National Microbial Monitoring Programme for Groundwater

Implementation Manual

Prepared for the Water Research Commission

by

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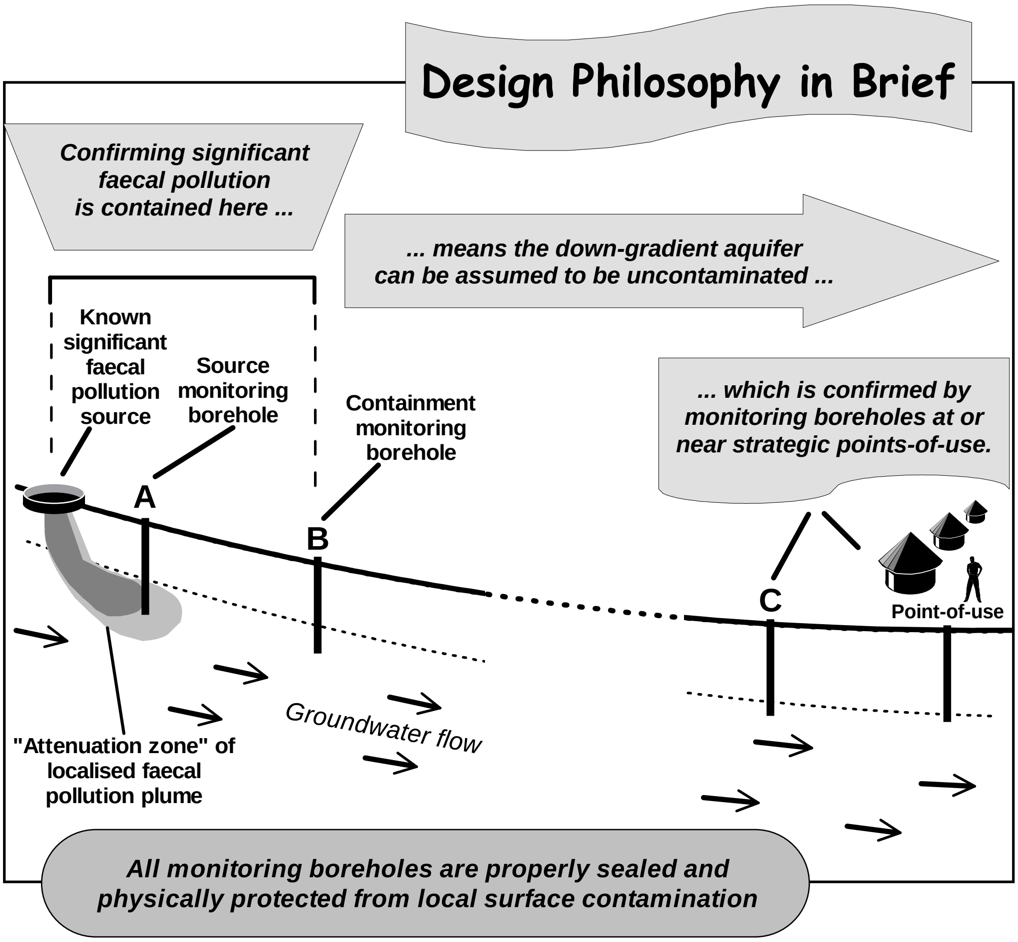
EXECUTIVE SUMMARY



Examples of typical analyses and associated assessments:

E. coli at ...			Assessment of ...		
A	**B**	**C**	**... impact of source**	**... containment**	**... microbial quality down-gradient of B**
Low or zero	***Zero***	***Zero***	Within expectations	Effective	Unlikely to be contaminated
Always high	***Zero***	***Zero***	Worsening	Effective	Unlikely to be contaminated
Always high	***Sometimes detected***	***Zero***	Worsening	Ineffective	Unlikely to be contaminated. Some concern over future contamination.

National Microbial Monitoring Programme for Groundwater
DWAF National Objectives

To measure, assess and report on a regular basis
the status and trends
of the microbial water quality
that reflects the degree of faecal pollution
(because of the associated human health risks)
of South African groundwater resources
in a manner that is
soundly scientific and
that will support strategic management decisions
in the context of sustainable fitness for use of those water resources.

This programme is one of a number of national "status and trends" monitoring programmes that address the requirement of the National Water Act (No. 36 of 1998) to establish national information systems on South African water resources. More specifically, it is aligned with the policy and strategy for groundwater quality management in South Africa. The Department of Water Affairs and Forestry (DWAF) as the custodian of the nation's water resources has the mandate to establish monitoring programmes such as this one.

Microbial groundwater quality in South Africa, relating in particular to faecal pollution, is not well characterised at present. However, many potential faecal pollution sources exist, such as dense informal settlements with inadequate sanitation and large sewage treatment works. Groundwater is now seen as being of primary importance in supplying safe drinking water, especially to inhabitants of rural areas. However, groundwater studies in the past have generally not focused on faecal pollution, although this is now changing. This may be due partly to the technical difficulties associated with obtaining representative and uncontaminated samples.

Groundwater monitoring on a national scale is carried out by the Department. This focuses on water quantity variables (such as water level) and chemical quality. The microbial monitoring programme described in this manual is intended to supplement the existing monitoring and should be regarded as a separate programme in its own right.

The behaviour of faecal microorganisms in groundwater is influenced by a wide variety of factors. Transport is facilitated primarily by the bulk movement of groundwater. However, although microscopic, faecal microorganisms are filtered and immobilised to varying extents by the medium through which they are transported. The extent is dependent on the aquifer type and microorganism size. For example, bacteria are generally larger than viruses so tend to be filtered more effectively. More importantly, most faecal microorganisms have very limited survival periods outside their optimum environment (namely, mammalian intestinal tracts). However, some can remain viable for very long periods (sometimes months) in the form of cysts or spores.

These factors, coupled with the generally relatively slow movement of groundwater, usually results in a localised impact. This is in contrast to conservative chemical pollutants that can be transported long distances in groundwater. This localisation concept is the basis of the philosophy of microbial monitoring of groundwater for which a design is presented in this manual.

In order to support strategic decisions in the context of fitness for use, general statements ideally need to be made about faecal contamination of aquifers as a whole. Because impacts are usually localised, monitoring a microorganism, like the indicator bacterium *Escherichia coli* (*E. coli*) chosen for this programme, in a single monitoring borehole provides very little information about the likely distribution of that microorganism in the aquifer as a whole. This suggests that a finely-spaced network of monitoring boreholes throughout an aquifer might be necessary. However, this is prohibitively expensive and impractical in the context of a national monitoring programme.

Therefore, the basic philosophy of this monitoring programme is to shift emphasis of the monitoring away from where the groundwater is used, or is likely to be used, to where it is known, or suspected, to be faecally contaminated. More specifically, the philosophy is to monitor the effectiveness with which faecal pollution from known significant faecal pollution sources is contained in a localised area. It is then assumed, albeit with caution, that the remainder of the aquifer is then likely to be of acceptable microbial quality. As a precautionary measure, monitoring is also done at strategic points of use. These include both current and potential future use.

Three types of boreholes are recommended, the purposes of which are summarised as follows (A, B and C refer to the figure above):

Borehole type	Purpose
Source (Borehole A)	Monitors behaviour of the source more confidently than the containment borehole, in particular detecting worsening trends at the source that can be used to invoke source directed controls.
Containment (Borehole B)	Confirms local faecal pollution plume effectively contained allowing reasonably confident statements to be made about likely microbial quality elsewhere down-gradient.
Point-of-use (Borehole C)	Provides backup monitoring near strategic points of groundwater use that confirm, or otherwise, that faecal pollution from known significant sources is indeed well contained. Also necessary because of uncertainties associated with defining the attenuation zone and down-gradient flow paths.

Of particular concern when establishing monitoring boreholes is that they are well protected from faecal contamination occurring in the immediate vicinity on the surface. This contamination can use the disturbed zone along the outside of the borehole casing as a conduit to reach the aquifer. Protection is achieved by equipping the borehole with a sanitary seal and by preventing unnecessary access to the borehole by animals and people. Extreme care needs to be taken while sampling to ensure that the sample is not accidentally contaminated by unclean hands or other local contaminated objects. Purging of the borehole is recommended, particularly in the case of infrequently-used boreholes, to ensure that the sample is adequately representative of the surrounding groundwater. Demanding logistical constraints also exist since samples need to reach the laboratory for analysis within 24 hours.

The monitoring data will be stored on the Department's Water Management System located near the Roodeplaat Dam, north of Pretoria. Annual assessments of the data should be carried out and reports prepared and sent to appropriate stakeholders. Particular care needs to be taken to ensure that reporting is accurate and unambiguous. A mechanism should be in place that allows for interim *ad hoc* reports to be prepared and delivered to appropriate stakeholders when monitoring results indicate a worsening of a problem to the extent that some source directed intervention might be required.

A National Coordinator should be appointed within the Department to coordinate implementation of the programme. The overall national implementation process must focus on many issues that ensure the successful implementation of the programme in the initialisation phase and its sustainability thereafter. The process involves successively including Water Management Areas (WMAs) in a phased way until sufficient national coverage is attained. A Regional Monitoring Coordinator should be appointed in each WMA. Initial emphasis should be placed on establishing successful monitoring programmes that can be used to drive further interest and hence resource allocation. It is the responsibility of the Regional Monitoring Coordinator and the National Coordinator to ensure that local monitoring programmes are designed in a standard way within the framework described in this manual.

A multitude of role players with very specific responsibilities are required to successfully implement a national monitoring programme. These range from the samplers, analysts, local managers, regional coordinators, a national coordinator, the Minister of Water Affairs and Forestry and concerned parties at local, regional, national and international level. Different management models can be envisaged. These differ in the degree to which responsibilities are delegated. The most likely models involve delegation of responsibilities to Catchment Management Agencies who may in turn delegate local responsibilities to specific organisations (like water boards).

This prototype implementation manual is supplemented with a research report that provides the rationale behind the design and implementation plan presented here (WRC Report No 1494/1/07).

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CHAPTER FOUR: MONITORING FRAMEWORK

CHAPTER FIVE: ROLES AND RESPONSIBILITIES

ABBREVIATIONS

ARM	Adaptive Resource Management
CMA	Catchment Management Agency
DEAT	Department of Environmental Affairs and Tourism
DO	Dissolved Oxygen
DoH	Department of Health
D:RQS	Directorate: Resource Quality Services
DWAF	Department of Water Affairs and Forestry
I&AP	Interested and Affected Party
ISO	International Standards Organisation
NEMP	National Eutrophication Monitoring Programme
NMMP	National Microbial Monitoring Programme
NWRS	National Water Resources Strategy
PCR	Polymerase Chain Reaction
QA	Quality Assurance
QC	Quality Control
RDM	Resource Directed Measures
RHP	River Health Programme
RQO	Resource Quality Objective
RWQO	Resource Water Quality Objective
TDS	Total Dissolved Salts
USEPA	United States Environment Protection Agency
WMA	Water Management Area
WMS	Water Management System
WRC	Water Research Commission
WUA	Water User Association

GLOSSARY

Aeolian. Pertaining to the action or the effect of the wind. Also spelled eolian.

Advection. The process of bulk movement of water (typically through a porous medium in the context of groundwater).

Adsorption. The retention of particles (*e.g.* microorganisms) on the surfaces of solid particles.

Alluvial. Pertaining to or consisting of alluvium, or deposited by running water.

Alluvium. Clay, silt, sand or gravel deposited in recent geological times by streams.

Anaerobic. A condition in which no dissolved oxygen is present.

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to store and transmit water; and to yield economical quantities of water to boreholes or springs.

Anthropogenic. Resulting from human activities.

Artesian water. Preferred term: Confined groundwater.

Attenuation zone. In the current context, that three-dimensional zone normally down-gradient of a faecal pollution source beyond which faecal contamination is unlikely to be significant because of natural filtering and die-off of the faecal microorganisms.

Autochthonous. Pertaining to substances or microorganisms indigenous to a particular environment.

Bacteria. Extremely small, relatively simple prokaryotic microorganisms.

Bacteriophage. Any of the viruses that infect bacterial cells; each has a narrow host range. Also known as phage.

Biofouling. The growth of microorganisms on surfaces leading to clogging that impedes water flow.

Biomonitoring. The gathering of biological information in both the laboratory and the field for the purpose of making an assessment or decision or for determining whether quality objectives are being met.

Biota. The animal and plant life characteristic of a given region.

Borehole. Includes a well, excavation, or any other artificially constructed or improved underground cavity which can be used for the purpose of intercepting, collecting or storing water in or removing water from an aquifer; observing and collecting data and information on water in an aquifer; or recharging an aquifer.

Catchment. The area that receives the rain that flows into a particular watercourse.

Catchment Management Agency. A Water Management Institution which is a statutory body governed by a board representing the interests of water users, potential water users, local and provincial government and environmental interest groups. It manages water resources within a defined Water Management Area.

Coliforms. Bacteria that are members of the *Enterobacteriaceae* family with the ability to ferment lactose. These bacteria make up about 10% of the intestinal microorganisms of human and other animals.

Coliphage. A bacteriophage infecting coliforms.

Confined aquifer. A formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.

Conservative variable. A substance or material whose amount in a water body remains constant with time although its concentration may decrease due to dilution or increase due to evaporation. Non-reactive chemicals like sodium and chloride are good examples.

Consolidated. Coherent and firm.

Cyst. A general term used for a specialised microbial cell enclosed in a wall. They may be dormant, resistant structures formed in response to adverse conditions or reproductive cysts that are a normal stage of the life cycle of protozoa and a few bacteria.

Diffuse-source pollution. Pollution that comes from a wide area that is not easily quantifiable, such as fertilisers draining off farmlands or pollutants in the runoff from urban areas.

Disinfection. The killing, inhibition, or removal of microorganisms that may cause disease.
Drawdown. The lowering of the water table or piezometric surface caused by the extraction of groundwater by pumping a borehole(s).
Ecosystem. The total community of living organisms and their associated physical and chemical environment.
Enteric. Found in the intestinal tract of humans and animals.
Eucaryotic cells. Cells that have a membrane-delimited nucleus and differ in many other ways from procaryotic cells. Protists, algae, fungi, plants and animals are all eucaryotic.
Faecal. Relating to animal waste matter.
Faecal coliforms. Thermotolerant (max 44.5°C) coliforms derived from the intestines of warm-blooded animals, including man. For water to be considered potable, faecal coliforms must not be present.
Fault. A fracture or zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.
Fissure. A surface of a fracture or crack along which there is a distinct separation.
Fracture. Any break in a rock including cracks, joints and faults.
F-RNA phage. A bacteriophage that can only infect certain *E. coli* cells.
Geohydrology. The study of the properties, circulation and distribution of groundwater.
Germ cell. A cell that is a primary source of growth and development (*i.e.* not a somatic cell).
Gravel. Unconsolidated accumulation of rounded rock fragments ranging in size from granules, pebbles, cobbles to boulders.
Groundwater. Water found underground in the zone of saturation.
Hazard. A situation with a potential to cause harm.
Helminth. A parasitic worm.
Heterotrophic. Using reduced, preformed organic molecules as the principal carbon source.
Hydrogeology. The geological aspects of groundwater occurrence, movement, recharge and discharge.
Hydrological cycle. The circulation of water within the earth's hydrosphere, involving changes in the physical state of water between liquid, solid, and gas phases and the exchange of water between atmosphere, land, surface and subsurface waters.
Hydrology. The study of water and its properties, movement and distribution in the hydrological system.
Hydrophilic. Having an affinity for, attracting, adsorbing, or absorbing water.
Hydrophobic. Lacking an affinity for, repelling, or failing to adsorb or absorb water.
Indigenous. Existing and having originated naturally in a particular region or environment.
Infiltration. The downward movement of water from the atmosphere into the ground.
Influent seepage. The movement of gravity water from the ground surface toward the water table.
Interstice. A pore space (void) within rock or soil.
Microbes. Microscopic organisms.
Microbiology. The study of organisms that are usually too small to be seen with the naked eye. Special techniques are required to isolate and grow them.
Microorganisms. Microscopic biological organisms such as bacteria, viruses, protozoa, etc. some of which cause diseases.
Microscopic. Unable to be seen with the naked eye.
Morbidity rate. The number of individuals who become ill as a result of a particular disease within a susceptible population during a specific time period.
Motile. Being capable of spontaneous movement.
Non-conservative variable. A substance or material whose amount in a water body can change with time irrespective of how much was originally added to the water. Reactive chemicals like phosphate or material that comprises living organisms like faecal coliforms and algae are examples.
Nutrient. Substance that supports growth and reproduction.
Oocyst. Cyst formed around certain protozoa.
Pathogen. An organism that causes disease. Derived from the Greek *Patho* (meaning disease) and *gen* (meaning giving rise to).
Permeability. The ease with which a fluid can pass through a porous medium and is defined as the volume of fluid discharged from a unit area of an aquifer under unit

hydraulic gradient in unit time (expressed as $m^3/m^2/d$ or m/d); it is an intrinsic property of the porous medium and is dependent of the properties of the saturating fluid.

Phage. See bacteriophage.

Phreatic surface. See water table.

Point-source pollution. Pollution that comes from a single source that is usually easily quantifiable *e.g.* sewage works or factory.

Porosity. Porosity is the ratio of the volume of void space to the total volume of the rock or earth material.

Potable. Drinkable.

Primary aquifer. An aquifer in which water is stored and which moves through the original primary interstices of the geological formation.

Primary interstices. Interstices formed at the same time as the rock was formed.

Prioritisation. The process of establishing an order of things based on the degree to which they require special attention.

Procaryotic cells. Cells that lack a true, membrane-enclosed nucleus. Bacteria are procaryotic and have their genetic material located in a nucleoid.

Protista. A kingdom containing eucaryotes with unicellular organisation, either in the form of solitary cells or colonies of cells lacking true tissues.

Protist. Member of the Protista kingdom.

Protozoan. A microorganism belonging to the Protozoa subkingdom. Defined as a usually motile eucaryotic unicellular protist. Most are free living though a few are parasitic in plants and animals. *Cryptosporidium* and *Giardia* are two protozoan genera that parasitise mammals.

Quality assurance. The implementation of all activities that minimise the possibility of quality problems occurring. These activities include (among others) training, instrument calibration and servicing, quality control, producing clear and comprehensive documentation, and so on.

Quality control. The process of ensuring that recommended monitoring procedures are followed correctly by detecting and correcting quality problems when they arise, so that the accuracy of primary observations or measurements is (a) defined, (b) within acceptable limits and (c) recorded. These monitoring procedures are sampling, sample preparation, sample preservation, sample analysis and data capture.

Recharge. The addition of water to the saturated zone, either by the downward percolation of precipitation or surface water and/or the lateral migration of groundwater from adjacent aquifers.

Resource directed measures. Management actions directed primarily at water resources.

Risk. The probability of observing a specified (unacceptable) effect as a result of exposure to a hazard (*e.g.* a toxic substance).

Runoff. Water from rain, snowmelt or irrigation that flows over the land surface into streams or other surface waters or land depressions.

Sanitation. Practical measures for preserving public health. Typically associated with the reduction of the microbial population to levels judged safe by public health standards.

Sanitation Services. The collection, removal, disposal or purification of human excreta, domestic waste-water, sewage and effluent resulting from the use of water for commercial purposes.

Saturated zone. The subsurface zone below the water table where interstices are filled with water under pressure greater than that of the atmosphere.

Secondary aquifer. An aquifer in which groundwater moves through secondary openings and interstices, which developed after the rocks were formed.

Secondary interstices. Interstices formed after the original rock formation was formed (*e.g.* by fracturing or dissolution).

Sedimentation. The process by which suspended solids settle downwards.

Settlement. A permanently populated area of high population density.

Sewage sludge. A decomposing, concentrated aqueous suspension of particulate organic material containing mainly biodegradable, but also inert, substances produced by waste water treatment plants.

Site-specific. Specific to a certain locality.

Somatic cell. Any cell of the body except germ cells.

Spatial variability. Change in some property in three-dimensional space at a specific time (*e.g.* change in temperature from the surface to the bottom of a water body).

Spore. A uni- or multicellular, asexual, reproductive or resting body that is resistant to unfavourable environmental conditions and produces a new vegetative individual when the environment is favourable.

Sterilisation. The process by which all living cells, viable spores, viruses, viroids are either destroyed or removed from an object or habitat.

Source directed controls. Management actions directed at sources of pollution.

Surface water. Water above the ground surface in impoundments, lakes, dams and rivers.

Survival. The maintenance of viability under adverse circumstances.

Suspended solids. Inorganic or organic matter, such as clay, minerals, decay products and living organisms, that remains in suspension in water. In surface waters it is usually associated with erosion or runoff after rainfall events.

Temporal variability. Change in some property over time at a specific point in three-dimensional space.

Thermotolerant. Tolerant of high temperatures.

Turbidity. A measure of the light-scattering ability of water. It indicates the concentration of suspended solids in the water.

Unconfined aquifer. An aquifer where the water table is the upper boundary and with no confining layer between the water table and the ground surface. The water table is free to fluctuate up and down.

Unconsolidated. Loose or soft (soil-like).

Unsaturated zone. That part of the geological stratum above the water table where interstices and voids contain a combination of air and water.

Vadose zone. The unsaturated zone. Also called the zone of aeration.

Viability. The ability of a microbial cell to reproduce (*i.e.* divide and form at least one daughter cell) when placed in a favourable environment.

Virus. An infectious agent depending on living host cells for its metabolism and reproduction.

Water Board. An organ of state established or regarded as having been established in terms of the Water Services Act (No. 108 of 1997) with the primary function of bulk water supply.

Waterborne disease. A disease resulting from infection from water that contains pathogens. Many important human pathogens are maintained in association with living organisms other than humans, including many wild animals and birds. Some of these bacterial and protozoan pathogens can survive in water.

Watercourse. A river or spring; a natural channel in which water flows regularly or intermittently; a wetland, lake or dam into which, or from which, water flows.

Water level. The water surface in a borehole or well.

Water Management Area. An area established as a management unit in the national water resource strategy within which a catchment management agency will conduct the protection, use, development, conservation, management and control of water resources.

Water Management Institution. A catchment management agency, a water user association, a body responsible for international water management or any person who fulfils the functions of a water management institution in terms of the Water Act No. 36 of 1998.

Water resource. Includes a watercourse, surface water, estuary or aquifer.

Water Services Institution. A water services authority, a water services provider, a water board or a water services committee.

Water table. The upper surface of the saturated zone of an unconfined aquifer at which pore pressure is equal to that of the atmosphere.

Water User Association. A statutory body of cooperative associations of individual water users who wish to undertake water-related activities for their mutual benefit. The broad role is to enable people within a community to pool their resources to more effectively carry out water-related activities.

Well. A hole dug in the earth to reach a supply of water. These are usually shallow and only penetrate the saturated zone for short distance. Also means borehole in the USA and Australia.

CHAPTER 1: BACKGROUND

This chapter should be read by anyone wanting a brief policy context and general background of the development of the national microbial monitoring programme for groundwater in South Africa or an overview of this manual.

1.1 PURPOSE OF THIS MANUAL

The general purpose of this manual is to describe how the national microbial monitoring programme (NMMP) for groundwater should be implemented on a national scale.

See National Water Act No 36 of 1998 Chapter 14 Section 143.

In respect of national information systems on water resources, the Minister may make regulations prescribing guidelines for monitoring and on the provision of monitoring data. This manual gives guidelines, procedures and methods for microbial monitoring of groundwater as well as how and when such data should be reported.

Accordingly, this manual is aimed at a variety of people and organisations. It is initially aimed primarily at DWAF officials who will have the primary responsibility to implement national water-related monitoring programmes. However, it is also aimed at Catchment Management Agencies (CMAs) and water management institutions to whom monitoring responsibilities may be delegated.

This manual resulted from the refinement of the prototype implementation manual [Murray *et al.*, 2004b] on the basis of one year of pilot study monitoring [Murray *et al.*, 2006]. The prototype manual was also accompanied by a research report [Murray *et al.*, 2004a] that summarises the rationale behind the original processes described in this manual and many of the decisions taken concerning its scope and content.

1.2 GROUNDWATER QUALITY MANAGEMENT POLICY

The policy and strategy for groundwater quality management in South Africa specifically refers to the need for a series of groundwater quality programmes, one of which relates to national monitoring [DWAF, 2000b]. The following table summarises, and sometimes quotes verbatim, sections that provide the regulatory framework for the implementation of a national microbial monitoring programme for groundwater. Also indicated is how the monitoring programme specifically addresses relevant issues and where in this manual these are described.

Table 1.1. Policy and strategy requirements [DWAF, 2000b] and how they are addressed by this monitoring programme.

Policy and strategy statement	How and where addressed
Section 4.2.3. In general, the groundwater quality programmes referred to in the policy must be established with specific objectives and should lead to improvements and refinement of the regulatory system.	Clear objectives for the NMMP for groundwater are defined in the National Implementation chapter. Assessment of monitoring data and some management actions are given in the Annual Data Assessment and Reporting section of the Monitoring Framework chapter.
Section 4.2.3. The programmes will generally serve a variety of purposes of which the identification of the need for and initiation of remedial action are some of the most important.	The NMMP for groundwater addresses this directly by enabling problematic groundwater zones and the extent of their impact to be monitored.
Section 4.2.4. The national groundwater quality information system provided for in the National Water Act provides a basis for routine auditing of the state of the groundwater environment and for assessing the performance of the regulatory system. The Department will execute an annual audit on the status of the national groundwater resources and will publish this report.	The Monitoring Framework chapter of this manual recommends a format for an annual national report for microbial groundwater quality.
Section 4.2.5. National groundwater quality guidelines will be set and published by the Department. Those developed for surface water will be adopted for groundwater.	The Annual Data Assessment and Reporting section of the Monitoring Framework chapter describes the use of faecal coliform/*E. coli* guidelines specially developed for reporting potential health risk for four sensitive water uses as one basis for data assessment and reporting.
Section 4.2.5. Action limits, which may specify the point at which intervention is necessary, may need to be set up for aquifers where degradation is anticipated. These action limits will become part of the aquifer management strategy.	The basic philosophy of the design of the NMMP for groundwater is such that action limits are well defined, as are the associated management actions. These are described in the Monitoring Framework chapter.
Section 6.8. A national information system must inter alia provide a basis for (1) establishing and tracking trends in groundwater quality and (2) prediction of macro impacts.	The NMMP or groundwater, by its very nature, allows for establishing trends in the faecal groundwater quality. Prediction of macro impacts is facilitated by the philosophy of monitoring effectiveness of containment of faecal pollution backed up by monitoring of strategic points of groundwater use.
Section 8.2. Operational guidelines are required to assist the Department in executing their work in a coherent and consistent manner. They comprise one type of instrument enabling the groundwater quality management strategy.	This implementation manual comprises operational guidelines, both managerial and technical, for the practical implementation of the NMMP for groundwater.

1.3 BALANCING COST AND RISK

When countries develop strategies for protecting public health, two factors are usually considered (Anderson, 2001).

1. The first, and most prominent, is cost. The economic viability of a water monitoring programme is usually the limiting factor when strategies are evaluated.

2. The second factor is the risk involved in a strategy. No single method will ensure 100% safe water supplies, but certain techniques and methods are more accurate in indicating health risks. Unfortunately, methods that are more accurate are generally more expensive (Anderson, 2001). This forces health authorities to choose between two basic approaches to health risk management. One is a high technology / high cost / low risk approach, the other a low technology / low cost / controlled risk approach (Anderson, 2001). In order to provide an effective health risk-monitoring programme, frequent and regular testing of numerous samples needs to be carried out, causing costs to escalate rapidly. In developing countries where health risk monitoring is urgently needed, a high technology approach is not economically viable (Anderson, 2001). The focus of routine water testing is therefore on simple inexpensive tests at high frequency rather than complicated time-consuming tests at low frequency (Grabow, 1996). This philosophy is applied to this national monitoring programme.

1.4 THE SPECIFIC NEED FOR MICROBIAL MONITORING

Water quality management policy in South Africa is based on a number of guiding principles. One of the environmental principles is that environmental change should be monitored so that improvements can be encouraged and detrimental impacts minimised. Monitoring microbial pollution in groundwater addresses this directly by providing sound data upon which informed actions can be based.

The National Water Act, No. 36 of 1998 specifically requires that national monitoring systems should be established. Microbial monitoring of groundwater is but one aspect of the monitoring desirable on a national scale.

See National Water Act No 36 of 1998 Chapter 14 Section 143.

There are also a number of practical issues that justify microbial monitoring of groundwater.

- There are numerous potential sources of faecal pollution (like unplanned settlements with inadequate sanitation, badly managed sewage treatment works, leaking sewer pipes, stormwater runoff, etc.). From a risk assessment point of view, there can be little doubt that ‘hazards’ exist. This means that there is potential for faecal pollution and associated pathogens to enter groundwater resources from a number of pollution sources and ultimately impact on human health. Some may regard this in itself as sufficient to justify national microbial monitoring of groundwater.
- Faecal pollution of groundwater has been largely ignored in groundwater pollution studies in the past, although this is now changing. The emphasis of groundwater quality monitoring has usually been on increased salinity and chemical constituents.

There are also considerable technical difficulties associated with obtaining representative groundwater samples that have not been microbially contaminated by the sampling procedure. These two issues have resulted in a situation where very little is known with certainty about the real extent of microbial pollution of groundwater in South Africa. This lack of knowledge is a reason for implementing a national monitoring programme.

- It is very difficult to make confident statements about survival of microorganisms in soils and groundwater that allow accurate prediction of the likely degree of microbial pollution of groundwater in specific scenarios. Direct monitoring is therefore the only way of establishing with certainty the real extent to which microbial pollution of groundwater is a problem in South Africa.

The extent to which such monitoring should occur should depend on the degree to which microbial pollution of the groundwater is actually likely to occur. This is determined by the mechanisms by which pathogens enter, move and survive in groundwater. Considerable emphasis is placed on the fact that behaviour of faecal microorganisms in groundwater is fundamentally different from that of dissolved chemical constituents. This has significant consequences for the design of a national monitoring programme.

Strictly, the existence of polluted groundwater still only constitutes the existence of a ‘hazard’. ‘Risk’ only becomes an issue when humans are exposed to the groundwater. (In principle, if nobody will ever use the water, there is no risk.) When human exposure exists, not only the level of pollution becomes relevant but also the exposure mechanism (*e.g.* ingestion, skin contact, etc.) and the duration (continuous, occasional, etc.).

This manual describes the design and implementation of a monitoring programme that is intended to monitor the degree of faecal pollution in groundwater on a comprehensive national basis.

1.5 CURRENT CONTEXT OF NATIONAL MICROBIAL MONITORING

This national monitoring programme for groundwater supplements the National Microbial Monitoring Programme for surface waters [DWAF, 2002a]. However, it should not be regarded as an extension of it. Monitoring groundwater is fundamentally different from monitoring surface water and accordingly has a completely different design.

The NMMP for surface waters is currently implemented in many Water Management Areas (WMAs). It monitors *E. coli* or faecal coliforms, turbidity and pH on a weekly or two-weekly basis.

Groundwater monitoring on a national scale is currently being carried out by the Department. However, it focuses mainly on water quantity variables (water levels, etc.) and chemical quality (TDS, major ions, pH, etc.). Three levels of monitoring are envisaged of which one (level 1) is extensively implemented. The three levels refer respectively to:

- Baseline monitoring (in unimpacted aquifers),
- Catchment monitoring (in impacted aquifers), and
- Local impact monitoring (typically project specific and focussed on aquifer zones).

The monitoring design described in this manual focuses only on water quality and only on one aspect of quality, namely microbial quality that reflects the degree of faecal pollution because of the associated human health risks. (See Groundwater Microbial Pollution section in Groundwater Basics chapter.)

The programme has a “national” emphasis though there are two distinct spatial tiers (see Figure 1.1), national and regional (equivalent to a Water Management Area). Water Management Areas refer to the 19 formal areas designated by the Department covering the whole of South Africa. Collectively these will provide the national picture. These spatial tiers are relevant primarily from a management point of view although single aquifers may cross such boundaries.

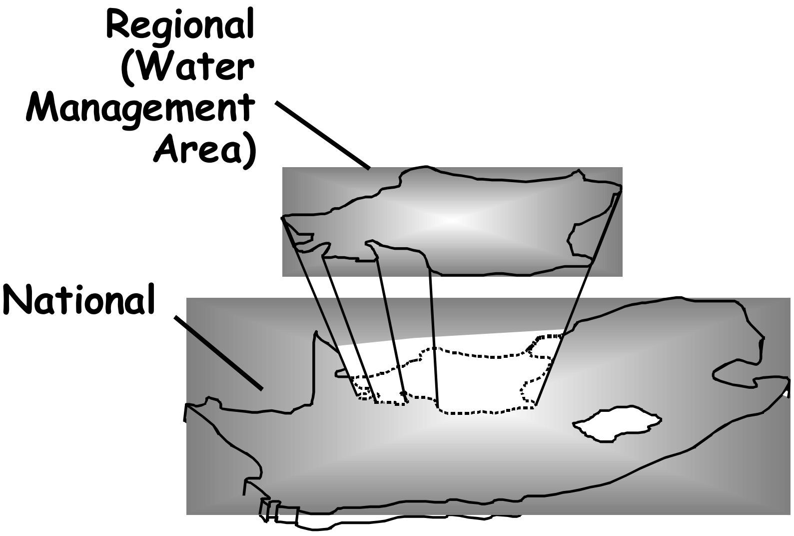

Figure 1.1. Schematic illustration of the two spatial monitoring scales assumed for the National Microbial Monitoring Programme for Groundwater.

1.6 THE STRUCTURE OF THIS MANUAL

Chapter 2 describes some groundwater basics and the causes and impacts of microbial pollution of groundwater

Chapter two describes some of the basic principles of geohydrology and microbiology in the context of pollution of groundwater.

Chapter 3 describes a national implementation process

Chapter three states the objectives of the monitoring programme and describes the overall national implementation process of the NMMP for groundwater. In particular it deals with the tasks of the National Coordinator.

Chapter 4 defines the detailed monitoring framework

Chapter four describes how and when the monitoring should be done, what should be measured and by what method, and how, when, and to whom, assessments should be reported.

Chapter 5 defines individual roles and responsibilities

Chapter five defines the individual roles from sampler to the national policy maker and summarises the data and information flow. Various management models are also presented.

CHAPTER 2: GROUNDWATER BASICS

This chapter should be read by anyone wanting a brief summary of some of the basics of groundwater and the causes and impacts of faecal pollution of groundwater.

2.1 INTRODUCTION

It is essential that the implementation of a national monitoring programme of microbial pollution of groundwater is based on a sound (albeit occasionally superficial) scientific foundation. Accordingly, this chapter is devoted to summarising basic concepts in the two disciplines of microbiology and geohydrology. It aims to facilitate good communication between the many people that will inevitably be involved in implementing the national monitoring programme, microbiologists and geohydrologists. The USEPA web site contains a very readable account of the basics of aquifers and groundwater movement [Purdue University, 1998]. Much of the following sections is based on this. The reader is also encouraged to peruse the glossary that defines many technical (and managerial) terms.

2.2 GROUNDWATER BASICS

2.2.1 Groundwater in South Africa

South Africa has a population of around 45 million and a largely semi-arid to arid climate. According to the definition of water scarcity as the available water per capita of a country, South Africa is among the twenty most water stressed countries in the world (United Nations, 1995). Groundwater contributes approximately 15% of the total bulk water supply of the country and has traditionally been relegated by planners and developers to a relatively minor role. However, the resource is now seen as being of primary importance in supplying safe drinking water especially to the inhabitants of rural areas. In many of the rural areas in the country, regional water supply schemes based on surface water are in most instances not economically feasible, resulting in groundwater based supply schemes being the only alternative.

Figure 2.1. Many rural communities rely heavily on groundwater.

Groundwater stored in porous rock formations often satisfies a large proportion of the water demand in many countries around the world. However, in South Africa groundwater occurs in approximately 90% of the country in fractures and openings in weathered hard rocks that have virtually no primary porosity. In general, this situation results in low yields from boreholes, and as a result has often led to over utilisation of the resource. This has created the perception that groundwater is an unreliable source for water supply. However, groundwater remains the most feasible and often only source of water in large parts of the country. This is illustrated by the acknowledgement by water resource planners, that groundwater should not only be regarded as a source of water in the more arid western part of the country, but also has the potential to serve over 80% of the 5 700 Eastern Cape communities with their basic needs for water.

The commonly held view that groundwater is an unsustainable source of water, highlights our general poor understanding of the nature, occurrence and behaviour of groundwater in fractured hard rocks. The importance of groundwater to the country, coupled with the poorly understood complexities of the nature and behaviour of groundwater, highlights the importance of proper protection of this resource from contamination. Groundwater should be well protected from unnecessary contamination because it is extremely difficult, if not impossible, and time consuming, to restore a contaminated groundwater resource. The often poorly understood nature of groundwater in primary as well as secondary aquifers, necessitates the design, planning and implementation of groundwater quality monitoring schemes to protect the users. Microbial contamination is one form of groundwater contamination that requires effective and well designed monitoring procedures. In order to provide the background for the philosophy used in the design of the monitoring procedures discussed in this report, a few basic concepts of the occurrence, nature and behaviour of groundwater under South African geological conditions is described in the following sections.

2.2.2 The hydrological cycle

The hydrological cycle describes the continuous movement of water above, on, and below the surface of the Earth. Groundwater is an integral part of the earth's water resources and therefore of the hydrological cycle. Most of the water that reaches the earth's surface through rainfall, snow or ice, returns to rivers through surface runoff and eventually flows into the oceans. However, a small proportion of the precipitation infiltrates into the ground, some of which is used by vegetation or evaporates, while the balance eventually becomes groundwater stored in the available openings in the rock formations. As part of the continuous cycle, most groundwater eventually returns to the surface where it decants in springs, wetlands or into rivers and streams contributing to the perennial nature of many of our rivers and streams. It is important to note that totally different time scales operate in the case of surface water and groundwater and that these can differ by orders of magnitude. Groundwater is therefore not an independent resource. As part of the hydrological cycle, abstraction of groundwater through pumping from a borehole, potentially affects spring and stream flow, surface runoff and the environment in general.

2.2.3 Aquifers

Aquifer is the term used to describe a geological formation saturated with water and capable of yielding usable volumes of water. The term is derived from the Latin words *aqua*, meaning water, and *ferre*, meaning to carry.

An aquifer is formed when permeable earth material such as porous sediments or weathered and fractured hard rock is saturated with water. The permeability should, however, be such that it is capable of transmitting and yielding usable quantities of groundwater to boreholes, wells or springs.

Water occurs in two distinct zones below the earth's surface; an upper zone which contains both water and air, and referred to as the unsaturated zone or zone of aeration, and a lower, water saturated zone. The term aquifer refers to the saturated zone only. "Saturation" in the context of groundwater refers to interstices between rocks and soil particles, or to the openings in rocks formed by fracturing of hard rocks, being filled with water.

Aquifers are broadly classified into two categories.

- Primary aquifers occur in unconsolidated or consolidated mainly sedimentary deposits or rock formations where the interstices between the rock forming particles were formed at the time of deposition or formation of the rock and which are saturated with water.
- Secondary aquifers are formed when openings or interstices are formed after the formation of the rock through external forces. For example, this may be external pressure applied to rocks resulting in fractures and faulting or the natural weathering of a rock formation. For these rocks to form an aquifer, these openings have to be interconnected, saturated with water and must allow water movement through them.

The rocks that compose aquifers can consist of unconsolidated deposits, such as alluvial deposits, or consolidated material such as hard rocks for example sandstone, quartzite, shale or dolomite. Most consolidated rocks consist of rock and mineral particles of different sizes and shapes that have originally been naturally deposited through water or wind action. They are often metamorphosed or 'welded' together (by heat and pressure or chemical reaction) into a single rock mass or were formed as a result of the cooling of molten rock following volcanic eruptions or intrusions. Water movement occurs in these rocks through fractures, joints, bedding planes, interstices between particles, dissolution channels or other openings in the rock.

Most unconsolidated materials consist of material derived from the disintegration and weathering of consolidated rocks. Unconsolidated deposits typically include some or all of the following: gravel, sand, silt, clay and the fragments of marine organisms.

South African geohydrological conditions are dominated by fractured hard rock or secondary aquifers. These occur over 80-90% of the surface area of the country. The remainder, occurring predominantly along the coast and in the Kalahari, consists of unconsolidated primary aquifers. The latter are deposited on older hard rock formations, which may or may not be fractured or water yielding, and thus may constitute an additional aquifer.

The hydraulic properties, physical dimensions and nature (like saturated thickness, depth, degree of fracturing, primary or secondary porosity) and prevailing hydraulic gradient determine the rate of groundwater movement in these aquifers and flow route as it moves through the aquifer. These same properties also determine how pollutants originating on the surface will move through the aquifer.

The position of the aquifer in the geological sequence, and the connection or not to the atmosphere, is described by the terms "unconfined", "confined" or "semi-confined".

In an unconfined aquifer the upper surface of the water saturated zone, also referred to as the water table, is connected to the atmosphere through the openings in the overlying material and therefore is at atmospheric pressure. This surface fluctuates depending on changes in atmospheric pressure, and also reacts to ocean tides. In South Africa, these aquifers are commonly found along the coast and are characterised by the following:

- Sandy coastal sedimentary deposits (for example along large parts of the West Coast, the Cape Flats near Cape Town, the Zululand coastal plain north of Richards Bay),
- The unconsolidated to partly consolidated deposits in the Kalahari, and
- The alluvium associated with the larger rivers in the country (for example the Limpopo, Crocodile, Bree, Caledon and others).

Apart from the coastal aquifers and those associated with alluvial deposits along river courses, and contrary to aquifers in many other countries, South Africa has no significant primary aquifers. Because of the geological history of South Africa, the original primary porosity in the rocks has in most instances been virtually destroyed through metamorphic processes.

A confined (Figure 2.2) or semi-confined aquifer on the other hand, is one in which water occurs and moves in a geological formation that is overlain by a layer that is impermeable or has a very low permeability respectively. This layer is referred to as the confining layer and often is represented by a shale or mudstone, or unfractured intrusive rock such as dolerite intruded in a sheet-like fashion. The groundwater in a confined aquifer is usually at a higher pressure than that of atmospheric pressure. When drilling into a confined or semi-confined aquifer, the static water level in the borehole, the water normally rises to a level above the level at which it was first encountered.

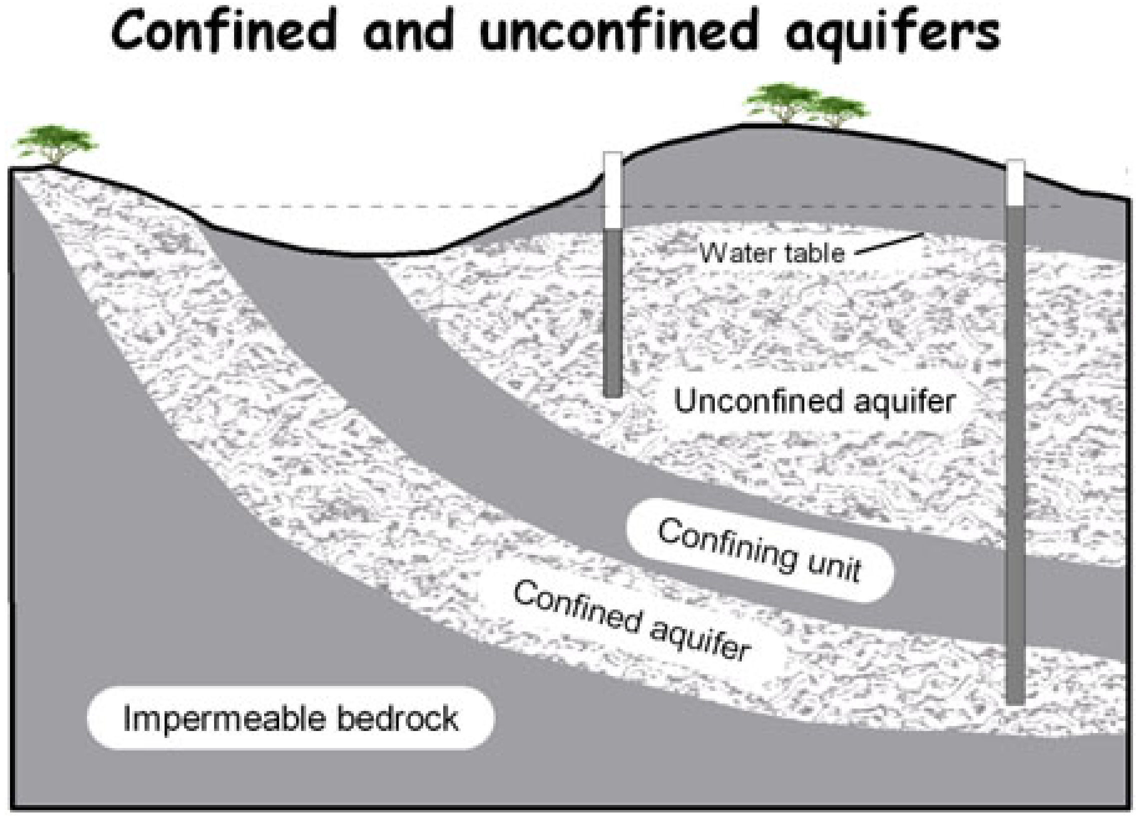

Figure 2.2. Schematic illustration of a confined and an unconfined aquifer (adapted from Purdue University, 1998).

Semi-confined aquifers are frequently found in South Africa. In these aquifers, the "confining" layer is not totally impermeable, but has a low intrinsic permeability that does allow some groundwater movement through it, or water transfer can occur through a low density of small fractures in the formation.

It should be noted that these are only conceptual models. A natural groundwater system may consist of a complex combination of unconfined and confined primary of secondary aquifers, partially permeable or laterally incomplete confining beds, perched water tables, intersecting lakes and streams, intrusions of rock such as dolerite or granite, faults and fractures, etc. In the national microbial monitoring programme for groundwater the focus will primarily be on the shallower aquifers, *i.e.* the unconfined and weathered hard rock aquifers, rather than the deeper confined aquifers.

Much like the flow of water in a river, the flow of groundwater is subject to gravity and pressure differences. It is almost always in motion. In unconfined aquifers it flows from areas of higher elevation to areas of lower elevation. In the case of confined aquifers, it is pressure rather than gravity that makes the water move. In this case it flows from areas of high pressure to areas of lower pressure. Just like when a sponge soaked with water is tilted, gravity forces water to flow from one pore space or fracture to another. Importantly, groundwater flow rates, especially in confined systems, are extremely slow compared to surface water flow rates.

2.2.4 Boreholes

Boreholes are used to provide water for anything ranging from drinking and irrigation to industrial processing. When water is pumped from an aquifer, the dynamics of groundwater flow change. When abstracting water from an aquifer through a borehole installed in an unconfined aquifer, water moves towards the borehole and enters the borehole through small holes or slits in the borehole casing. When pumping starts, the water level in the borehole and in the immediate vicinity of the borehole, drops below that of the original static water level of the aquifer. Groundwater then flows towards the borehole in a radial-like pattern, in contrast to the natural flow direction. As pumping continues, the water level in the borehole continues to decrease until the rate of flow into the borehole equals the rate of withdrawal by pumping. This movement of groundwater from an aquifer into a borehole results in the formation of a 'cone of depression' around the borehole. This is an inverted cone surrounding the borehole that is related to the volume of water removed by pumping. The term drawdown refers to the difference in the height between the water level in the borehole prior to pumping and the level during pumping.

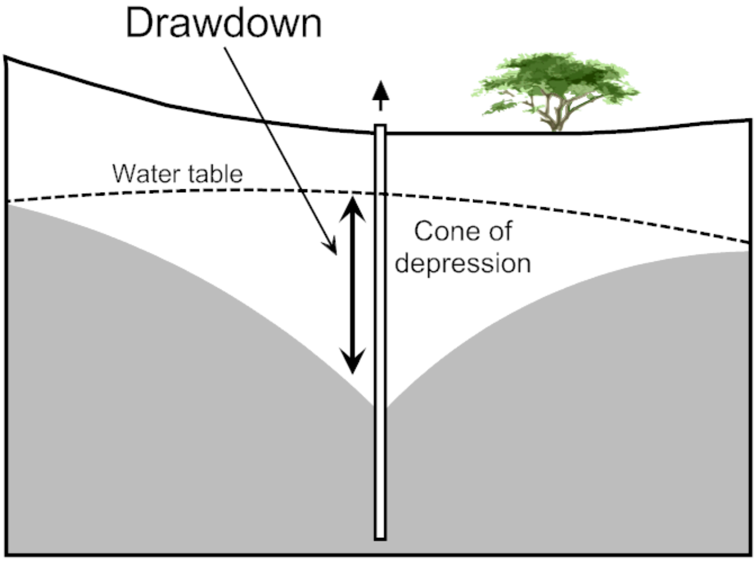

Figure 2.3. Illustration of drawdown and the cone of depression during borehole pumping.

Aquifer dynamics when pumping from a confined or semi-confined aquifer are much more complex. The natural groundwater flow direction is also changed, as water will now flow towards the borehole with a slight lowering of the pressure in the borehole. Under pumping conditions, the aquifer physically contracts and expands again when pumping is stopped. A detailed description of these dynamics is outside the scope of this manual.

2.2.5 Aquifer recharge

Recharge is the process by which aquifers are replenished with water typically from the surface. This occurs naturally as part of the hydrological cycle as rainfall infiltrates the land surface and percolates into underlying aquifers. The following factors influence recharge rates

- The physical characteristics of the soil;
- Plant cover and slope of the surface;
- Water content of surface materials;
- Rainfall intensity and duration; and
- The presence and depth of confining layers and aquifers.

In South Africa rainfall is by far the most important source of water to recharge aquifers. Surface water resources, such as rivers, lakes, dams can also recharge aquifers depending on the local hydrogeological conditions. If the water table in the underlying aquifers is below that of the river or dam, water may infiltrate from these water bodies into the aquifer.

Artificial recharge is also occasionally used. This is done by pumping or diverting water into a borehole where it replenishes the aquifer directly or through the spreading of water over the land surface where it can seep into the ground. Special attention must always be given to the water quality of artificial recharge to ensure that negative impacts on the aquifer are avoided. Interactions can occur between the water and the solid phases in the aquifer that change the physical properties of the aquifer adversely. Dissolution is one example.

Recharge to confined aquifers occurs through the physical connection of the geological formation hosting the aquifer with the surface (see Figure 2.2) and occurs normally at great distances (typically several tens of kilometres) from the position where water is abstracted from the aquifer. These are typically mountainous areas or elevated plains that receive high rainfall. Groundwater in confined aquifers is at a higher pressure than atmospheric pressure because of the difference in elevation between that of the recharge area and the lower contact of the confining layer with the aquifer.

Semi-confined aquifers are recharged by vertical infiltration (leakage from overlying aquifers) as well as by the confined aquifer mechanism.

2.2.6 Pollution and aquifer vulnerability

Groundwater may be contaminated with substances which occur as liquid (*e.g.* liquid waste products or oil) or by dissolving substances in the soil through which the water infiltrates, or by bacteria small enough to pass through the pores in soil. Typical contamination sources are fertilizers, waste disposal sites, sewage treatment facilities, mining activities, sewers, leaking underground storage tanks, etc. (See the Groundwater Microbial Pollution section in this chapter for more detail.) Groundwater is referred to as polluted when the contaminants occur at concentrations which make the water unfit for use.

Leaching is the process whereby substances are dissolved by infiltrating water and then transported to the groundwater. Typical examples of this process are leaching from mine dumps or fertilisers applied to agricultural land that are dissolved by rainwater and then infiltrate to become groundwater.

The ease by which aquifers can be contaminated or their vulnerability to contamination is influenced by a number of factors. Some aquifers are very vulnerable to contamination whereas others have a high degree of natural protection. Groundwater that is particularly vulnerable to contamination tends to occur in aquifers with the following characteristics (Conrad and Colvin, 1999):

- A shallow depth to the water table;
- The soil and unsaturated zone are highly permeable and relatively inert with low levels of organic matter or clay;
- Pathways for rapid migration to the water table exist, such as cracks in the soil, fractures in the rock or sinkholes; and
- There is a relatively high rate of recharge by either natural processes like rainfall, or by irrigation water.

A shallow unconfined aquifer covered by only a few metres of sandy soil, will thus be much more vulnerable to contamination than a deep aquifer with low permeability clay or shale in the overlying layer.

2.2.7 Groundwater management

A serious threat to the sustainable and cost-effective use of groundwater is pollution, either from salts, organic substances or microbial sources. The cost of treatment of polluted ground, if at all technically and economically feasible, is usually higher than the cost of implementing responsible groundwater management and pollution prevention measures.

In the context of this manual, a few fundamental groundwater management aspects should always be adhered to reduce the potential for contamination of groundwater. In the case of relatively shallow unconfined aquifers, the groundwater level (or water level) tends to mimic the surface topography. It is desirable that boreholes used for water supply should generally be located up-slope of potential sources of contamination although for various reasons it may not always be possible.

A borehole provides a direct link to the aquifer, and as such, can easily act as a direct pathway for pollutants to reach the groundwater. A casing (usually steel or PVC) is installed in the upper sections of the borehole (typically the upper 10-20 metres) because of the unconsolidated and weathered nature of the formation into which a borehole is drilled. As part of the construction of the borehole the uppermost few metres of the borehole between the casing and the soil or rock should be filled with grout to seal the lower sections of the borehole from the surface. This will prevent the easy infiltration along the side of the casing of undesired contaminants into the groundwater. Cement or bentonite/soil mixture (bentonite is a clay mineral that expands when becoming wet) are typically used for this purpose. Furthermore, the casing should extend for at least 0.5 m above ground and secured in surrounding concrete, the elevation of which should be well above that of the natural ground level. The area around the borehole should preferably also be shaped such that water is not allowed to accumulate around it.

2.3 GROUNDWATER MICROBIAL POLLUTION

2.3.1 Introduction

This document is primarily concerned with microbes that enter groundwater systems from pollution sources, not those that occur naturally in groundwater. “Pollution” is defined in the National Water Act (Act No.36 of 1998) as the direct or indirect alteration of the physical, chemical or biological properties of a water resource so as to make it

1. less fit for any beneficial use for which it may reasonably be expected to be used; or
2. harmful or potentially harmful
    a. to the welfare, health or safety of human beings;
    b. to any aquatic or non-aquatic organisms;
    c. to the resource quality; or
    d. to property.

Microbial pollution is the particular focus in the current context. Of particular importance is the potential health risk to humans associated with the possible use of faecally polluted groundwater. Although algae and fungi are microorganisms, they are not of faecal origin (Figure 2.4). Furthermore, of the waterborne pathogens, only viruses and bacteria are of particular concern in groundwater (since the larger organisms such as helminths and protozoa of faecal origin are unlikely to occur in groundwater because they are effectively filtered).

The degree of microbial pollution of groundwater depends on many factors, some of which are summarised in the sections below.

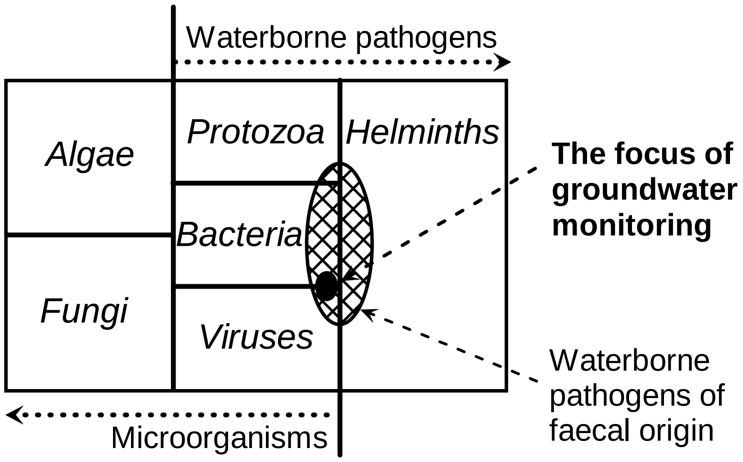

Figure 2.4. The specialised microbiological focus of groundwater monitoring.

2.3.2 Potential sources of microbial pollution

There are many land uses that can result in microbial pollution of groundwater. Figure 2.5 illustrates some of these.

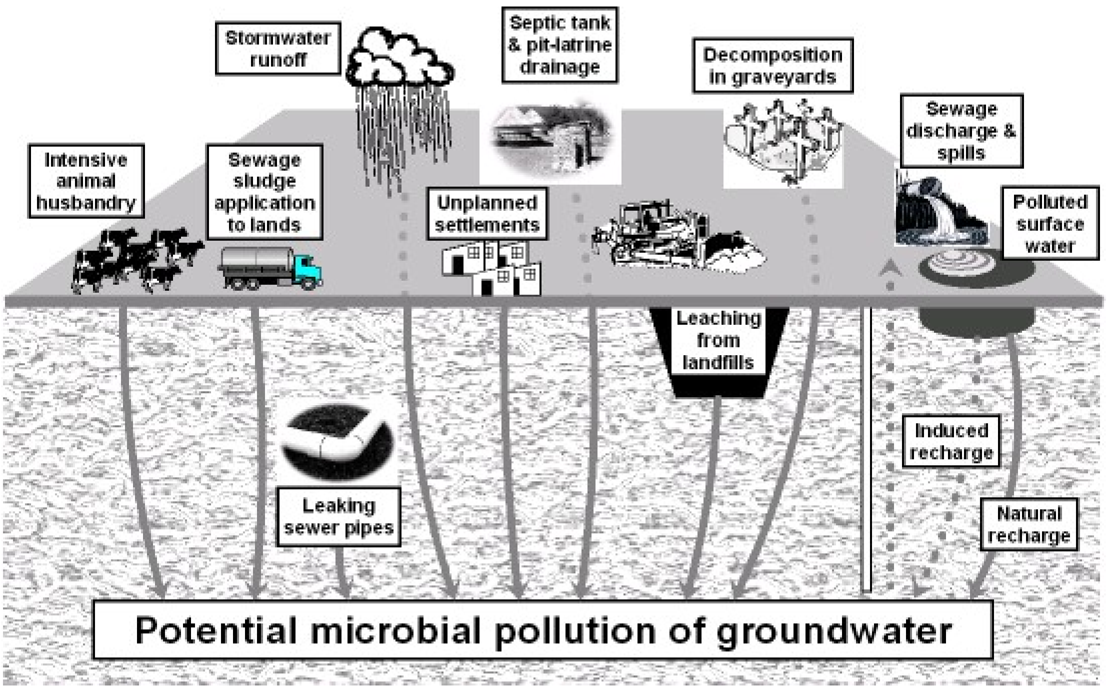

Figure 2.5. Some potential sources of microbial pollution of groundwater.

Intensive animal husbandry

Intensive farming (*i.e.* involving substantial capital and labour inputs per unit area) typically results in a large volume of animal waste being produced in a limited area [Conrad *et al.*, 1999]. This can pose a serious threat to groundwater quality if the waste is not properly managed [Conrad *et al.*, 1999, Sililo *et al.*, 2001].

Sewage sludge application to land

Internationally, this activity has been associated with microbial pollution of groundwater, though the extent to which this might be a problem locally is uncertain [Conrad *et al.*, 1999]. The occurrence of pathogens varies according to the health of the population served by the waste water treatment plant and the effectiveness of the treatment plant.

Leaking domestic sewage networks

Well designed and maintained sewage networks do not typically cause significant problems. When problems do occur, they are generally the result of leaks or ruptures which tends to be worse in older systems [Butler *et al.*, 2001, Sililo *et al.*, 2001].

Unplanned settlements

Urban development of an informal nature represents a significant groundwater pollution threat [Wright, 1999]. Specific potential microbial pollution sources include on-site sanitation systems (or the lack thereof), communal water supply points and storm water drainage systems.

Storm water runoff

Storm water runoff can be significantly microbially polluted, particularly from informal settlements that do not have adequate sanitation facilities. Although the direct effects are most severe on surface waters receiving such runoff, it can ultimately pollute groundwater.

Septic tanks and pit-latrines

The actual degree of pollution of groundwater due to these sources is highly site-specific and especially aquifer-specific. In some instances (though by no means all) local pollution caused by pit-latrines has been detected. Problems are less likely in dry areas where the water table is far below ground level. Significant faecal pollution of groundwater caused by septic tanks is also possible [Jiwan and Gates, 1998].

Landfills

Domestic waste disposal into landfills is not recognised as being a major contributor to microbial pollution of groundwater. However, depending on the type of landfill, there can be a high level of microbial activity in such waste disposal sites. If pathogens do survive and are discharged in leachate, then the possibility of groundwater pollution exists [Sililo *et al.*, 2001]. However, it is more likely to be a problem with unlicensed and illegal sites. Typically the sources of faecal pathogens in domestic landfills will be disposable nappies and pet faeces.

Sewage discharge and spills

Sewage networks that are not well designed and maintained, or that have an inadequate design capacity, could discharge inadequately treated waste. Spills also have a greater likelihood of occurring. In either case, there is a greater potential for ultimate pollution of groundwater, usually first by pollution of surface waters.

Decomposition in graveyards

Although cemeteries are not generally considered as posing a significant pollution threat to groundwater (from a national perspective), some concerns have been raised [Sililo *et al.*, 2001]. However, impacts are typically site-specific and local in extent.

Induced and natural recharge from polluted surface water

Pumping of boreholes in the vicinity of polluted surface water, like an unlined dam or river, could induce movement of the polluted water downwards into the aquifer. This, in effect, recharges the aquifer with the polluted water. If the polluted surface water is up-gradient of the groundwater, there may also be natural recharge of the polluted water into the down-gradient groundwater.

In conclusion, there can be little doubt that the ‘hazards’ do exist. That is, there is potential for pathogens to enter groundwater resources from a number of different kinds of pollution sources and ultimately this impacts on human health if that groundwater is used. In effect, this corresponds to the “threat factor” identified by Parsons and Jolly (1994). This is one of three factors identified as important in the assessment of a site’s suitability for waste disposal (the others being the “barrier factor” and the “resource factor”). However, the extent to which monitoring of groundwater should occur should depend on the degree to which microbial pollution of the groundwater is actually likely to occur. This is determined by the mechanisms by which such pathogens reach and survive in groundwater.

2.3.3 Survival of microorganisms

Microorganisms behave as non-conservative water quality variables. That is, the amount in water can change with time, irrespective of how much was originally added to the water. Although some coliform bacteria can multiply in the environment, *E. coli* reportedly cannot [Grabow, 1996]. Some microorganisms have special mechanisms that facilitate survival and viability for long periods in a dormant state. Parasitic protozoa like *Cryptosporidium* can survive in the environment for long periods in a cyst form. They can only multiply when ingested by a suitable host. Viruses also need a host to multiply but can survive for some time in the environment. *E. coli* has an average die-off rate such that in about 7 days about 90% will die and in 14 days about 99% will die [Murray *et al.*, 2004a]. These two times have standard deviations of 4 and 7 days respectively.

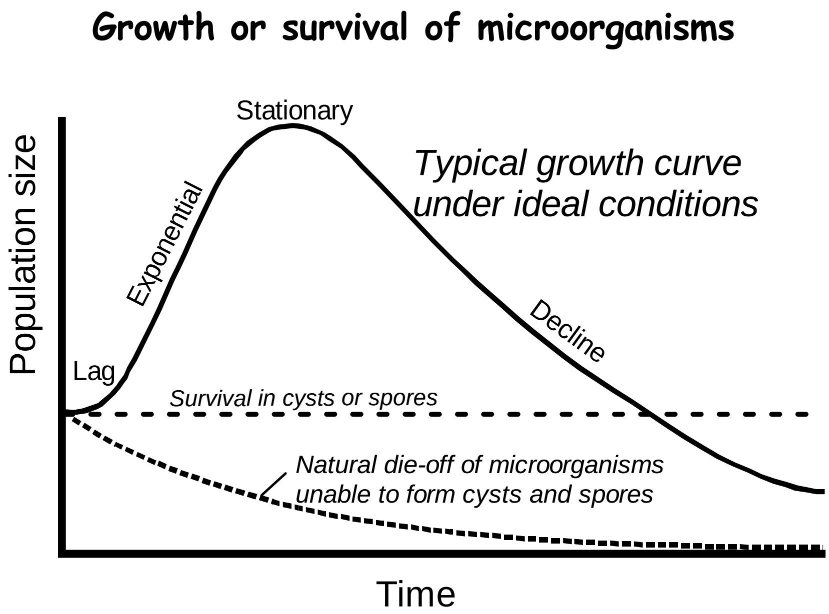

Figure 2.6. Schematic microbial population growth curves under different conditions.

Once microorganisms have entered the soil at the primary pollution source a wide variety of factors affect their ability to survive long enough to enter groundwater and hence pose a health risk to humans who use the water. Some of these factors are illustrated in Figure 2.7.

Cysts are specialised microbial cells enclosed in a wall and their formation is a stage in the life cycle of some microorganisms. These cysts can also form in response to adverse conditions allowing the microorganism to survive for long periods (sometimes many months). Spores of some microorganisms can also survive for long periods. Nutrient availability to microorganisms that are metabolically active like bacteria can also play an important role.

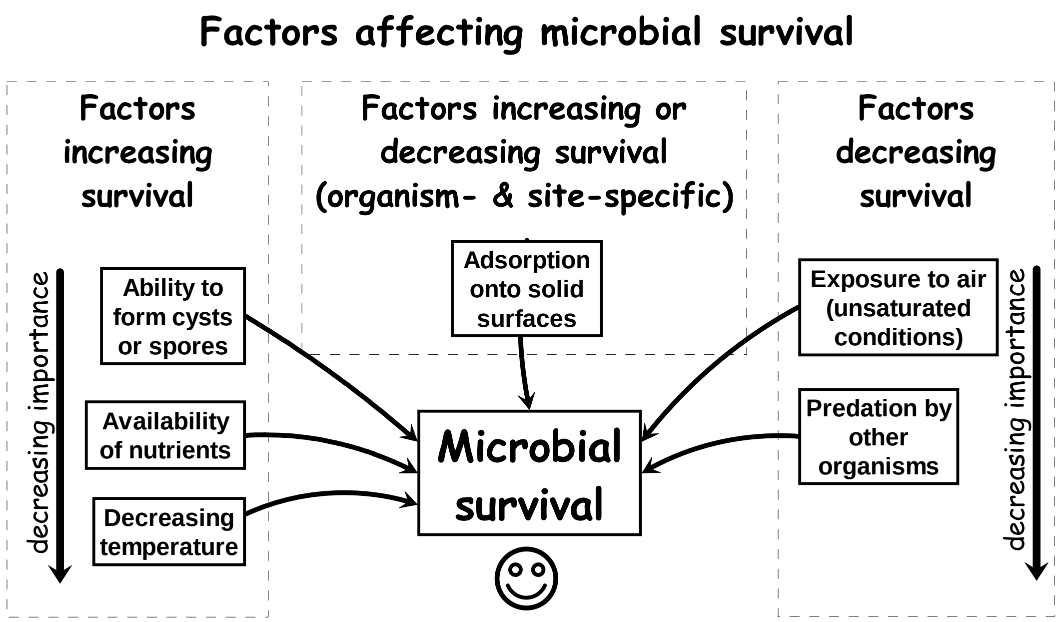

Figure 2.7. Factors affecting the survival of microorganisms in soil and groundwater.

The adsorption of microorganisms to solid particles in the soil can increase or decrease the survival rates, depending on the nature of the particles and the microorganisms. Usually (but not always) the survival of viruses tends to be increased by adsorption.

The oxidising conditions typically associated with the unsaturated (vadose) zone are usually unsuitable for microorganisms. However, the sensitivity to this factor is highly dependent on the type of microorganism.

On the whole, the survival of microorganisms in soils and groundwater is a function of many factors: physical, chemical, microscopic and macroscopic. This means that it is almost impossible to make simple general statements about the likely degree of microbial pollution of groundwater [Fourie and van Ryneveld, 1995]. The situation is highly site-specific and organism-specific.

2.3.4 Movement of microorganisms

Groundwater contamination occurs more readily in unconfined coarse alluvial aquifers than in less porous environments. In the latter cases, contamination on the surface is more likely to result in polluted surface runoff.

Movement of microorganisms through soils and aquifers is primarily facilitated by water flow. Without water, there is likely to be little or no movement. Furthermore, to reach the groundwater, movement through the unsaturated (vadose) zone is necessary. High recharge rates create pressure gradients that increase water flow and hence movement of microorganisms.

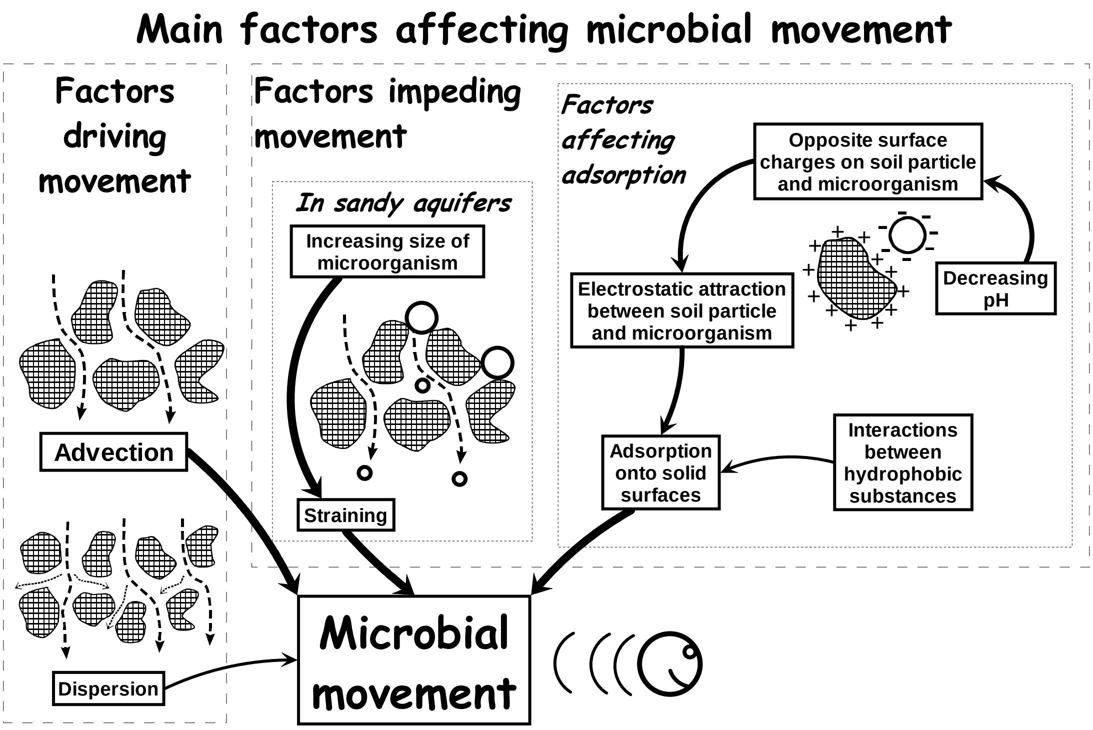

Figure 2.8. Illustration of main factors driving and impeding the movement of microorganisms in soils and groundwater.

Advection, or the mass movement of water through the soil or aquifer, is the primary mechanism transporting microorganisms from one place to another. Dispersion in lateral directions can also occur if the medium through which the water is passing is porous. Figure 2.8 illustrates these two factors and others that impede the movement of microorganisms.

An important mechanism that impedes the flow of microorganisms is the physical blocking (filtering) of larger organisms simply because they are too large to pass through the interstices of the soil or aquifer. Figure 2.9 illustrates the approximate relative sizes of the three groups of microorganisms of relevance. All other things being equal (*i.e.* constant), this filtration factor suggests that viruses are likely to be a greater pollution threat in groundwater than the other types of microorganisms.

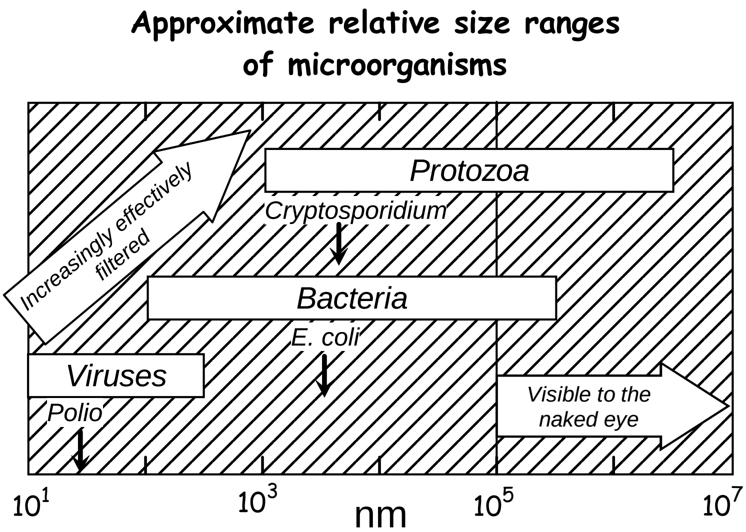

Figure 2.9. Approximate relative sizes (nm) of microorganisms.

In essence, to pollute groundwater, microorganisms need to reach the groundwater in a viable state. How long this takes depends on conditions along the route to the aquifer and on the type of aquifer. The longer it takes, the less likely the microorganism is to remain viable and hence ultimately pose a risk to human health.

Depending on conditions in the unsaturated zone
***i.e.* soil properties**
(such as permeability, moisture content and temperature),
depth to saturated zone,
and the driving force for water movement
(*e.g.* rainfall intensity and duration),
the time it takes for microorganisms to move
from the surface to the saturated zone
can vary from hours to decades
(*i.e.* over four orders of magnitude).

Adsorption is a complicated mechanism mainly driven by the relative electrical charges on the surfaces of the microorganism and the soil particles. The larger the difference (*i.e.* the more positive the one is and the more negative the other) the greater the electrostatic attraction between them. The most important factor affecting this is the pH of the water. Generally, the lower the pH, the greater the proton (H^+) concentration and hence the greater the likelihood of protonation of surfaces (*i.e.* the binding of these protons to surface functional groups). However, different surfaces (*e.g.* those of large organic molecules like humic substances, solid phases like clays or oxides, or the microorganisms themselves) protonate to different extents. Therefore the different surfaces generate different surface charges.

2.4 IMPACTS

Microbial pollution of groundwater may pose a health risk to humans who may use the water for a variety of purposes. As with surface water [DWAF, 2002a], sensitive water uses may include the following:

- Drinking untreated water;
- Drinking partially treated water;
- Partial or full contact; and
- Irrigation of crops that are eaten raw.

Groundwater known to be polluted will need to be treated before use. Costs for corrective action can have significant economic impacts.

The health risks range from asymptomatic infections to mild diarrhoea, to severe disorders requiring a doctor's care or hospitalisation, to death. Those most at risk are the young, the elderly, pregnant woman, the immunocompromised, those predisposed with other illnesses and those with a chemical dependency [Schijven, 2001].

The spread of waterborne diseases impacts socially and economically. Morbidity rates increase that in turn decrease productivity and increase medical treatment costs.

CHAPTER 3: NATIONAL IMPLEMENTATION

This chapter should be used primarily by the National Coordinator for overall guidance on the implementation process of the NMMP at a national level.

3.1 NATIONAL OBJECTIVES

3.1.1 The objectives defined

The National Microbial Monitoring programme for groundwater is primarily an initiative (and the responsibility) of the Department of Water Affairs and Forestry (DWAF). It is a "status and trends" monitoring programme, the design of which is described in this manual.

See National Water Act No 36 of 1998 Chapter 14 Section 137.

The most generic expression of the highest level national management needs is provided by the National Water Act No. 36 of 1998. At a national level, government departments such as DWAF or DEAT need to have a national picture of the degree to which microbial pollution is a problem and how this is changing over time. It is the creation of this national picture that ultimately makes this a national programme.

More specifically, microbial monitoring addresses certain aspects of the "information management" function of water resource management. This is described as "managing the monitoring, collection, storage and assessment of water resources, social, economic and institutional data and information required, as a support to the other water resource management functions" [DWAF 2001b]. These other functions include policy and strategy, water use regulation, physical implementation, institutional support and auditing.

The policy and strategy for groundwater quality management in South Africa specifically refers to the need for a national information programme [Section 6.8, DWAF, 2000b]. In the specific context of microbial monitoring, the NMMP for groundwater has the following objectives.

National Microbial Monitoring Programme for Groundwater
DWAF National Objectives

To measure, assess and report on a regular basis
the status and trends
of the microbial water quality
that reflects the degree of faecal pollution
(because of the associated human health risks)
of South African groundwater resources
in a manner that is
soundly scientific and
that will support strategic management decisions
in the context of sustainable fitness for use of those water resources.

The objectives of a monitoring programme define the reasons for the existence of that programme. They provide the primary statement by which the success of the monitoring programme will ultimately be assessed.

3.1.2 The objectives described

It is important that the objectives are clearly understood because they will affect decisions made during initialisation and execution of the programme. To ensure a common understanding of the objectives, the meaning of the various terms are summarised as follows.

Measure: This means “perform an experimental measurement of some property of the water resource”. In the current context this property is, for example, the concentration of *E. coli*. Such measurements will comprise the raw data of the monitoring programme.

Assess: This means “add value to the raw data by providing information based on that raw data and perhaps specific knowledge relating to the source or other site-specific issues”. A common and simple mechanism of assessment of monitoring data is comparison of a measurement with a guideline value (if one exists). Such guidelines are typically specific to the nature of the intended water use.

Report: Monitoring data must never be collected simply for the sake of having data. Data, and their assessment, must always be reported to well-defined target users in an appropriate format.

On a regular basis: Monitoring is not a once-off activity. The measurements, assessments and reporting should be done at regular intervals, or at intervals determined by the target users. In the current context, the temporal scale for reporting is annual. This means that reports must be prepared and submitted annually to the target users. These reports are usually based on data collected at an appropriate frequency.

Status: This refers to the current situation relating to the nature and extent of the problem. Since the temporal scale is annual, this refers to the current year.

Trends: These are the statistically significant changes in the status from one reporting period (*i.e.* year) to the next, or shorter period if necessary, to meet the monitoring objectives.

Microbial water quality that reflects the degree of faecal pollution: Groundwater contains natural-occurring (autochthonous) microorganisms. However, the focus of this monitoring programme is the microorganisms of faecal origin (human and animals) that are introduced into groundwater resources. This programme is therefore concerned with introduced microorganisms, not indigenous microorganisms or other microbial aspects of groundwater quality.

Because of the associated human health risks: This phrase specifically defines the reasons why water resource managers need to know about faecal pollution and thus one of the contexts in which management decisions will be required.

Of South African groundwater resources: In principle, all groundwater resources in South Africa are included in this national programme. However, it is likely that a phased implementation of the programme will occur that will focus initially on areas of particular concern. These would typically include areas where there are significant faecal pollution sources, vulnerable aquifers and strategically-important groundwater use, particularly when used for drinking purposes.

In a manner that is soundly scientific: It is essential that the monitoring is based on sound science. Furthermore, it should not be compromised when the conflicting constraints of financial and capacity limitations arise. If the “scientifically ideal” monitoring design cannot be achieved, this must simply be reflected in the reported assessment (unless the data are obviously completely inadequate). For example, less data may mean information is more uncertain. As long as this increased uncertainty is properly reported, the user of the information is still in a position to make an informed decision, albeit with greater risk.

In respect of implementation of the programme, “scientific” means not deviating from the design. However, tasks like choosing sampling sites, variables and monitoring frequency and, in particular, assessing the data will require decisions to be made before and during implementation over which this design manual can only provide general guidance. It is at these times that special care should be exercised that decisions are made that are absolutely defensible in terms of scientific observation. As a check, it may be useful to imagine that the decision might need to be defended in court.

Support strategic management decisions: The ultimate objective of the monitoring is to allow informed decision making by those responsible for management of water resources. Strategic decisions are regarded here as those that are large in scale, both spatially and temporally. A large spatial scale refers to regional (water management area) and national scales. A large temporal scale refers to decisions that have implications over periods of a year or more.

In the context of sustainable fitness for use of those water resources: Water quality management functions mainly in the context of resource directed measures, *i.e.* management actions directed at the water resources themselves. These include classification of resources, setting the reserve and ultimately setting resource quality objectives. These are tools intended for the management of those water resources in a way that achieves sustainable fitness for use, whatever the use might be. *In essence, the core monitoring objective is ultimately to support this overarching management objective.*

3.2 IMPLEMENTATION ISSUES

3.2.1 Introduction

A process with well-defined actions for national implementation is defined later in this chapter (section National Implementation Process). However, there are many generic issues that have to be borne in mind during this process. This section describes these issues. They should be especially carefully considered and implemented by the person acting as the National Coordinator of the NMMP for groundwater.

3.2.2 Responsibilities

As noted above, the NMMP for groundwater (more specifically, meeting the above-stated national objectives) is the responsibility of the Department. However, regional operation and maintenance of the programme in Water Management Areas is likely to be performed by the Catchment Management Agencies (CMAs), acting as agents for the Department. Non-DWAF and non-CMA organisations may also be sub-contracted to perform specific tasks like sampling, sample transport, analysis and so on. Departments like Department of Environmental Affairs and Tourism (DEAT) and Department of Health (DoH) are likely to have significant interest in this monitoring programme and may well be able to contribute resources for its execution. A more detailed description of roles and responsibilities can be found in the Roles and Responsibilities chapter.

3.2.3 Balancing bottom-up and top-down management

Similar to the River Health Programme, the successful implementation of the NMMP for groundwater will involve a careful combination of bottom-up and top-down approaches [Murray, 1999]. The top-down approach will have its basis in the current legislation and the creation of an infrastructure to implement national information systems. The bottom-up approach involves identifying those regional and local concerned parties who will themselves benefit from involvement in the NMMP for groundwater.

It is very likely that prior to the formal establishment of fully-functioning Catchment Management Agencies that a bottom-up approach will be more applicable. Thereafter, the approach may gradually become more top-down, but probably never exclusively so.

3.2.4 Anticipating the problems

It is important that the implementation of the NMMP for groundwater learn from the experiences of other national monitoring programmes. An obvious one is the NMMP for surface water [DWAF, 2002a]. The National Coordinator of that programme should be consulted and problems encountered and methods by which they were solved should be discussed.

The River Health Programme (RHP) encountered a number of problems in its endeavours at implementation on a national basis [Murray, 1999]. Although fundamentally more complex than the NMMP for groundwater, it is appropriate to take note of those problems and ensure that the implementation strategy of the NMMP is able to avoid or minimise them as much as possible.

At the highest level, lack of accountability and resource constraints were the two main driving forces of ineffective implementation in the early stages.

- Lack of accountability involved (1) a lack of clarity on responsibility for implementation, (2) the non-statutory status of the RHP and (3) the lack of support from superiors (especially in government departments). The lack of accountability tends to be associated with an inability to apply (or inappropriateness of) a top-down approach to implementation. With the advent of CMAs funded through water charges, this approach is likely to become more appropriate and therefore less problematic.

- Resource constraints entailed (1) the high cost of consultants, (2) the lack of trained personnel and (3) time constraints. The NMMP can deal with the resource-related problems in the following ways. First, a tool is available from Directorate: Resource Quality Services (DWAF) that allows costing of local, regional and national monitoring programmes. So the costs (human resource, capital and operating) can be quantified up front. Monitoring and analysis methods are kept as simple and as cheap as possible (without sacrificing scientific integrity). This means that the required expertise, and hence training requirements, are minimised. Simple sampling and analytical methods also minimise the time requirements.

3.2.5 National coordination

A person within the Department must be formally assigned the role of National Coordinator. (See Roles and Responsibilities chapter for more information.)

The primary role of the National Coordinator is to facilitate the nationwide implementation of the NMMP so that the national objectives are achieved. The National Coordinator will need to be familiar with all aspects of microbial monitoring in groundwater and should be able to provide technical and managerial advice to the various role players. The National Coordinator must also ensure effective and efficient transfer of knowledge and experience gained by those already involved in the programme. The National Coordinator should be the driving force behind initial and ongoing implementation on a national basis.

The National Coordinator should play a hands-on management role. A significant commitment is required from the National Coordinator (and therefore that person's superiors). The National Coordinator should be a 'doer' not a 'delegator'. In this way, the work of the National Coordinator will achieve more depth. National coordination is then likely to be more consistent and efficient since the execution of tasks will be less fragmented, because they are being done primarily by a single person.

To ensure sustainability of the programme an assistant National Coordinator must also be appointed. This person should work closely with the National Coordinator and be sufficiently involved to ensure that he/she can immediately take over national coordination in the event of the absence or resignation of the National Coordinator. Given the relatively high turnover of staff in DWAF, the importance of this issue should not be underestimated.

3.2.6 Demonstrating early successes

The River Health Programme has implemented a so-called 'Demonstration-for-Resource Allocation Spiral' model (Figure 3.1). A similar approach should be adopted for the NMMP for groundwater, particularly when a bottom-up approach is deemed more appropriate.

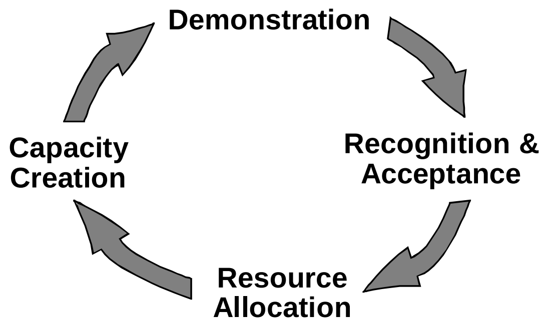

Figure 3.1. The "Demonstration-for-Resource Allocation Spiral" model [Roux, 1997].

In the case of the RHP, small-scale demonstration of the role of biomonitoring in water resource assessment and management led to recognition of its usefulness. This recognition, and the acceptance of a need for the technology, resulted in the further allocation of resources (financial and human). Basically, this approach assumes that demonstrating good results leads to increased support.

Initially, the National Coordinator should choose a few Water Management Areas (WMAs) that can be used to demonstrate the usefulness of microbial monitoring to other WMAs. However, a failed attempt could have very negative consequences and delay ultimate implementation significantly. Therefore, the NMMP must endeavour to ‘get it right first time’. Accordingly, these initial areas must be carefully chosen. A prioritisation process is given below for the initialisation phase of the project.

3.2.7 Creating awareness

Generic mechanisms (applicable nationwide) must be identified for conveying information on the NMMP to all interested parties.

One mechanism is the development and regular updating of a web site specifically focussed on the NNMP for groundwater. This should contain information that deals with the following kinds of issues.

- Demonstrating the usefulness of the NMMP to encourage recognition and acceptance (*i.e.* applying the ’Demonstration-for-Resource Allocation Spiral’ model for implementation).
- Enabling potentially interested parties to identify whether they can benefit from the programme.
- Keeping readers up to date with implementation progress (*e.g.* what areas are currently included).
- Educating stakeholders about the causes and impacts of faecal pollution of groundwater.
- Describing how one becomes involved in the national programme.
- Educating water users how to avoid causing faecal pollution of groundwater.

3.2.8 Creating capacity

Monitoring microbial pollution in groundwater requires special skills. These skills not only involve sampling but also establishing the attenuation zone down-gradient of a faecal pollution source (see the Establishing the Attenuation Zone section in the Monitoring framework chapter). It will be important to ensure that sufficient capacity (of appropriate quality) is created in South Africa to meet the needs of the national programme.

The National Coordinator should oversee the design and implementation of all training courses and on-going development of appropriate documentation that ensures standardisation and use of current best practice throughout all Water Management Areas.

The rate at which new capacity needs to be created in South Africa will depend on strategic decisions made by DWAF senior management. In particular, the rate at which the NMMP for groundwater should be implemented (*i.e.* the number of new areas contributing to the NMMP each year), will be a critical determining factor.

3.2.9 Sustaining commitment

It is proposed that a 'contractual win-win reward' model be implemented in order to create and sustain an appropriate culture of commitment to the NMMP for groundwater, particularly among the samplers. (More detail in this respect can be found in the research report associated with the National Eutrophication Monitoring Programme implementation manual [DWAF, 2002b]). This model has three primary components.

1. *Formal contracts with local agents*.

   a. For non-DWAF and non-CMA agents, this should be a binding contract in which the tasks to be performed are well-defined, including when, where and how they should be performed. Direct financial payments are then made on completion of the tasks.

   b. For DWAF/CMA employees, these contracts should take the form of formal, clear modifications to their job descriptions (in the form of key performance areas).

   c. The purpose of contractual agreements is to ensure, as far as is possible, that neither party (DWAF/CMA or the local agent) can unilaterally change the conditions of the contract. This ensures that local agents cannot simply change or terminate their involvement in the NMMP without negotiation when their local priorities change.

2. *'Win-win' for DWAF/CMA and local agents*. Local agents should be chosen who themselves see direct or at least indirect benefits from involvement in the programme. That is, they must be local stakeholders with a vested interest in the microbial water quality of the groundwater resource, for example either polluters or users. This further minimises the likelihood of a local agent not fulfilling the conditions of the contract.

3. *Reward commitment*. A system should be considered that rewards significant commitment to sampling and creates a culture of commitment. This supplements the 'win-win' situation by further encouraging sound and frequent sampling.

3.2.10 Future research needs

All water quality monitoring programmes require regular revision. One aspect that can lead to changes in design is insight gained by relevant research. Such research should be encouraged and preferably coordinated with the express purpose of improving the NMMP design and making the information it produces more useful. This manual, in particular, should be seen as simply providing the NMMP with a kick-start. As problems and new knowledge emerge, these should be dealt with and used in ways that ensure that the national objectives are still met.

The complexity of causes, impacts and behaviour of groundwater microbial pollution will inevitably necessitate research and development that focuses on better monitoring design. This may include other indicators of microbial pollution and improved sampling and analytical methods and so on.

3.2.11 Implementation timetable

The NMMP for surface water was implemented in a phased way in which a certain number of new local programmes were implemented annually. It is proposed that the NMMP for groundwater follow a similar approach.

A feasible number of new aquifers should be chosen by the National Coordinator for inclusion every year. This number will depend largely on internal DWAF resources allocated to the NMMP. The National Coordinator should also decide what period of time is appropriate to achieve the ultimate aim of including all priority aquifers in South Africa in the NMMP.

Given the numerous other priorities of the Department and the many unknowns in respect of the NMMP itself (and, indeed, the Department) it is inappropriate that this document prescribe a detailed timetable at this time.

3.3 PRIORITISATION PROCESS

The selection of the most appropriate monitoring areas in the initialisation phase of the national monitoring programme should be driven primarily by the need to ensure that monitoring successes can be demonstrated as soon as possible. A number of factors determine this (Figure 3.2).

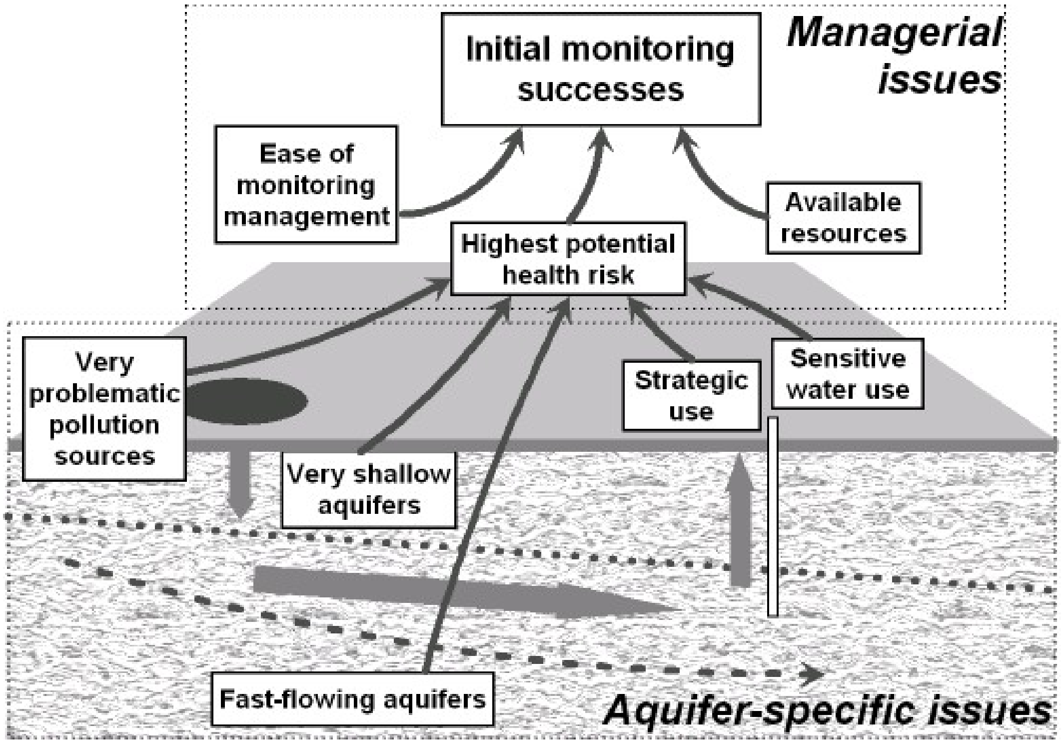

Figure 3.2. Optimum factors determining monitoring successes in the initialisation phase.

The process that follows (depicted in Figure 3.3) can be used for the selection of the most appropriate monitoring areas. For more detail on the rationale behind this process, see the Research Report [Murray *et al.*, 2004a] associated with this manual.

3.3.1 STEP 1: Identify regions of possible concern

- **Identify regions with important strategic groundwater use**: Use the groundwater classification map [Parsons and Conrad, 1998] and the information in Usher *et al.* (2004) to identify general regions of possible concern. In particular, focus on regions containing sole source aquifers and special aquifers as these both suggest a strategically important groundwater use. Particular emphasis should be given to regions in which high numbers of water users are likely to be present.

- **Identify regions with vulnerable aquifers and problematic land uses**: Using the map showing groundwater vulnerability to faecal contamination [DWAF, 2000a], determine whether the above aquifers occur in regions of medium or especially high vulnerability to faecal contamination. If they do, then the region potentially has problematic land uses, strategically important groundwater uses, possibly high numbers of users and vulnerable aquifers. This combination suggests a possibility of human health risk.

3.3.2 STEP 2: Confirm local cause for concern

The broad scale of the above maps does not necessarily mean that the problematic land uses are actually close enough to the points of groundwater use to contaminate, or potentially contaminate, the groundwater being used. It is precisely this aspect that the authors of the classification and vulnerability maps [Parsons and Conrad, 1998] warned against. Accordingly, having identified a region in which a health risk may occur, it is now imperative to establish whether there is actually cause for concern. This can typically only be established using local knowledge.

The following steps should be carried out:

3.3.2.1 Identify potential hazard

Establish the exact location of problematic land uses, whether they are inadequately managed, and therefore whether they are significant faecal pollution hazards.

Usher *et al.* (2004) also prioritise a number of regions and cities in South Africa in terms of sources of contaminants. Zaporozec (2002) contains a summary of sources of groundwater contamination (chemical and faecal) as well as methods for rating such sources.

A number of land uses have been classified into expected low, medium and high impact categories in the context of Resource Directed Measures [DWAF, 1999] (see Table 3.1). This can also be used as a simple guide to the likelihood of significant faecal pollution.

Table 3.1. Land use categories potentially causing faecal pollution of groundwater [adapted from DWAF, 1999].

Expected impact	Land use
High	Urban area Sewage works - large (> 20 ML/day)
Medium	Sewage works - small and medium (< 20 ML/day) Rural areas - high population density
Low	Rural area - farms Rural area - low population density Kraals

These documents can be used as a general checklist of pollution sources that should be borne in mind in this task.

It does not fall within the mandate of national monitoring to monitor the impacts of very small individual faecal pollution sources (single pit latrines, for example). These, by definition, are unlikely to have significant impacts on an aquifer as a whole. On the other hand, high concentrations of small pollution sources, like an informal settlement with inadequate sanitation, or single large point sources like sewage works may have significant impacts on an aquifer.

3.3.2.2 Identify points-of-use

Establish the location of the sole source or special aquifer and exactly where the groundwater is being abstracted for local use.

3.3.2.3 Establish potential risk

Establish whether this groundwater is in a position to be contaminated by faecal pollution from the identified problematic land uses (*i.e.* is it down-gradient, in the flow path and reasonably close to a pollution source?).

The vulnerability of the local aquifer to pollution in general must also be taken into account. For example, aquifers with a high water table would rate more highly for inclusion than deeper aquifers. A confined aquifer is of less concern unless the pollution source is located in the recharge zone. The degree to which the groundwater is, or will be, used must also be taken into account.

3.3.3 STEP 3: Consider managerial issues affecting success

Should the local situation be such that a human health risk is probable, then consideration should be given to the following:

- The internal (DWAF) and potential external resources available for groundwater monitoring in that local area.
- The willingness of local stakeholders to contribute to the monitoring.
- Any other issue that affects the general likelihood of successful monitoring in that area.

These factors and the appropriateness of the specific local areas should all be considered simultaneously with the ultimate objective of ensuring a successful monitoring programme in the area.

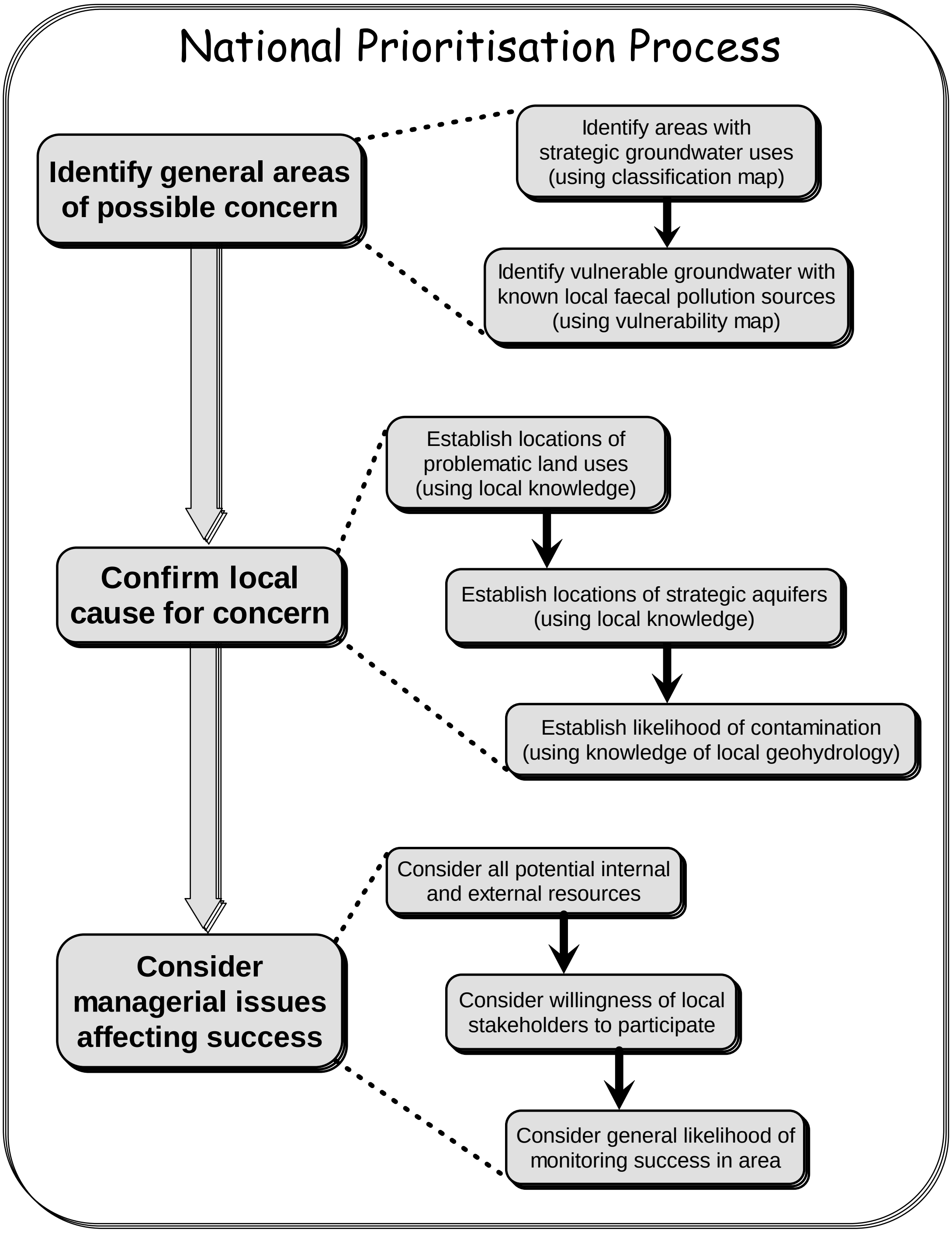

Figure 3.3. Prioritisation process for the initialisation period.

3.4 NATIONAL IMPLEMENTATION PROCESS

3.4.1 Overview

A "national implementation process" is that series of actions required to set up and sustain a successful national monitoring programme throughout South Africa. Figure 3.4 shows the steps in the process. It assumes a national coordinator has been appointed. The sections that follow refer to this figure and give details of the individual steps.

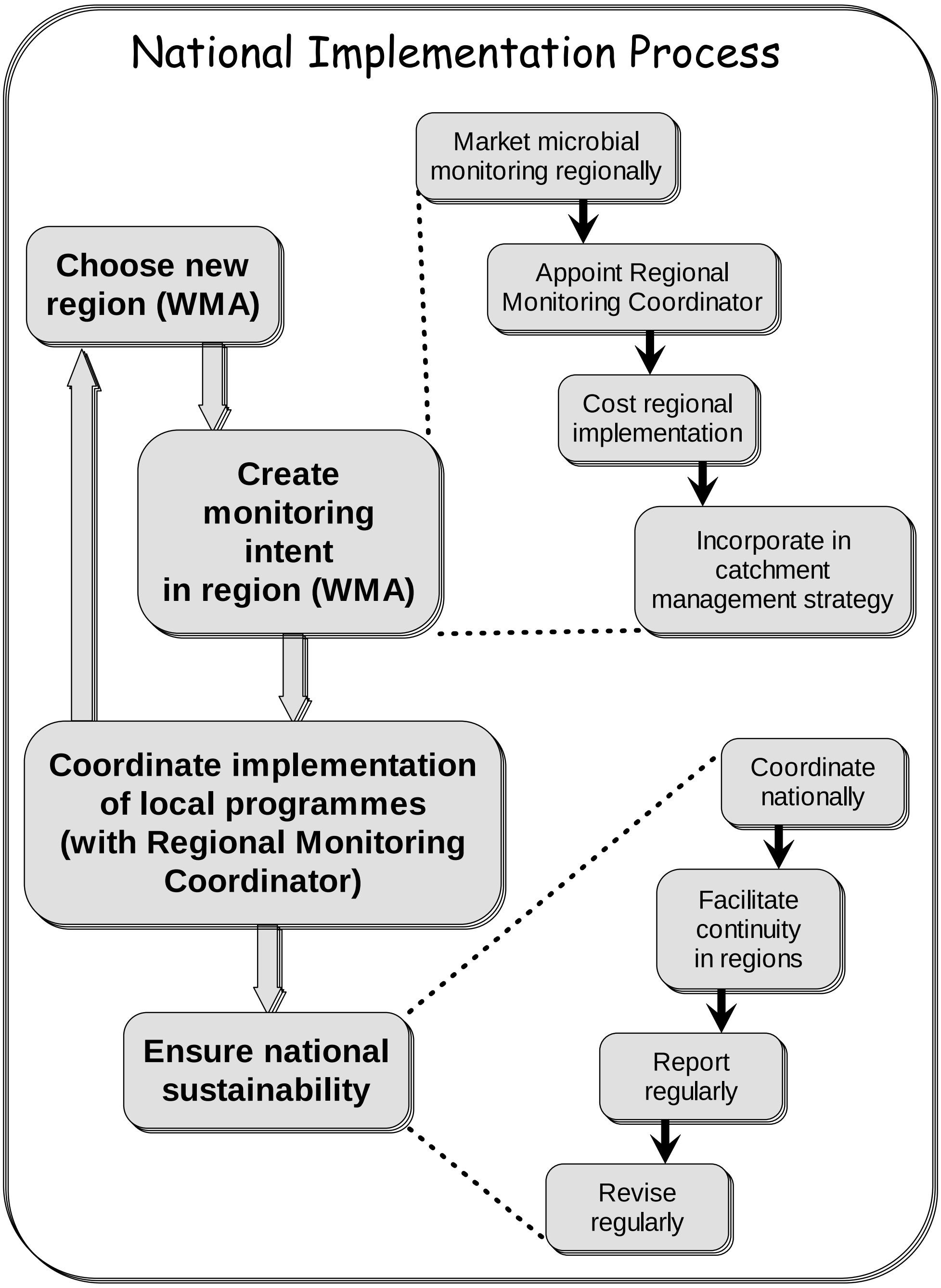

Figure 3.4. Summary of tasks in the national implementation process.

3.4.2 Choose new area (WMA)

The number of regions (Water Management Areas) should be increased in a phased manner, until ideally all 19 areas and their aquifers are contributing to the national programme. Experience will dictate the practical rate at which regions can be included. Targets should be set by the National Coordinator for the number of regions included in five and ten year's time. The rate of inclusion should increase in later years as experience increases efficiency.

Initially, regions should be chosen in which a significant health risk is likely to exist and yet where there is a good chance of successful implementation of the NMMP for groundwater. The prioritisation process above should be used to choose areas during the initialisation phase. However, in subsequent years this emphasis on ‘priority areas’ can be balanced with other factors that ultimately ensure the long term objective of adequate national coverage is achieved.

For example, pristine catchments may ultimately also be included. Although these may not have specific local anthropogenic pollution sources, the recharge zone may, for example, be traversed by a watercourse from a nearby catchment that may be polluted. In the current context, the recharge zone of the aquifer can be regarded as the potential pollution source, although, by its very nature, it may be unlikely to have a high impact. Recharge zones may cover very large areas. In this case they should be treated as diffuse sources. In cases where recharge occurs in more localised “preferential recharge zones”, these should be treated more like point sources.

The monitoring programme’s objectives refer to “South African groundwater resources”. This is an all-encompassing term. The basic criterion in the current context for distinguishing between groundwater resources is whether the water quality of one unit can influence the water quality of another (assuming water quality variables that behave conservatively). If this can occur, then these could be regarded as a single unit for monitoring purposes. If it cannot occur, then they should be regarded as independent and treated as such in the monitoring.

3.4.3 Create monitoring intent in region (WMA)

3.4.3.1 Market microbial monitoring regionally

Groundwater monitoring does already exist in some areas. In such cases, there already exists some degree of monitoring intent and therefore marketing of the NMMP for groundwater should focus less on initialising monitoring and more on coordinating existing efforts.

The National Coordinator should visit the DWAF regional offices or CMAs responsible for the chosen WMA. The primary purposes are to make them aware of the NMMP for groundwater and create an intent to become involved (if no monitoring exists). They should at least be given a copy of this implementation manual.

They should also be told the reasons why their WMA was chosen. A general introduction to the causes and effects of microbial pollution of groundwater should be given (if necessary).

3.4.3.2 Appoint Regional Monitoring Coordinator

A single person in the region should be appointed as the Regional Monitoring Coordinator. This person would ideally be from the DWAF regional office (prior to CMAs) or a member of the CMA (if one exists). An Assistant Regional Monitoring Coordinator should also be appointed to ensure continuity during any absence of the Regional Monitoring Coordinator.

The primary tasks of this person include managing the regional implementation process. This person will also be responsible for day-to-day management of the programme subsequently (*i.e.* once up and running).

3.4.3.3 Cost regional implementation

If there are any doubts regarding potential costs, the National Coordinator should collaborate with the Regional Monitoring Coordinator and use the implementation costing model to obtain rough cost estimates for implementation in the region.

3.4.3.4 Incorporate in catchment management strategy

It is important that faecal pollution management strategies be included in the overall catchment management strategy of the (current or future) CMA. The National Coordinator should work closely with the Regional Monitoring Coordinator to ensure this happens. Management strategies of other existing regions can be adapted to suit the current region. A DWAF report is available that provides guidelines for developing the water quality management component of a catchment management strategy [DWAF 2001a.]

The costing estimates can be used to ensure that microbial monitoring is included in the following year's budget.

3.4.4 Coordinate implementation

The Regional Monitoring Coordinator should work closely with the National Coordinator in coordinating initial implementation. Lessons learned from other regions should be carefully considered and problems anticipated and avoided.

Training programmes should be carried out and appropriate laboratories (preferably accredited) and samplers identified.

3.4.5 Ensure national sustainability

3.4.5.1 Coordinate nationally

The National Coordinator should address all the issues described above (see section Implementation Issues in this chapter). The 'coordination' role has two primary aims. The first aim is to enthusiastically drive the NMMP at all levels. This will be primarily at national level. The second aim is to ensure a sufficient degree of standardisation among programmes so that the national objectives are met. Coordination should include obtaining funding, quality assurance and quality control activities.

3.4.5.2 Facilitate continuity in regions

Monitoring programmes should be designed to be as self-sustainable as possible. However, in the initial years, active engagement by the Regional Monitoring Coordinator is likely to be significant. This means that there is likely to be a significant reliance on the Regional Monitoring Coordinator initially. Therefore, a sudden resignation (for example) of a Regional Monitoring Coordinator may have serious consequences for the continuity. The National Coordinator must ensure that in such a case, continuity is maintained. This could be achieved by the early appointment of an Assistant Regional Monitoring Coordinator.

3.4.5.3 Report regularly

Information contained in any national monitoring system established in terms of the Water Act must be made available, subject to any limitations by law. Raw data can be made available via access to Water Management System (WMS) at Directorate: Resource Quality Services. Information can be made available in the form of the annual reports. These reports should be presented in a format appropriate to the requirements of the intended users.

3.4.5.4 Revise regularly

Best practices, technologies, objectives and relative priorities change all the time. It is an essential component of any monitoring programme that the overall programme be carefully revised from time to time. The actual time between revisions can be left to the discretion of the National Coordinator. However, a period of three years is recommended initially.

The revision should be fundamental and consider the appropriateness of all aspects of the monitoring programme design, including the following:

- *Extent to which objectives are actually being achieved*. This is the most important issue. In particular, the main target users of the reports being produced by the programme should be consulted. It should be established whether they perceive true usefulness. If not, suggestions should be elicited regarding what they would like to see in future.
- *Objectives of the programme*. If no longer entirely relevant, they should be changed to ensure that they are properly aligned within the water resource management context of the time.
- *Monitoring variables*. New research, either local or international, may suggest variables with improved characteristics that allow the objectives of the programmes to be achieved either more accurately, more efficiently or more cost-effectively.
- *Monitoring frequency*. Decreasing the monitoring frequency in some areas without significant loss of information may lead to significant cost saving. On the other hand, frequencies may need to be increased in areas in which data objectives are not being met.
- *Analytical and sample preparation techniques*. New analytical techniques may be able to deliver results cheaper or even allow for relaxation of the 24 hour logistical problem for sample delivery.
- *Data management protocols*. The efficiency with which the monitoring data are transmitted, stored and retrieved for reporting purposes should be assessed. Improvements should be implemented where necessary.

- *Quality assurance and quality control methods*. These methods need to be carefully examined to ensure that the monitoring data is of an appropriate quality and that all quality assurance activities are appropriately focused on the real requirements of the programme.
- *Assessment and reporting protocols*. New methods of conveying the results of the monitoring programme in more appropriate ways to the intended target audience should always be considered.

CHAPTER 4: MONITORING FRAMEWORK

This chapter should be used by the National Coordinator and Regional Monitoring Coordinator for designing detailed local monitoring programmes and for providing procedure specifications to other role players.

4.1 INTRODUCTION

A monitoring programme must be designed to address well-defined objectives (see the National Implementation chapter for the objectives of this programme). In so doing, finding a balance between the best scientific and ecological approach and available resources is inevitable. In some contexts (like deciding precisely where to locate a monitoring borehole), this implementation manual can give little more than a framework and general guidelines. In other contexts, it is more prescriptive (*e.g.* concerning the monitoring variables and analytical methods to be used). This chapter also describes a few generic factors in monitoring design that need to be considered, irrespective of the precise objective.

It is important that all monitoring procedures be as standard as possible if comparable results are to be obtained for different Water Management Areas. If the procedures in this chapter are not adhered to, interpretation of the results may be seriously compromised.

4.2 GENERIC DESIGN CONSIDERATIONS

4.2.1 Introduction

Irrespective of the precise management objective, there are many aspects of monitoring system design that are entirely generic. The following sections summarise these aspects. They should be thoroughly considered before proceeding to a design for any specific management objective.

4.2.2 Overlap with existing programmes

Potential overlap with other monitoring programmes must be considered in some detail. Existing programmes may already be collecting samples in the area of interest. Given the high costs of sampling (compared to all other costs associated with a national or regional monitoring programme), being able to ‘piggyback’ on other sampling rounds (and even sharing the costs) will contribute to significant savings. This may even allow extra sampling sites to be chosen beyond those that would have been possible if piggybacking was not done.

Notwithstanding the enormous cost-saving advantages of such piggybacking, the precise design of the other monitoring programme must be examined in detail. It must conform sufficiently well to the design contained within this manual in all aspects from sampling and analytical methods through to monitoring frequency, site selection and quality control. A loss of standardisation in monitoring design can have significant implications for the subsequent interpretation of data. If any loss of information is anticipated through use of an external monitoring programme, this must be clearly defined, the ramifications understood and made clear to all concerned.

4.2.3 Borehole site selection

The location and number of sampling sites is always a critical aspect in the design of a monitoring system. The following are some general factors that influence the choice of sites. The factors more specific to the current design are discussed later in this chapter (see Section 4.4.4).

- *Available resources*. Available resources are the most important factors affecting the number of sampling sites and their precise locations. Before proceeding with the selection of individual sites in a Water Management Area, perform a preliminary costing exercise. Establish the approximate number of sampling sites that can be reasonably managed with the available resources. Then proceed to consider the other factors determining site selection.

- *Health and safety*. The health and safety of people monitoring and sampling should be carefully considered. If there is any potential danger from wild animals, local people, or any local hazard (like steep slopes), appropriate steps should be taken to minimise or avoid the risk, including choosing another sampling site (if appropriate).

- *Site accessibility*. The site should be easily accessible to the person taking the sample. Valuable time and resources are wasted if this is not the case. Sampling is an expensive item in an overall monitoring programme. Considerable attention should be given to making it as efficient as possible.

- *Spatial correlation*. Ideally, spatial correlation should not occur between samples taken at different sites. This means that a sample at one site should not vary in composition in a way that can be predicted from the composition of a sample taken at some nearby sampling site. If correlation occurs, then resources are being wasted because the second sampling site is not providing information that cannot be obtained from the first site. This factor should be particularly carefully considered in the current context when the faecal pollution is diffuse.

4.2.4 Monitoring frequency

Determining the optimum monitoring frequency requires consideration of a number of factors.

- *Costs*. It is important that frequency be balanced against the associated costs. If the required resources preclude frequent monitoring, then less frequent monitoring can be adopted. However, the manager must realise that the decreased information content may contain inherent risks. For example, short-lived impacts (that come and go between sampling rounds) may not be detected. The consequences of this must be considered and explicitly accepted.

- *Serial correlation*. If observations are taken close enough in time, the observations may exhibit serial correlation (*i.e.* be closely related) [Sanders *et al.*, 1987]. This means that there may be some degree of redundancy in successive observations. (Statisticians use a so-called ‘autocorrelation function’ to characterise this correlation.) Sampling times must be sufficiently far apart to ensure they are truly independent. However, they must also be sufficiently close to ensure that sufficient data are collected to meet the objectives of the programme.

- *Information content*. A common misconception is that information content must increase if samples are taken more frequently. This is not necessarily the case. This depends on the specific management objective. One example of a case where information does not increase is when the increased frequency results in serial correlation (described above). Statistical analysis of results often demands individual measurements are independent. Serial correlation means the measurements are dependent. Information content therefore decreases because the statistical analysis is being incorrectly applied.

- *Local knowledge*. Local knowledge of groundwater behaviour and a good understanding of local conditions will greatly enhance the capacity to design the most appropriate monitoring system.

4.3 QUALITY ASSURANCE AND QUALITY CONTROL

4.3.1 Introduction

The following sections are entirely based on the quality assurance (QA) and quality control (QC) proposed for the national toxicity monitoring programme (NTMP) [DWAF, 2005]. Although addressing toxicity, not microbial contamination, many QA & QC procedures are common to both. Only a summary is presented here. The NTMP manual can be consulted for more detail.

Quality Assurance. The implementation of all activities that minimise the possibility of quality problems occurring. These include, among others, training, instrument calibration and servicing, quality control, producing clear and comprehensive documentation, and so on.

Quality Control. The process of ensuring that recommended monitoring procedures are followed correctly by detecting and correcting quality problems when they arise, so that the accuracy of primary observations or measurements is (a) defined, (b) within acceptable limits and (c) recorded.

Importantly, it should be noted that quality control is a quality assurance activity.

"Quality" simply means the degree of excellence that at least meets the needs of the target users. Although the highest quality is usually desirable, this is always associated with increased costs. The higher the quality achieved, the higher the cost of achieving it. The challenge to perform QA and QC is to achieve the degree of excellence that is necessary to achieve the objectives of the NMMP for groundwater at an affordable cost.

QA and QC are overarching activities that affect every aspect of the NMMP. The following sub-sections describe how QA and QC should be applied to the NMMP.

4.3.2 Overall framework

4.3.2.1 ISO 9001:2000

The ISO 9001:2000 [SANS, 2000] quality management system should be applied to the NMMP. The principles that underpin this system are customer focus, leadership, involvement of people, process approach, systems approach to management, continual improvement, factual approach to decision making, and mutually beneficial supplier relationships.

4.3.2.2 Continual improvement

This is a critical principle of ISO 9001:2000. This should be achieved by broadly basing it on the cyclical "Plan, Implement, Check, Review" process associated with adaptive management. In essence, QA must be planned carefully, implemented thoroughly, checked regularly for effectiveness and periodically reviewed.

4.3.2.3 Achieving NMMP objectives

At the highest level, the overall objective of QA and QC is to help ensure the objectives of the NMMP for groundwater are achieved (Chapter 3: National Implementation). Strictly, each of the individual phrases within the NMMP objectives should be assessed from a QA perspective (as described in Section 3.1.2).

A QA "review period" is also necessary. This refers to the interval between assessments of the degree to which each QA procedure or focus area has been successful in addressing the identified phrase in the objectives. At these times changes to individual procedures can be introduced if necessary.

4.3.2.4 Attitudes

Perhaps the single issue that can most effectively contribute to an overall high level of excellence in implementation is the attitudes of those involved. Pride and ownership in all the role players (sampler, analysts, assessors, data managers, water resource managers, etc.) of their contribution to making the NMMP for groundwater a high quality programme is also something that can potentially be achieved at relatively low cost.

4.3.3 QA procedures

4.3.3.1 Sampling and sample transport

The importance of proper sampling procedures cannot be overemphasised. However, cost-effective quality control of sampling and sample transport activities is difficult. This is because these activities are often performed by a single person under circumstances where frequent supervision is not possible (or affordable). Nevertheless, the following single quality control activity should be implemented:

- A suitably qualified person (*i.e.* someone familiar with the required procedures) can accompany the sampler/monitor on his/her rounds once a year. Sampling and sample transport procedures should be observed. If problems are evident they can be corrected immediately.

However, emphasis should be placed on other QA activities because this measure cannot guarantee a sustained high level of quality. These include effective training when the sampler/monitor is appointed. This should ideally be done in the field. Actual samples should be taken to ensure that each detail and the reason for it, is clear to the sampler/monitor.

4.3.3.2 Sample analysis

The ultimate aim for the NMMP should be that all laboratories performing analyses should be accredited for them. This inherently imposes various QA and QC requirements on the procedures adopted.

4.3.3.3 Data management

Data management generally encompasses a wide range of activities:

- Registering the monitoring programme (monitoring points, monitoring frequency, etc.),
- Receipt of analytical results (measured either in a laboratory or on-site),
- Capturing these results on WMS, and
- Making results available for subsequent processing (*e.g.* reporting).

The Water Management System (WMS) based at Directorate: Resource Quality Services (near Roodeplaat Dam north of Pretoria) will be the database used for all water quality data associated with the NMMP for groundwater.

4.3.4 Review

The overall cost-effectiveness of the chosen QA and QC procedures should be reviewed initially on an annual basis. It is important to remember that the ultimate aim is to ensure that the objectives of the NMMP for groundwater are achieved. If changes are necessary to improve cost-effectiveness, these should be implemented in all participating organisations.

4.4 NATIONAL MONITORING DESIGN

4.4.1 Introduction

This section describes the general design and procedures for the national microbial monitoring programme for groundwater. The research report [Murray *et al.*, 2004a] and the pilot study report [Murray *et al.*, 2006] should be consulted for more detail on the rationale behind the design.

4.4.2 Objectives

The objectives of the programme are given in Section 3.1 in the National Implementation chapter. The precise meanings of the words and phrases in the objectives are also discussed in more detail.

4.4.3 Monitoring variables

- *Bacteria*. The primary variable upon which the monitoring is based is the concentration of the bacterium *Escherichia coli* (*E. coli*). Concentrations should be reported in counts/100 mℓ. Every effort should be made to report high results as absolute counts, not using the "greater than" symbol, >. Reasons for inclusion: *E. coli* is a widely used indicator of the presence of faecal contamination and is relatively easy and cheap to detect.

- *Viruses*. The next most important monitoring variable is the presence or absence of enteroviruses. *Reasons for inclusion:* This group of viruses contains a number of particularly problematic viruses associated with human infections. These viruses, which are acid-resistant, replicate primarily in the gastro-intestinal tract [Prescott *et al.*, 1993] and are spread by the faecal-oral route. Enterovirus infections are common in children and poor sanitation increases the chances of childhood infection [Timbury, 1994]. A single analytical test detects all 64 serotypes known to infect man.

- *Potassium*. The concentration (mg/ℓ) of potassium (K) should be measured. *Reason for inclusion*: The primary reason is to confirm that boreholes are in the flow path of the pollution plume emanating from the pollution source.

- *pH, electrical conductivity, temperature*. The final values of these variables should be recorded after stabilisation during purging. *Reason for inclusion*: These are basic water quality parameters that are being measured anyway.

- *Static water levels*. The static water levels should be measured (before purging).

4.4.4 Location of monitoring boreholes

4.4.4.1 Flow direction

Resources permitting, it is recommended that the groundwater flow direction be ascertained by drilling three boreholes down-gradient and triangulating the flow direction from static water levels.

4.4.4.2 General philosophy

Three types of monitoring boreholes, each with a different purpose, are used in this monitoring programme. These are illustrated in Figure 4.1.

In general, the containment borehole and the point-of-use monitoring borehole are the most important of the three and both are essential. The source monitoring borehole is very useful but not necessarily essential for national monitoring purposes if resources are limited. The purpose of each borehole type is summarised in Table 4.1.

Table 4.1. Purpose of the different monitoring boreholes (A, B and C refer to Figure 4.1).

Borehole type	Purpose
Source (Borehole A)	Monitors behaviour of the source more confidently than the containment borehole, in particular detecting worsening trends at the source that can be used to invoke source directed controls.
Containment (Borehole B)	Confirms local faecal pollution plume effectively contained allowing reasonably confident statements to be made about likely microbial quality elsewhere down-gradient.
Point-of-use (Borehole C)	Provides backup monitoring near strategic points of groundwater use that confirm, or otherwise, that faecal pollution from known significant sources are indeed well contained. Also partly necessary because of uncertainties associated with defining the attenuation zone and down-gradient flow paths.

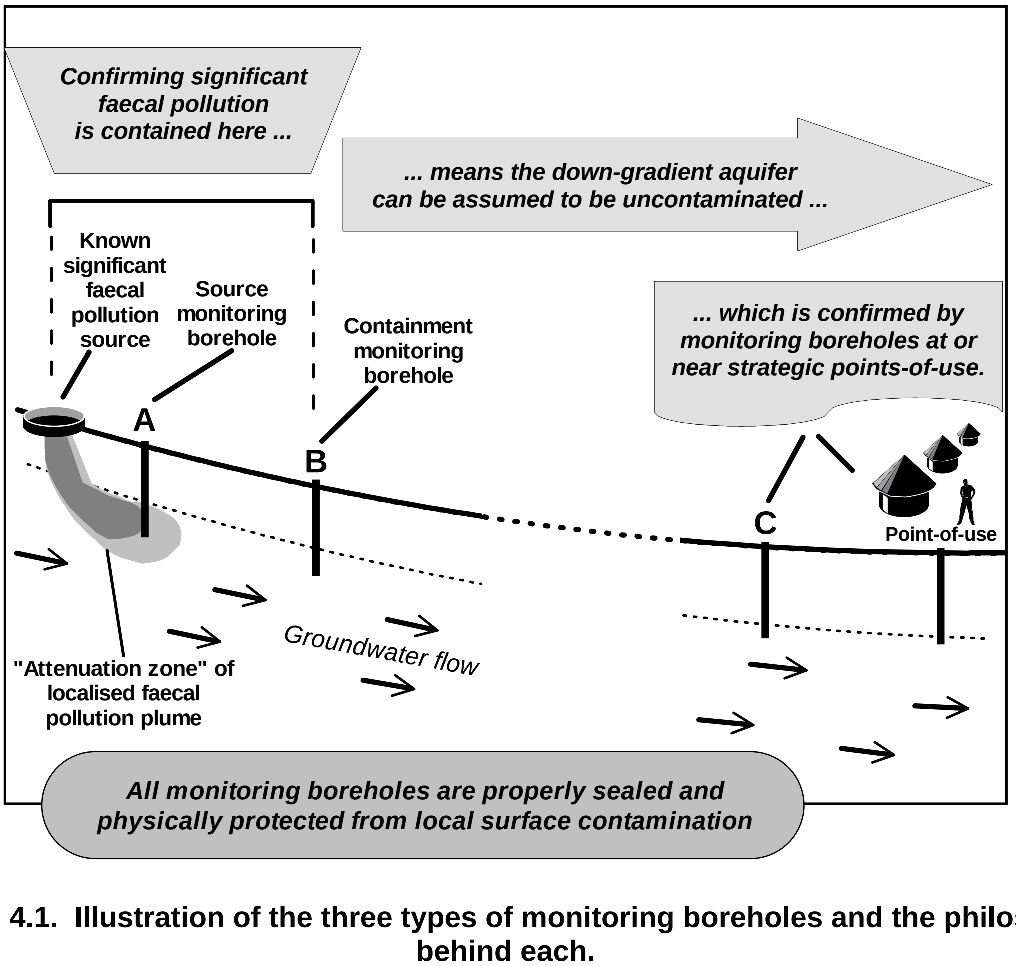

Figure 4.1. Illustration of the three types of monitoring boreholes and the philosophy behind each.

Procedures for choosing the general area and then a specific local cause for concern are outlined in the section National Implementation Process in Chapter 3: National Implementation.

An “attenuation zone” should be established and boreholes sited for each significant pollution source causing local concern so that the containment of the faecal pollution in that zone can be monitored. The procedure is given in the following sub-sections.

> The **attenuation zone** is defined as that three-dimensional zone down-gradient of a faecal pollution source beyond which faecal contamination is unlikely to be significant, because of natural filtering and die-off of the faecal microorganisms.

The importance of the attenuation zone is directly related to the likelihood of faecal contamination of groundwater being highly localised. This localisation occurs because (a) groundwater often moves relatively slowly, (b) microorganisms are physically filtered and immobilised (by processes such as adsorption and aggregation) and thus restricted in their movement and (c) most faecal microorganisms have a limited survival time in groundwater.

Ideally, the containment monitoring borehole is placed at a conservative distance from the outer limit of the attenuation zone (borehole B in Figure 4.2). The intention is that it always indicates zero *E. coli* if the pollution source and faecal pollution plume are behaving within expectations.

The source monitoring borehole is placed at the outer limit of the attenuation zone (borehole A in Figure 4.2). This position provides the maximum amount of information about the behaviour of the faecal pollution plume. If correctly placed it will always indicate low or possibly zero *E. coli* counts.

The precise locations of these two boreholes depend on three main factors:

- The flow path and rate of groundwater flow down-gradient of the pollution source.
- The likely effectiveness of the unsaturated and saturated zone media to attenuate (either immobilise or inactivate) faecal microorganisms.
- The likely lifetimes (travel times) of faecal microorganisms.

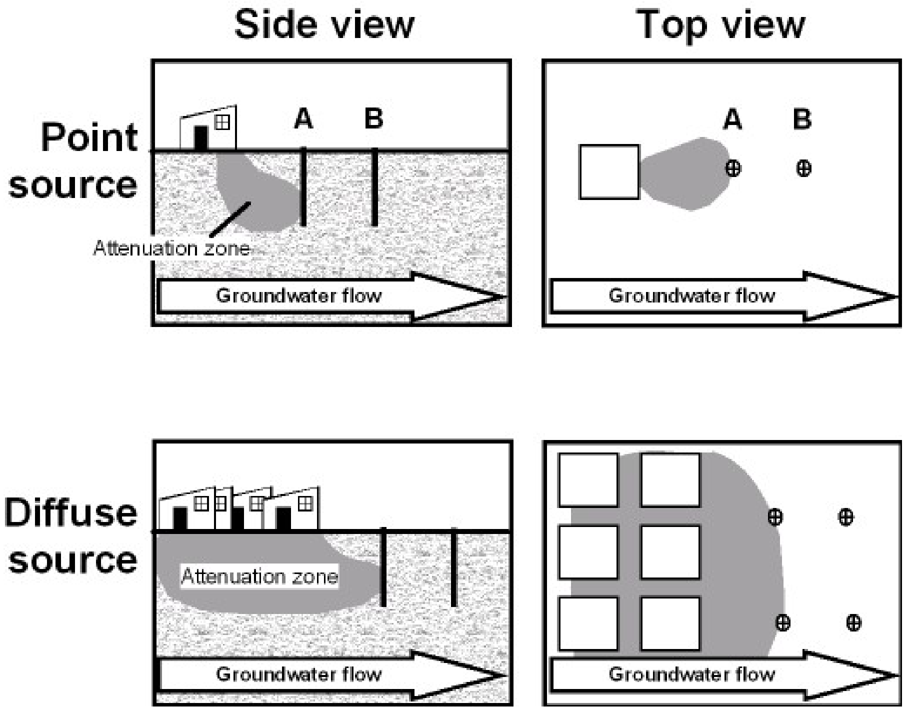

Figure 4.2. Schematic illustration of optimum source monitoring (A) and containment monitoring (B) borehole locations.

4.4.4.3 Establishing groundwater flow characteristics

Establishing the flow characteristics of an aquifer down-gradient of a pollution source requires the expertise of an experienced geohydrologist. In essence, the following general procedure should be applied.

- If possible, determine static groundwater level elevations around the pollution source.
- In the case of fractured rock aquifers, establish the dominant geological structural directions which may influence flow paths.
- Take account of any nearby borehole pumping or artificial discharges that might alter natural flow regimes.
- Establish the most likely down-gradient flow path(s), drilling extra boreholes if possible.
- If water level elevations cannot be determined, then judge from the surrounding topography the most likely down-gradient direction and estimate flow rate.
- If water level elevations are available, assume an appropriate hydraulic conductivity for the unsaturated and saturated zone (based on their general type) in the down-gradient direction and estimate the likely groundwater flow rate.
- If this is not possible, use professional judgement for likely flow rate based on best estimates of local hydraulic parameters of the aquifer.

4.4.4.4 Establishing filtration effectiveness

The unsaturated zone can play a very effective role in attenuating microorganisms before they reach the saturated zone. A simple model has been developed that allows the estimation of the potential that microorganisms will reach the saturated zone [ARGOSS, 2001] (Table 4.2).

Table 4.2. Potential for microorganisms reaching the saturated zone [adapted from ARGOSS, 2001]. [Shaded cell = significant or uncertain; Blank cell = low to very low.]

<table>
<tr><th></th><th colspan="3">Minimum depth to water table (metres below ground level)</th></tr>
<tr><th>Lithology of the unsaturated zone</th><th>< 5 m</th><th>5 – 10 m</th><th>> 10 m</th></tr>
<tr><td>Fine sand, silt and clay</td><td style="background:#ccc"></td><td></td><td></td></tr>
<tr><td>Weathered basement (soft, not consolidated)</td><td style="background:#ccc"></td><td style="background:#ccc"></td><td></td></tr>
<tr><td>Medium clean sand</td><td style="background:#ccc"></td><td style="background:#ccc"></td><td></td></tr>
<tr><td>Coarse sand and gravels</td><td style="background:#ccc"></td><td style="background:#ccc"></td><td style="background:#ccc"></td></tr>
<tr><td>Fractured rock</td><td style="background:#ccc"></td><td style="background:#ccc"></td><td style="background:#ccc"></td></tr>
</table>

Effective filtration occurs when the pore sizes are smaller than the microorganisms. Since this monitoring programme has as its primary indicator the bacterium *E. coli*, it is the filtration of this specific microorganism that is of central importance. Its smallest dimension is about 1300 nm (0.0013 mm) [Prescott *et al.*, 1993]. Any solid medium with fissures or pores much larger than this will allow this bacterium to travel freely with the groundwater. Much smaller fissures or pores will greatly restrict movement. Using this value as a guide, the geohydrologist should use local observations and knowledge of the underlying lithology and geology to estimate whether filtration is likely to be a significant factor in reducing the size of the attenuation zone based on travel times.

4.4.4.5 Travel time estimate

The travel times of faecal microorganisms are critically important for defining the attenuation zone. The following table summarises recommended minimum travel times to be used when locating source and containment monitoring boreholes. (For the rationale behind these travel times, see the associated research report [Murray *et al.*, 2004a].)

Table 4.3. Recommended minimum travel times to be assumed for *E. coli* for locating source and containment monitoring boreholes.

Borehole	Recommended minimum travel time (days)
Source	10-20
Containment (when points of use relatively close to faecal pollution source)	30-40
Containment (when points of use very far from faecal pollution source)	60-80

The likely distance travelled by *E. coli* is estimated based on estimated groundwater flow rates. This distance can be referred to as the “travel time” estimate.

4.4.4.6 Protection Zone 2 estimate

An alternative method to estimating the distance from the pollution source to the containment borehole can be based on the concept of a "Protection Zone" [van Wyk *et al.*, 2001]. A software package is also available that facilitates its calculation [Usher *et al.* 2004]. Three zones are referred to although it is Protection Zone 2 that is relevant in the current context. This zone is "established to protect a borehole from contact with pathogenic microorganisms (*e.g.* bacteria and viruses) which can emanate from a source (*e.g.* septic system, etc.) located close to the borehole …".

Using as much local geohydrological information as possible (such as transmissivity, effective porosity, hydraulic gradient, and saturated thickness), a distance to the containment borehole can be calculated.

4.4.4.7 Location of the containment borehole

The most conservative (*i.e.* longest) distance of the travel time and protection zone estimates should be used as the minimum distance to the location of the containment borehole. If possible and convenient, the actual location can be even further away.

This conservatism is important to ensure that containment of the faecal pollution can be confidently deduced from what is expected to be consistent detection of zero *E. coli* counts. It in effect sacrifices a zone between the containment borehole and the actual outer limit of the attenuation zone. However, this is deemed to be a minor loss in the overall context of enabling general statements to be made about the down-gradient aquifer as a whole.

If flow rates are so slow that the source and containment monitoring boreholes are unreasonably close to one another, only the containment borehole should be established.

Fractures may be suspected to be present that may facilitate high groundwater flow rates. In extreme cases, calculations based on bacterial survival times may indicate the containment borehole should be many hundreds of metres, or even kilometres, away from the source. In these cases, pragmatism must rule and the borehole placed as far away as practically possible while still being as sure as possible that it remains in the flow path. Should the position ultimately not be ideal (*i.e.* too close to the pollution source), then this should shift emphasis to improved management of the pollution source and more frequent monitoring at points-of-use.

It is conceivable that, in some locations, it will not be possible to locate the containment borehole sufficiently far from the source. The pollution source may be near a river or other buildings. In particular, careful account must be taken of distances from down-gradient rivers, particularly if such rivers are "losing rivers" (or, equivalently, "influent rivers" [DWAF, 1999]) that release water into the local aquifer in the direction of the pollution source. If such a river does exist, boreholes must not be placed in the zone likely to be fed by the river.

In such cases, the containment borehole should simply be placed as far as possible away from the pollution source. Although such a position may not be ideal, it simply means that the monitoring data that is obtained will need to be interpreted slightly differently.

A borehole should not be placed in a local depression. This minimises the chances of local contamination from the surface (despite the sanitary seal). A depression may also impede access to the borehole if it becomes muddy.

4.4.4.8 Learning from experience

Given the above-mentioned uncertainties it is inevitable that some source and containment monitoring boreholes may not be accurately placed, particularly in fractured rock aquifers. It is therefore important that there is a mechanism in place that facilitates learning from initial experiences.

Accordingly, the geohydrologist commissioned to determine the precise monitoring sites should carefully record in a written report all factors that led to the final choice of source and containment monitoring sites. These reports should be written in such a way that other geohydrologists can understand why each decision was taken. Even if "professional judgement" is used, an attempt must be made to justify it.

At regular intervals (annually initially), the national coordinator should combine all such reports with a summary of the actual monitoring results obtained from each monitoring borehole. Each borehole should be classified as having been successfully placed or otherwise. Table 4.4 recommends criteria that can be used for this classification. Classification should be based on data collected over the preceding year.

This information should be provided to and carefully assessed by a competent geohydrologist. If possible, the procedures for defining the attenuation zones and for choosing the precise location of the monitoring borehole(s) should be refined. These updated procedures must then be made available to all future geohydrologists performing these tasks.

Table 4.4. Criteria for classifying monitoring boreholes as successfully or unsuccessfully located.

Borehole	Successful	Unsuccessful	Implication
Source	All *E. coli* counts small (< 100 counts/100 mℓ).	All *E. coli* counts zero.	Too far from source or not in flow path.
		All or most *E. coli* counts high (> 100 counts/100 mℓ).	Too close to source.
Containment	All counts zero.	Some counts positive and this is known not to be due to a recent worsening in impact of the pollution source.	Too close to source. Cannot confidently make useful statements about containment and hence down-gradient faecal quality.
		Containment borehole counts zero but point-of-use borehole counts positive.	If (1) local contamination in vicinity of point-of-use borehole and (2) another major pollution source can be ruled out, short-circuiting around containment borehole may be occurring.

4.4.4.9 Location of strategic point-of-use boreholes

Strategically-important points of use are:

- Points at which groundwater is used as a "sole source" or for special purposes as designated by the Minister [DWAF, 2000a]; or
- Any point at which a groundwater resource might potentially be used in future to supply a significant fraction of the water that will be required to support the needs of a local population; or
- Any point at which groundwater contributes significantly to the base flow of a river that has strategic importance.

The "point-of-use monitoring boreholes" are regarded as providing "backup" monitoring data that supplements the primary data collected from the containment monitoring boreholes. This is necessary because statements made about groundwater faecal quality down-gradient of pollution sources (based on the monitoring data from containment boreholes) inevitably contains uncertainty. This uncertainty is increased in fractured rock aquifers compared to sandy aquifers, simply because flow paths are more difficult to predict. Assuming the same depth to the water table, this suggests that more emphasis should be given to monitoring points of use (either in the sense of more such boreholes or more frequent monitoring) when the uncertainty about containment effectiveness increases (Figure 4.3). Uncertainty will also be increased when containment boreholes cannot be placed sufficiently far from the pollution source (because of, for example, the proximity to a river or some physical structure).

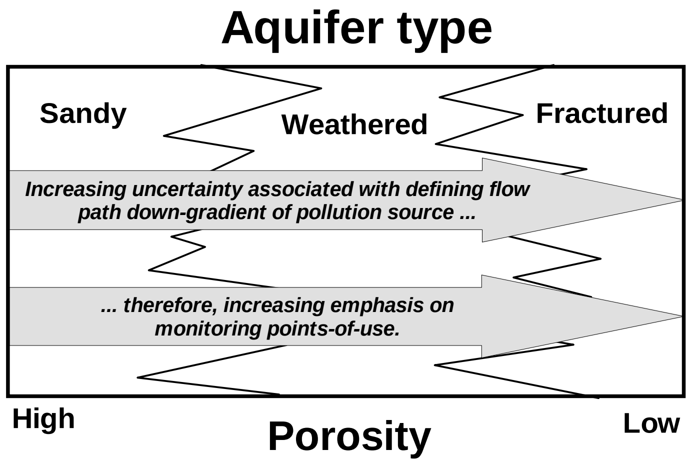

Figure 4.3. The dependence of emphasis on monitoring points-of-use as a function of aquifer type.

4.4.4.10 Dedicated versus pumping boreholes

After the attenuation zone of which containment needs to be monitored has been chosen, the precise site for the monitoring borehole needs to be identified. Every precaution needs to be taken to avoid faecal matter reaching the local groundwater down the very hole used for monitoring purposes. Ideally dedicated boreholes should be used for national monitoring. These are boreholes drilled and subsequently used only for national monitoring purposes. They must also be equipped with a “sanitary seal” which forms an effective seal preventing local surface contamination entering the ground around the casing.

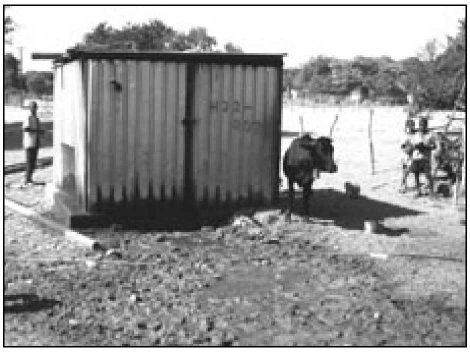

Figure 4.4. An inappropriate groundwater pump station for monitoring purposes.

However, drilling boreholes is expensive. If it is found that there is an existing borehole in an appropriate position for source, containment or point-of-use monitoring, then this may be used if certain requirements are satisfied. The decision-making process in Figure 4.5 should be used as a guide.

The most important principle driving this process is the need to ensure that no contamination of the groundwater occurs because of the presence of the monitoring borehole (whether a new or existing borehole). However, various other practical considerations also need to be taken into account. The SABS code of practice for location of water boreholes can be consulted [SANS, 2003] although this cannot replace the expertise of an experienced geohydrologist. Although that document is focused on the location of boreholes for water use, not monitoring, it can be used as a checklist of other factors (*e.g.* legal) that should be considered.

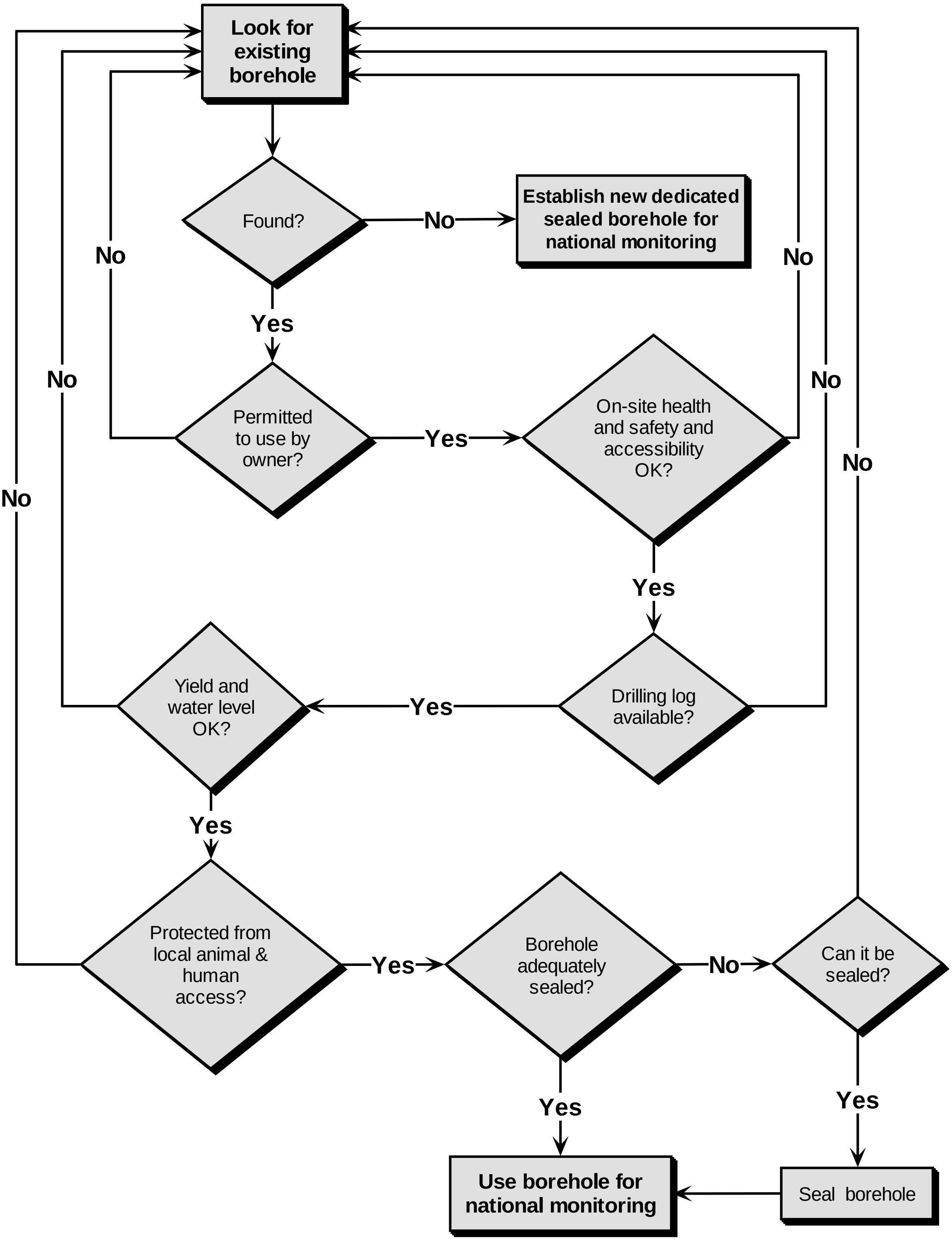

Figure 4.5. Factors determining the use of an existing borehole for national monitoring purposes.

4.4.5 Borehole construction

The object of groundwater sampling is to obtain samples that are representative of the groundwater down-gradient of identified faecal pollution sources. Microbial contamination from these sources is what is measured. It is important to ensure that, for example, contamination of the groundwater does not occur from surface contamination in the immediate vicinity of the borehole (*i.e.* that the borehole itself does not result in groundwater contamination). The very nature of the pollution sources likely to be monitored in the national programme makes local surface contamination a distinct possibility. Correct construction of the borehole is therefore critical.

During actual construction any obvious surface contamination in the immediate vicinity of the borehole location should be removed to minimise the chances of borehole contamination during construction. At all times reasonable care should be taken to avoid faecal contamination from any potential source.

Specifications laid down by the Department must be followed (Appendix A). An important quality control measure is for the geohydrologist to be on-site during drilling to ensure that borehole construction is carried out according to specifications. Borehole depths should be based on water strike information with emphasis on the most likely depth at which contamination will occur.

Figure 4.6. Borehole construction must prevent local surface contamination entering the aquifer.

Fractured hard rock aquifers require boreholes while for primary (sandy) aquifers with a high water table (like those that occur in the Cape) wellpoints will suffice.

4.4.6 Monitoring frequency

A pilot study involving monthly monitoring in a series of boreholes up-gradient and down-gradient of sewage treatment works over a period of only one year, suggested that the monitoring frequency can be monthly without suffering from serial correlation [Murray *et al.*, 2006]. Given the current lack of data, and the short duration of the pilot study, it is recommended that the monitoring frequency remain as high as available human and financial resources allow for at least two more years.

Sampling of source and containment boreholes should be more frequent than groundwater monitoring typical of unimpacted sites because effectiveness of containment of faecal pollution is an important focus of the philosophy of the monitoring programme.

Furthermore, given the strategic importance of the point-of-use monitoring boreholes, these should also be monitored relatively frequently. At least every three months is recommended although more frequently is preferable until more data are available.

4.4.7 Sampling procedures

4.4.7.1 Introduction

Extreme care needs to be exercised when sampling to ensure that contamination of the sample does not occur because microbiological analyses are required for this national programme. Precautions to avoid sample contamination are much more demanding than that required for sampling for typical chemical analyses. Therefore, besides the more obvious precautions noted below, the sampler must use common sense at all times to avoid sample contamination.

One single cell of the bacterium E. coli accidentally entering the sample bottle can give an analytical result that will indicate that a groundwater that is actually not contaminated is unfit for drinking if not treated.

The most obvious sources of contamination include the following.

- Unclean hands (from contact with contaminated groundwater, local surface contamination or unhygienic toilet practices of the sampling crew).
- A portable pump and pipe contaminated by a previous borehole.
- Faecal contamination on the surface in the immediate vicinity of the borehole.
- A contaminated tap or other water outlet (if the groundwater is sampled in this way).

The following publications provide general information on sampling and should be consulted for more detail on sampling.

- Quality of Domestic Water Supplies. Volume 2. Sampling Guide. [DWAF, DoH, WRC, 2001].
- Groundwater Sampling. A Comprehensive Guide for Sampling Methods. [Weaver *et al.*, 2006].

4.4.7.2 Equipment

In Table 4.5 a few essential items are listed that are required for a sampling trip specific to this monitoring programme. Consult Weaver *et al.* (2006) for a complete checklist of equipment required.

Table 4.5. Essential equipment for microbial sampling.

Equipment	Reason
If an *in situ* pump is not present, a portable submersible pump must be used.	The borehole must be purged before sampling
Teflon pipes (for shallow wellpoints). (This is impractical and too costly for deeper boreholes.)	These pipes minimise the formation of biofilms. In deeper boreholes, purging is relied on to remove microbial contamination from the pump and pipe.
Sterile sample bottles for each borehole being sampled.	Sterilisation removes all microorganisms from sample bottles that may have been used previously for microbial sampling.
Water and soap for washing hands.	This (a) improves personal health when working at contaminated sites and (b) minimises the chances of unclean hands contaminating the samples.
Container or cool box containing ice or "ice bricks" for transport of sample bottles for bacterial analysis. However, the samples must not be frozen.	This ensures the bacteria remain viable (alive) yet do not multiply (grow in numbers) between the time of sampling and time of analysis. (Virus samples need not be kept cold since only their presence or absence is detected. Detection of dead viruses is regarded as a positive result.)

4.4.7.3 Personal health

The sites being monitored have been chosen because they are suspected to be causing faecal contamination of the local groundwater. To be conservative, it should be assumed that contamination on the ground surface always exists. Appropriate care should be taken to minimise any physical contact (especially with hands). To avoid being infected with local bacteria or viruses wash hands routinely upon leaving such sites (Figure 4.7).

Figure 4.7. Washing hands and/or protecting hands with gloves are important.

4.4.7.4 Borehole sampling sequence

If multiple boreholes are to be sampled at one site, sample the least contaminated boreholes first (*i.e.* those furthest away from the pollution source). This minimises the chances of contamination from one borehole contaminating the sample from the next borehole.

4.4.7.5 Disinfection

At least the lower portion of water level measuring devices (that can become immersed in the water in the borehole) should be disinfected with a dilute disinfectant and rinsed with clean water before each use.

If a portable pump is to be used, the pump and pipe must be disinfected before and after each sampling trip. This may need to take place at the base (not at the sampling site) since water may not be available, or conveniently available, at the site.

- Disinfection before a sampling trip is intended to remove any contamination in the pump or pipe caused by any previous sampling.
- Disinfection after the trip is to avoid microbially contaminated water remaining in the pump and pipe for any extended period during which biofilms might form on the inner surfaces.

The disinfection process is as follows:

1. Fill an appropriately-sized container almost full of water (200 ℓ for deeper boreholes) (Figure 4.8). Add 12 mℓ of sodium hypochlorite (like the household disinfectant Jik). One level teaspoon of HTH granules can also be used. However, Jik is more convenient because the chlorine is already dissolved.
2. Place the pump and at least the end of the pipe (from which samples are taken) into the disinfectant drum, ensuring that the pump is fully immersed. If possible (*e.g.* when sampling shallow wellpoints), immerse the whole pump and pipe in the disinfectant solution.
3. Pump to circulate the water for a few minutes. This should complete disinfection of the pump and pipe.
4. If safe (*i.e.* there is no possibility that it is microbially contaminated) municipal water is available, use this to rinse the pump and pipe to remove the disinfectant solution. If not available, then rely on the borehole purging process to remove the solution. With large pumps and wide and long pipes, there are practical difficulties associated with disinfecting the outside surface of the pipe (that will be immersed in the borehole). Although contamination of the sample can potentially occur from this source, it is simply recommended that general care be taken to avoid obvious contact of the outside of the pipe with any potentially contaminating surface (ground, unclean hands, etc.). The purging of the borehole is then relied on to adequately remove any outer surface contamination that might exist.

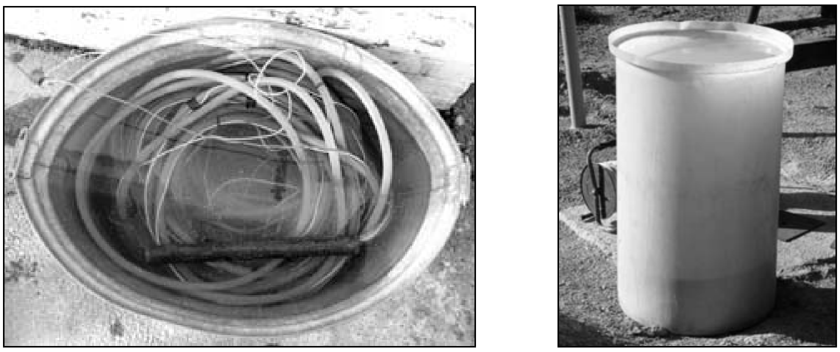

Figure 4.8. Pump and pipe disinfection containers for shallow wellpoints (left) and deeper boreholes (right).

In all subsequent handling of the pump and pipes while placing it into the borehole, care must be taken not to contaminate the hands or the pump or pipe in any way.

4.4.7.6 Borehole purging

Purpose

The purpose of purging each borehole is:

- To remove stagnant water from the borehole to ensure that a representative sample can be taken of the surrounding groundwater [Weaver *et al.*, 2006]; and
- To flush sufficient fresh groundwater through the pump and pipe to remove water from the pump and pipe existing from the previous application (or from disinfection).
- To flush away any possible contamination on the outside of the pump, pipe, water level meters, etc.

Note: During full-scale implementation of the programme, it is possible that the borehole being sampled is one used for some water use (like drinking by a local community or for irrigation). It is important to remember that the aim is to obtain a sample representative of the aquifer as a whole, not necessarily what local users may be drinking. Obtaining a sample of possibly stagnant water within the borehole will therefore not achieve the objectives of this national monitoring programme. Stagnant water must be therefore discarded.

Rationale

The issue of borehole purging immediately prior to sampling, and the subsequent sampling rates, require balancing a number of issues. These are summarised in Table 4.6.

Table 4.6. Summary of problems associated with inappropriate purge and sampling volumes and rates.

Purge and sampling volumes	Problems	Pumping rates	Problems
Too low	(1) If stagnant water in the borehole is not removed the sample may be unrepresentative of the aquifer as a whole. This increases the probability of false positive microbial result (*i.e.* reporting a problem when there is not actually a problem). (2) If groundwater is not adequately circulated through the pump and pipe, possible microbial contamination from a previous application may not be flushed out. The sample is unrepresentative (again increasing the probability of a false positive result).	**Too low**	Times required for sampling may become impractically long.
Too high	The greater the volume removed, the closer the groundwater to the faecal pollution source will be sampled. This increases the chances of detection of microorganisms at the containment borehole (where none may actually exist). As above, this increases chances of a false positive result.	**Too high**	An unacceptable degree of drawdown can occur. This can cause the pump to run dry and burn out.

Procedure

The following process briefly outlines the purging process. For more detail consult Weaver *et al.* (2006).

1. Monitor the electrical conductivity (EC) and pH and continue to purge until both EC and pH have stabilised (Figure 4.9). At least two, though preferably three, borehole volumes should be purged. Whatever is chosen for a particular site must be applied consistently at that site thereafter. The purging time for three volumes can be calculated as follows.

$$\textbf{V(litres) = 1000x[Total Depth(m) – Water Level(m)]x3.14x[Borehole diameter(m)/2]}^2$$

$$\textbf{Purging time (mins) = 3xV(litres) / [pump rate(litres/s)x60]}$$

2. Discharge the purged water as far as conveniently possible from the borehole site while taking reasonable care not to allow the pipe to come into contact with any surface contamination in the vicinity. (Remember that there can be significant surface contamination in the vicinity of sites like sewage treatment works.)
3. Monitor the water level to ensure that excessive drawdown is avoided.

Figure 4.9. Purging (left), water level monitoring (middle) and monitoring of electrical conductivity (right).

4.4.7.7 Sampling

Precautions

The following precautions should be taken when sampling [adapted from DWAF, DoH, WRC, 2001]. Also consult with the laboratory that will be performing the analyses for guidance on special precautions that should be taken. The following assumes that the laboratory will supply sterile sample bottles.

- Practice sound toilet hygiene during a sampling round.
- Take reasonable precautions to ensure that the pump and pipe (especially the end of the pipe used to fill the sample bottle) do not come into contact with faecal pollution that may exist on the surface in the immediate vicinity of the borehole. Remember that this is a distinct possibility given the nature of the faecal pollution sources being monitored.
- Keep the sample bottle closed and clean up to the time when it is filled with the water to be sampled.
- Do not rinse the bottle with any water prior to taking the sample.
- If separate samples for chemical and microbiological analysis are to be collected from the same point, take the microbiological sample first. This avoids the possibility of contamination of the sampling point (pipe, taps, etc.) occurring while taking the chemical samples.

Procedure

- If the sample is being taken from a tap, allow the tap to run for two minutes before sampling. Note that only taps at the wellhead should be sampled (not those part of a local reticulation system).
- Hold the end of the pipe away from the sample bottle while the sample is being taken. Do not allow it to touch the sample bottle (Figure 4.10).
- Replace caps on sample bottles immediately and tighten well.
- Use the recommended sample volumes in Table 4.7.

Table 4.7. Recommended sample volumes.

Analysis	Sample volume
Virus	20 litres
Bacteria	100 mℓ (directly into sealed Colilert® sample bottle)
Potassium	100 mℓ

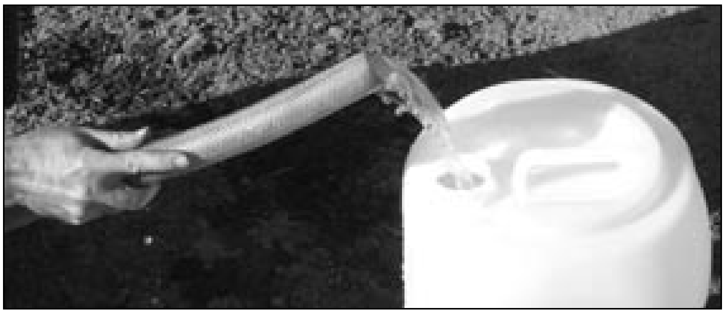

Figure 4.10. Correct sample collection procedure (end of pipe not touching the sample bottle).

4.4.7.8 Sample preparation

No preservatives should be added to the sample. The tightly closed and properly labelled sample bottle should be placed immediately in a cool box/bag (Figure 4.11). Bacterial samples must be kept on ice. The larger virus samples need not be kept on ice but must be kept cool. The cool box/bag should ideally be kept out of direct sunlight, if possible.

Figure 4.11. Transport samples in a cooler box/bag.

4.4.7.9 Sample delivery

Samples must be delivered to the laboratory within 24 hours. Virus samples must be kept cool and bacterial samples cold (on ice) for the entire period between sampling and delivery to the laboratory. If samples are to be transported by air, use "ice bricks" (minimum 5 per bag).

Special arrangements may need to be made to achieve this if distances are significant. For example, contracts may be drawn up with local courier companies. Some laboratories do not operate over weekends so delivery of samples on a Friday or even Thursday may need to be avoided. Liaise with the laboratory beforehand to ensure that the samples can be processed on the day of delivery.

4.4.8 Analytical procedures

4.4.8.1 Potassium

Potassium can be measured by any widely-used standard method.

4.4.8.2 Bacteria

E. coli should preferably be measured using the Colilert-18® method (Figure 4.12) according to the manufacturer's instructions. However, the membrane filter procedure using M-FC (Membrane Faecal Coliform) agar can be used with confirmation of *E. coli* colonies using the indole test [APHA, 1998].

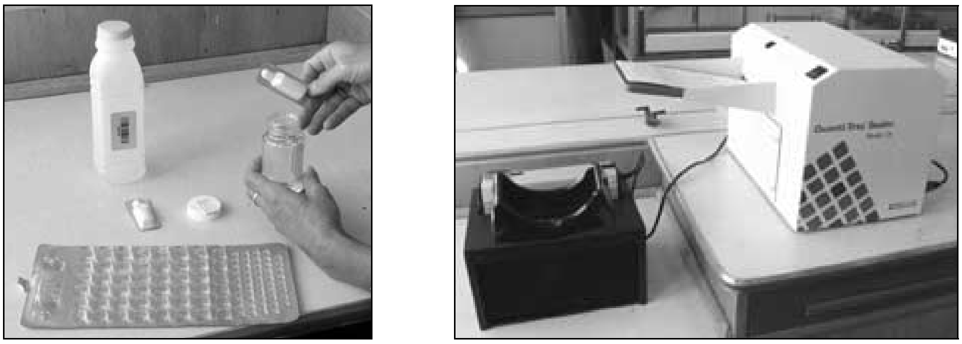

Figure 4.12: Colilert-18® Quanti-Tray (left) and Quanti-Tray sealer (right) used to detect *E. coli*.

4.4.8.3 Virus recovery

Viruses can be recovered from the sample by one of two methods (Figure 4.13).

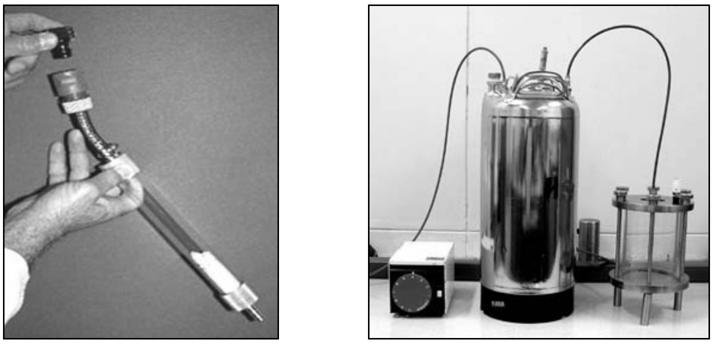

Figure 4.13: Glass wool column (left) or pressure vessel and filtration unit (right) for recovery of viruses from large sample volumes.

Glass wool

This procedure has the following advantage:

- It allows large sample volumes to be filtered in the field, avoiding the need for transportation of large volumes.

It has the following disadvantages:

- Each column must be individually packed with the glass wool and some difficulty can be experienced in achieving adequate consistency in the packing.
- The glass wool is imported and batch-to-batch variations in recovery efficacy have been reported.
- Lower recovery rates than ultrafiltration are obtained.

The glass wool method used by the Department of Medical Virology, University of Pretoria is a modification of the column described by Vilaginès *et al.* (1993). Ten grams of glass wool (R.725, St. Gobain, Isover-Orgel, France) is compressed into a perspex column (260 mm x 30 mm) (Figure 4.13 - left).

The glass wool is divided into three equal amounts and each section teased and compressed separately into the column to form a glass wool plug approximately 10 cm high with a final density of 0.5 g/cm^3 (glass wool dry w/v basis). The glass wool is soaked with sterile distilled water and pre-treated consecutively with 40 mℓ 1 M HCl, 100 mℓ sterile distilled water, 40 mℓ 1 M NaOH and 100 mℓ sterile distilled water to adjust the pH to pH 7.0 and to positively charge the glass wool. 15 g of hydrochlorex (USF Wallace and Tiernam, Günzburg, Germany) is added to the column above the glass wool to remove any chlorine not neutralised by the $Na_2S_2O_3$ [Venter, 2005].

The water is filtered through the positively charged glass wool columns by negative pressure at a rate of 10 ℓ/h. The negatively charged viruses, which adsorbed to the glass wool, are eluted twice with 50 mℓ glycine-beef extract buffer (GBEB) (3.754 g/ℓ glycine (Merck), 5 g/ℓ beef extract V [Becton Dickinson and Co., Cockeysville, MD]), pH 9.5, which reverses the ionic charge of the viruses and releases them from the glass wool. Immediately after elution, the pH of the eluate is adjusted to pH 7 with 1 M HCl (pH 1) (Merck). The eluate is subjected to secondary concentration using PEG/NaCl.

Ultrafiltration

This procedure has the following advantage:

- Greater recovery efficiency is possible than with glass wool.

It has the following disadvantages:

- Large sample volumes must be transported back to the laboratory.
- Filtration can take many hours, even overnight.

Ultrafiltration of water is done using a flat membrane diaflo ultrafiltration system consisting of a pressure vessel connected to a 2 ℓ filtration cell and a membrane with a molecular cut-off of 50 000 (Figure 4.13 - right). Recovery may require many hours, even an overnight run, to filter as much as 20 ℓ. Once the viruses have been eluted from the filter, they can be subjected to any number of detection methods for specific viruses or groups of viruses.

4.4.8.4 Virus detection

Enteroviruses should be measured using the Polymerase Chain Reaction (PCR) method. This can be performed in a relatively small bench-top thermocycler (Figure 4.14, left figure). Gel electrophoresis is then used to separate amplicons on the basis of their electrical charges in a suitable buffer when subjected to an electrical current (Figure 4.14, right figure). The PCR products are then visualised by ethidium bromide staining and ultraviolet illumination.

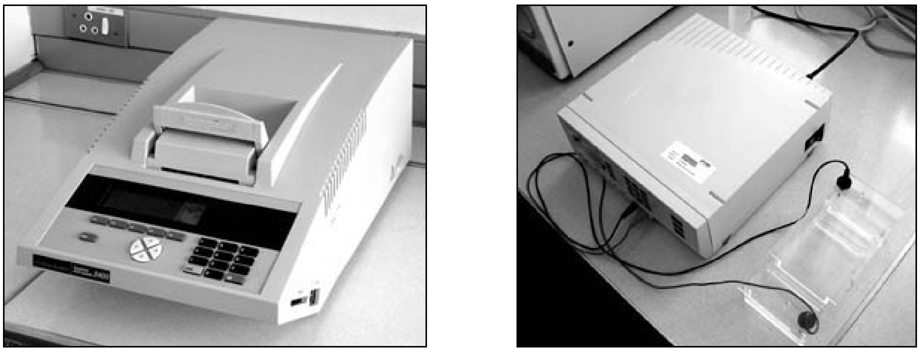

Figure 4.14. PCR thermocycler (left figure), electrophoresis power supply (right figure, top left) and electrophoresis unit (bottom right).

4.4.9 Data management

Analytical data obtained in a laboratory should be transmitted, preferably by Email, to the Regional Monitoring Coordinator or the National Coordinator for importing into the primary data storage system (depending on the management model applicable - see Roles and Responsibilities chapter). This applies to all laboratories except the laboratory based at Resource Quality Services (DWAF) at Roodeplaat Dam whose data will automatically be captured.

Water quality data should be stored on the Water Management System (WMS) located at Directorate: Resource Quality Services (DWAF) near Roodeplaat Dam, north of Pretoria.

Catchment Management Agencies delegated with the responsibility of implementing the programme in their Water Management Areas should ensure that all data is captured on WMS directly and as soon as possible. Should they subsequently require this data for their own purposes, it is their responsibility to set up access to WMS so that the data can be retrieved.

4.4.10 Annual data assessment and reporting

4.4.10.1 Typical data assessments

Table 4.8 shows typical assessments upon which annual reporting and management actions can be based. The term “hazard” refers to the pollution source. It is assumed that it has been established that the containment borehole is in the flow path of contamination emanating from the pollution source.

A useful context in which to understand the usefulness of the containment borehole and the requirement that bacteria and viruses not be detected relate to so-called “resource water quality objectives (RWQOs). The policy on resource directed management of water quality [DWAF, 2006] defines these as follows:

“*RWQOs are numeric or descriptive (narrative) in-stream (or in-aquifer) water quality objectives typically set a finer resolution (spatial or temporal) than resource quality objectives (RQOs) that provide greater detail upon which to base management of water quality.*”

Resource quality objectives (RQOs) are “*numeric or descriptive (narrative) goals for resource quality within which a water resource must be managed. These are given legal status by being published in a Government Gazette.*”

In the current context the objective is to ensure that microbial contamination at the location of the containment borehole is zero. Should this be achieved, then useful statements can be made regarding the down-gradient aquifer. Should it not be achieved, this provides motivation for improved management of the pollution source responsible.

4.4.10.2 Annual report structure and contents

Reporting the degree of faecal contamination of groundwater resources nationwide is prone to misinterpretation if careful attention is not given to the following.

- *Accuracy of reporting*. The concept of localised faecal pollution must be conveyed accurately to the reader of the annual report. In particular, it must be ensured that neither the report text nor the associated maps can create exaggerated perceptions of the real degree of faecal pollution in groundwater. Statements about the faecal quality of an aquifer as a whole should be suitably guarded yet accurate and unambiguous. They should imply, or state explicitly, the uncertainty that will inevitably exist.

- *Emphasising site-specificity*. When groundwater quality is reported for individual boreholes (*e.g.* as potential health risk), it must be ensured that the reader understands that these are highly site-specific statements. The natural inclination of uninformed readers to interpolate between such points and draw conclusions about groundwater quality significant distances away from the specific boreholes should be explicitly discouraged.

Table 4.8. Typical data assessments of annual monitoring data for reporting purposes.

***E. coli* and enterovirus analyses (over annual reporting period)**		**Assessment relating to …**		
		Containment borehole	**Aquifer down-gradient of containment borehole**	
At containment borehole	**At point-of-use borehole**	**Effectiveness***	**Microbial (faecal) quality**	**Management recommendation**
Both *E.* coli & enterovirus always zero	**Both *E.* coli & enterovirus always zero**	Effective (RWQO attained)	Contamination not detected. However, risk to human health for domestic and recreational use remains uncertain.	Maintain effective management of hazard.
***E.* coli or enterovirus sometimes detected**	**Always zero**	Partial	Aquifer may be contaminated. Possible risk to human health for domestic and recreational use.	Urgently implement effective management of hazard to reduce discharge of faecal contamination.
***E.* coli or enterovirus detected in all samples**	**Always zero**	Inadequate		
Both *E.* coli & enterovirus always zero	**Either *E.* coli or enterovirus sometimes detected**	Effective (RWQO attained)		Check whether contamination at point-of-use might be originating from another source. Also consider possibility of short-circuiting around containment borehole.

* reflected on map

- *"Likely general picture" not "safe to use".* This national monitoring programme can only provide a "likely general picture" of selected South African groundwater resources. It must therefore be emphasised that the reported results of the programme should under no circumstances be used as confirmation that groundwater at any particular point is safe, or otherwise, to use for any purpose whatsoever. If such information is required, the groundwater from the point of interest must be analysed independently for the full set of variables appropriate to the intended use.

The annual report should contain a combination of text and colour maps. The report should at least contain the following sections:

Monitoring objectives

The objectives of the programme should be clearly stated so that the expectations of the reader are properly aligned with what the monitoring programme is actually meant to deliver.

Monitoring philosophy

This should contain the figure in the executive summary above that illustrates the philosophy in diagrammatic form. This should be supplemented with text that provides a simple and clear explanation of the philosophy. In particular, the concept of "effectiveness of containment" should be clearly defined as follows:

Effectiveness of containment is the degree to which known faecal pollution in groundwater is limited to a well defined zone. Unlike many kinds of chemical pollutants, microorganisms are physically filtered and immobilised through adsorption and aggregation, by the substrate through which the groundwater passes. Furthermore, not being in their natural environment, many also die off. The result is that much faecal pollution is highly localised in its impact. This national monitoring programme focuses on monitoring the effectiveness with which this localised pollution is contained. If shown to be contained near a specific pollution source, the groundwater down-gradient of these zones is unlikely to be significantly contaminated from that source.

Current monitoring sites

This section should tabulate locations at which all monitoring is currently occurring in such a way that their exact positions on the maps can be ascertained.

When tabulating source and containment monitoring boreholes, care should be taken not to name individual organisations as being polluters unless legally defensible evidence is available. However, obtaining such evidence is outside the mandate of this monitoring programme, as is evident from the objectives of the programme. Therefore, the location should rather be described using geographical features and distances (including longitude and latitude).

The source monitoring borehole of this programme strictly only provides evidence of faecal pollution at that point, not the identity of the polluter causing it. The latter is only confirmed if a monitoring borehole is placed up-gradient of the pollution source and this is shown to be unpolluted and there are not other polluters in the vicinity. However, such a borehole is also not required to achieve the objectives of this national monitoring programme.

Maps illustrating containment and health risk

The following kinds of colour maps should be depicted in the annual report:

- Maps showing effectiveness of containment of known significant pollution sources.
- Maps showing trends in containment of known significant pollution sources.
- Maps showing the potential health risk due to *E.* coli at boreholes monitoring strategic points of use.
- Maps showing the potential human health risk due to viruses at boreholes monitoring strategic points of use.

Some examples are given in Figures 4.15, 4.16, and 4.17.

A separate map should be produced for each Water Management Area (WMA). Boreholes indicated on the maps should be numbered and linked to the above-mentioned tables of borehole locations.

Overall assessment

A section of the report must contain an overall assessment of the monitoring results presented in the tables and maps. General statements should be made that relate to fitness-for-use of groundwater from the point of view of faecal contamination. Particular care should be given to the above-mentioned principles of ensuring comments are accurate, scientifically sound and unambiguous. Emphasis should be placed on the degree to which the objectives of the monitoring programme have been achieved. Equivalently, to ensure absolute transparency, important areas in which the objectives have not been achieved should be stated explicitly.

Before the National Coordinator submits the final national report, the report should be circulated among the WMAs for comment. This is to ensure that assessments are well aligned with regional interpretations of the data.

Management actions

The nature of the monitoring in this programme is such that various management actions to address specific problem areas can be invoked. The extent to which such corrective actions have been taken can also be reported.

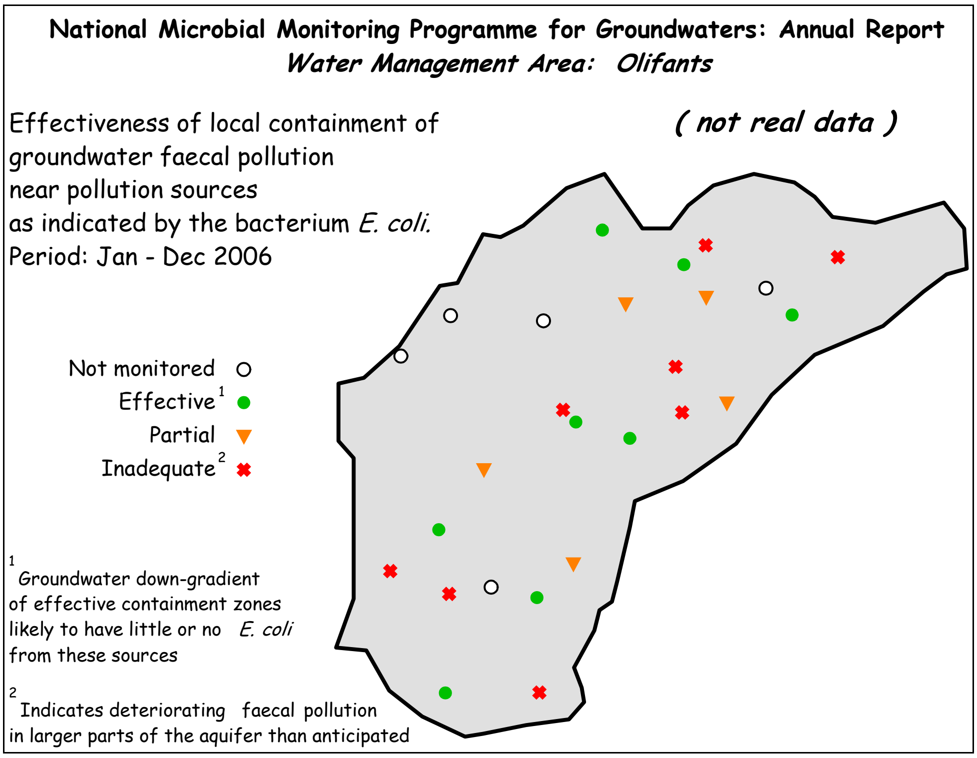

Figure 4.15. Example of a map illustrating containment effectiveness.

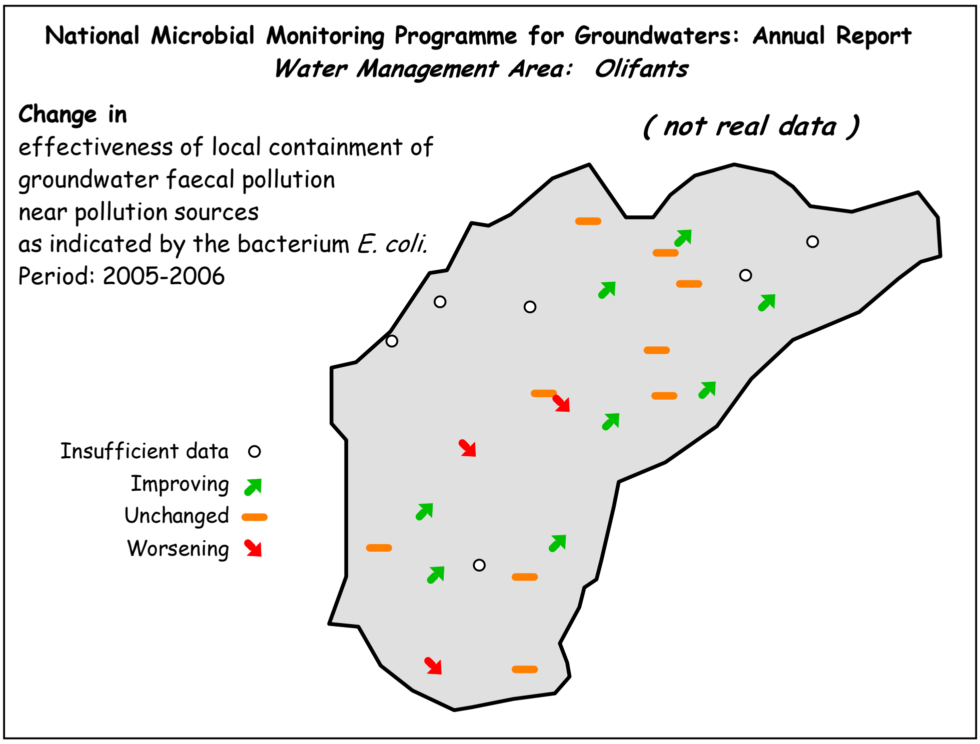

Figure 4.16. Example of a map illustrating change in containment effectiveness.

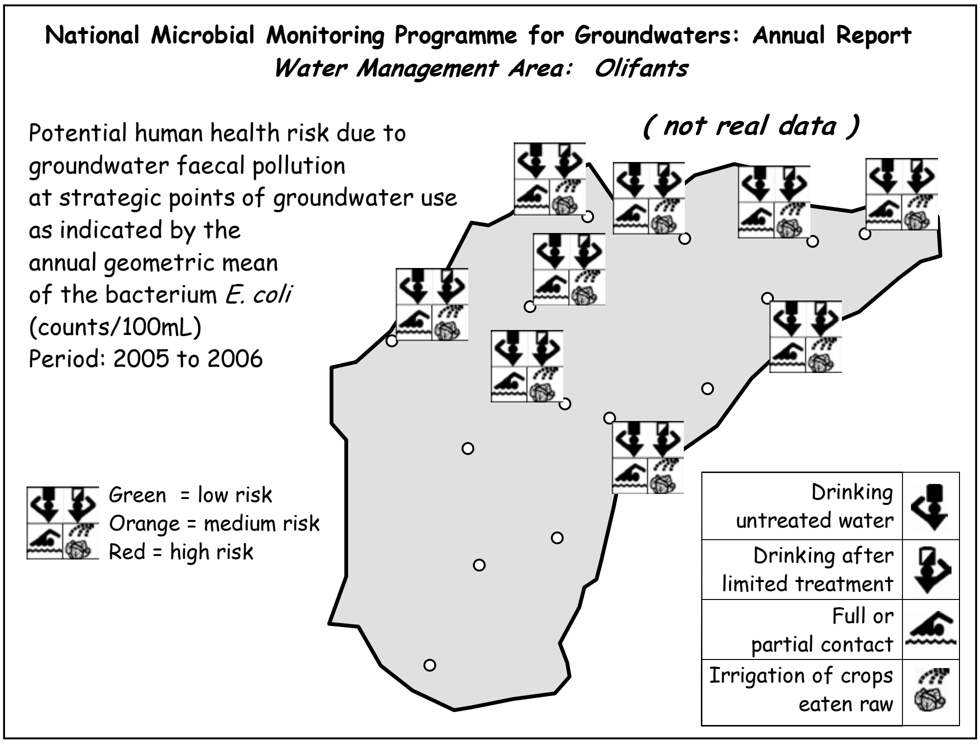

Figure 4.17. Example of amap illustrating potential human health risk at strategic points of use.

4.4.10.3 Water quality guidelines

Bacteria (E. coli)

The potential human health risk for each of the four sensitive water uses can be based on the guidelines in the following table:

Table 4.9. Guidelines for assessing the potential health risk relating to *E.* coli for four sensitive water uses [DWAF, 2002a].
(Note that these guidelines were developed specifically for use in the NMMP and were not tested in other contexts.)

	Potential Health Risk		
	Low	**Medium**	**High**
Water use attribute	***E. coli* counts/100 mℓ**		
1. Drinking untreated water	0	1 - 10	> 10
2. Drinking water after limited treatment (see explanatory note* below)	< 2 000	2 000 – 20 000	> 20 000
3. Full or partial contact	< 600	600 – 2 000	> 2 000
3. Irrigation of crops to be eaten raw	< 1 000	1 000 – 4 000	> 4 000

* Note: In this case, the water is used (*i.e.* for drinking) after limited treatment though the guidelines necessarily refer to the raw water before such treatment. For example, raw water with < 2 000 counts/100 mℓ subjected to limited treatment ***and then used for drinking***, will be associated with a low

potential health risk. “Limited treatment” means not conventional treatment. Conventional treatment means all of flocculation, sedimentation, filtration and disinfection.

Although these were specifically developed for surface water, they are tentatively adopted here as also being appropriate for groundwater. This is in accord with general groundwater quality management policy [Section 4.2.5, DWAF, 2000b].

The meaning of “full or partial contact” should be interpreted in basically the same way as for surface water. This is usually considered in the context of recreation. Full contact is typically swimming or diving. Although the number of swimmers and divers in a groundwater context is obviously fewer than those in a surface water context, people like cavers may in some instances be exposed to full-body water contact. However, partial or intermediate contact is a more likely scenario in a groundwater context. This encompasses all forms of water contact excluding activities defined as full contact. Although the swimmer icon used in the map in Figure 4.11 seems therefore somewhat inappropriate, it is retained to be consistent with the icons used in the NMMP for surface waters.

Enteroviruses

Currently South African guidelines exist for enteric viruses. This is a broad group of viruses containing enteroviruses as one sub-group. The guidelines are based on quantitative viral counts.

However, the detection of viruses for this national programme is based on a procedure (namely, PCR – refer to Section: Analytical procedures) that detects presence or absence, not actual counts. The above guidelines are therefore not entirely appropriate. Furthermore, detection by PCR is not a guarantee of viability (*i.e.* their ability to cause infection).

In order to maintain a degree of simplicity for the national programme, the following are proposed as the guidelines:

- ***Viruses detected***. Brief assessment: Possible human health risk for domestic and recreational use.
- ***Viruses not detected***. Brief assessment: Uncertain human health risk for domestic and recreational use.

Importantly, should viruses not be detected, the following caveats must appear in the report to ensure that interpretation and possible management action (or inaction) based on the reported non-detection is sufficiently well-informed.

Although 20 litre sample volumes are recommended (Section 4.4.7: Sampling procedures), this can result in false negative results (*i.e.* reporting there is no problem when there is actually a problem) [Murray *et al.*, 2006]. Therefore, the following caveat must <u>always</u> appear in reports:

Sample volume caveat. *"These results are based on only 20 litre samples where at least 100 litre samples are theoretically more desirable. There is therefore a significant probability that results reported as zero viral particles/100 litres (i.e. not detected) may be erroneous, i.e. low, yet problematic, numbers of viral particles may have been present but not detected. Firm conclusions cannot therefore be drawn directly about the extent to which such water is drinkable."*

If the glass wool filtration method is used for recovering viruses from the sample (and not ultrafiltration) (see Section 4.4.8: Analytical procedures), then the above caveat should be replaced with the following:

> ***Sample volume and glass wool caveat***. *"These results are based on only 20 litre samples where at least 100 litre samples are theoretically more desirable. Furthermore, the virus concentration technique has inherently low virus recovery rates. There is therefore a significant probability that results reported as zero viral particles/100 litres (i.e. not detected) may be erroneous (i.e. low, yet problematic, concentrations of viruses may have been present but not detected). Firm conclusions cannot therefore be drawn directly about the extent to which such water is drinkable."*

Since turbidity levels may be high for some period after borehole construction, data reported within the first three months after construction should have the following additional caveat when viruses are reported as undetected:

> ***Turbidity caveat***. *"Since the borehole was recently constructed, turbidity levels may still be relatively high. Virus recovery rates are therefore even lower than they would be had the water been clear. This further increases the probability that results reported as zero viral particles (i.e. not detected) may be erroneous."*

4.4.11 Interim *ad hoc* reports

Although this is a national programme, it is a relatively straightforward task to ensure a mechanism is in place that facilitates the production of interim reports that can act as an early warning system under special circumstances. For example, if a containment borehole or a point-of-use borehole suddenly indicates a significant *E. coli* count (say greater than 10 counts/100mℓ) where it had previously been zero, this is an indication of a possible significant impact. These reports should be simple and not involve the production of maps. They can take the form of a fax or an email that is sent to the stakeholder most likely to be concerned with the detected impact. The report should indicate the fact that a significant count has been detected. Site specific circumstances will then dictate the most appropriate follow-up action.

4.4.12 Report delivery

The annual report should be sent to the following parties:

- The Minister of Water Affairs and Forestry.
- The Minister of Health.
- Director: Hydrological Services (DWAF).
- Director: Resource Quality Services (DWAF).
- Appropriate directorates in the Department of Health.
- Each Catchment Management Agency.
- Each regional DWAF office.
- Any concerned party that has expressed an interest in obtaining the report.

CHAPTER 5: ROLES AND RESPONSIBILITIES

This chapter should be used by any role player to establish the tasks required to be implemented by any of the role players in the NMMP for groundwater.

5.1 INTRODUCTION

A multitude of parties are involved in a national monitoring programme. All individual roles need to be smoothly executed for the overall programme to be successful. This chapter describes each individual role and associated responsibilities.

The roles cover the whole range from sampler to national policy maker. This has been done to ensure that each role player understands where they fit into the overall picture. This should facilitate buy-in to the process by all involved. This can be regarded as contributing to quality assurance and hence ultimately sustainability of the programme.

5.2 MANAGEMENT MODELS

5.2.1 Introduction

The exact responsibilities associated with each monitoring role, and who is accountable for them, will depend on the specific management model being applied. A number of management models can be envisaged. The following sub-sections describe three models, though others are also possible. In practice, it is likely that effective national management will involve a combination of all the models, depending on local and regional capacity. The three models reflect management from the point of view of the organisation with the primary responsibility for national implementation, namely the Department.

The words “national”, “regional” and “local” refer to spatial coverage and associated responsibilities. Regional responsibility will typically reside with the Departmental regional office or the catchment management agency (CMA). Local responsibilities for groups of one or more monitoring sites, typically in close proximity, will reside with organisations with the interest and capability to manage the necessary sampling in their local vicinity.

5.2.2 Model 1: Direct management of samplers and analysts

This model involves the National Coordinator in the Department directly managing the day-to-day activities of samplers and laboratories (Figure 5.1). Contracts would be drawn up between the Department and the local samplers and laboratories. If the laboratory in question is the one based at Directorate: Resource Quality Studies (at Roodeplaat Dam), analytical results will be automatically captured onto the central database, namely Water Management System (WMS). Other laboratories will need to transmit the analytical results directly to the National Coordinator who would be responsible for capturing the data in WMS.

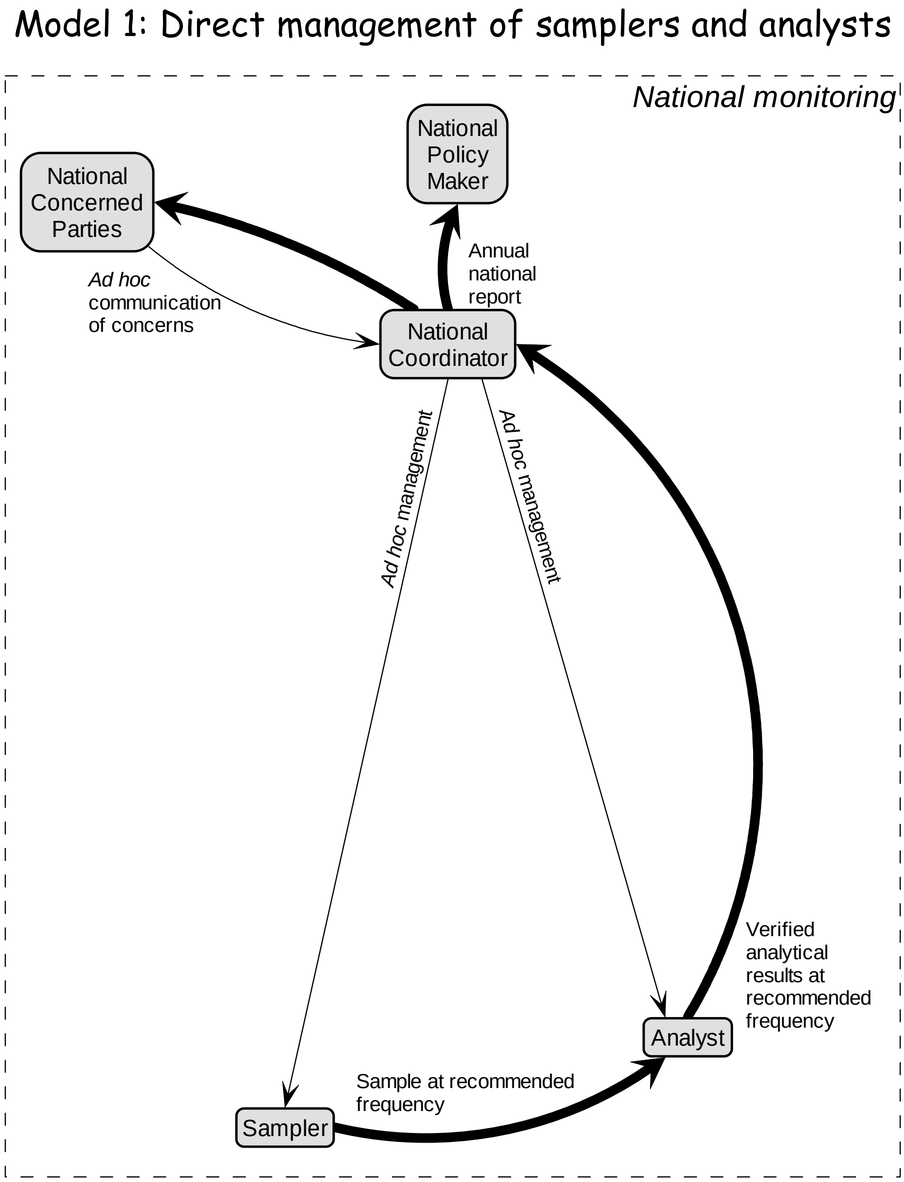

Figure 5.1. Model 1: Roles and information flow.

5.2.3 Model 2a: Using CMAs as agents

This model differs from model 1 in that the National Coordinator delegates the responsibility of sampling and analysis to a catchment management agency (CMA) or DWAF regional office (Figure 5.2). The CMA either uses its own staff to collect samples and analyse them or sub-contracts external samplers and analysts. The CMA is entirely responsible for day-to-day management of the samplers and analysts. It is conceivable, and indeed preferable, that the CMA benefits directly from such data collection. The CMA provides feedback of assessed results to regional concerned parties and submits data (and possibly reports) at agreed intervals to the National Coordinator.

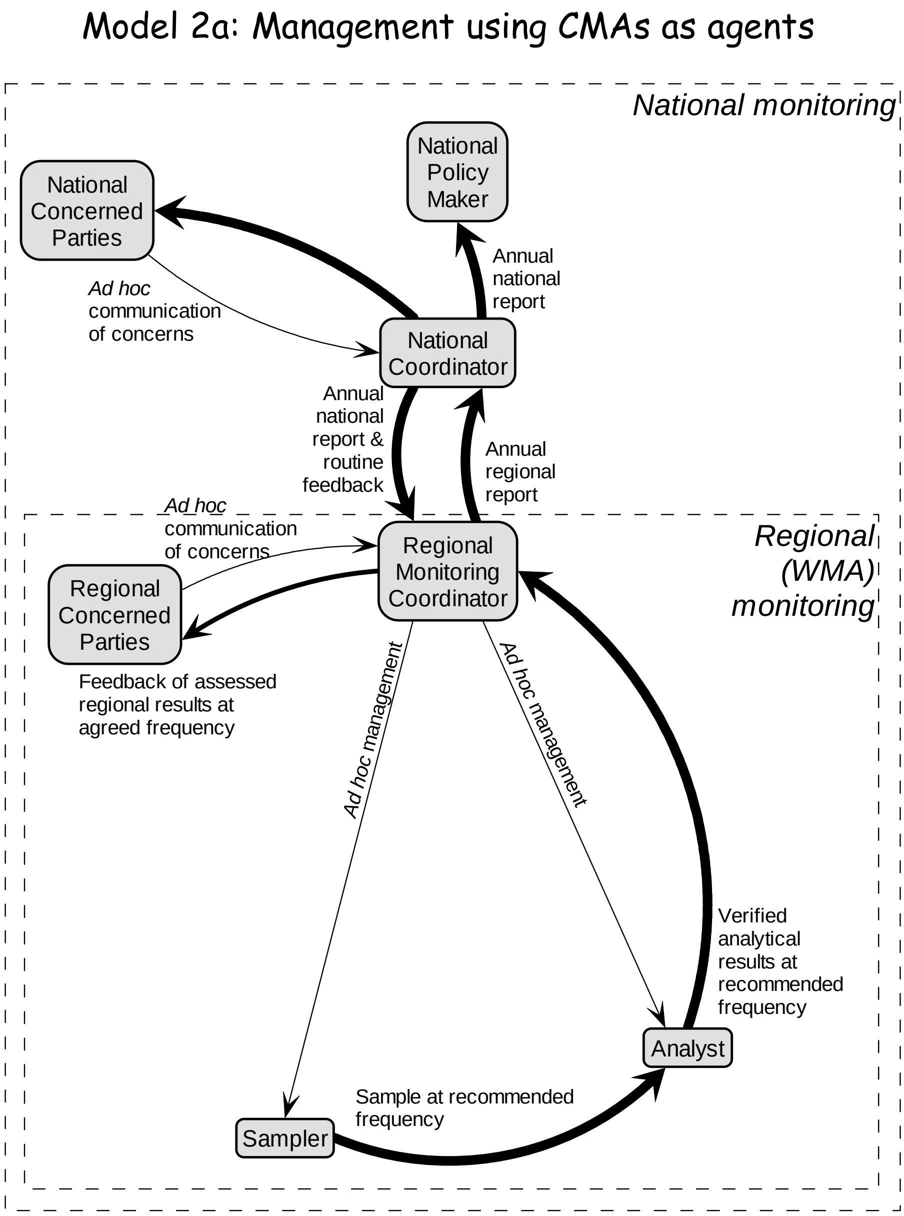

Figure 5.2. Model 2a: Roles and information flow.

5.2.4 Model 2b: Using CMAs sub-contracting local managers

From the point of view of the Department, this model is similar to model 2a because the Department delegates responsibility to a CMA (Figure 5.3). How the CMA manages sampling and analysis is of no primary concern to the Department. However, in this model the CMA further delegates responsibility to a local manager (a water board might be one example) so that direct management by the CMA of samplers and analysts is avoided. These local managers would be under contract to submit data and possibly reports to the CMA who then submits these to the National Coordinator.

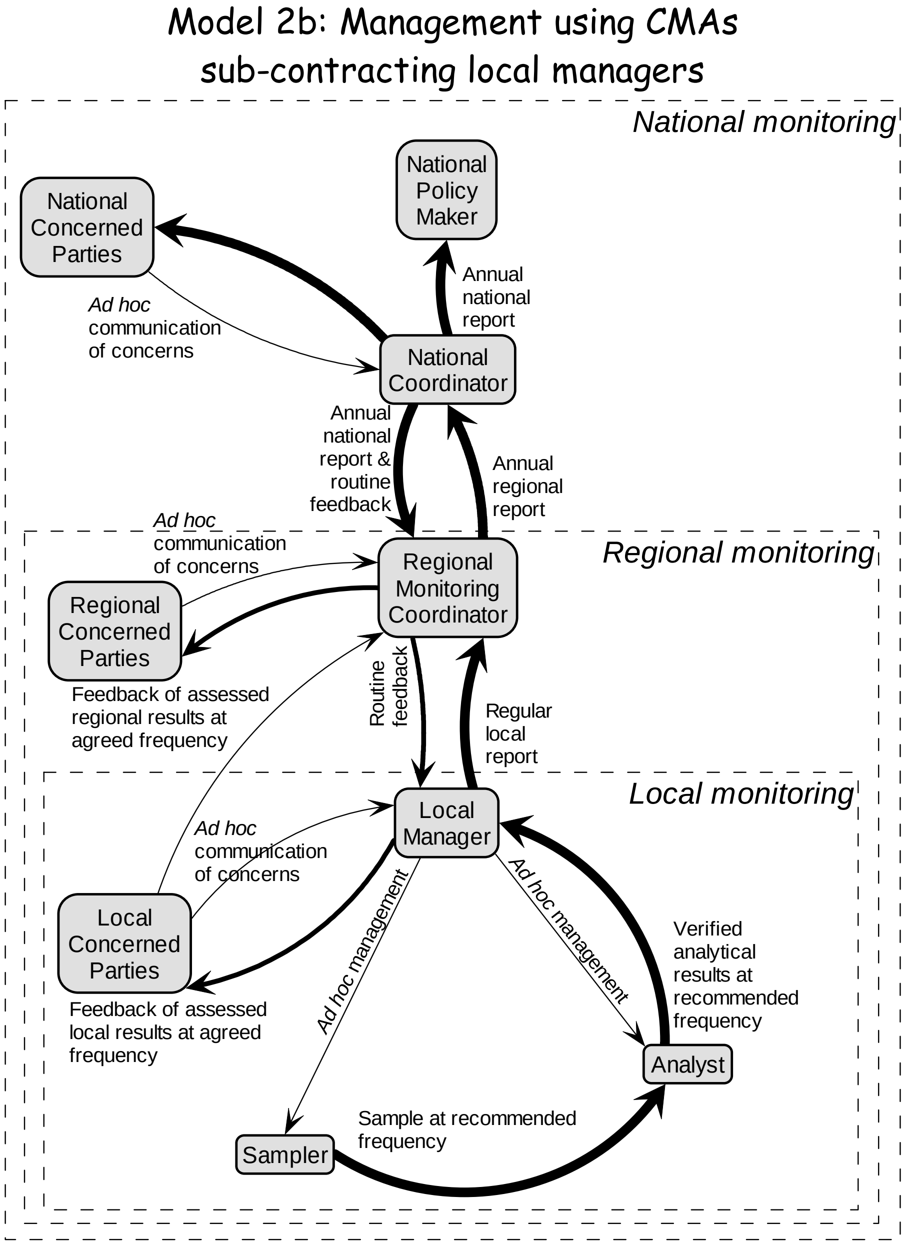

Figure 5.3. Model 2b: Roles and information flow.

5.3 NATIONAL POLICY MAKER

5.3.1 Summary of Role

The National Policy Maker receives annual reports from the National Coordinator. These reports are the “information products” that address the objectives of this monitoring programme. It is the responsibility of the National Policy Maker to use this information to implement current policy and facilitate the development of new policy if necessary for the national management of groundwater resources.

5.3.2 Typical Role Player

Minister of Water Affairs and Forestry, water affairs management committee.

5.3.3 Responsibilities

A Minister is generally responsible for the powers and functions assigned to him/her by the President. As a Member of Cabinet, he or she is accountable to Parliament for the exercise of these powers and the performance of their functions. A Member of Cabinet must (a) act in accordance with the constitution and (b) provide Parliament with full and regular reports concerning matters under their control.

The following extract from the National Water Act summarises in general terms the ultimate responsibility of the Minister of Water Affairs and Forestry.

Sustainability and equity are identified as central guiding principles in the protection, use, development, conservation, management and control of water resources. These guiding principles recognise the basic human needs of present and future generations, the need to protect water resources, the need to share some water resources with other countries, the need to promote social and economic development through the use of water and the need to establish suitable institutions in order to achieve the purpose of the Act. National Government, acting through the Minister, is responsible for the achievement of these fundamental principles in accordance with the Constitutional mandate for water reform. Being empowered to act on behalf of the nation, the Minister has the ultimate responsibility to fulfil certain obligations relating to the use, allocation and protection of and access to water resources.

5.4 NATIONAL COORDINATOR

5.4.1 Summary of Role

The function is to facilitate, coordinate and manage the nationwide implementation of the monitoring programme so that the objectives are achieved. The National Coordinator will typically represent the Department in negotiations with regional and local parties, ensuring that the minimum requirements are in place to meet the national objectives. The National Coordinator will need to be familiar with all aspects of microbial monitoring of groundwater and should be able to provide technical and managerial advice to role players at all levels. The National Coordinator must ensure effective and efficient transfer of knowledge and experience gained by those involved in the programme. To ensure sustainability of the programme an assistant National Coordinator must be appointed as a shadow to the National Coordinator who can take over national coordination in the event of the absence or resignation of the National Coordinator.

5.4.2 Typical Role Player

A person from the Department of Water Affairs and Forestry (DWAF) with good managerial capabilities and a sound technical knowledge of geohydrology and preferably microbiology.

5.4.3 Responsibilities

5.4.3.1 Facilitate National Implementation

The National Coordinator should be the driving force behind initial and ongoing implementation on a national basis (see National Implementation chapter). This will involve choosing appropriate areas for initial implementation. A wide variety of issues must also be explicitly considered irrespective of which management models (1, 2a or 2b) are applied.

5.4.3.2 Facilitate Regional Implementation

With the experience gained from implementation in other areas, the National Coordinator should facilitate the implementation of monitoring programmes in new areas (see National Implementation chapter).

5.4.3.3 Communicate with National Concerned Parties

The National Coordinator must provide reports and feedback at an appropriate frequency to the extent deemed necessary to keep National Concerned Parties adequately informed.

5.5 NATIONAL CONCERNED PARTIES

5.5.1 Summary of Role

The National Concerned Parties receive the same annual reports from the National Coordinator that are sent to the National Policy Maker. It is their responsibility to communicate concerns and comments to the National Coordinator.

5.5.2 Typical Role Player

Any person or organisation with an interest in the national status of faecal contamination of groundwater. These include government departments like the Department of Water Affairs and Forestry (the custodian of the monitoring programme), the Department of Environmental Affairs and Tourism and the Department of Health. Non-governmental organisations may also be role players.

5.5.3 Responsibilities

Government departments should use the products of the monitoring programme to contribute constructively to strategic national decisions in the context of the fitness for use of groundwater.

National Concerned Parties must communicate their concerns and comments to the National Coordinator. It is the responsibility of the National Concerned Parties to become involved in the monitoring programme to the extent necessary to ensure that the programme produces information products that adequately reflect the status and trends of faecal contamination of groundwater.

5.6 REGIONAL MONITORING COORDINATOR

5.6.1 Summary of Role

The Regional Monitoring Coordinator has responsibilities assigned by the Department in respect of management and coordination in a particular Water Management Area (WMA). The primary role of the Regional Monitoring Coordinator is to initialise regional monitoring, ensure sustainability and ensure the regional monitoring data are forwarded to the National Coordinator. To ensure sustainability of the programme an assistant Regional Monitoring Coordinator must be appointed as a shadow to the Regional Monitoring Coordinator who can take over regional coordination in the event of the absence or resignation of the Regional Monitoring Coordinator.

5.6.2 Typical Role Player

Representative of Catchment Management Agency (CMA) or a regional Department of Water Affairs and Forestry (DWAF) office.

5.6.3 Responsibilities

5.6.3.1 Initialisation of new monitoring programmes

The Regional Monitoring Coordinator must collaborate closely with the National Coordinator to initialise microbial monitoring programmes of groundwater in a WMA until sufficient coverage of that WMA is achieved. A very similar process to that adopted by the National Coordinator should be carried out. See National Implementation chapter for details. Either of the two management models 2a or 2b may be applied, depending on available capacity within the CMA.

5.6.3.2 Ensure sustainability

The Regional Monitoring Coordinator must address the same kinds of issues as the National Coordinator to ensure sustainability of regional monitoring. See National Implementation chapter for details.

5.6.3.3 Communicate with Regional Concerned Parties

To the extent deemed necessary to keep Regional Concerned Parties (should they exist) adequately informed, the Regional Monitoring Coordinator must provide reports and feedback at an appropriate frequency.

5.7 REGIONAL CONCERNED PARTIES

5.7.1 Summary of Role

Regional Concerned Parties receive regular reports which serve their own regional (*i.e.* Water Management Area) interests. They can communicate concerns and comments to the Regional Monitoring Coordinator or the National Coordinator.

5.7.2 Typical Role Player

Water Quality Managers of regional offices of the Department of Water Affairs and Forestry (DWAF), Catchment Management Agencies (CMAs), regional offices of the Department of Health (DOH) and the Department of Environment and Tourism (DEAT) or any other regional organisation that regards itself as a stakeholder in the faecal contamination of groundwater resources in their Water Management Area.

5.7.3 Responsibilities

Regional Concerned Parties should communicate concerns and comments preferably to the Regional Monitoring Coordinator or to the National Coordinator. It is the responsibility of the Regional Concerned Parties to become involved to the extent necessary to ensure that the programme produces information products that adequately reflect the status and trends of faecal contamination of groundwater.

5.8 LOCAL MANAGER

5.8.1 Summary of Role

This role is applicable to management model 2b. Although typically under contract to the CMA, local day-to-day management will primarily be at the discretion of the Local Manager. The exact responsibilities of the Local Manager will be defined in the contract negotiated between the relevant organisation and the CMA. The Local Manager would typically ensure that the agreed samples are collected and analysed according to the requirements of the national monitoring programme and the data transmitted to the Regional Monitoring Coordinator at the agreed intervals.

5.8.2 Typical Role Player

Any organisation with an interest in the faecal contamination or use of a local groundwater resource. For example, the organisation may be wholly or partly responsible for some degree of faecal pollution or potentially be impacted by it.

5.8.3 Responsibilities

The Local Manager, in collaboration with the Regional Monitoring Coordinator, will initialise, manage and sustain a local monitoring programme according to the specifications of the national monitoring programme.

5.9 LOCAL CONCERNED PARTIES

5.9.1 Summary of Role

Local Concerned Parties receive regular reports which serve their own local interests. They can communicate concerns and comments to either the Local Manager or Regional Monitoring Coordinator.

5.9.2 Typical Role Player

Any organisation with an interest in the faecal contamination or use of a local groundwater resource.

5.9.3 Responsibilities

Local Concerned Parties should communicate concerns and comments to either the Local Manager or Regional Monitoring Coordinator. It is the responsibility of the Local Concerned Parties to become involved in the implementation of the programme to the extent necessary to ensure that the programme produces information products that adequately reflect the status and trends of faecal contamination of local groundwater.

5.10 ANALYST

5.10.1 Summary of Role

The Analyst receives samples from the Sampler. The samples should be analysed for the necessary monitoring variables within the specified timeframe. The results must be stored locally and transmitted to the Local Manager (management model 2b), Regional Monitoring Coordinator (management model 2a) or National Coordinator (management model 1) for inclusion in the national database.

5.10.2 Typical Role Player

A laboratory preferably accredited for the designated analytical methods.

5.10.3 Responsibilities

5.10.3.1 Sample Preservation

Before and after analysis, samples must be stored in a cool room.

5.10.3.2 Sample Analysis

Samples must be analysed using the agreed analytical method. Appropriate laboratory quality assurance and quality control procedures must be adhered to. See Monitoring Framework chapter for details.

5.10.3.3 Results transmission

Results must be transmitted to the appropriate managing organisation at the agreed frequency in the recommended format.

5.11 SAMPLER

5.11.1 Summary of Role

The Sampler physically travels to the designated sampling sites at the agreed frequency, takes the samples, prepares and preserves them following the recommended procedures, labels the containers with the date and sample site identification and delivers the sample containers to the Analyst.

5.11.2 Typical Role Player

Laboratory, Catchment Management Agency or a regional Department of Water Affairs and Forestry officer, the water board, a local authority or local officials of the Department of Health who has undergone adequate training in the sampling methods necessary for this monitoring programme.

5.11.3 Responsibilities

5.11.3.1 Preparation

All the necessary equipment should be checked and it should be ensured that report sheets are at hand before departing for the sampling site.

5.11.3.2 On site

The recommended procedures specifications (or the agreed alternatives) should be followed closely. See Monitoring Framework chapter for more details. The necessary samples should be collected, prepared and preserved according to specifications and sample containers labelled.

5.11.3.3 Delivery

Samples should be delivered to the assigned laboratory within 24 hours.

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APPENDIX A: *PRO FORMA* DRILLING SPECIFICATIONS

Text in italics should be modified as appropriate

A.1 Services

(a) The services to be rendered are the drilling, insertion of casing/screen, development and blow testing of *6 (six) to 8 (eight)* boreholes.

(b) The drilling areas are within a radius of approximately *150 km from Pretoria* as indicated on the attached map.

(c) Tenderers are urged in their own interest to acquaint themselves with the nature of the terrain. No allowance will be made for the improvement of the access to the drilling sites.

A.2 Equipment

Percussion drilling equipment is required for hard-rock aquifers. In sandy aquifers shallow boreholes should use water jetting while, for deeper boreholes, air flush rotary drilling can be used (though only when absolutely necessary).

A.3 Workmanship

The Contractor shall perform all work entrusted to him in an efficient, thorough and workmanlike manner in accordance with this contract and to the satisfaction of the engineer.

A.4 Geological formations

The geological formations encountered will probably be:

(a) A few metres of soil (or decomposed norite) cover followed by weathered and solid Bushveld norite. Groundwater levels are expected to be from a depth of approximately 10 m, although shallower groundwater may be expected in places.

(b) A few metres of soil (or decomposed shale or sandstone) cover followed by weathered and solid shale and/or sandstone (Karoo Sequence). It is possible that dolerite/diabase may be encountered in places. Groundwater levels are expected to be from a depth of approximately 10 m, although shallower groundwater may be expected in places.

A.5 Drilling of boreholes and casing installation

It is envisaged that *SIX (6) to EIGHT (8)* monitoring boreholes will be required for the above. The engineer reserves the right to terminate this contract prior to the completion of 6 boreholes at his discretion or to increase the number to more than 8.

A.5.1 Technical requirements – monitoring boreholes

(a) The average depth of the boreholes will be approximately *30 m*. The maximum depth is expected to be *50 m*.

(b) Borehole diameter shall be *165 mm*.

(c) Solid steel casing (*165 mm* diameter) shall be installed in the upper section of the borehole (depending on site specific conditions) to prevent collapse of the borehole.

(d) Upon completion of drilling, solid and perforated *127 mm ID (140 mm OD*) threaded uPVC casing (for example type produced by Water Technology Plastic Industries (WTPI), Kya Sands) shall be installed according to the following specifications:

- A uPVC end cap shall be placed at the lower 3 m solid uPVC section of the casing. Depth of the perforated sections will be specified by the Engineer supervising the drilling on completion of the borehole. It is expected that no more than 9 m of perforated casing will be required per borehole. Depending on site conditions, this length may however be increased at the discretion of the Engineer.
- The annulus between the uPVC casing and the drilled borehole will be backfilled with 6 mm crushed rock chips.

(e) The uPVC casing/screen will be centralised in the *165 mm* ID bore (using centralisers).

(f) All boreholes shall be sealed to prevent ingress of potentially contaminated surface water in the first 5 metres below ground surface by means of the cement/bentonite grouting method which comprises the grouting of the annulus between the borehole and the casing (Figure 1). The seal must consist of Portland cement mixed to a slurry with bentonite and water which is free of oil and organic matter. The bentonite and water should be thoroughly mixed in the ratio of 2 kg bentonite to 25 ℓ of water prior to adding and mixing in 50 kg of Portland cement.

(g) The contactor shall provide new borehole casing and screens for the installations.

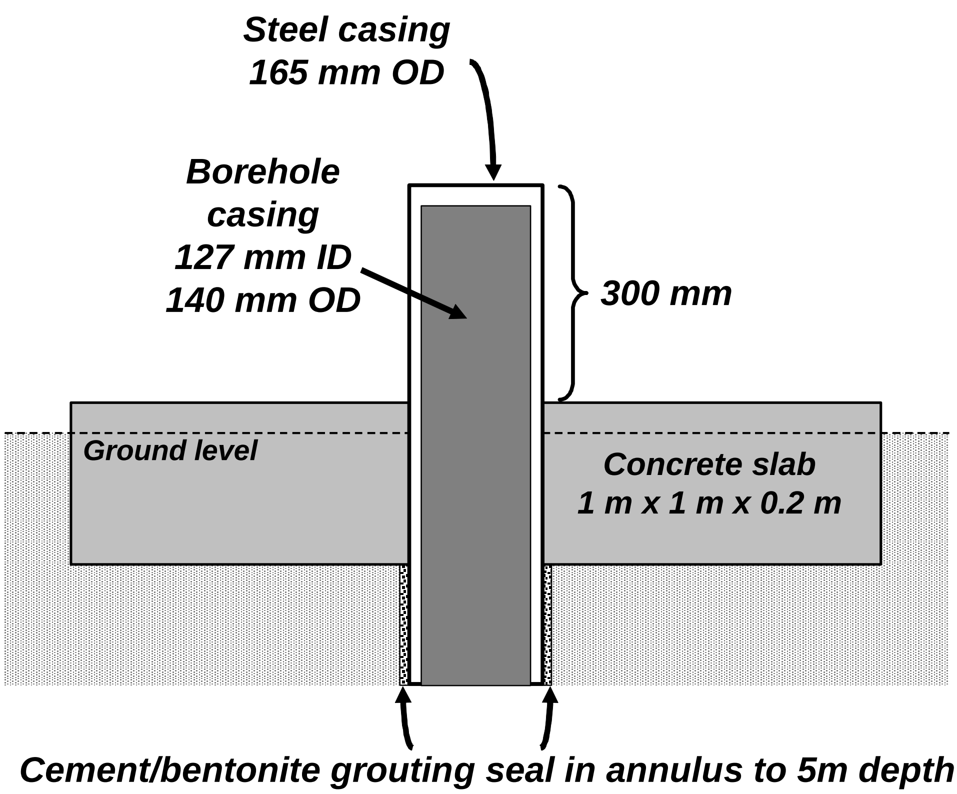

Figure 1: Illustration of borehole sealing specifications.

A.6 Straightness and verticality of boreholes

According to the SANS water borehole standards (SANS 10299-2:2003).

A.7 Borehole development and blow yield test

After the completion of the drilling, the borehole and site shall be cleaned of all drilling debris to ensure that a reliable blow yield test can be done. A 30-minute blow yield shall be done on each borehole and the flow rate shall be tested with a 200 ℓ drum.

A.8 Sampling and Drilling notes

(a) Samples of the formations shall be taken at one-metre intervals and at any formation change, or as directed and shall be kept at the drilling site while drilling is in progress. After drying, the samples shall be placed in plastic bags.
(b) Records of water interception, penetration rate, and other relevant drilling information shall be kept and supplied to the Engineer on completion of each borehole drilling rate. DW77 Geohydrological Data Entry Form (obtainable from the Department of Water Affairs and Forestry, Pretoria, Directorate: Hydrological Services) will be used to record these data.

A.9 Borehole completion

(a) Completed boreholes shall be capped with concrete slabs of 1 m x 1 m x 0.2 m (Figure 1).
(b) All boreholes are to be sealed with the standard lockable DWAF caps.
(c) The casing shall extend 300 mm above the concrete slab but no higher.

A.10 Completion forms

DW77 Geohydrological Data Entry Form.

A.11 Cleaning up of drill sites

All equipment and debris shall be removed and the site left in a state that facilitates future easy access to the borehole.

References

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