues can be fully discussed and explained.

Whenever communities undertake monitoring they should have access to field staff who undertake monitoring of water supplies so that they can seek clarifications or explanations when problems arise. This may form part of a larger community development or hygiene education programme.

Summary of key points from Chapter 5

- Monitoring is an important and integral part of any water supply and sanitation programme and is an essential component of the risk assessment process.
- Monitoring is required to:
  - provide confidence in design;
  - establish cause of contamination, wherever contamination is observed;
  - ensure supply meets drinking water standards;
  - observe water quality trends with time.
- Monitoring includes not only the determination of microbiological and chemical quality of the water (principally faecal indicators and nitrate) but also inspection of the sanitary condition of the water supply and the associated headworks.
- Monitoring is not just about collecting data but also interpreting the data and acting upon the results. Follow-up actions may include:
  - send results to design team to confirm acceptability of design criteria;
  - modify/improve design/maintenance;
  - install new water supplies or install domestic treatment.
- For the long-term sustainability of water supply and sanitation schemes, community participation in monitoring is important. This participation may include: the community undertaking sanitary inspections of the water supply headworks and immediate area; and informing the community of the results and interpretation of water quality monitoring data. Provision of information allows the community to make informed decisions on the future design and siting of water supplies and sanitation.

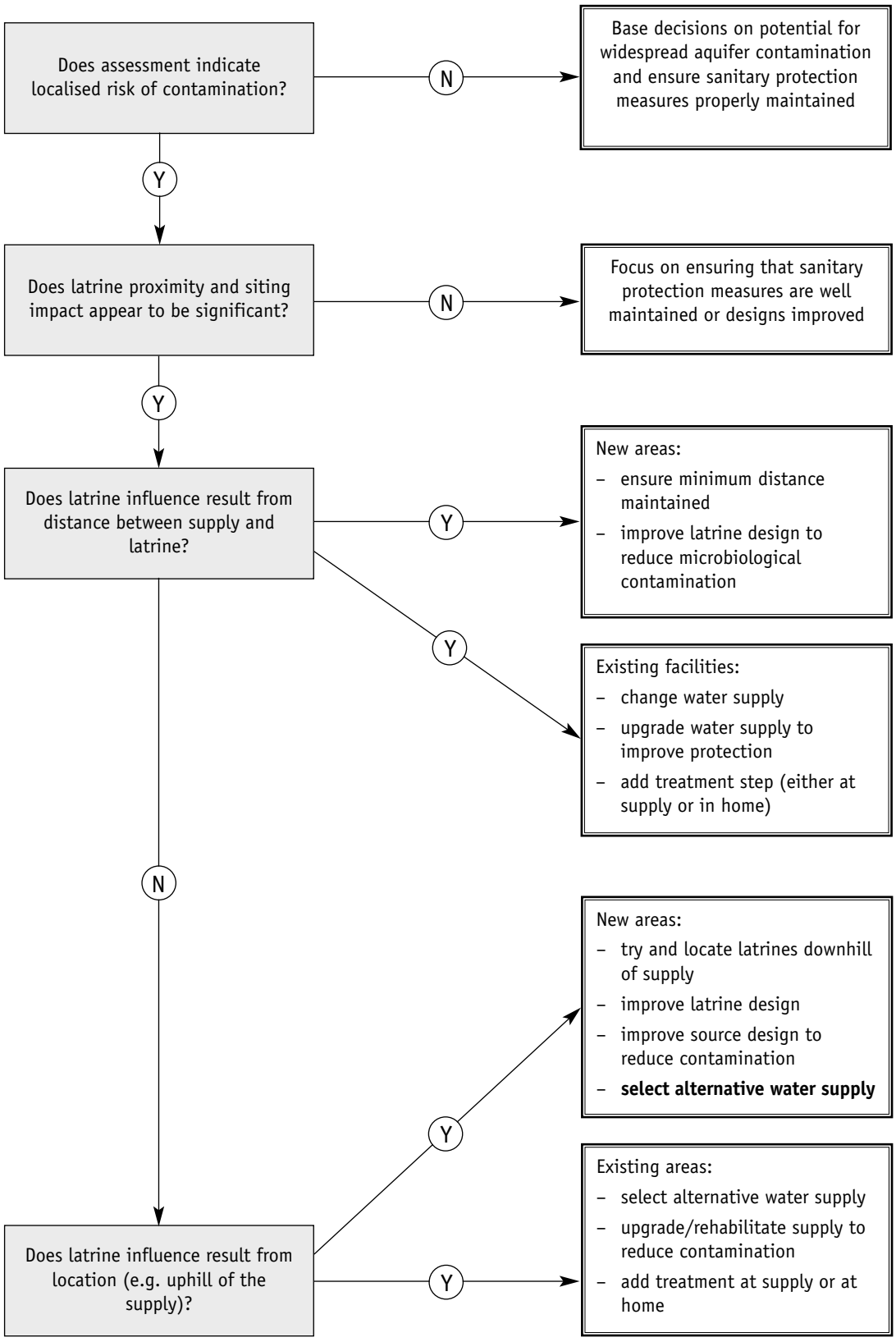


Figure 5.3. *Flow chart for identifying the appropriate response to localised contamination of groundwater supplies*

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Glossary

adsorption	a process whereby micro-organisms or chemicals become attached to particles in the sub-surface and are thus effectively removed from water in the soil. The process is dependent on the charge on the organism or chemical and on the minerals, and the pH of the water
anaerobic	an environment that is deficient in oxygen; bacteria then utilize other chemicals such as nitrates for their metabolic needs
aquifer	a saturated permeable geological unit that can yield economic quantities of water to wells and springs
aquifer pollution vulnerability	the potential for an aquifer to be affected by an imposed contaminant load. The greater the travel time for water to move from the ground surface to the aquifer, the greater the opportunity for attenuation and the lower the risk to the aquifer
attenuation	processes in the subsurface such as adsorption, filtration which remove or reduce contaminant concentrations
backfill	material used to build-up and protect the area between the eye of a spring and the spring-box
bedrock aquifers	ancient crystalline rocks with little or no primary porosity, that have subsequently undergone weathering and fracturing which render them capable of storing and transmitting groundwater
best-practice	widely accepted as the best method or approach
black water	wastewater containing faeces
caissons	concrete rings sunk below the water-table in dug wells designed to provide water security while digging
cement seal	cement placed between the casing of a well or borehole and the surrounding ground from the surface down to a pre-determined depth, to secure the casing in place and prevent localised contamination of the borehole
clay	a very fine-grained material (less than 0.002mm in diameter) which is plastic when wet. It has high porosity (~40%) but as the pores are not well-connected has low permeability
onsolidated sediment	sediment that has undergone burial and has become compact and hard over time
contaminant migration	the movement of contaminants through the subsurface
contamination	natural processes or man's activities that, lead to degradation of natural water quality
contamination risk	the risk of a source of contamination causing a groundwater supply to become contaminated by movement from source to supply along a natural or man-made pathway
crystalline basement	ancient non-sedimentary rock underlying younger sedimentary rock
cyst	membrane enclosing an organism in a resting stage
desorption	release of adsorbed contaminants from adsorption sites and re-introduction into the groundwater
diversion ditch	ditch dug at the headworks of a groundwater supply to divert run-off

E.coli (Escherichia coli)	widely used faecal indicator bacteria
epidemiological studies	studies of disease patterns in communities
faecal coliforms	bacteria found in large numbers in the faeces of humans and other warm-blooded animals, including *E.Coli*
faecal matter	animal (including human) excrement
faecal-oral route	route that permits faecal material to pass into the mouth, e.g. eating faecally contaminated food, drinking faecal matter in water
fissures	narrow cracks in hard rock
fractured aquifer	geological material that has undergone deformation to produce cracks in the rock which store and transmit water
gravel	a class of sediment the particles of which are between 2 and 60 mm in diameter
grey water	domestic wastewater not containing excreta, for instance bath and laundry water. Also called sullage
headwall	the extension of the lining of dug wells above the ground surface
headworks	surface protection system constructed above groundwater supplies to prevent contamination while providing access by means of a handpump (wells and boreholes) or supply pipe (springs)
helminths	worms existing in man as free-living or parasitic forms
human wastes	human faeces and urine
hydraulic load	the amount of liquid contaminant entering the subsurface from a sanitation system over a given period of time
hydrodynamic dispersion	the process by which groundwater containing a contaminant mixes with and is diluted by uncontaminated groundwater as it moves through the aquifer
hydrogeological environment	aquifer type and environment within which it was formed
hydrogeology	the study of water within the earth's crust, including its physics, chemistry and environmental relationships
hydrological cycle	the continuous circulation of water from the atmosphere to land and oceans by rainfall or snow and back to the atmosphere by evaporation and by transpiration by plants
indicator bacteria (faecal)	bacteria that normally live in the intestinal tract of man and other warm-blooded animals without necessarily causing disease. They are always and naturally present in faeces in large necessarily numbers, and their presence in drinking water indicates faecal contamination
karst limestones	carbonate sedimentary rocks that have undergone dissolution due to flowing groundwater producing enlarged fractures
Leaching	movement of soil particles, chemicals and micro-organisms as water percolates through a permeable medium
lithology	rock classification based on macroscopic features such as grain size and texture

Glossary cont...

localised contamination	contamination that occurs via pathways resulting from the design or construction of a groundwater supply, or its deterioration with time
methaemoglobinaemia/ infantile cyanosis	a disease in young infants associated with the consumption of water with high nitrate concentrations. Nitrate in the saliva and stomach is reduced to nitrite, which then binds with haemoglobin, preventing the latter from binding with oxygen as it should
microbes	microscopic organisms
monitoring	the periodic sampling and determination of chemical and microbiological quality of a water supply, and survey of the sanitary conditions of the supply and its immediate environs. It aims to ensure that water quality is fit for consumption and to identify any sources of contamination
on-site sanitation systems	systems in which the wastes produced within sanitation facilities are stored at the point of disposal where they undergo some degree of decomposition. They require periodic emptying or the construction of new facilities once they fill up
operation and maintenance	the use and care of a facility in a way that ensures it provides continued and satisfactory service. This includes having procedures in place for its correct use, and carrying out breakdown and preventative maintenance
pathogenic micro-organisms	microscopic organisms that cause disease
pathways	routes by which contaminants reach a receptor (e.g. a groundwater supply) from a source (e.g. a pit latrine)
permeability	the ability of a rock, sediment or soil to permit fluid to flow through it
pH	a measure of the acidity or alkalinity of a solution. It is numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity
pit latrine	the simplest sanitation system in which excreta fall into a hole in the ground
point source pollution	pollution originating from a point (or small area), resulting in localised impact on the aquifer
pollution	the introduction of chemical and microbiological substances into the subsurface at concentration levels that restrict the potential use of groundwater
porosity	the total of all pore spaces in a rock. The proportion of the rock that consists of pores that are interconnected and can thus transmit fluids is the effective porosity
predatory micro-organisms	micro-organisms that feed on others
primary porosity	the porosity that represents the original pore openings present when a rock or sediment formed
protozoa	the lowest and simplest of animals, existing as single cell forms or colonies. Many live in the intestinal tract of man and other animals and faecal protozoa may infect humans causing diseases such as diarrhoea and dysentry
recharge	the water that moves downward from the soil to the water-table in a given period of time

remediation	removal of contamination from the aquifer
residual risk	risk still remaining after risk of contamination of groundwater supply has been assessed and the necessary steps taken
rural	countryside/village environments, with low population density
sand	a class of sediment the particles of which are between 0.06 and 2mm in diameter
sandstone	rock formed by the burial and compression of sand particles, bound together in a fine-grained matrix by mineral cement
sanitary protection measures	steps taken at the headworks to prevent the contamination of groundwater supplies
sanitation	facilities for excreta disposal
secondary porosity	the porosity caused by fractures or weathering in a rock or sediment after it was formed
sediments	unconsolidated material derived mostly from pre-existing rock through erosion, weathering etc
septic tanks	a sealed settling chamber receiving all sewage and sullage from a dwelling
silt	a class of sediment the particles of which are between 0.002 and 0.06mm in diameter
source protection	measures taken to protect a groundwater supply from contamination
sullage	domestic wastewater derived from laundry, bathing, cooking, not usually containing excreta
traditional supplies	groundwater supplies based on designs used by communities prior to the involvement of outside organisations and constructed using 'low-technology' methods and equipment
unconsolidated granular sediments	sediments that are loose, not cemented together
unsaturated zone	zone below the soil layer in which pores are only partially filled with water; the remainder is usually filled with air
urban	city and town environments, with high population density
viruses	very small parasitic organisms that can only reproduce inside the animal in which they live, although some can survive for long periods in an extracellular environment
water-table	the level below which a geological formation is completely saturated with water
weathered basement	bedrock formations that have disintegrated and become unconsolidated over time by the action of the elements, resulting in low to medium permeability aquifers
widespread aquifer contamination	contamination of an aquifer over a wide area, not restricted to the vicinity of the contamination source

Appendix A
Worked Examples

Example 1: Unconsolidated sediments in Southern Asia
Project to provide water supply and sanitation for several villages

Risk assessment: microbiological contamination of groundwater supplies via aquifer pathways

STEP 1: Collect background information
The area where the villages are located is underlain by sediments of a major river system – the hydrogeological environment is therefore thick unconsolidated sediments associated with rivers and coastal plains.

- Records from the UNICEF office suggest that sediments consist of shallow silts and clays with fine-medium sands at depth. Total thickness of sediment exceeds 80 m depth.
- The minimum depth to water-table can be less than 3 m below ground level (based on discussions with the residents of the villages) and the deepest water-table can be as much as 10 m bgl.
- Existing sanitation coverage is poor, but includes simple pit latrines (based on survey of villages).
- Population density is generally low but can exceed 30 persons per hectare in village centres (based on population figures and approximate area of settlement).
- Daily pumping rate for hand pump is <0.3 litres per second (over 24 hour period).
- Annual rainfall is about 2000 mm/year.

STEP 2: Will the unsaturated zone provide sufficient attenuation?
Since the water-table can be less than 3 m, the unsaturated zone cannot provide sufficient protection for the water-table (Table 4.3).
Need to go to step 3.

STEP 3: If supply inlet is placed at depth will the saturated zone provide sufficient attenuation?
The sediments extend to depths greater than 80 m, therefore it should be possible to provide sufficient vertical separation between the water-table (which is potentially contaminated) and the screen of the borehole to reduce risk of contamination to 'very low'. Using Figure 4.4 for clayey sediments, the design for the borehole would be to allow a minimum separation of 10 m between the deepest water-level and the top of the screen. Where the sediments are fine-medium sand, a vertical separation of 25 m is more appropriate. Instructions to the driller would be that where there is any doubt about the nature of the sediments a conservative approach should be adopted i.e. assume the sediments are fine-medium sands. In this case a vertical separation of 25 m would be recommended.
No need to go to step 4.

Where on-site sanitation is also being installed then any type of latrine could be permitted because the water supply design accepts that the water-table may be contaminated.

Risk assessment: widespread nitrate contamination of the aquifer

STEP 1: Collect background information

Assume that eventually all the people in the village will use pit latrines. Recharge to groundwater, based on average annual rainfall of 2000 mm/year and using Figure 4.9 is approximately 400 mm/year. Use an 'average' population density of 30 persons per hectare for the populated village area.

STEP 2: Estimate nitrate concentration in recharge

With a population density of 30 per hectare and a recharge rate of 400 mm/year, Figure 4.10 estimates the nitrate concentration in recharge at about 150 mg/1, assuming all organic nitrogen deposited in the pit latrine is oxidised and leached to groundwater.

Using Table 4.5, the fraction of nitrate likely to be leached for fine-grain alluvial sediments is probably less than 0.3 (and could be much lower especially as the water- table is quite shallow). Therefore nitrate concentration in recharge beneath the village is likely to be less than 50 mg/l (the WHO guideline value). The use of on-site sanitation is therefore likely to be acceptable although concentrations may approach the WHO guideline value eventually.

STEP 3: Consider time delay

The nitrate concentration in the recharge beneath the village settlement has now been estimated, however, the concentration in the groundwater may be lower because of mixing and diluting with recharge derived from outside the settled area. In addition there is likely to be a time delay between the leaching of nitrate from the pit latrine and its arrival at the borehole screen because the screen could be more than 35 m below ground level (screen set at least 25 m below maximum depth to water-table, 10 m bgl, see previous assessment). Thus, there is a high delay potential (Table 4.6) and, given its significant dilution because of rural setting, on-site sanitation is likely to be sustainable in the short term (with respect to nitrate) and probably in the longer term. It is important to monitor nitrate to confirm this.

Risk assessment: microbiological contaminations due to pathways created by construction of the groundwater supply

All criteria relating to the surface completion are listed in Table 4.7 and will be included in the design. Within the village, the water supply boreholes will need to be close to the houses and therefore pit latrines are likely to be within 10 m of the borehole. Thus the risk of localised contamination cannot be considered as insignificant. Further, the cheapest and only practical drilling technique in Bangladesh is the hand-drilling method, which precludes the insertion of a cement seal from the ground surface to the top of the screen. This represents another significant risk of localised microbiological contamination.

Appendix A cont...

The possible options include:

i. accept risk and instigate an enhanced monitoring programme.

ii. treat water supply – this is likely to be a more expensive option

iii. install borehole by machine operated drilling rig - expensive and impractical option for Bangladesh.

Summary of recommendations

A borehole with a screen at least 25 m below the deepest water-table is the preferred option even though there is a significant residual risk associated with localised contamination. This is because of the absence of a cement seal around the outside of the casing and the fact that pit latrines are likely to be within 10 m. Since the formation is unconsolidated and likely to collapse around the borehole casing, the design is acceptable provided a programme of enhanced monitoring is instigated which shows that the water quality is acceptable.

Example 2: Weathered basement aquifer in Central Africa
Project to provide water supply and sanitation for several villages

Risk assessment: microbiological contamination of groundwater supplies via aquifer pathways

STEP 1: Collect background information

The area where the villages are located is underlain by deeply weathered basement, relief is generally low (flat) and there is no evidence of rock outcrop at the surface. The hydrogeological environment is therefore weathered basement.

- Records from local groundwater agency suggest the deeply weathered rock extends to 20-30 m depth. The shallow weathered zone is clayey and is generally underlain by a layer that yields water and which progressively becomes less weathered and harder with depth until bedrock is reached typically at depths of 30 m.

- The minimum depth to the water-table can be less than 5 m below ground level and the deepest water-table can be as much as 10 m bgl (based on discussions with the residents of the villages).

- Existing sanitation coverage is poor but includes simple and VIP pit latrines (based on survey of villages).

- Population density is low, less than 10 people per hectare (based on population figures and approximate area of settlement).

- Annual rainfall is 1000 mm/year.

STEP 2: Will the unsaturated zone provide sufficient attenuation?
Since the water-table can be less than 5 m the unsaturated zone cannot provide protection for the water-table (Table 4.3)
Need to go to Step 3.

STEP 3: If supply inlet is placed at depth will the saturated zone provide sufficient attenuation?
It is not possible to say with certainty that the lining of a dug well is sufficient to avoid the ingress of contaminants at the water-table. Therefore if the supply type is dug well go to Step 4.

The deeply weathered layer extends to depths greater than 20 m therefore it should be possible to provide sufficient vertical separation between the water-table (which is potentially contaminated) and the screen of the borehole to reduce risk of contamination to 'very low'. Using Figure 4.5, for 'basement with clayey weathered layer', the borehole design should allow a minimum separation of 10 m between the deepest water-level and the top of the less weathered, and more permeable, layer. If there is less than 10 m of the saturated deeply weathered clayey layer then it is necessary to go to Step 4.

STEP 4: What is the lateral separation such that the saturated zone will provide sufficient attenuation?
Where the deeply weathered clayey layer is insufficiently thick to reduce the risk that pathogens may migrate downwards to the borehole screen to 'low' or 'very low', then it will be necessary to consider whether it is possible to provide sufficient horizontal separation between the water supply and the pit latrine. (The water supply may be either a borehole or a dug well.)

Using Table 4.4 and based on a rock type of 'weathered basement (not fractured)' the required separation is several metres. However, to reduce the likelihood of localised contamination (see later) a nominal horizontal separation of 10 m is recommended.

(Note: if the well or borehole was dug or drilled into the more permeable layer then the 10 m separation may not be sufficient to attenuate all pathogens. However, some attenuation of pathogens will occur between the base of the pit latrine and the water-table and further attenuation occurs during migration through the saturated weathered zone to the more permeable layer. Thus in all likelihood the 10 m lateral separation should provide sufficient additional attenuation, even so, monitoring of water quality would be recommended. Of course, if the deeply weathered layer had been much thinner, for example less than 10 m, then the risk would be significant.)

Where on-site sanitation is also being installed then any type of latrine could be permitted because the water supply design accepts that the water-table may be contaminated. However, where the deeply weathered clayey layer is insufficient to provide sufficient attenuation with depth in the saturated zone then it is probably advisable to select dry-type sanitation systems. This is because this will provide greater attenuation in the unsaturated zone.

Appendix A cont...

Risk assessment: widespread nitrate contamination of the aquifer

STEP 1: Collect background information

Assume that eventually all the people in the village will use pit latrines. Recharge to groundwater, based on average annual rainfall of 1000 mm/a and using Figure 4.9 is approximately 150 mm/year. Use an average population density of 10 persons per hectare for the village area.

STEP 2: Estimate nitrate concentration in recharge

With a population density of 10 per hectare and a recharge rate of 150 mm/year, Figure 4.10 estimates that nitrate concentration in recharge at about 120 mg/l, assuming all organic nitrogen deposited in the pit latrine is oxidised and leached to groundwater.

Using Table 4.5, the fraction of nitrate likely to be leached in thick weathered basement is probably less than 0.3 (and could be much lower). Therefore nitrate concentrations in recharge beneath the village is likely to be less than 40 mg/l (and thus lower than the WHO guideline value of 50 mg/l). The use of on-site sanitation is therefore likely to be acceptable.

STEP 3: Consider time delay

Given that the nitrate concentration in recharge is less than the WHO guideline value there is no real need to consider either the time delay or the dilution with low nitrate from outside of the village. However (from Table 4.6), moderate delay potential and significant dilution is anticipated.

Risk assessment: microbiological contamination due to pathways created by construction of the groundwater supply

All criteria relating to the surface completion are listed in Table 4.7 and will be included in the design.

Given the relatively low density of the village, water supply boreholes can be located to ensure that pit latrines are located at least 10 m away from the water supply. Further, where boreholes are being constructed using powered drilling rigs, then a sanitary cement seal behind the casing can be installed. Likewise, hand dug wells can be constructed so that the upper part of the well lining, from the surface to the deepest water-table is made impermeable.

In addition to those features included in the design of the borehole and headworks, there is also the need for regular inspection and effective operation and maintenance.

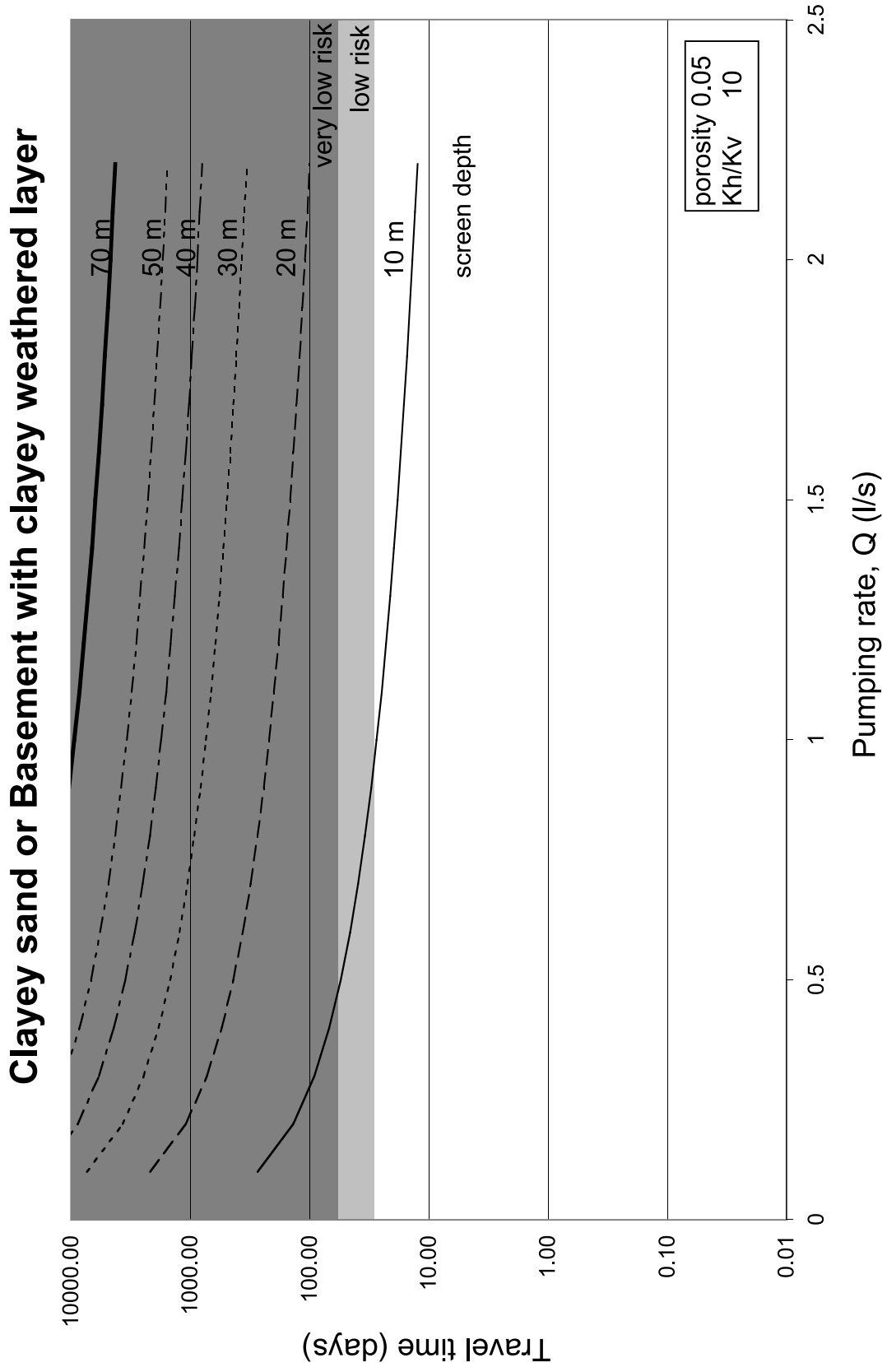
Summary of recommendations

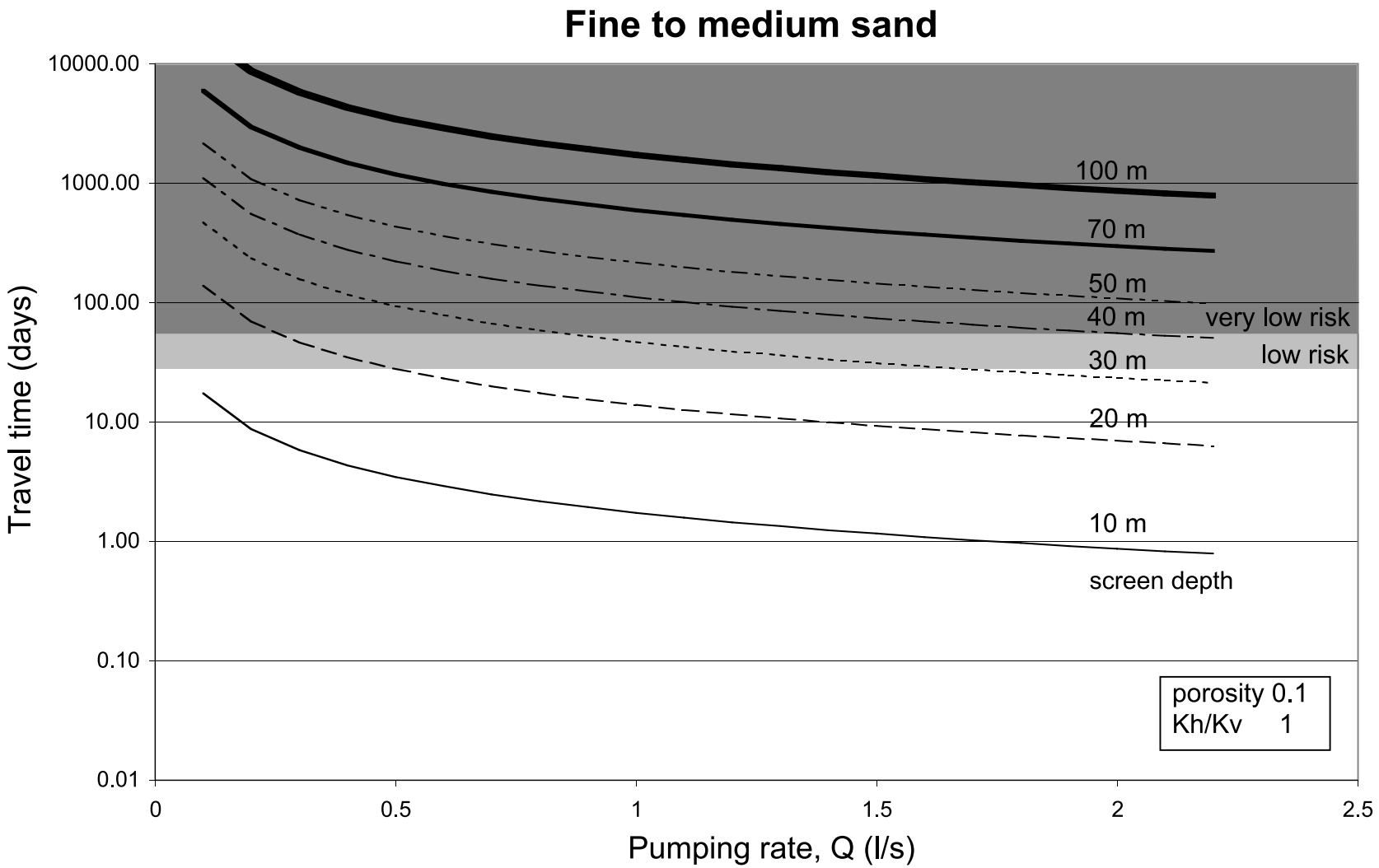
Where the deeply weathered clayey layer is sufficiently deep that the depth from the top of the intake (or screen) to the water-table is more than 10 m, then a drilled borehole is recommended. Pit latrines should be located at least 10 m away to avoid localised contamination problems.

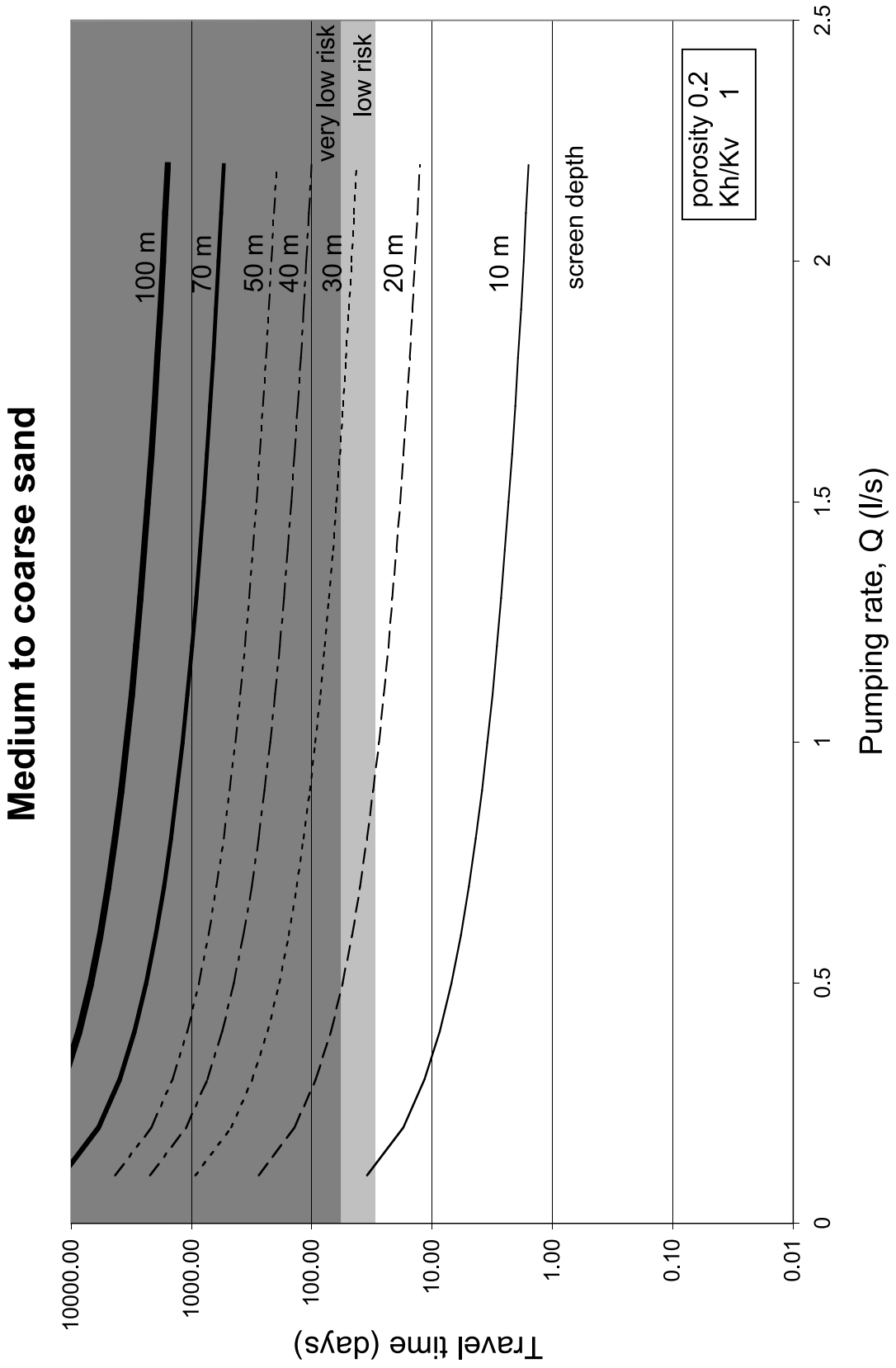
Where the deeply weathered layer is not sufficiently thick to provide more than 10 m saturated thickness, or where a dug well is the preferred choice of the community, then the water supply will need to be located at a sufficient horizontal distance from the pit latrine to reduce the risk of pathogens reaching the water supply. This lateral separation would need to be at least 10 m which is the same separation required to avoid localised contamination problems.

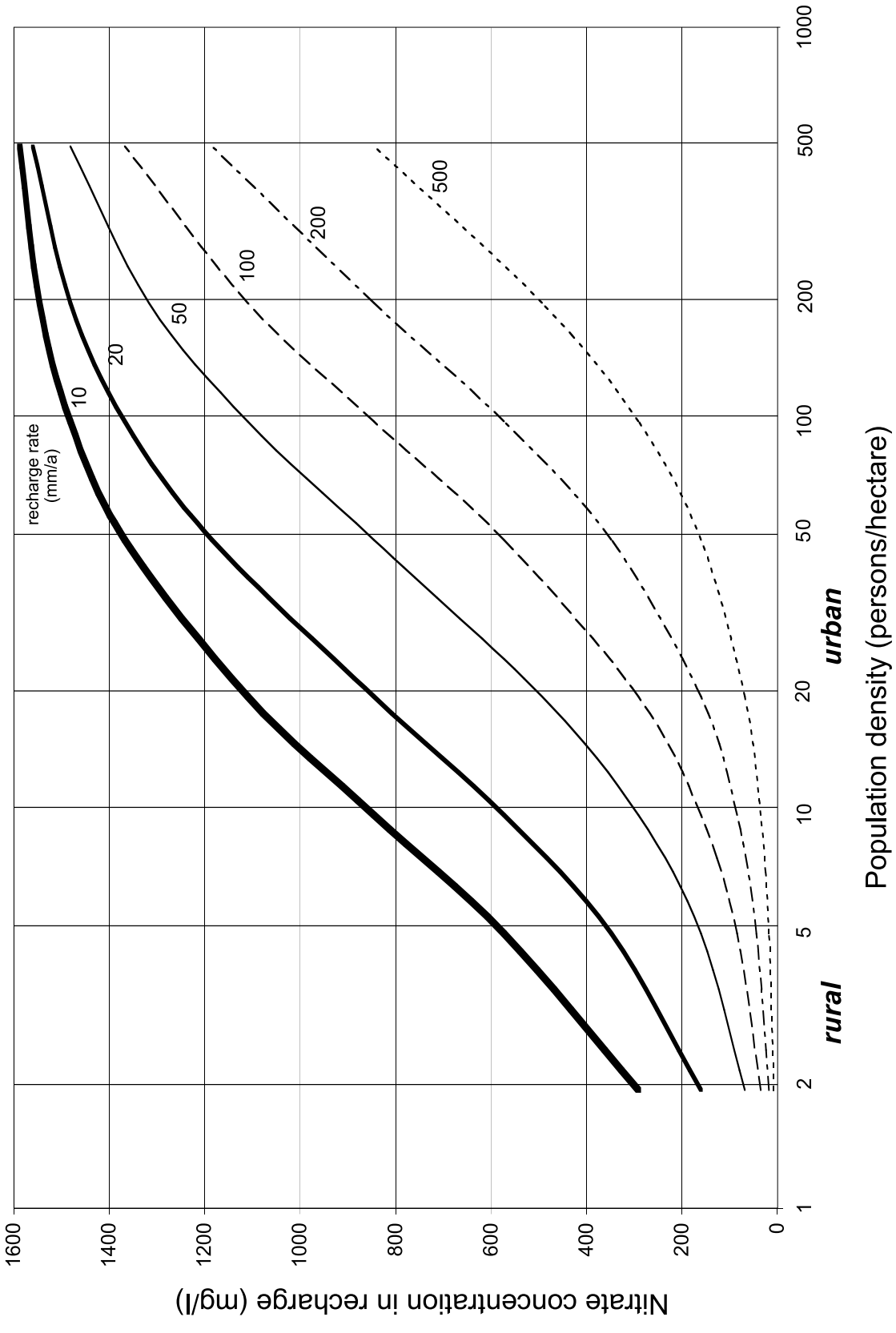
No special measures to reduce nitrate leaching are required.

Appendix B
Full page versions of selected graphs




Fine to medium sand
Travel time (days)
10000.00
1000.00
100.00
10.00
1.00
0.10
0.01
0
0.5
1
1.5
2
2.5
Pumping rate, Q (l/s)
100 m
70 m
50 m
40 m
30 m
20 m
10 m
screen depth
very low risk
low risk
porosity 0.1
Kh/Kv 1


Medium to coarse sand
Travel time (days)
10000.00
1000.00
100.00
10.00
1.00
0.10
0.01
Pumping rate, Q (l/s)
0
0.5
1
1.5
2
2.5
very low risk
low risk
100 m
70 m
50 m
40 m
30 m
20 m
10 m
screen depth
porosity 0.2
Kh/Kv 1


Nitrate concentration in recharge (mg/l)
1600
1400
1200
1000
800
600
400
200
0
recharge rate (mm/a)
10
20
50
100
200
500
1
2
5
10
20
50
100
200
500
1000
rural
urban
Population density (persons/hectare)

Appendix C
Sanitary inspection forms

I Type of facility **BOREHOLE WITH HANDPUMP**

1. General Information District:

   Parish

   Organisation

2. Village/zone:

3. Date of Visit

4. Water sample taken? ……. Sample No. …… FC/100ml ……..

II Specific diagnostic information for assessment	Risk
1. Is there a latrine within ……m of the borehole (please put in distance calculated from the manual)	Y/N
2. Is there a latrine uphill of the borehole?	Y/N
3. Are there any other sources of pollution within 10m of borehole? (e.g. animal breeding, cultivation, roads, industry etc)	Y/N
4 Is the drainage faulty allowing ponding within 2m of the borehole?	Y/N
5. Is the drainage channel cracked, broken or need cleaning?	Y/N
6. Is the fence missing or faulty	Y/N
7. Is the apron less than 1m in radius?	Y/N
8. Does spilt water collect in the apron area?	Y/N
9. Is the apron cracked or damaged?	Y/N
10. Is the handpump loose at the point of attachment to apron?	Y/N
Total Score of Risks Risk score: 9-10 = Very high; 6-8 = High; 3-5 = Medium; 0-3 = Low	…./10

III Results and recommendations:

The following important points of risk were noted: (list nos. 1-10)

Signature of Inspector:

Comments:

I Type of facility **PROTECTED SPRING**

1. General Information District:

   Parish

   Organisation

2. Village/zone:

3. Date of Visit

4. Water sample taken? ……. Sample No. …… FC/100ml ……..

II Specific diagnostic information for assessment	Risk
1. Is the spring unprotected?	Y/N
2. Is the masonry protecting the spring faulty?	Y/N
3. Is the backfill area behind the retaining wall eroded?	Y/N
4. Does spilt water flood the collection area?	Y/N
5. Is the fence absent or faulty?	Y/N
6. Can animals have access within 10m of the spring?	Y/N
7. Is there a latrine uphill and/or within ….m of the spring? (please put in distance calculated from the manual)	Y/N
8 Does surface water collect uphill of the spring?	Y/N
9. Is the diversion ditch above the spring absent or non-functional?	Y/N
10. Are there any other sources of pollution uphill of the spring? (e.g. solid waste)	Y/N
Total Score of Risks	…./10

Risk score: 9-10 = Very high; 6-8 = High; 3-5 = Medium; 0-3 = Low

III Results and recommendations:

The following important points of risk were noted: (list nos. 1-10)

Signature of Inspector:

Comments:

I Type of facility **DUG WELL WITH HANDPUMP/WINDLASS**

1. General Information District:

   Parish

   Organisation

2. Village/zone:

3. Date of Visit

4. Water sample taken? ……. Sample No. …… FC/100ml ……..

II Specific diagnostic information for assessment	Risk
1. Is there a latrine within ….m of the well? (please put in distance calculated from the manual)	Y/N
2. Is the nearest latrine uphill of the well?	Y/N
3. Is there any other source of pollution within 10m of well? (e.g. animal breeding, cultivation, roads, industry etc)	Y/N
4. Is the drainage faulty allowing ponding within 2m of the well?	Y/N
5. Is the drainage channel cracked, broken or need cleaning?	Y/N
6. Is the fence missing or faulty?	Y/N
7. Is the cement less than 1m in radius around the top of the well?	Y/N
8. Does spilt water collect in the apron area?	Y/N
9. Are there cracks in the concrete apron?	Y/N
10. Is the handpump loose at the point of attachment to well head?	Y/N
11. Is the well-cover insanitary?	Y/N
Total Score of Risks	…./11

Risk score: 9-11 = Very high; 6-8 = High; 3-5 = Medium; 0-3 = Low

III Results and recommendations:

The following important points of risk were noted: (list nos. 1-11)

Signature of Inspector:

Comments:

I Type of facility **DEEP BOREHOLE WITH MECHANICAL PUMPING**

1. General Information District:

   Parish

   Organisation

2. Village/zone:

3. Date of Visit

4. Is water sample taken? ……. Sample No. …… FC/100ml ……..

II Specific diagnostic information for assessment Risk

1. Is there a latrine or sewer within ……m of the pumphouse? (please put in distance calculated from the manual) Y/N

2. Is the nearest latrine unsewered? (a pit latrine that percolates to soil) Y/N

3. If there any other source of pollution within 10m of the borehole? (e.g. animal excreta, rubbish, surface water) Y/N

4. Is there an uncapped well within 15-20m of the borehole? Y/N

5. Does the apron at the wellhead extend for less than 2m radius? Y/N

6. If the drainage area around the pumphouse faulty? (is it broken, permitting ponding and/or leakage to ground) Y/N

7. If the fencing around the installation damaged in any way which would allow animals access or any unauthorised entry? Y/N

8. Is the floor of the pumphouse permeable to water? Y/N

9. Is the well seal insanitary? Y/N

10. Is the top 3m of the borehole sealed with an impermeable lining? Y/N

Total Score of Risks ……/10
Risk score: 9-10 = Very high; 6-8 = High; 3-5 = Medium; 0-3 = Low

III Results and recommendations:

The following important points of risk were noted: (list nos. 1-10)

Signature of Inspector:

Comments: