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Guidance on the design and installation of groundwater quality monitoring points

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Steve Killeen

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Head of Science

Executive summary

This report offers practical guidance on the design, construction and installation of groundwater quality monitoring points (GQMP) that will help to improve industry practice along with the quality of monitoring data. The main objective in designing a GQMP is to ensure that representative groundwater samples can be collected. Good design and installation are essential to achieving this goal.

This guidance concentrates on the more common procedures for GQMP design, installation, borehole development, maintenance, rehabilitation and decommissioning. Where unusual or novel practices are employed, users may need to adopt additional measures on top of the general advice in this report to ensure that the GQMP meets monitoring objectives.

It is assumed that, prior to undertaking the design process, a decision to drill and install a GQMP has been taken and that the reasons for installing that point are clearly defined. The design process requires the monitoring objectives to be clearly defined from the start, although these may be revised during the design process, where additional information and other considerations such as cost may arise.

Monitoring objectives

Groundwater monitoring objectives can be divided into three broad categories.

Strategic monitoring is employed to obtain background water quality information, which can be used to determine broad groundwater quality, diffuse pollution trends, problems and long-term changes in groundwater quality.

Defensive monitoring is normally undertaken within and around an actual or potential problem site, or a sensitive receptor, to provide information on the impact of a known or suspected source of contamination. It can also indicate the absence of contaminants and can be used to assess the success of a clean-up operation.

Investigative drilling is used to improve the conceptual understanding of a site. It can detect contaminants on known problem sites and can identify interactions between groundwater and the greater environment, such as interactions between groundwater and surface water or a habitat.

There may be other reasons for drilling a GQMP which will also influence the design process, particularly the choice of drilling technique. It is important to determine at an early stage whether all objectives can be accommodated in a single borehole drilling operation without compromising the monitoring ones.

Design

Initial design should be a quick and relatively simple process, focussing on the design basics such as drilling method, GQMP positioning and objectives. It is

undertaken primarily to identify potential pitfalls and problems, the likely budget for the work and significant health and safety issues. This stage also serves to refine the monitoring objectives to ensure they are achievable. A brief outline design should be undertaken prior to beginning detailed design. This process may be iterative to permit consideration of different options.

At the detailed design stage, the initial design is refined to sufficient detail for the work to be commissioned from drilling contractors. Health and safety requirements should be formalised and accurate costs produced. The user should also confirm the suitability of the design with a regulator.

Construction

The guidance covers the requirements of the construction process, including the need for supervision and the role of the supervisor; necessary documentation; the sequence of construction; and borehole development (the process of returning the conditions around the GQMP to as close to those prior to drilling).

Post-construction activities other than groundwater sampling include:

- maintenance, which involves routine activities to maintain the performance of the GQMP. Correctly installed GQMPs should not, in general, need much maintenance;
- rehabilitation, involving both major and occasional work to restore the performance of the GQMP;
- decommissioning, to ensure that the GQMP does not become a pathway for contaminant migration.

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Glossary and abbreviations

ABS	Acrylonitrile butadiene styrene. A rigid thermoplastic.
Absorption	The incorporation of a chemical within a solid or liquid.
Adsorption	The attachment of a chemical to the surface of a solid or liquid.
Aquifer	A permeable geological stratum or formation that is capable of both storing and transmitting water in significant quantities.
Artesian	The condition where the true level of groundwater is above ground surface but is prevented from rising to this level by an overlying continuous low permeability layer, such as clay.
Bentonite	A naturally occurring clay that swells when mixed with water. Refined bentonite is used to make a watertight seal. Sodium is often added in the refining process to enhance the swelling properties.
Borehole	A hole drilled into the ground, usually with a relatively small diameter.
Blow/blowing	The flowing of (commonly fine) fluidised sand upwards into a length of temporary casing or borehole due to pressure imbalances.
Casing (well casing)	A solid-wall tube installed within a borehole.
Confined	The condition where groundwater is prevented from rising to its true level by an overlying low permeability layer, such as clay.
Creep	The slow movement of ground as it slips or is displaced.
Dense non-aqueous phase liquid (DNAPL)	A liquid that is immiscible with water and that has a greater density than water and so sinks in water.
Filter (pack)	A zone of granular material placed around the well screen, which limits ingress of solid materials.
Free-phase contamination	Product (such as gasoline or diesel) which is present in its original (undissolved) liquid state.
Geotextile	A synthetic fabric used for environmental

	applications.
Groundwater	All water which is below the surface of the ground, in the saturated zone, and in direct contact with the ground or subsoil.
Groundwater level	The water level measured in a borehole.
Grout	A pumpable cement-based liquid that dries to form a seal.
GQMP	Groundwater quality monitoring point.
Headworks	The surface completion of a borehole.
HDPE	High density polyethylene. A rigid thermoplastic.
Hydraulic conductivity	A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity (dimension length/time). Hydraulic conductivity is often reported in units of m/s or m/d.
Hydraulic gradient	The change in hydraulic head with distance in the direction of groundwater flow.
Hydraulic head	The sum of the elevation head, the pressure head, and the velocity head at a given point in an aquifer.
Intergranular	Occurring between the grains of a rock or soil.
Light non-aqueous phase liquid (LNAPL)	A liquid that is immiscible with water and that has a lower density than water and so floats on water.
Multi-level sampling device	A device which permits the collection of water samples from a number of discrete locations within a single borehole.
ODEX	A rotary percussive drilling technique in which the casing is advanced while simultaneously drilling a borehole. It is used to support the walls of a borehole in unstable formations.
pH	The pH of a solution is the negative logarithm of the hydrogen ion activity in moles per litre. In pure water, there are an equal number of hydrogen ions and hydroxide ions. The concentration of these ions (in moles per litre) is deduced from the dissociation constant (K_D) for water, where $$K_D = [H^+].[OH^-]$$

	At 25ºC, K_D is approximately equal to 1×10^{-14}.
Permeability	General measure of the ability of a medium to transmit a fluid. More specifically measured as hydraulic conductivity and intrinsic permeability.
Photolysis	Chemical transformation caused by exposure to light.
Plume	A continuous region of groundwater containing dissolved contaminants. Plumes form down hydraulic gradient of contaminant sources. Contaminants within plumes are subject to advection and dispersion and may be subject to degradation and retardation.
Porosity	The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.
PTFE	Polytetrafluoroethylene. Fluoropolymer plastic with a very high resistance to weathering and chemical attack.
PWS	Public water supply.
Response zone	The section of a borehole or GQMP that is open to the host strata.
Screen	The section of borehole casing that is perforated with either slots or holes to allow the entry of groundwater.
SAC	Special area of conservation. Sites protected under the Habitats Directive because they are important for species other than birds.
SPA	Special protection area. Sites protected under the EC Direction on the Conservation of Wild Birds (1979).
SSSI	Site of special scientific interest. Conservation sites of particular interest for their flora, fauna, geological or physiographical features. The sites are protected under the Wildlife and Countryside Act 1981, as amended by the Countryside and Rights of Way Act 2000.
Saturated zone	The zone in which the voids of the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

Sorption	Absorption and adsorption considered jointly.
Surface water	Water standing on, or flowing over the ground surface (for example, in rivers, lakes, streams, ditches, ponds).
Surface water runoff	Flowing surface water resulting from rainfall.
Tremmie pipe	A pipe placed in the annulus of a borehole during installation for the purpose of placing filter materials and sealants. Typical diameters are 25 or 50 mm.
Unsaturated zone (vadose zone)	The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies, such as perched groundwater may exist in the unsaturated zone. Also called the vadose zone.
uPVC	Unplasticised polyvinyl chloride. A rigid thermoplastic.
Water table	The depth at which groundwater pressure is equal to atmospheric pressure.
Water strike	The depth at which groundwater is encountered during drilling. This may be different to the water table due to the presence of confining layers.
Well screen	See screen.

Underlined words appear elsewhere in the glossary.

1. Introduction

1.1 Aims of the report

The purpose of this report is to provide practical guidance on the design, construction and installation of groundwater quality monitoring points (GQMP) that will help to improve industry practice along with the quality of monitoring data. Good design and installation ensures that representative samples of groundwater can be collected, which is.essential for accurate measurements of groundwater chemistry.

GQMP design and installation is often undertaken on an *ad hoc* basis, with little consistency of approach between and within organisations. There is, at present, no single UK guidance document that sets out a comprehensive approach to the design and installation of GQMPs. As a result, design is often based on experience, instinct, or simply repeating what was done last time. A consequence of the lack of guidance is that many inappropriate GQMPs have been installed, leading to problems in understanding and interpreting groundwater quality data.

Whilst it is generally recognised that any water quality information is better than none, good quality information is significantly better than information that is not fit for the purpose. Representative groundwater quality information can only be obtained through the use of appropriate drilling techniques, monitoring installations and sampling and analytical techniques. Good quality data is best achieved by following good procedures such as those set out in this report, and by documenting the design, installation and completion processes.

This report outlines existing procedures and guidance on GQMP design and installation. It is compiled from diverse existing UK guidance information, supplemented where appropriate by international good practice guidance, and from accepted good practice within the UK.

There is an inherent difficulty in prescribing the design and installation of GQMPs, which arises from a typical lack of information on geological and hydrogeological conditions prior to the start of drilling. For example, a mapped gravel deposit may be found to contain clay or silt layers, and thus the length or depth of installation agreed prior to the fieldwork require modification in the field. Users will need to combine judgement and experience, particularly those working or supervising in the field.

This report concentrates on the more common procedures for GQMP design, installation, development, maintenance, rehabilitation and decommissioning. Where unusual or novel practices are employed, users may need to adopt additional measures on top of the general advice in this report to ensure that the GQMP meets monitoring objectives

The guidance covers issues and considerations associated with GQMPs of less than 100 m depth and installation diameters of less than 150 mm; installations of greater dimensions are rarely used in the UK for the sole purpose of monitoring. However, for GQMPs of greater dimensions the report offers a process for design and installation.

Activities associated with GQMP installation which are not covered in this report include:

- setting of monitoring objectives;
- leachate monitoring within waste (see Environment Agency 2003a);
- horizontal boreholes and directional drilling;
- site investigation techniques for obtaining samples or undertaking *in situ* tests (see BS5930:1999);
- groundwater sampling, other than consideration of installation size (see ISO 5667-18);
- groundwater monitoring network design (Environment Agency 2003b);
- legal/legislative issues, except where they influence the design or installation;
- health and safety issues associated with contaminated land, borehole drilling and installation other than those that influence the design;
- contractual issues (such as types of contract to be used or dispute resolution);
- access (in other words difficult ground conditions, limited headroom or drilling over water) which should not greatly influence the design;
- assessing the suitability of existing installations for groundwater quality monitoring.

1.2 How to use the technical guidance

It is assumed that, prior to undertaking the design process, a decision to drill and install a GQMP has been taken and the reasons for the installation of that point are clearly defined.

In this report, the user's objectives for monitoring are categorised and used to undertake an initial or outline design before moving to detailed design. The initial stage helps to identify critical design issues and establish whether these will affect the monitoring objectives. Preliminary information is shared with clients, drillers, landowners and other involved parties before finalising the design in the detailed design stage.

Once the design is finalised, materials, quantities and techniques are specified and communicated to the driller or installer. The installation stage outlined in this report covers the operation of constructing the GQMP. Other issues are considered in final section of the report.

The process of initial design, detailed design, drilling and installation is summarised in a flow chart (Figure 1.1). Figure 1.2 provides a more detailed flow chart in which references to the relevant sections and tables of this report are given for each step.

Following the construction and development of the GQMP, the installation can be considered complete and sampling can commence. However, there may be a need for regular inspection and/or maintenance during the active life span of the GQMP.

Upon completion of a monitoring programme, and where the GQMP is suspected as a preferential pathway for groundwater or contaminant migration, there may be a need to decommission the installation.

1.3 Other sources of guidance

There are a number of existing sources of UK guidance on various aspects of the design and installation of GQMPs. This report is designed as a stand-alone, but reference is made to other guidance documents where applicable. Guidance documents of particular relevance are given in Box 1.

Box 1: Relevant guidance documents

Guidance on the monitoring of landfill leachate, groundwater and surface water, Environment Agency (2003), Ref. LFTGN02. Provides technical guidance on the monitoring requirements around landfill sites. Appendix 4 describes borehole drilling methods; Appendix 5 describes borehole completion methods and Appendix 6 explains borehole inspection and maintenance.

A guide to monitoring water levels and flows at wetland sites, Environment Agency (2003c). This booklet describes good practice for monitoring water levels around wetland sites, including appropriate GQMP design.

BS 5930: 1999 *Code of practice for site investigations*.

Specification for ground investigation, Site Investigation Steering Group (1993a). Provides detailed specification for many aspects of GQMP installation, including a bill of quantities.

Water supply borehole construction and headworks guide to good practice, Environment Agency Information Pamphlet (undated).

Decommissioning abandoned boreholes and wells, Environment Agency Information Pamphlet (2004).

Health and safety manual for land drilling: a code of safe drilling practice, British Drilling Association (2002). This manual describes safe working practices, compliance with health and safety legislation and compliance with relevant standards.

BS 6068-6.18: 2001 (ISO5667-18:2001) *Water quality sampling*: *guidance on sampling of groundwater at contaminated sites*. This reference briefly describes borehole drilling and installation materials, sampling equipment and sample collection.

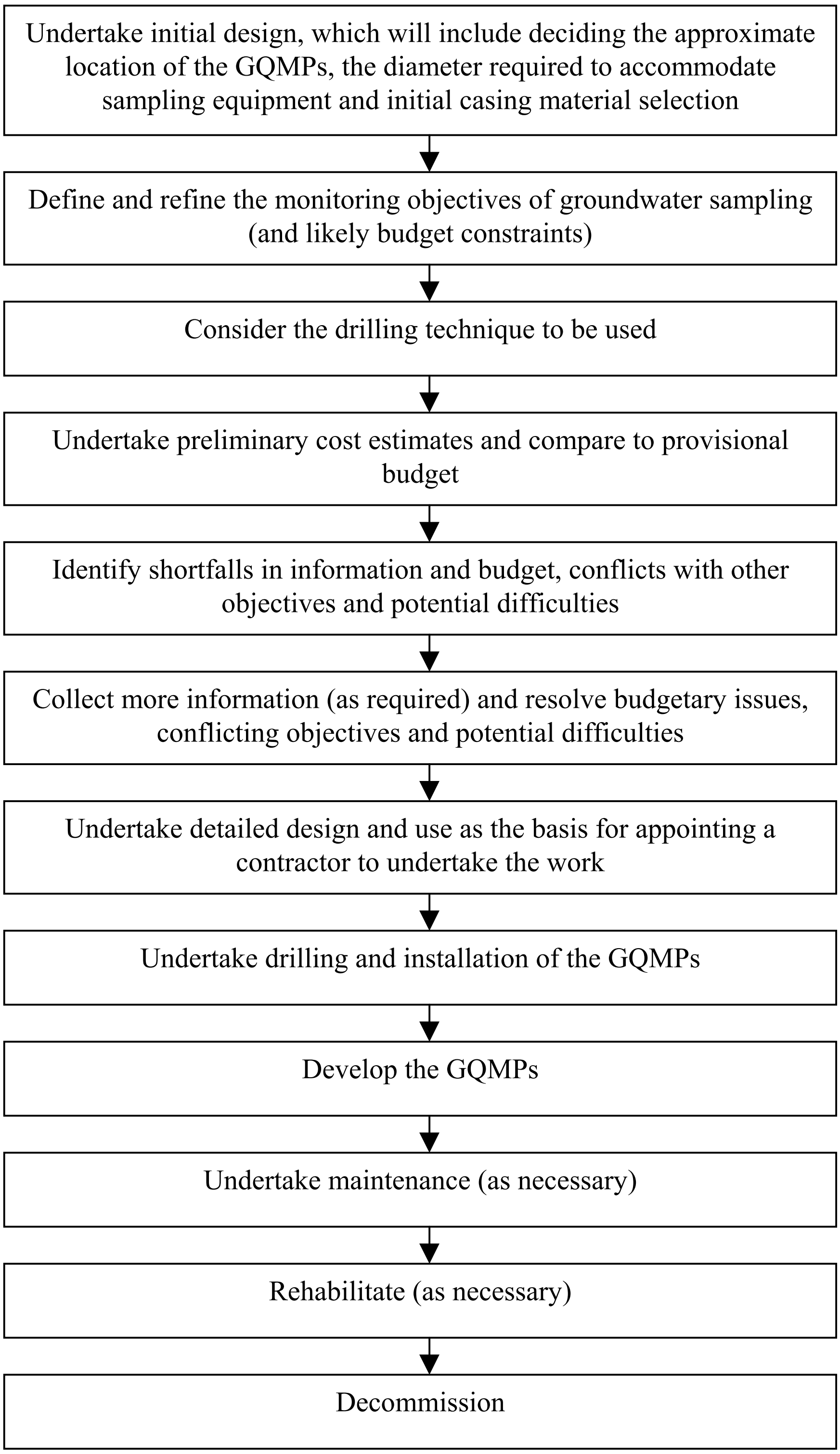

Figure 1.1 GQMP design and installation summary flow chart

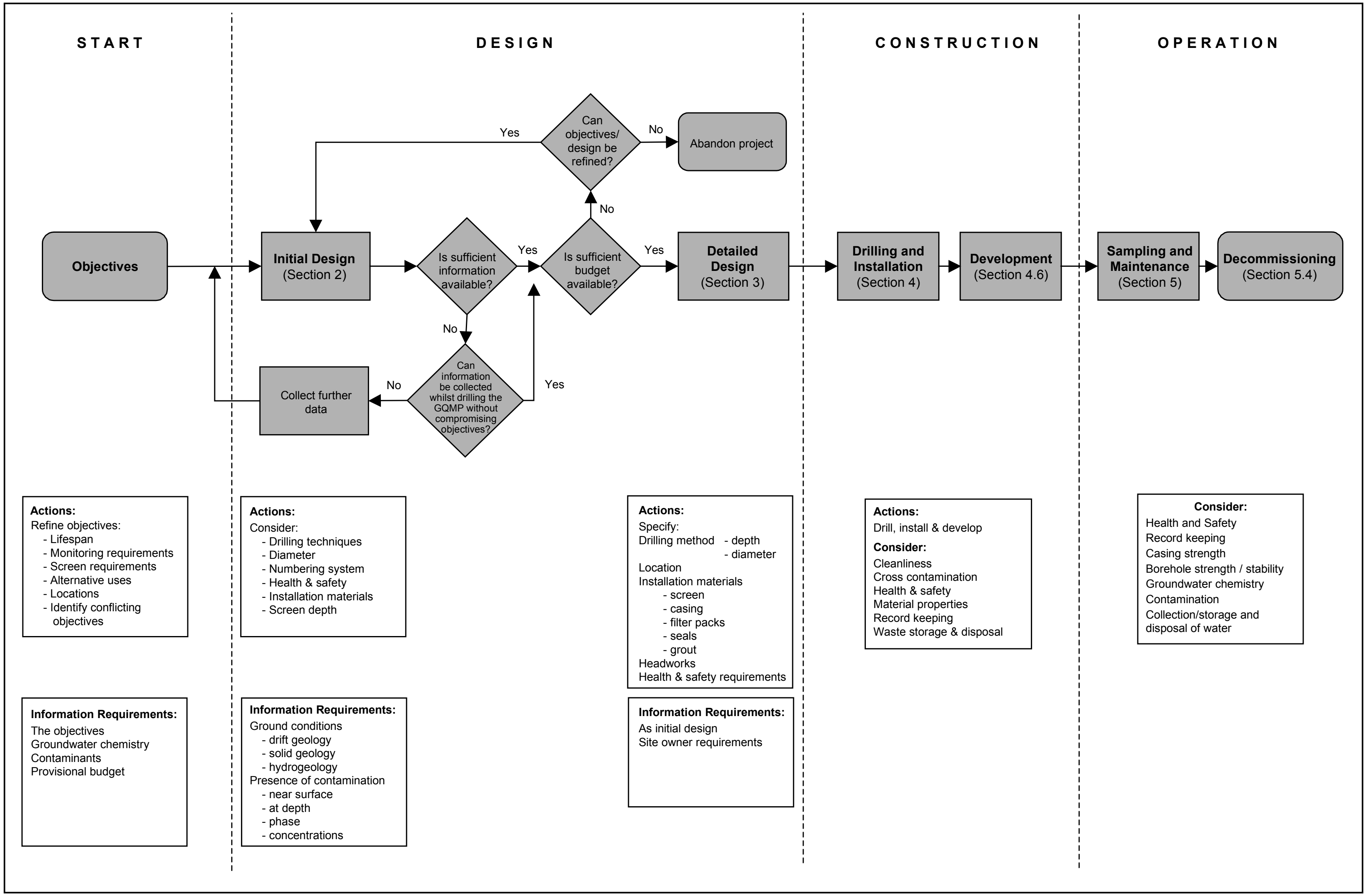

Figure 1.2 GQMP design and installation detailed flow chart

2. Monitoring objectives and initial design

2.1 Introduction

To ensure compatibility between the monitoring objectives and the GQMP design, different drilling techniques and installation options should be considered in the initial design process. This step permits the designer to identify and prioritise decisions which need to be made and helps in the initial budget estimate. It is assumed that the reasons for the GQMP installation are clearly understood at the outset.

The initial design may also be used as the basis of preliminary discussions with interested and participating groups including regulators, the client, drillers and landowners.

Users then move on to the detailed design (Section 3). At this stage, specifications are prepared and quantities defined (if this is the route for procuring drilling services).

The initial design process may go through a number of iterations during which additional detail is added or different options considered. There will be some overlap between the two design stages and this is reflected in a degree of repetition in the text.

At the end of the initial stage the following aspects of the design should be established:

- borehole depth and diameter;
- screen and casing depth and diameter;
- preferred drilling technique;
- headworks design (in principle);
- cost estimates;
- organisations which may need to be consulted

A checklist is included in Appendix A to aid the compilation of information required in the initial design process.

2.2 Monitoring objectives

2.2.1 Definitions

The principal monitoring objective of all GQMPs is to ensure that representative groundwater samples of known provenance can be collected.

It is essential that monitoring objectives are clearly defined at the outset. These may be revised during the design process as additional information and other considerations such as cost are added. The design may also be refined during site work (Section 4) as more data becomes available.

Groundwater quality monitoring objectives can be divided into three broad categories: strategic, defensive and investigative monitoring (see Tables 2.1 to 2.3).

Strategic monitoring collects background water quality information which can be used to identify broad groundwater quality, diffuse pollution trends, problems and long-term changes in groundwater quality;

Defensive monitoring is undertaken within and around an actual or potential problem site to assess the impact of a known or suspected source of contamination, or to indicate the absence of contamination. This type of monitoring may be carried out around landfills or authorised disposal operations such as sewage disposal or pesticide and sheep dip disposal. Defensive monitoring may also be used to assess the performance of groundwater clean-up operations such as natural attenuation, permeable reactive barriers, groundwater pump and treat schemes.

Groundwater investigations are typically employed at known or suspected sites of land contamination, to monitor contaminants such as free-phase liquids and characterise plumes of contaminated groundwater. They may also be used to explore the impact of human activity such as abstraction or construction.

Table 2.1 Groundwater monitoring objectives - Strategic monitoring

Main objective	**Subsidiary/Potentially conflicting objective** [1]	**Key design issues**
General		Trace concentrations of diffuse contaminants REDOX conditions at the borehole
To obtain representative groundwater samples for an aquifer unit or groundwater body	Monitor diffuse pollution	Screen length and depth Sealing Contamination during drilling and construction
To obtain samples to permit monitoring of the effect on water quality of surface water/groundwater interaction		Headworks flooding Drilling at a sensitive location such as SSSI or SAC

[1] All GQMP are likely to be used for water level measurements.
SSSI = Site of special scientific interest
SAC = Special area of conservation

Table 2.2 Groundwater monitoring objectives - Defensive monitoring

Main objective	Subsidiary/Potentially conflicting objective[1]	Key design issues
Monitoring of groundwater quality around a licensed activity site to: determine upgradient groundwater quality; give early warning of adverse impacts of the activity on groundwater; monitor any existing contamination or pollution	Determine background water quality pre-landfilling Obtain soil and rock samples Soil gas monitoring	Long-term use Contamination during drilling and construction
To obtain information on local natural groundwater quality at a sensitive site		Long-term use Drilling at a sensitive location such as SSSI or SAC
'Requisite surveillance' for authorised discharges to ground		Long-term use Casing/contaminant compatibility
Monitoring at a sensitive receptor		Long-term use Drilling at a sensitive location such as SSSI or SAC
Monitor the performance of groundwater clean-up schemes		Long-term use Casing / contaminant compatibility

[1] All GQMP are likely to be used for water level measurements.
SSSI = Site of special scientific interest
SAC = Special area of conservation

Table 2.3 Groundwater monitoring objectives - Investigative monitoring

Main objective	Subsidiary/Potentially conflicting objective [1]	Key design issues
Determine the quality of groundwater beneath	Obtain soil and rock samples	Avoidance of cross-contamination during

potentially or known land contamination Determine characteristics of groundwater contamination in a plume	GQMP may be required for long-term monitoring Soil gas monitoring	drilling Avoidance of contaminant migration pathway creation Monitoring of free-phase liquids

[1] All GQMP are likely to be used for water level measurements.

This report assumes that the reasons for setting up a GQMP are identified prior to starting the design process. However, some GQMPs will undergo a change in monitoring objectives during their lifespan. For instance, a borehole installed as part of an investigation of land contamination may later be required to serve as defensive monitoring borehole for a remediation scheme. Likely and potential changes in use should be considered at the design stage and accommodated where possible.

The principal differences between the objectives that will influence the design process include the concentrations and understanding of of substances of interest. For example, monitoring which requires analysis of background or trace concentrations will require more careful consideration of materials used. The design process may also be influenced by the estimated lifespan of the monitoring scheme. Short-term and long-term boreholes will differ in the quality of the installation, particularly the headworks, and the time and effort spent on borehole development.

2.2.2 Other objectives

Boreholes may be drilled for a number of reasons in addition to the need for a GQMP. These include the recovery of disturbed/undisturbed soil or rock samples; monitoring and downhole geophysical logging

Accommodating these further objectives will influence a number of factors within the design process, particularly the choice of drilling technique. It is important to determine at an early stage whether all objectives can be accommodated in a single borehole drilling operation without compromising the monitoring ones.

2.3 Initial design

2.3.1 Introduction

Initial design should be a quick and relatively simple process, focussing on the design basics and available options for drilling methods (particularly flushing medium), borehole placement and installation design. It is undertaken to identify potential pitfalls and problems, the likely budget for the work, significant health and safety issues and the need to consult interested or involved organisations.

There will be a degree of overlap between the initial and detailed design (Section 3), and as such reference is made in the text to the detailed design section to avoid undue repetition.

2.3.2 Drilling methods

Some understanding of the site geology and the anticipated depth and diameter of drilling is required to enable a drilling method to be selected.

Commonly-available drilling techniques are summarised in Appendix B, along with their main advantages and disadvantages. More detailed information will be available from specialist contractors. The inclusion of drilling contractors and equipment suppliers in the design process will depend on the contractual environment. It is recommended that specialist advice - paramount for complex installations - is obtained at the earliest possible stage.

In the UK, drilling in soils to depths of 50 m is generally undertaken using cable tool methods. Depths in excess of 50 m and drilling into rock typically involve rotary techniques. Other methods less commonly used in soils include augering to shallow depths and direct push. Jetting is sometimes used in granular materials where a large number of GQMPs are to be installed.

The presence and type of contamination within soil and groundwater at the drilling location will also influence the selection of the drilling technique. For example, the presence of volatile organic compounds (VOCs) may exclude the use of air flush which could volatilise these compounds and, where concentrations are high, create explosive and inhalation risks.

The need for specialist drilling techniques to minimise the risk of cross-contamination from mobile contaminants between aquifer units may also affect the choice of drilling technique. A common method of isolating contaminants is telescopic drilling - see Box 2.

Box 2: Telescopic drilling

Telescopic drilling is a technique used to minimise cross-contamination in layered aquifer systems. In brief, a borehole and temporary casing is advanced until a low permeability layer is encountered. The temporary casing is sealed into this layer and a second, narrower string of temporary casing is installed within it to permit drilling to continue.

The technique may require the borehole to be started at a larger diameter than conventional drilling and may also require the use of additional lengths of casing.

When undertaking telescopic drilling with a cable tool rig, the surging of the shell within the temporary casing (and the action of moving the casing deeper into the borehole) may dislodge the outer casing. Therefore in gross contamination situations, consideration should be given to installing a double seal with three strings of casing. This will reduce further the opportunity for contaminants to migrate into lower aquifer systems. Where critical, casing can be sealed into place with bentonite and cement grout.

Inclined boreholes may be drilled to investigate the interaction of groundwater and surface water, or where direct vertical access is not possible. These boreholes are drilled at a steep angle (typically 70° from the horizontal or steeper) using rotary techniques. It is not possible to drill inclined boreholes using cable tool techniques. Inclined drilling in unconsolidated deposits may require the use of a drilling mud to stabilise the borehole walls, although this may compromise subsequent sample reliability.

The drilling of inclined boreholes entails a number of considerations, including the use of temporary or permanent driven casing which may be required in formations that are prone to collapse, slumping or slipping under gravity but which will stand open in vertical boreholes.

Care is needed to ensure that the borehole maintains the correct angle throughout its length; where this is critical, down borehole surveying may be required. Consideration should be given to use of suitable sampling equipment and centralisers, where the well screen and casing may require centralisers to hold it clear of the sides of the borehole.

A longer inclined borehole may be required to reach the same depth as an equivalent vertical one and this could impact on the quantities required and the waste generated during drilling.

Boreholes at shallower angles are the realm of directional drilling and require specialist equipment. Such boreholes raise a number of further issues not covered in this guidance and specialist advice should be sought if such boreholes are being considered for GQMPs.

2.3.3 Response zone depth and length

The response zone is the section of installation that is open to the aquifer and includes the filter pack and the well screen. The well screen allows contact between the filter pack and the casing via a series of slots or other openings. The filter pack may be longer than the well screen and the filter pack's (response zone) length is constrained by sealing (such as bentonite) in the annulus of the borehole.

The depth of the drilled borehole and the length and location of the well screen will be determined by the monitoring objectives - in other words, the depth to the aquifer required to be monitored, the type of liquids to be monitored such as groundwater and/or non-aqueous phase liquid (NAPL) and the depth to the water table. Boreholes may be over-drilled to provide stratigraphical information on deeper strata, and then backfilled to the required installation depth. Table 2.4 provides a summary of suggested screen lengths.

Screen installations should be designed to minimise the risk of interference with groundwater flow regimes (long screens can induce vertical flow within an aquifer) and to allow the collection of a sample that meets the requirements of the monitoring objectives. In general, the screen should be the minimum length required to meet the objectives whilst ensuring that mixing and sample dilution within the borehole does not affect the sample results or the interpretation of those results.

The screen should be located such that at least part of the screen remains within the saturated zone during the period of monitoring, given the likely annual fluctuation in the water table.

In layered aquifer systems, the response zone should be of an appropriate length to prevent connection between different aquifer layers within the system; in other words, it should be no greater in length than the thickness of the strata being monitored.

In thick granular aquifers the benefits of a short response zone are limited, given that mixing and sample dilution will occur within the aquifer itself. However, long response zones should be installed with caution as vertical gradients may still exist.

Screen location and length are important considerations when monitoring the presence of free-phase NAPLs. For monitoring of light NAPLs (LNAPLS) which float on the water table, it is necessary to monitor across the zone of fluctuation of the water table. For monitoring of dense NAPLS (DNAPLS) which will sink in groundwater until they reach a layer through which they cannot pass, the lowest part of the open screen should coincide with, or be slightly lower than, the base of the aquifer unit.

Appropriate response zone lengths will be determined by a number of factors, such as background sampling, discrete horizons and multi-level monitoring.

For background sampling, a long response zone which draws water from all parts of the aquifer may be appropriate, provided that this will not connect separate aquifer systems or induce vertical flows.

For discrete horizons, where geological conditions or contaminants may cause vertical variations in groundwater quality, short response zones are likely to be more appropriate.

Where detailed information on the vertical distribution of water quality is required, users may consider installing more than one monitoring zone within a single borehole. In general, because of the difficulties of achieving an adequate seal, no more than two monitoring locations should be installed in a single borehole using separate installations. Where more sampling points are required, a proprietary multi-level installation is needed. An alternative is to install a series of closely-spaced boreholes to different depths at a single location.

Monitoring dissolved contaminants in plumes requires an appreciation of the likely characteristics of the plume and its behaviour in the aquifer. Plumes will be elongated in the direction of groundwater flow and will undergo longitudinal, lateral and vertical dispersion. They will also tend to ‘plunge’ as additional recharge is added to the aquifer downgradient of the plume source area. In locating the GQMPs, users will also need to consider the rate of contaminant movement, which will be affected by advection, dispersion, retardation and degradation.

Table 2.4 Guide to monitoring interval selection

Aquifer conditions/ Monitoring objectives	Response zone/Screen length			
	Multi-level	Very short (<1 m)	Short (1 to 2 m)	Long (3+ m)
Monitor general background water quality in thick aquifer	✓✓	x	✓✓	✓✓✓
Monitor general background water quality in thin aquifer	x	✓	✓✓✓	✓
Monitor LNAPL	x	x	✓✓	✓✓✓
Monitor DNAPL	x	✓	✓✓✓	✓✓
Detailed examination of contaminant distribution	✓✓✓	✓✓	✓✓	x

Key: x Not appropriate; ✓ Appropriate but not ideal; ✓✓ Appropriate; ✓✓✓ Most appropriate

2.3.4 Borehole and installation diameter

The borehole diameter will be primarily dictated by the installation diameter and the need to provide an annular space for the installation of a filter pack.

The installation diameter is typically defined as the nominal internal diameter of the casing. The method of groundwater monitoring and sampling (along with any foreseen alternative uses) will dictate size and type of installation and the headworks design. In some cases the groundwater sampling method will be determined by existing practice, for example where additional GQMPs are added to an existing network which has established sampling protocols. In other situations, consideration of sampling methods will be concurrent with borehole design. In all situations the sampling method should be chosen with regard to practicality, to ensure that the installation can provide the appropriate volume of water, the equipment can obtain water from the required depth and the design and materials are consistent with the monitoring objectives.

Allowance should be made for deviations and kinks in the well casing; sampling equipment which is a tight fit within a straight piece of casing may jam where the casing is deflected. Allowances should also be made to insert monitoring equipment where necessary. Additional space may be required to install water level, water quality or other logging equipment in addition to sampling instruments. Finally, users should consider flow compatibility – whether the formation will deliver sufficient water to supply the pumping device. For example, there is little point in using a high-flow pump in a low permeability formation that will run dry in a short space of time.

2.3.5 Material selection

The selection of materials for use as well screen and casing will be based on:

- the monitoring objectives;
- the environment into which the installation is placed;
- the type and concentrations of the target determinants;
- the available budget (where this does not compromise the objectives).

Section 3.5 offers advice on identifying suitable, commonly-available casing materials for typical groundwater environments. During the initial design phase, designers are likely to choose between thermoplastic (HDPE or uPVC) material or stainless steel, depending upon the objectives and groundwater chemistry. At the detailed design stage, the suitability of specific materials should be further assessed according to the below-ground environment.

When planning additional GQMPs within an existing monitoring network, it may be appropriate to use a consistent design and the same materials as those previously installed to allow better correlation of sampling results. However, users should ensure that this approach does not affect the quality of groundwater samples or compromise the monitoring objectives.

2.3.6 Duration of sampling

The length of time required to undertake groundwater sampling will influence the quality of and work involved in GQMP installation and borehole development.

For strategic monitoring, the length of time is likely to be indefinite, whereas for defensive monitoring the sampling period is likely to be defined, although it may be many years or decades. Investigative monitoring GQMPs may have a short lifespan.

Selecting materials for longer-term installations requires consideration of long-term processes such as weathering, which can cause corrosion or photolysis leading to loss of strength. Other processes to consider include long-term ground movements or creep, and clogging or fouling of screen materials. Long-term monitoring may require the use of robust installations resistant to degradation and capable of withstanding maintenance and renovation activities.

2.3.7 Location

An approximate location for the GQMP will be identified during the initial design process. In determining the exact location the designer will need to consider a number of factors, including:

- health and safety implications of the location (see Section 2.6);
- headworks requirements;

- particular conditions and requirements of the landowner such as access, disturbance during drilling and present and future site uses.

2.3.8 Borehole identification

Each borehole requires a unique identity number which should be unambiguous to avoid confusion with other boreholes on the same site or at other sites.

A site-specific two- or three-letter prefix is recommended and users may wish to include the phase of investigation or the year of construction in the tag number. Where more than one aquifer horizon is monitored, users should identify different aquifer units separately.

For multi-level sampling devices, care should be taken to number these in the same order at all locations. It is recommended that these are numbered in sequence from top (shallowest) to bottom (deepest).

The identification system should be meaningful and logical; in other words, the logic of the numbering system should be obvious to those using it and to others who may have to take over responsibility for the borehole. It should also be as short as possible.

Borehole identification should be decided upon at the initial design stage and adhered to on all correspondence, contract documents, drillers log sheets and reports and sampling sheets. Boreholes should never be re-numbered as this will lead to confusion and may result in records being misplaced.

In the event that a proposed borehole which has been assigned a number is not drilled, subsequent reporting should identify it as an undrilled borehole.

2.4 Costs

Prior to initial design, it is likely that a provisional budget will have been assigned to the work. The initial design stage will determine whether the objectives are compatible with the provisional budget. Evaluation of different design and installation options should include costings to determine which options are more economically attractive. At this stage cost estimates are usually derived from the designer's experience or by means of preliminary enquiries of experienced contractors.

Costs can be divided into capital costs (Box 3) and operating costs (Box 4). Capital costs include the cost of obtaining or leasing the land for drilling and installation of the GQMP (Section 3.5.2), the cost of permanent equipment such as data loggers or dedicated pumps and the cost of reporting the works.

Operating costs should also be considered in the overall cost framework, and will depend upon:

- the number of GQMPs;
- the required lifetime of GQMPs;
- the sampling method;

- the frequency of sampling;
- the analytical suite and analytical reporting limits;
- reporting requirements;
- maintenance and decommissioning costs.

Box 3: Capital cost items for a GQMP

Typical capital cost items include the following:

- land access and lease costs;
- designers costs (costs for design, specification, procurement);
- establishment, including:
  - mobilisation of drilling rig;
  - mobilisation/hire of ancillary equipment;
  - provision of temporary storage space;
  - decontamination and cleaning equipment;
  - provision of traffic management and site security (where applicable);
  - provision of welfare facilities.
- drilling costs, including:
  - personal protective equipment (PPE);
  - drilling;
  - standing time/day works such as waiting for decisions, cleaning equipment, attending health and safety briefings;
  - *in situ* sampling or testing;
  - disposal of drilling wastes (significant if contaminated, because of legislative issues and waste transfer notes).
- installation costs, including:
  - provision of equipment and materials (casing, screen, backfill, headworks, loggers);
  - installation of materials (including headworks);
  - borehole development.
- location and elevation surveying;
- supervision and reporting;
- decommissioning (when anticipated in advance).

Box 4: 0perating cost items for a GQMP

Typical operating cost items include the following:

- sampling staff time (purging, sampling and travel time);
- disposal of purge water (where applicable);
- pumping equipment (purchase, depreciation, equipment hire);
- field testing equipment (purchase, depreciation, equipment hire);
- consumables during sampling (PPE, single use equipment);
- maintenance of water level and water quality logging equipment (if required);
- couriers (for shipping samples to the laboratory);
- analytical laboratory costs, which will depend upon:
    - the number of samples;
    - the analytical suite (number of different determinand suites specified);
    - method (including required accuracy, detection limit).
- project management;
- reporting;
- maintenance;
- rehabilitation.

Installation costs should be balanced against operating costs for the lifetime of the GQMP (such as sampling and maintenance costs). A slightly increased initial layout may be insignificant in terms of the overall cost but could potentially save money by reducing maintenance or avoiding replacement.

Operating costs will increase in direct relation to the number of sampling occasions and points and the extent of the analytical suite. Other factors that will influence costs are the quantity and quality of the water to be purged and the rate at which purging equipment can remove it..

Multi-level sampling devices can increase the overall costs markedly due to the number of samples to be collected and analysed. For long-term sampling, operating costs are likely to be significantly greater than installation costs.

Should the estimated costs exceed the provisional budget, the user has a number of options:

- abandon or postpone the project;
- use lower cost materials/drilling techniques, although this may compromise the monitoring objectives;
- reduce/refine the proposed scope of works;
- seek additional funds.

2.5 Collecting additional information

Depending on the complexity of site geology, there may be insufficient information to confidently design every aspect of a GQMP from the start. In any event, it will be necessary to collect additional ground information whilst drilling and installing GQMPs. The method of collecting information should not compromise the quality of the final installation. If ground conditions are substantially different from those expected, the GQMP may need to be redesigned..

If sufficient data is not available from the start, site-specific drilling investigations may be necessary before undertaking detailed design. It is essential to collect enough information to properly design the GQMP. A poorly designed GQMP can create environmental and sampling problems, such as the mobilisation of contaminants or the misinterpretation of results.

2.6 Health and safety

This report does not aim to provide comprehensive health and safety guidance; detailed advice is available in BDA (2002). However, some health and safety issues are considered briefly, although detailed site-specific considerations will always be essential.

Common health and safety considerations related to the design and installation of GQMPs should be considered within a comprehensive, site-specific framework and should include the following:

- the risk of striking underground and overhead services (gas, electricity, telephone, water, sewage, drainage etc);
- the risk of injury associated with a drilling rig and its ancillary equipment (moving parts, heat, noise, falls, crushing);
- exposure to potentially contaminated soils and groundwater;
- the risk of explosive sub-surface atmosphere;

- confined spaces;
- the storage and use of hazardous materials (such as fuels, lubricants, cement, grouts) on site;
- traffic hazards.

Health and safety considerations should be incorporated into a health and safety plan, which should be read and understood by all site workers and site visitors. Copies of the plan should be kept on site.

With regard to drilling on contaminated land, reference should be made to the classification of sites provided by the BDA (2002) and the requirements for PPE (personal protective equipment) associated with each classification.

Health and safety issues that may affect borehole design can be divided into four main areas:

- final site selection of the borehole to avoid the creation of a hazard;
- working in a potentially explosive environment, particularly where high concentrations of volatile substances are anticipated;
- potentially hazardous materials used in construction;
- the suitability of the headworks.

Site selection should avoid creating a hazard to vehicles, pedestrians and livestock, or to people using the borehole during drilling or monitoring. Consideration should be given to both current and future planned use of a site.

The use of hazardous materials and equipment should be minimised with appropriate protection and storage provided.

The headworks design will depend on borehole placement in terms of posing minimal risk to others, but the safety of samplers or maintenance workers should also be considered. There should be consideration of confined spaces risk (especially on contaminated sites) and manual handling issues (such as weight of covers or height of standpipes). A separate risk assessment should be undertaken for sampling issues.

2.7 Quality assurance

GQMP design and installation should follow a verifiable quality assurance (QA) and quality control (QC) procedure and make use of recognised standards where appropriate. It is particularly important that all steps in the process are documented in a traceable manner.

GQMPs should be appropriate for their purpose - for instance, there is little point worrying about sorption in the presence of free-phase liquids. However, consideration should always be given to the alternative uses for which an installation may be required.

British Standards exist for the specification of casing and installation materials and suitable equipment should be used as a matter of course. In addition to material specifications, the British Standards Institute (BSI) provides references on drilling and sampling procedures. Relevant publications include:

- BS 879 (Part 1 and 2) for water well casing;
- BS 5930 Code of practice for site investigations;
- BS 10175 Investigation of potentially contaminated sites - code of practice.

2.8 Consultation

A number of organisations have either regulatory controls or specific interests in the drilling and installation of a GQMP. They should be identified and consulted, and licences obtained where necessary. Potential stakeholders include:

- the Environment Agency and other regulatory bodies (such as planning authorities, internal drainage boards);
- landowners or their agents (for drilling/monitoring sites and access routes);
- insurers and financiers;
- conservation bodies (such as English Nature, National Trust, wildlife trusts);
- highway authorities (for works on or adjacent to highways);
- utilities and owners of underground services;
- water companies or other major groundwater abstractors (for works near their groundwater sources);
- prospective purchasers or their agents;
- the Coal Authority - investigations which involve the intersection of mine shafts, mine workings or seams of coal require prior written permission from the Coal Authority.

3. Detailed design

3.1 Introduction

At the detailed design stage, the GQMP design is set out in sufficient detail to verify its fitness for purpose, and the user can proceed to specification, procurement, construction and commissioning.

This guidance makes a number of assumptions regarding GQMP design and these should be borne in mind when reading the following sections. Much of the literature on borehole construction relates to water well construction; however, the objectives of the design of GQMPs are different from those for water wells - see Box 5.

At the end of this stage, the design should enable detailed specifications to be made, including:

- drilling technique;
- depth and diameter of the borehole;
- screen length;
- materials to be used (screen, casing, filter pack, seals, grout);
- headworks design.

Users should also be able to estimate quantities of materials and unit costs, draw up a health and safety plan and establish the requirements of organisations involved.

Typical borehole layouts given in Appendix C can be used to base working drawings from; these include space for the dimensions of casing and screen and the depths of the backfill required.

Box 5: Comparison of GQMP and water well designs

The purpose of a water well is to maximise the yield from an aquifer. As a result, a significant amount of time may be spent on developing the well, using both chemical and mechanical techniques. Greater time and effort may also have been spent on investigating the aquifer and deciding on appropriate hydraulic design prior to construction. Furthermore, water wells are generally deeper and of larger diameter than monitoring boreholes, to enable users to access a large part of the aquifer and to permit access for a sizeable pump.

In contrast, GQMPs are smaller to minimise the risk of foreign materials entering the groundwater environment. They often have minimal time spent on their development and the level of information available prior to borehole drilling may be limited.

Box 5- Comparison of GQMP and water well designs - continued

Thus, the following points may be assumed with respect to GQMPs:

- borehole development will be the minimum necessary to remove any flush or other material added;
- the use of additives and flushes will be limited to the minimum necessary to drill the borehole;
- an artificial filter pack will almost always be used in drilled boreholes. In water wells, the borehole may be left open (in hard rock) or a naturally developed filter pack may sometimes be used, but this requires considerable effort during well development to achieve the necessary properties and is not generally undertaken in monitoring boreholes;
- well screen will be positioned to achieve the required monitoring objective, rather than against the most permeable horizons; it will also generally be short, to ensure that the groundwater sampled represents a discrete monitoring zone.

3.2 Conceptual site model

An understanding of the sub-surface environment is required for GQMP design, and is best developed within a conceptual site model. The degree of understanding required to draw up a suitable design will be determined by:

- the complexity of the environment;
- cost-benefit; in other words, whether the cost of further investigation can be justified by improved design or understanding;
- type of monitoring installation required; for example, more information will be required for a multi-level device compared to a single monitoring borehole.

An assessment of existing information will determine whether it is sufficient to permit design decisions to be made. This should cover the extent and type of previous investigations and existing knowledge of the sub-surface environment in terms of geological and hydrogeological properties.

Where there is insufficient information to complete the final design, further investigations will be required. These may be made in advance of the installation or more commonly, at the time of installation. In the latter case, users should remain flexible until decision points are reached.

3.2.1 Geology

3.2.1.1 Strata

For the purposes of drilling, strata can be classified according to their general physical characteristics. Important geological factors which will govern the GQMP design are considered in terms of soils and rocks.

The following groups of soils and rock are based on the nomenclature reported in BS5930. Soils can be divided into:

- fine (formerly 'cohesive') - very soft to hard clays and silts with no cobbles or boulders;
- fine with cobbles and boulders (such as glacial till);
- coarse (formerly 'granular') - sands, gravels, cobbles and boulders which are dense or loose;
- composite soils (a mixture of fine and coarse materials);
- made ground.
- rock, which can be further subdivided into weak/friable or weathered rock; fissured rock; and strong rock.

Strata type and thickness will influence strongly the choice of drilling method and materials, the design of screen lengths and slot and filter pack sizes. Installations within hard fissured rock will be significantly different from those in loose fine sands.

For soils, the following factors may influence drilling technique selection:

- degree of cohesion, where fine soils are more likely to stand open than coarse soils;
- density of coarse, granular deposits, where temporary casing will almost always be required in granular deposits, which will tend to 'blow' below the water table and will require the addition of water;
- absence/presence of cobbles and boulders, where some soil drilling techniques may be unable to penetrate cobbles and boulders;
- thickness, where difficult drilling conditions may often be overcome if the soil is thin, but may require specialist techniques when they are thick;
- saturated/unsaturated conditions, where unsaturated sands may run into the hole while saturated sands may blow.

For rock, the important factors will be:

- rock strength, where weak rock can often be penetrated using soil drilling techniques, while strong rock will slow drilling progress and will cause refusal of some techniques;

- depth or thickness to be penetrated;
- presence of weathered/weak zones, which may require the borehole to be supported by temporary casing;
- presence of voids such as fractures, solution features and mine workings, which may cause loss of flushing medium.

3.2.1.2 Strength

The relative strength of a geological deposit will affect the rate of drilling, the need for support of the borehole walls and the strength required of the installation materials.

Loose, coarse and soft, fine deposits will always need support with temporary casing or the use of drilling muds, except where direct push installation methods are used. Support may also be needed in highly-fractured rock where blocks or wedges may move into the borehole. Drilling through mine workings may encounter loose ground which can block the borehole.

Swelling clays are relatively unusual in the UK, but they can lead to difficulties during drilling and installation as these deposits can swell into the borehole void, reducing the effective diameter. If support cannot be given to the borehole walls (either because of the drilling method or the risk of having temporary casing seize in the hole) then installation should immediately follow drilling to reduce the potential loss of the hole. Chemical additives may slow or eliminate the swelling effect; however, because of their potential effect on groundwater chemistry, additives should only be used after careful consideration.

Loose sands below the water table will often ‘blow’ into the borehole. This results from a head difference between the water level inside the temporary casing and the surrounding soil, leading to sand moving into the casing. This effect may be further enhanced by suction created by the drilling action, which draws more material inwards. The potential outcome is that the temporary casing fills with sand at a faster rate than the drilling operation can remove it, and it can then become difficult to remove the temporary casing. To minimise the effect of blowing, it may be necessary to maintain the water level inside the temporary casing above that of the outside, by adding water. The quality requirements of the added water are considered in Section 3.3.

3.2.1.3 Depth

The required depth of the GQMP will influence the choice and quantity of casing materials and the choice of drilling technique. Most techniques are capable of drilling shallow boreholes but as depth increases, so does its impact on the design.

Some drilling techniques are limited in the depth to which they can penetrate because of physical constraints, such as excessive frictional resistance in augering and direct push techniques.

Cable tool drilling is usually limited by the rate of progress, which decreases with depth, and by the size of equipment needed, where larger rigs are required for deeper holes.

Rotary drilling techniques can be used in shallow boreholes, but the ancillary equipment and relatively expensive mobilisation can constitute a large outlay.

Common practice in the UK is to drill shallow boreholes in soils using cable tool drilling, while deeper holes in soils and all boreholes in rock are drilled using rotary techniques. A marked advantage of cable tool drilling is that it does not require large volumes of fluid or air.

The depth of the borehole and the depth to the water table determine the choice of installation materials and casing diameter. The casing string must be of sufficient strength to accommodate the extensional stresses incurred by its own weight when hanging in the borehole. The weakest point on a casing string is usually the joints and material suitability will be an important consideration for deep boreholes. For buoyant materials, the critical length when calculating the maximum extensional stress is the depth to the water table.

Most problems can be minimised by ensuring continuity of operation, with no undue delay between the drilling and installation. Schedules where drilling ends on Friday and installation begins on Monday should be avoided where possible.

3.2.2 Hydrogeological considerations

The depth to the water table will influence the choice of drilling method, casing and screen materials. For the drilling technique, some materials may behave differently when saturated or unsaturated and the drilling penetration rate and strata stability may be affected. When drilling with a percussive rig, there may be a requirement to add water or flush to aid the recovery of drill cuttings.

Some casing materials are limited by the length that can be suspended in a borehole before failure occurs, usually at the joints. Many plastics have some buoyancy in water which means that the suspended length can be increased in a saturated borehole compared to a dry one.

Artesian conditions will affect the drilling method, the headworks design and the installation method. Special precautions must be taken where artesian heads are expected, as uncontrolled release of water could affect the environment or create a health and safety risk.

Locating the water table and understanding its likely fluctuations are necessary to establish the depth and length of the screen. The location of the screen should be linked to the objectives and should be cut or preferably manufactured to size. Casing and screen sections come in standard lengths, typically one or three metres; if necessary these can be cut to size on site.

In general, monitoring zones will be located within permeable horizons and will need to be accurately located. In multi-layered aquifer systems, and where contamination is present, care will be required to prevent different permeable horizons from becoming connected during drilling or installation. The driller's awareness of the objectives prior to the start of work will benefit data recording during drilling and will ensure that important changes in lithology and water strike information are not missed.

The hydraulic properties of the strata will affect the filter pack and screen design (Section 3.5), the choice of development technique (Section 4.6) and the potential for loss of flush during rotary drilling.

Groundwater chemistry will be a consideration in casing, screen and filter selection and may affect the choice of drilling technique. A guide to material selection is given in Section 3.5. Where the groundwater chemistry could be hazardous to health, additional health and safety requirements may be necessary. Groundwater conditions may also affect the choice of backfill, as bentonite and cement are both affected by saline conditions (Section 3.5.4).

The presence of separate phases (LNAPLs and DNAPLs) in the monitored horizon will influence the design of the screen, the choice of casing material and the drilling technique. The presence of NAPL and its implications for screen design are discussed in Section 3.4. In the presence of free-phase organics, the casing must withstand corrosion from NAPL (Section 3.5.3).

The presence of free-phase contaminants will also have implications for health and safety and for contaminant migration during drilling. The contaminants likely to be encountered will affect the choice of material (suitability in terms of sorption, contaminant release, risk of corrosion), the drilling method and the health and safety assessment. Contaminated spoil and groundwater will require special handling, storage and disposal.

3.3 Drilling technique selection

3.3.1 Factors affecting the choice of drilling technique

There are a number of ways of forming a borehole. The choice of technique will depend upon:

- depth and diameter required;
- depth to the water table;
- ability to penetrate the formations anticipated (determined by soil/rock strength and structure);
- impact on groundwater quality (particularly the use of a flushing media);
- requirements to obtain samples for the purposes of borehole logging;
- extent of disturbance of the ground materials around the boreholes (such as smearing of side walls);
- access restrictions;
- cost considerations including the size of contract (number of boreholes) and relative costs;
- availability, particularly for novel or unusual techniques;
- other objectives, such as requirements for geotechnical or hydraulic testing.

Detailed descriptions of various drilling techniques can be found in a number of references (for example, Driscoll 1986 and Aller *et al*. 1989). A summary of common methods currently available in the UK is given in Appendix B.

The most commonly used techniques are cable tool drilling in soils and weak rock, conventional rotary drilling in soils and rocks and auger drilling in soils.

3.3.2 The influence of geology

The nature of the underlying geology will be the most significant factor in the selection of drilling techniques. For example, the presence of hard rock may preclude the use of cable tool rigs, while a need to employ temporary casing to prevent caving or collapse of loose deposits will favour its use.

In difficult ground conditions or where substantial drift overlies competent strata, a combination of cable tool and rotary drilling techniques may be required.

Since geological conditions are often complex and may be poorly understood prior to drilling, a number of generic situations have been considered and are outlined in the following tables.

Tables 3.1, 3.2 and 3.3 rate the different techniques for a range of ground conditions. These ratings are generic and will be significantly affected by modifying techniques such as the use of drilled casing with rotary techniques(for example, ODEX) or the use of coring equipment. Site specific information should be assessed prior to making a decision on drilling technique.

Table 3.1 Drilling techniques for fine soils

Drilling method	Very soft to firm			Firm to hard			Deposits with cobbles / boulders
	Suitability	Stability	Sampling	Suitability	Stability	Sampling	Suitability
Cable tool*	✓✓	✓✓✓	✓✓	✓✓	✓✓✓	✓✓✓	✓✓
Rotary**	✓✓✓	✓✓	✓	✓✓	✓✓	✓	✓✓
Sonic*	✓✓✓	x	✓✓✓	✓✓	✓✓✓	✓✓✓	x
Direct push / jetting	✓✓✓	x	-	✓	-	-	x
Hollow stem auger	✓✓	x	✓✓	✓	✓✓	✓✓	x

Key:

-	Not relevant	* Using temporary casing
x	Inappropriate	** Drilling without cores
✓	Appropriate but not ideal	
✓✓	Appropriate	
✓✓✓	Most appropriate	

Table 3.2 Drilling techniques for coarse soils

Drilling method	Dense sand			Loose sand[1]			Dense gravel			Loose gravel		
	Suitability	Stability	Sampling	Suitability	Stability	Sampling	Suitability	Stability	Sampling	Suitability	Stability	Sampling
Cable tool*	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	✓✓	✓✓✓	✓✓✓	✓✓	✓✓	✓✓✓	✓✓
Rotary**	✓✓✓	✓✓	✓	x	x	✓✓	✓✓✓	✓✓	✓	✓	✓	✓✓
Sonic*	✓✓	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	✓✓	✓✓✓	✓✓✓	✓✓	✓✓	✓✓
Direct push / jetting	x	-	-	✓✓✓	-	-	x	-	-	✓	-	-
Hollow stem auger	✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓	✓✓	✓✓	✓✓

[1]in blowing sand difficulties may be encountered with all techniques
Key: as for Table 3.1

Table 3.3 Drilling techniques for rock

Drilling method	Weak to moderately weak rock (including weathered rock)	Moderately strong and strong rock
Cable tool	✓✓	x
Rotary	✓✓✓	✓✓✓
Rotary percussion	✓✓✓	✓✓✓

Key: as for Table 3.1

3.3.3 The influence of depth

Deeper boreholes - that is, those generally greater than 50 m - are principally the realm of rotary drilling techniques, where cable tool drilling is suitable for depths of up to 50 m bgl, depending upon the size of the drilling rig. Depths greater than this exceed the capacity of readily-available cable tool drilling rigs, although specialist rigs can go deeper. This distinction between techniques arises principally from economic considerations of the balance between set up costs and 'time on site' costs which can become significant.

Cable tool rigs, in general, are easy to mobilise and require minimal ancillary equipment. Rotary rigs are commonly larger, costing more to transport to a site, and may require circulation tanks, compressors and other equipment.

Costs are influenced by geological conditions, site access and drilling objectives. However, monitoring and other objectives, such as lithological sample quality or the use of downhole geophysics must also be considered in conjunction with the project costs.

3.3.4 Borehole diameter

The diameter of the borehole will be dictated by the required installation diameter and the need to leave space around the casing (known as the annulus) to:

- ensure effective installation of filters and sealing materials;
- allow for uneven sidewalls;
- permit the use of installation equipment such as tremmie pipes;
- minimise bridging of installation materials.

A minimum annulus of 38 mm is recommended (Environment Agency, undated).

Depending on depth, ground conditions and drilling technique, it may be necessary to start the borehole at a large diameter to achieve a suitable final diameter at depth. This may also be required for telescopic drilling (see Box 2). Standard drilling and casing sizes are often defined in inches.

Drilling costs generally increase with borehole diameter. Equipment able to drill at a larger diameter can be more expensive and the volume of spoil requiring disposal will increase. In addition, sampling and development may require the removal of a larger volume of water to achieve stable, representative conditions, which will add costs to the time required on site and, where applicable, to the storage and disposal of any arising water.

Larger diameter cable tool drilling may improve the rate of penetration into deposits with cobbles and boulders, because of its ability to recover larger objects through the temporary casing string.

3.3.5 Rotary drilling: choice and use of flush

Rotary drilling requires a flushing medium to cool the drill bit and to remove cuttings. Five types are currently available:

- compressed air;
- water;
- mist (air and water);
- drilling mud - a mixture of clays such as bentonite, water and other additives designed to increase the density of the water and provide stability to the borehole walls;
- polymer flushes - a mixture of water and a thickening or foaming agent

However, flush fluids can coat the borehole sidewalls, reducing hydraulic performance. They can also invade the monitoring zone and alter the groundwater chemistry. For example, air flush may change the redox conditions or increase volatilisation, while the introduction of electron receptors or donors can increase the oxygen demand from biological activity.

Water may also be required for cable-percussive drilling in ‘blowing’ sands and stiff clays and for drilling in the unsaturated zone.

For some water quality applications, the use of a drilling flush fluid may compromise some of the monitoring objectives. Users should adopt the following good practices:

- use a flush which is appropriate to the investigation – for example, avoid the use of an air flush where volatile substances or reducing conditions are anticipated;
- minimise the formation invasion of the drilling fluid, for example by using low pressures or reverse circulation;
- using the cleanest source of water available, which is usually mains water - in remote operations other water sources may be more practical but these should be considered before the site is set up;
- chemically characterise the flushing medium and anticipate any effects that it may have on the groundwater environment;
- recycle the flush in the drilling process to minimise the volume used;

- maintain accurate volume measurements from which fluid losses to the formation can be calculated, and site records;
- remove as much of the flush as possible during borehole development.

For sensitive operations additional work may be required, for example by de-oxygenating water-based flushes to maintain reducing conditions around the borehole.

3.3.6 Indicative costs

Section 2.4 lists typical cost items associated with the installation of a GQMP. However, the actual costs incurred will depend upon a number of factors; drilling costs alone will be influenced by the following:

- remoteness of the site;
- distance between boreholes;
- the drilling technique selected;
- depth and diameter of boreholes;
- requirements for temporary casing;
- the anticipated rate of drilling progress – strength of strata/presence of difficult conditions;
- costs associated with contamination - health and safety requirements, cross-contamination prevention, cleaning and spoil disposal;
- costs associated with removal of flushing media and disposal of contaminated water;
- quality of specification and quantities.

A typical bill of quantities for drilling a borehole and installing a GQMP can be found in SISG (1993a).

3.4 Installation design

3.4.1 Location and length of response zones

A key decision when installing a GQMP is the type, location and length of the response zone to be installed in the borehole following drilling. Where the strata are stable there may be less of a requirement for a screen and an open hole may be considered, which has the benefit of fewer materials introduced into the GQMP but is often inappropriate.

At an early stage in the design process, the approximate location of the response zone will have been identified (see Section 2.3). Factors that will influence the chosen location and length include:

- stability of the formation;

- presence of LNAPL or range of water table elevations;
- thickness of unit to be monitored;
- plume characteristics;
- hydraulic performance requirements;
- avoidance of vertical flows and cross-contamination.

Standard lengths will also be a factor. Well screen can be made to virtually any length, but most casing is manufactured to standard sizes, typically 3 m lengths for most casing. Longer sections can be created by joining sections, and shorter sections by cutting down standard lengths. If non-standard lengths are used, the manufacturer should be contacted to establish minimum order times. Piezometer tubing (commonly used in geotechnical applications) may also use ceramic tips of 0.3 m length.

Long response zones should be avoided where possible, as these can induce vertical flow and contaminant movement and may therefore disturb the natural flow patterns and geochemistry. They may also form preferential pathways for contaminant migration. In this report, long response zones are assumed to be greater than 3 m.

Where monitoring for the presence of dense NAPLs is required, users should note that the lower parts of most screen lengths do not contain slots or holes, as this is where the threads are located. Where the intention is to measure DNAPL at the base of a permeable unit, the hole should be slightly overdeepened to permit DNAPL sitting at the base of the unit to enter the GQMP, although care should be taken to ensure that DNAPL does not infiltrate deeper in to the aquifer system. Where this approach has been adopted, allowance should be made in subsequent measurements of DNAPL thickness to take account of the ‘sump’ created at the bottom of the GQMP.

The use of sumps - sections of plain pipe at the bottom of boreholes sometimes used to collect fines passing through the filter pack - should be avoided except where free-phase DNAPLs are anticipated. The presence of fines in stagnant sump water may alter groundwater chemistry, although development and purging should reduce this. The addition of a sump also increases the effective response zone length if the sump is surrounded by gravel - this may be an issue if targeting thin monitoring horizons.

Screen aperture considerations are dealt with in Section 3.5.4.

3.4.2 Multi-level monitoring

Multi-level monitoring (MLM) systems (Box 6) represent a cost-effective and efficient method of installing a number of GQMPs through an aquifer system where an understanding of vertical hydrogeological processes and contaminant distribution is required.

Clustered piezometers in separate boreholes can also be used to monitor the vertical variation in groundwater quality in a similar manner to MLM systems. However, there will be a potential lateral variation in the sampling results, which may be significant in some settings, and in general there will be increased drilling and installation costs.

The use of MLM systems can considerably increase the cost of sampling per location, both in terms of time spent acquiring the samples and the cost of increased numbers of analyses. However, MLM systems allow more targeted sampling and better precision in detecting and characterising contaminant plumes. Furthermore, not all sample points need to be sampled on every occasion.

Only a limited number of MLM systems are currently available, which restricts choice. Most MLM systems are proprietary and their use may restrict the opportunity for competitive tendering.

Box 6 - Types of multi-level monitoring systems

There are a number of proprietary multi-level monitoring systems currently available in the UK. These can be divided into two principal types.

Bundled pipes are made up of a number of pipes or tubes, often of narrow diameter, combined in a single device. Each tube has a monitoring zone at a different depth. The narrow diameter of bundled piezometers limits the instrumentation and sampling devices that can be installed and may require specialist equipment for sampling. It may not be possible to undertake concurrent water level monitoring and sampling.

Port systems involve a single access tube used to access ports which open to the groundwater environment. A tool is lowered down the access device that can connect to and open the port to permit sampling.

Seals between monitoring zones are either conventional bentonite seals or packer devices. Conventionally-sealed monitoring zones still require a filter pack to be installed around them. The different systems have their advantages and disadvantages and selection will require both careful assessment and knowledge of the market.

3.5 Material selection

3.5.1 Introduction

A variety of materials are introduced into the ground as part of borehole construction, such as:

- well screen and well casing (for example, HDPE, uPVC, PTFE, stainless steel);
- multi-level sampling devices;
- geotextile wraps;
- filter packs (sand and/or gravel);
- sealing materials (bentonite seals and cement grouts);
- headworks;
- pumping and sampling equipment.

Introducing these materials into a previously undisturbed environment can result in chemical and biological alteration of both the materials and the groundwater. This in turn may reduce material performance, for example through clogging, or failure through weakening and collapse. If the groundwater is altered, the samples obtained may not be representative, which defeats the purpose of monitoring. Consequently, materials and method of installation are major considerations in the design process. Some considerations are listed below:

- the chemical environment in which the installation is placed - aggressive environments (saline, free-phase, low or high pH) will rapidly degrade or corrode some materials;
- effect of materials on contaminants, such as sorption, oxidation, reduction;
- effect of contaminants on materials - corrosion, solution, strength, leaching;
- effect of materials on groundwater - leaching, oxidation, pH;
- effect of flushing fluids on the environment - aeration, mixing, clogging, reducing environment;
- economic considerations.

The likely concentrations of key determinants should also be considered and can be divided into the following broad categories:

- gross - present at high concentrations or as free-phase;
- low - substances thought to be present as minor constituents but at concentrations well above their detection limits;
- trace concentrations - substances assumed to be absent or present at concentrations close to detection limits.

3.5.2 Indicative costs

Typical installation material costs will come from some or all of the following:

- casing and screen, where cost will depend upon diameter, slot size, pipe length and material;
- geotextile wrap;
- backfill materials, such as primary and secondary filter packs (bridge sand), bentonite and cement:bentonite grout.

Material costs will be affected by bulk ordering, choice of supplier and choice of material amongst other things. Costs of materials are subject to change but at the time of writing, of the commonly available materials HDPE and uPVC were similar in price and represented the lowest cost option, PTFE was more expensive and stainless steel was the most expensive (with a number of grades available)[1].

Evaluating material costs is further complicated by variable overheads and profit margins via a contractor where casing and screen are provided on a supply-and-install basis. These additional costs will depend upon the availability of the casing

[1] Imported stainless steel is currently subject to an alloy tax within the UK which is updated several times a year, therefore unit rates will vary frequently.

and difficulty of installation of a particular material and may be significant. Varying procurement routes should be considered as an alternative, for example by client supply of pertinent installation materials.

3.5.3 Casing materials

Components and materials in the borehole will need to survive for the projected lifespan of the installation. Pressures on materials can come from corrosion, gravitational forces, water pressure differentials (especially during development and sampling) and lateral pressures from ground movement and swelling clays.

3.5.3.1 Degradation, corrosion and chemical stability

Metals other than stainless steel are not generally suitable for use in a GQMP (Aller *et al* 1989) as they are subject to corrosion. Metal corrosion will reduce the lifespan of an installation, through weakening and possible collapse, and may also affect groundwater chemistry in the GQMP and the surrounding aquifer, for example through the release of iron and trace metals.

The choice of casing material is therefore limited to plastics (HDPE, PTFE, ABS, uPVC), stainless steel and in some cases unusual materials such as fibreglass, silica or ceramics.

As discussed in Section 3.5.1, the casing material has the potential to affect the surrounding water quality through both release and sorption of determinants. Parker and Ranney (1994), Ranney and Parker (1997) and McCaulou *et al* (1996) list the results of comprehensive literature surveys and experiments comparing the suitability of casing types in terms of degradation and sorption in a range of chemical environments. A summary of this data is presented in Tables 3.4 to 3.6. For unusual contaminants it is recommended that the literature be consulted.

Table 3.4 Susceptibility of casing materials to degradation in the presence of free-phase contaminants

	LNAPL (hydrocarbons)	DNAPL (chlorinated solvents)
Stainless steel	✓✓✓	✓✓✓
Plastics		
HDPE	x	✓✓✓
uPVC	✓✓✓	x
ABS	✓✓	x
PTFE	✓✓✓	✓✓✓

Key:
? Insufficient data available to draw conclusions
x Not appropriate
✓ Appropriate but not ideal
✓✓ Appropriate
✓✓✓ Most appropriate

Table 3.5 Susceptibility of casing materials to corrosion in aggressive groundwater conditions

Casing type	Groundwater conditions			
	Acidic	Alkaline	Reducing	High salinity
Stainless steel	✓✓	✓✓✓	✓✓	x
Plastics:				
HDPE	✓✓✓	✓✓✓	?	✓✓✓
uPVC	✓✓✓	✓✓✓	?	✓✓✓
ABS	✓✓	✓✓	?	✓✓✓
PTFE	✓✓✓	✓✓✓	?	✓✓✓
fibreglass	✓✓	✓✓✓	?	✓✓✓

Key: as for Table 3.4

Table 3.6 Casing suitability for target determinants

Casing type	Dissolved contaminants				
	Metals	Minerals or major ions	BTEX or PAHS	Chlorinated solvents	Pesticides or PCB
Stainless steel	x	✓✓	✓✓✓	✓✓✓	✓✓✓
Plastics					
HDPE	✓✓✓	✓✓✓	x	✓✓✓	✓✓
uPVC	✓✓✓	✓✓✓	✓✓✓	x	✓
ABS	✓✓✓	✓✓✓	x	x	?
PTFE	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Fibreglass FEP	✓✓✓	✓✓✓	✓✓✓	✓✓✓	?
Fibreglass FRE	✓✓✓	✓✓✓	✓✓	✓	?

Key as for Table 3.4

Consideration should also be given to materials associated with the casing. Rubber O-rings, for example, may be unsuitable for use between casing lengths in the presence of organic contaminants since they may degrade or cause sorption. More suitable O-rings manufactured from proprietary materials may be available.

When joining lengths of casing, the use of glues and welds should be avoided because of the risk of introducing additional chemicals into the environment. Screw threads are the most commonly used and generally the most appropriate joining mechanism, although the threads represent weak points in the casing length. All joints should be flush on the inside of the casing to reduce the risk of snagging or trapping of sampling equipment. They should also be flush on the outside to permit the insertion of a tremmie pipe down the annulus and to avoid bridging of backfill materials.

Threaded joints between casing lengths should not be lubricated by any material that may compromise the GQMP. Greases containing metals or hydrocarbons should never be used.

3.5.3.2 Strength

All casing manufacturers produce their own material specification tables with strength as a function of material type, wall thickness and casing diameter. Important considerations are collapse pressure and tensile strength.

Table 3.7 compares relative material strength, assuming that the materials are of the same diameter and wall thickness. All casing materials can be manufactured to higher strengths than standard specifications, at the cost of increased walls thickness.

Table 3.7 Relative casing material strength

Casing material	Compressional strength	Tensile strength	Fragility/Impact strength
Stainless Steel	✓✓✓	✓✓✓	✓✓✓
Plastic			
HDPE	✓	✓	✓✓
PTFE (Teflon)	✓	✓	✓
uPVC	✓✓	✓✓	✓

Key: ✓ Low
✓✓ Moderate
✓✓✓ High

HDPE has a low tensile strength but is buoyant in water. Provided that water levels are close to the surface, long lengths of HPDE can be installed without a significant risk of failure from extension stresses. However, this buoyancy can pose a health and safety risk; it is necessary to apply sufficient pressure to hold the casing in place below the water table, but if the pressure is released suddenly the casing may rise rapidly, striking any obstructions with considerable force. Casing made from uPVC is routinely used to depths of 200 m and can be used in deeper boreholes.

For a given strength requirement, wall thickness will increase as material strength decreases. For large-diameter or high-strength casing in a relatively weak material such as HDPE, the wall thickness may be considerable and must be allowed for when determining borehole diameter and the annulus thickness required for the installation.

3.5.3.3 Other issues

Well caps of the same material as the casing should be secured to the top and bottom of the installation. The bottom cap prevents influx of aquifer material and sediment in the borehole during and after installation and the top cap prevents debris entering the casing. Headworks are likely to be vulnerable to dust and insects and a top cap should prevent these from entering the hole. Push-on and screw-on caps are available along with a type of cap containing a rubber seal that can be expanded with a key for additional security. Screw-on caps have a tendency to stick either from corrosion, frost or debris in the threads. Caps should be vented though a one-way valve to allow pressure release.

3.5.3.4 Filter packs

A filter pack is required to prevent the influx of fines into the borehole and to stabilise the flow to the sampling point. Turbid samples - samples with high suspended solids - can affect analysis. Silt entering the borehole can clog the screened section.

The filter pack must be matched to the aquifer and to the size of the screen openings (usually referred to as slot size). An appropriately designed filter pack and screen will prevent or limit the entry of fine material into the casing. Accurate filter design requires a particle size distribution (PSD), preferably from sieve analysis but an estimate of the PSD can be made from visual inspection for the target formation. Filter design is explained in detail in Driscoll (1986) and Clark (1988).

A simple rule for the design of a filter pack (Clark 1998 after Terzaghi and Peck 1948) is as follows:

$$D_{15}(\text{filter material})/D_{85}(\text{aquifer material}) < 4 < D_{15}(\text{filter material})/D_{15}(\text{aquifer material})$$

where D_{15} is the sieve mesh diameter through which 15% of the material will pass and D_{85} is the mesh size through which 85% of the material will pass.

It is also good practice to match the grading curve of the filter pack to that of the formation – in other words, they should have the same shape but the filter pack should have a larger grain size by a factor of four to six times as shown in Figure 3.1.

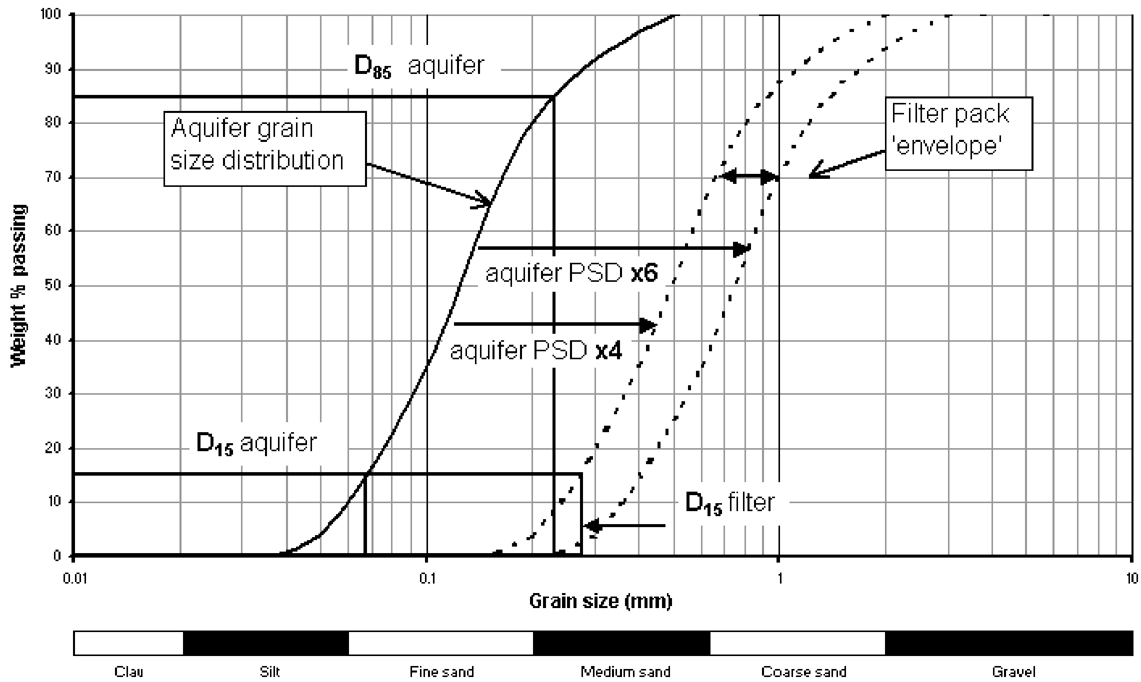

Figure 3.1. Filter pack design (after Clark 1988)

In practice, filter packs with a grain size smaller than a fine sand (0.2 to 0.6 mm diameter) are not readily available and may be difficult to install due to the slow rate of settlement. Therefore in fine materials and in coarse materials containing a significant proportion of fine materials, a fine grained sand will form the default filter material.

The filter pack material should also be inert - greater than 95 per cent silica or preferably 99 per cent silica. It should also be free of reactive minerals such as:

- iron, which can form an electron acceptor for degradation of organics;
- carbonates, which may alter the groundwater chemistry and can dissolve and re-crystallise leading to a reduction in the permeability of the filter pack;

- organic material (such as unwashed fluvial sands) that can sorb organic materials.

The filter pack should contain rounded grains, where angular sand can consolidate to give low permeability conditions.

The addition of a second sand filter of a smaller grain size above a coarse-grained filter pack is recommended, to reduce the risk of invasion of the filter pack by bentonite or grout used to seal the borehole. A second filter increases the distance between bentonite seals and screened sections and reduces the potential for the bentonite to affect water quality (through CEC or pH effects).

The filter pack should cover the top of the slots by between 1000 and 1500 mm where possible to allow for settlement. Where the filter pack consists of coarse sand or gravel, a second filter (a sand bridge) should be added above the primary filter, comprising 300 - 600 mm of finer material.

Table 3.8 shows the likely volume of material required for a given casing and borehole diameter.

Table 3.8 Calculation of typical annulus backfill volumes

Borehole diameter (mm)	Casing outside diameter (mm)	Filter pack volume (litres/ linear m)	Filter pack weight[1] (kg/linear m)
150	50	16	29
200	50	29	55
200	100	24	44
250	100	41	77
250	150	31	58
300	150	53	100
300	200	39	73
350	250	47	88

Notes
[1] assumes 30 per cent porosity and particle density of 2.65

A number of prefabricated installations are available with bonded filter packs and seal. While these may be suitable in many situations such as for monitoring major ions, care should be taken to ensure the chemical stability and suitability of any materials used, particularly the material used to bind the filter pack to the screen.

3.5.3.5 Screen selection

Installation design must also consider the size of openings (slot size), screen type and open area of the GQMP to emsure protection from fouling through silting and biological activity and to allow sufficient ingress of water for sampling. Well screen must be obtained from recognised suppliers to the water well industry.

Four different screen types are commonly available in the UK:

- continuous slot (steel or plastic) with pre-determined slot width;
- cut slots to pre-determined size;
- porous, permeable plastic casing;
- multilevel screens.

The continuous wire wrap screen is formed from a single length of wire coiled into a cylinder around a number of supporting struts. The wire is wedge-shaped in section with the apex pointing toward the centre of the borehole. This shape minimises the potential for clogging, allowing small grains to be pulled into the installation rather than clogging the screen. Continuous slot screens are currently available in plastics and stainless steel and have the highest proportion of open area to facilitate water inflow.

Slotted well screen in uPVC or other plastics is the cheapest and most frequently used screen type. Slots are produced by the manufacturer to the required width and frequency. Open area is determined by the number of slots, their width and the screens diameter. High open area screens with narrow slots can lead to fragile and flimsy casing. Very narrow cut slots, in weak material and in deep boreholes where large loads may be imposed, may deform and partially close. Appropriate wall thickness and material specifications are critical for deep installations.

Permeable plastic casing (available from a single supplier) is manufactured from HDPE. The screen has a range of pore sizes and porosities which will allow water to penetrate through the casing. These screens are designed for boreholes where filter packs may not be suitable or cannot be used.

Screen aperture size should be selected to minimise the ingress of fine materials into the borehole and to maximise the hydraulic performance. In fine formations it is difficult to construct slot sizes which are sufficiently small to prevent the ingress of fine particles and a geotextile wrap is often used.

The required slot size of the screen is determined from the grain size of the filter pack, which in turn is designed with reference to formation grain size. The screen slots should be small enough to prevent 90 per cent of the filter pack material entering the GQMP - that is, equivalent to the grain size of the finest 10 per cent (the D_{10} of the PSD) of the filter material. In fine deposits (silts and clays) or in formations where there is a high proportion of silt or clay, the screen and filter should be supplemented with a geotextile wrap and a fine sand filter pack used. Where a geotextile wrap is used, consideration should be given to its mesh size, particularly when hydraulic testing of the borehole is proposed, and to the material employed due to the potential risk of release or sorption of organic substances. Geotextiles may be prone to clogging, although this may be remedied with backwashing (see Section 4.6).

A number of proprietary multi-level installation systems are available with different designs (see Box 6). These systems should be selected with care, as many different materials could be present in the installation. Multi-level systems are available in stainless steel and a range of plastics and it is recommended that the manufacturer or supplier is consulted about the performance and chemical stability of the material used.

3.5.4 Sealing and backfilling the borehole

The annular space from the top of the filter pack to ground level (or other monitoring zones in multiple installations) should be backfilled with a material that will:

- prevent interconnection of aquifer units;
- prevent preferential flow of contaminants or recharge
- support and protect the casing.

This is achieved by placing a seal immediately above the filter zone and then backfilling the remainder of the annular space with a low permeability grout.

The choice of material will depend upon the geological and hydrogeological setting, the risk of contaminant mobilisation along the borehole and the available budget. In general, seals are made from bentonite (pellets, granules or slurry) and grouts are made up of cement grout, bentonite grout or a cement:bentonite mix. To prevent these materials entering the screened section of the borehole - grout contamination is a common problem with installations - a seal should always be placed on top of the filter pack.

3.5.4.1 Seals

A bentonite seal of 1.0 to 1.5 m above the secondary filter pack (sand bridge) is recommended in accordance with UK and US guidance (Aller *et al* 1989, US Army 1998 and Environment Agency 2003a). The seal can be formed either from granular, pelleted or slurried bentonite. In installations above the water table granular bentonite is recommended; for sub-water table installations the use of bentonite pellets which sink to the top of the filter pack are more appropriate. Where backfilling is via a tremmie pipe, the bentonite must be capable of being added to the borehole via the pipe.

Bentonite is an appropriate sealing material for most situations; however, in the presence of free-phase NAPLs there is a potential for degradation and failure of the seal. McCaulou and Huling (1999) investigated the effect of a DNAPL contaminant on a bentonite seal and found that the presence of free-phase TCE (trichloroethylene), methylene chloride and creosote led to desiccation cracking and increased conductivity of the seal. When drilling in a location with the possible presence of free-phase chlorinated solvents, over-deepening of the borehole and subsequent backfilling with bentonite should only be undertaken with great care. Backfill techniques using bentonite below a monitoring installation should not be used where the bentonite provides a seal between different aquifer layers and where DNAPL may be present in the upper layers. An alternative to a bentonite seal in the presence of chlorinated solvents is a permanently installed packer constructed from material resistant to DNAPL.

Bentonite is alkaline (pH 8 to12) and has a very high CEC potential. It is therefore important that the bentonite seal is installed sufficiently far above the screened section of the borehole to ensure that the impact of the sample hydrochemistry is minimised.

In general, refined sodium bentonite has a greater swelling capacity and ready availability when compared to other forms of bentonite. Bentonite in contact with groundwater with an elevated calcium concentration may be affected by shrinkage resulting from ion exchange between calcium and sodium. In these situations the use of a calcium bentonite may be more appropriate.

Under saline conditions the swelling capacity of bentonite can be significantly reduced and modifications to the design of the seal may be required.

3.5.4.2 Grout

The material used to backfill the annulus of the borehole between the seal and ground level is referred to as grout. A number of materials can be used, but the most common is a combination of bentonite and cement. All grout seals should be mechanically rather than manually mixed, should consist of a thick, lump-free fluid suitable for pumping and should be placed by tremmie methods.

Different types of cement are available with varying resistance to erosion by aggressive (sulphate) groundwater conditions. The commonest type is Ordinary Portland Cement (OPC), which is generally suitable for use in grout and provides an inexpensive and structurally strong installation. The use of OPC (either neat or with bentonite) in saline water will require the use of additives, since the elevated sodium chloride levels will inhibit curing.

A number of additives can be used in conjunction with OPC including bentonite (discussed later in this section), pulverised fly ash, gypsum, aluminium and proprietary accelerants and retardants. The use of chemical additives in a GQMP installation should be undertaken with care and with an understanding of how they may affect groundwater quality and the stability of the casing.

Once installed, cement-based grouts will undergo a curing process during which they will harden, generate heat and undergo shrinkage. Temperature increases are related to the mass of cement in a body and may become significant in deep boreholes where temperature-sensitive casing material is used.

Shrinkage during curing can be minimised by reducing the water added to the cement. Sufficient water should be used to allow a pumpable mix; additional water will increase the shrinkage and decrease the strength of the cured grout. Shrinkage of the grout column may pull the grout away from the walls of the casing and of the hole. It may also result in the formation of long cracks, all of which will create preferential pathways for groundwater flow and contaminants. Cement devoid of additives is not recommended as a grout since it will undergo shrinkage with the same possible results.

The addition of bentonite to a cement mix increases the plasticity of the mix and the cured grout while decreasing the strength and shrinkage on curing. Bentonite also decreases the density of the grout. There is little consensus on the appropriate quantity of bentonite to be added to form a cement:bentonite grout. Driscoll (1986) recommends that no more than 6 per cent of bentonite is added to avoid excessive shrinkage of the cement. ASTM (2002) suggests 10 per cent is allowable while the

US Army (1998) recommends between 2 and 5 per cent. Other US research (discussed in Smith 1994) indicates that the addition of bentonite will have no effect on shrinkage but will reduce the potential for long crack formation in the cured grout. In general a bentonite:cement grout represents the most suitable backfill material.

The use of bentonite pellets or slurry as a grout may be suitable when a high strength grout is not required. The advantages of bentonite over cement are:

- flexibility but only when hydrated;
- ease of placement;
- no heat of hydration;
- no shrinkage when hydrated;
- reasonably chemically inert (in terms of health and safety).

Potential disadvantages are increased cost (the unit volume cost of bentonite is higher than that of cement), the low strength of the material and the potential for the bentonite to be washed out in fast-flowing aquifer systems.

Saline water is known to cause flocculation of bentonite; it also causes bentonite grout to lose viscosity and to undergo a more limited expansion. Brackish water or water with a high TDS (other than NaCl) may still have the potential to cause flocculation and the installation of GQMPs in these environments should be undertaken with care.

3.6 Headworks

Borehole headworks form the interface between the borehole and the surface environment and serve to complete the borehole and to allow continued access over time. In designing headworks a number of issues require consideration:

- security - headworks should prevent unwanted access to the borehole by humans or burrowing animals;
- protection - headworks should protect the borehole from the elements, from entry of water or other foreign material and from activities at the surface (such as vehicle movements);
- accommodation of equipment - headworks may be required to have space for the storage of equipment such as data loggers and dedicated sampling devices;
- visibility - where headworks need to be clearly visible, an appropriate design and colour scheme should be chosen; where visibility is not desired, the design should reduce visual impact.

A variety of commonly used headworks designs are described in Table 3.9 and example diagrams are given in Appendix C. The diagrams are intended to be generic baselines which can be copied, annotated and used in specifications.

In general, where no particular preference is stated an above-ground design should be used. The above-ground design is less likely to suffer from inundation, is easier to find in the field and is generally easier to secure. In most cases, however, the headworks design will be determined by consideration of the requirements of the site owner or user and by the need to incorporate monitoring equipment.

All headworks designs should provide a degree of protection to the borehole to prevent access of recharge and contaminants to the grout/casing interface or the grout/ground interface.

To encourage flow away from these interfaces, an impermeable concrete collar should be placed at the surface of all headworks, extending beyond the borehole with the concrete sloped away from the casing to promote runoff.

The Environment Agency's Good Practice document for water supply boreholes is a useful source of information; however, it is directed at abstraction boreholes where projected life spans are longer and initial investment is likely to be much higher.

Drainage of headworks is an important consideration for both above and below-ground installations. Above-ground standpipes can be drained via a small drain hole positioned close to the bottom of the headworks. This hole reduces the potential for stagnant water to collect in the annulus between the casing and the standpipe, and the potential for frost damage.

For below-ground installations (stopcock cover and chamber types), drainage provision can be problematic. Water can invade permeable concrete walls and as the concrete shrinks during curing, cracking may occur. In underground chambers there is also the potential for condensation to form. The addition of a drain hole or pipe can help to remove water entering the installation but can also provide a pathway for inflows and should be installed with care where high or perched water tables are anticipated. Where drainage cannot be provided, or where inflows occur, additional care in the installation may be required and increased maintenance necessary.

Where covers and caps are used, threaded seals should be avoided because of their tendency to rust, seize or freeze, making removal difficult.

Where artesian conditions are anticipated, completion of the casing and the headworks design will require additional care. The casing will need to be sealed to prevent groundwater discharge. The casing seal needs to allow access for pressure (head) measurement and groundwater sampling. Should water levels fall and become sub-artesian, the seal should also allow for dipping and a one-way air vent for pressure release. Where only small artesian heads are expected (to a maximum head of 1.5 m above ground level), it may be possible to contain the water within a length of casing, by extending the casing above the ground to the required height.

Where a GQMP installation programme includes a number of sites, access to headworks and boreholes should be standardised if possible. It is much easier to undertake sampling and maintenance when installations all have the same opening tools and keys.

Additional headworks protection may be required in vulnerable situations, for example in arable fields which are regularly ploughed, active quarries and landfills. Protection can take the form of post-and-rail fences, boulders or manhole rings filled with gravel placed around the borehole.

Table 3.9 Headworks types

Headwork type	Advantages	Disadvantages
Raised tube	• less likely to flood • easy to find • visible and therefore less likely to be run-over or ploughed up • easy to secure (such as with a padlock) • easier to work with for sampling (no need to bend right down); does not involve heavy lifting • able to contain small artesian heads (up to 1.5 m)	• highly visible making it prone to vandalism • forms an obstruction to vehicles. • storage of instruments may be limited • risk of collision damage (risk to and from livestock)
Flush stop cock type cover	• unobtrusive • less susceptible to ground disturbance • suitable to be walked or driven over	• vulnerable to flooding and inundation • difficult to locate in vegetated areas and may be inadvertently buried during site works • may be difficult to secure effectively • can be mistaken as a disposal point (sewer or soakaway) • access is limited • storage of instruments may not be possible
Manhole chamber	• unobtrusive • can be driven over, if carefully installed • permits storage of instruments	• vulnerable to flooding and inundation • can be heavy to lift

3.7 The surface environment

3.7.1 Pre-drilling site visit

Prior to drilling a GQMP, a visit to the chosen location is advisable to identify any issues that may not be apparent from documented sources of information. Considerations during the site visit will include the following:

- ease of access for drilling rigs and for subsequent sampling;
- facilities (water, power, storage areas);

- potential for disturbance or damage;
- health and safety - need for security, uneven ground, hazard identification;
- nuisance potential of the works (disturbance to occupants from noise and dust) and working hours;
- nuisance potential to the works (unwanted access such as vandalism).

The site visit is usually an appropriate time to undertake some of the consultation process (see Section 2.8). Where appropriate, the drilling organisation should be involved.

The site visit should be documented and photographs of the proposed drilling sites and access routes taken. This will help others to identify the drilling site and may help to resolve potential disputes over the condition of the site and access routes prior to the works and following re-instatement.

3.7.2 Access

Access routes to the GQMP and access limitations must be identified prior to construction as this may limit the drilling and construction process. In addition, arrangements for ongoing access should be considered, particularly where the site layout is likely to change over time, for example around a working mineral excavation, redevelopment site or landfill site. In these situations the following should also be considered:

- sampling equipment to be brought to the site - some sampling arrangements may require vehicular access to a point close to the borehole;
- the need for maintenance or rehabilitation requiring access for appropriate equipment.

3.7.3 Site owner requirements

Boreholes will often be installed on sites that are used for a variety of purposes (agricultural, industrial, commercial, landfill, mineral exploitation) or are in the process of being redeveloped. The owners of these sites may have requirements for the location of boreholes (although this should not compromise the monitoring objectives) and the type of headworks.

On sites where redevelopment activity will take place, the borehole should be sufficiently protected to ensure its survival and prevent it from acting as a pathway. Site workers may need to be briefed on the locations and importance of preserving the boreholes as well as precautions to ensure their survival during any construction or demolition phases.

3.7.4 Borehole labelling

Numbers should be permanently marked on, or attached to, an immovable part of the borehole or headworks such that they cannot be removed or switched during sampling or maintenance. Where boreholes are in public places, users may wish to add a data plate with a contact telephone number in case of accidental damage to the borehole.

3.8 Consultation and licensing

Potentially-affected organisations identified in the initial design stage (Section 2.8) should be consulted or informed of the proposed works to ensure their co-operation or appreciation of the works. Licences or permissions, where required, must be obtained prior to the start of the work.

The results of consultation may inform some aspects of the design process, particularly the location of the GQMP and the design of headworks.

4. Construction of groundwater quality monitoring points

4.1 Introduction

The quality of the GQMP installation will depend upon the design being correctly and competently implemented. The installation of GQMPs will require supervision by an appropriately qualified and experienced person. The supervisor's principal role is to ensure that the monitoring installation is constructed in accordance with the specification and good practice. The supervisor is also responsible for keeping accurate 'as built' records.

4.2 Construction Monitoring

4.2.1 Record keeping

It is of little use to carefully construct a GQMP if the details of the construction are not accurately and permanently recorded. Records should be adequate for accurate completion of 'as built' drawings, giving details of observations during drilling, water encountered and installation depths and dimensions. A lack of essential information on the construction details, even where a high quality installation has been built, means that the quality of the subsequent samples will not be known.

At the time of construction, records need to be kept of:

- dates of drilling;
- location of borehole and accurately-dimensioned sketch plan;
- type of drilling rig and technique used;
- drilling contractor;
- measures taken to avoid cross-contamination;
- measures taken to clean equipment before drilling and installation;
- rate of progress during drilling;
- formations encountered with an appropriate level of description;
- water strikes and rest water levels;
- problems encountered during drilling such as sidewall collapse – this will help subsequent drilling operations;
- type of flush used;
- quantities of water or other flushing media added and source of water/flush;
- well development measures undertaken (such as type of development, duration, volume and quality of water removed);

- hydraulic and geotechnical testing undertaken and results of such testing;
- depth and type of installation (screen depth, length and design, seal depth, type of construction used, source and type of materials used including supplier/manufacturer) - annotated diagrams are usually the easiest way to present the data;
- soil and groundwater samples taken during drilling and installation and results of any tests on those samples;
- survey level and location of datum;
- other relevant information such as verticality.

The key record is the borehole log, which should provide a record of the geology encountered (described in accordance with BS5930:1999), samples taken and *in situ* tests performed, hydrogeology (water strikes), installation details, drilling technique, datum and location. Other information should be collated within a post-construction report.

The borehole log and accompanying reports should be as detailed as possible. The log should be provided to the appropriate regulatory authorities where applicable.

Record keeping during sampling and maintenance of the borehole is equally important and is discussed in Section 5.1.

The Water Resources Act 1991 requires that borehole logs for water wells of greater than 15 m depth are submitted to the British Geological Survey (BGS). Similarly, the Mining Industry Act 1926 requires that borehole logs of mineral exploration boreholes of greater than 30 m depth are also submitted to the BGS. Other borehole logs should also be submitted to BGS to aid their geological survey work. Logs can be labelled as confidential if required, to prevent dissemination to third parties.

4.3 Borehole drilling practice

A description of standard drilling techniques and practices can be found in numerous publications, including the British Standard (BS: 5930). A number of basic best practices are presented below, but these should be considered in line with other guidance documents.

4.3.1 Cleanliness

All equipment should be washed with clean water prior to or upon arrival at the site, to prevent contamination from the previous job or from equipment transportation.

When drilling in to contaminated land or where movement of contaminants may be a problem, washing should also be undertaken between boreholes and between stages if telescopic drilling is being used. When drilling multiple boreholes, users should work from the least contaminated to the most contaminated location.

Steam cleaning or jet washing is the most suitable technique for removing debris and contaminants and should be used at locations where the discharge water will not pose an environmental risk.

4.3.2 Use of lubricants

Lubricant use should be minimised and should only be used on temporary casing or drilling equipment and not on well screen or permanent casing. Lubricants should be restricted to degradable or inert lubricants, such as vegetable oil or PTFE (Teflon) based. Metallic greases such as those containing copper or lead and hydrocarbon-based lubricants must not be used.

If lubricants of any description are used, this should be noted in the drilling records and the presence considered when interpreting sampling results.

4.3.3 Geological descriptions

BS 5930:1999 provides a detailed method for the logging and description of geological materials. This standard should be used for consistency in nomenclature and to reduce the potential for misunderstanding. Records of formations encountered and samples taken should form part of the driller's daily site report, but detailed logging should be undertaken by a suitably-trained geologist or engineer.

4.3.4 Waste collection and disposal

The collection and disposal of drill cuttings and water resulting from drilling, GQMP development and testing need to be considered prior to site work, as does the potential presence of contaminated spoil. There may be a requirement for on-site storage depending on how the waste is produced - rotary drilling has settlement tanks while cable tool will have bailers to empty. As far as possible, a clean working environment should be maintained around the borehole during drilling to reduce cross-contamination and in some cases for health and safety considerations.

None of the waste generated by drilling, such as overalls and gloves, should be allowed to enter the borehole during drilling or installation.

Waste generated by the drilling process must be appropriately disposed of. Contaminated material will require testing to determine the most appropriate disposal route. Disposal of waste imposes a duty of care on those responsible for generating the waste. Disposal must be documented through the use of waste transfer notes.

4.4 Installation practice

Prior to undertaking the installation the drill site should be cleaned up, particularly when drill cuttings are contaminated, so that installation materials do not come into contact with contaminated material.

Unless installation materials arrive on site wrapped and cleaned at point of dispatch they should be washed down to remove any lubricants or degreasers that may have been used during their manufacture.

Where materials arrive on site unwrapped, or if they are stored for significant periods of time, it may be necessary to wash down materials even if factory cleaning has taken place, to remove road dirt and other contaminants. As with the cleaning of drilling equipment, this should be undertaken with clean water in a location where the water generated will not pose an environmental risk.

The order of installation will be:

- backfill (if the borehole has been over-drilled) to the installation depth;
- screen and casing;
- filter pack;
- sand bridge (if required);
- bentonite seal;
- grout seal;
- protective headworks.

Where backfill has been added to the borehole, sufficient time must be allowed to ensure that the backfill material has settled in the borehole and, in the case of bentonite pellets or slurry, has hydrated. Installation over a surface of unhydrated bentonite pellets may lead to adverse pressure on the casing, resulting in damage or collapse as the pellets swell.

4.4.1 Well screen and casing

Screen and casing materials need to be installed into a clean hole with a minimum of suspended debris in the water column. The borehole should be bailed or flushed prior to placing the materials.

In boreholes deeper than 20 m (US Army 1998), and where the straightness of an installation is important, the use of centralisers should be considered. When using centralisers there is an increased risk of bridging and snagging and as such, additional care will need to be given to the installation of the filter pack and other backfill materials. Centralisers will also be required for inclined boreholes to ensure that the installation does not rest on the lower sidewall of the borehole.

During installation, the casing and screen should be suspended in the hole at the required level and must not be allowed to rest on the base of the hole during addition of the filter pack and other backfill materials. This will ensure that the screened section is not embedded in the sediment at the bottom of the hole and will improve the straightness of the finished installation.

4.4.2 Filter pack

The filter pack is installed around the well screen. The annulus of a borehole deeper than 15 to 20 m (Environment Agency 2003a) should be backfilled with the aid of a tremmie pipe to ensure an even distribution of materials and to reduce the risk of materials bridging in the annulus. The filter pack must be added in small volumes and regularly measured using a weighted tape. An indication of the required volume and weight of filter materials is given in Section 3.5; however, because of the irregular nature of borehole walls this is only intended as a guide. Following the installation of the filter pack, the sand bridge (or secondary filter pack) should be undertaken in an identical manner.

A tremmie pipe is typically a narrow (25 to 50 mm) diameter plastic pipe placed down the annulus of an installation for the purpose of adding filter materials and sealants.

The pipe should be big enough to accommodate the fill materials but small enough to fit comfortably in the annulus. The base of the pipe should be maintained at least 1 m above the base of the annulus to allow materials to settle freely without clogging the tremmie pipe.

The use of tremmie methods is strongly recommended for a good quality installation at any depth. However, in shallow boreholes with a large annular space, and where there is a short column of water in the annulus, direct placement of the filter pack into the annulus may be permitted.

Water may need to be added down the tremmie pipe to prevent clogging, particularly when adding a sand filter. The volume of water added should be recorded and should be kept to a minimum.

4.4.3 Bentonite seal

A bentonite seal is installed above the filter pack. In boreholes with a long column of water above the installation, there is a potential for bentonite pellets to become hydrated before reaching the top of the filter zone/sand bridge (Driscoll 1986). Specially-treated pellets (either baked or coated) are available to slow the rate of hydration and prevent bridging. An alternative suggested in Driscoll (1986) is to chill the pellets where site conditions allow. Coated pellets should be used when employing tremmie methods. In deep boreholes where the potential for bridging of pellets is an issue, bentonite may be added to the borehole as a slurry via a tremmie pipe.

Following the addition of the bentonite seal, it must be allowed to hydrate sufficiently prior to the injection of the grout. US Army (1998) recommends three to four hours as appropriate, and that in dry boreholes clean water should be added to promote hydration.

4.4.4 Grout

In deeper boreholes (greater than 15 m depth) grout should be added to the top of the seal using a tremmie pipe. Addition of grout will displace water in the annulus back in to the formation or out of the top of the borehole. When grouting shallow boreholes, it may be acceptable to add the grout to the top of the borehole and allow it to settle to the base of the hole. US Army (1998) suggests 15 m as a cut-off where pouring grout from the top may be acceptable. Grouting should be undertaken after suitable time is left for bentonite seals to hydrate, to reduce the potential for grout contamination of the filter pack.

4.4.5 Headworks

The headworks complete the borehole and may be installed before or after well development. On completion, the top of the borehole casing should be horizontal to allow a consistent dip datum and cut-off pipes should be avoided where possible. The top of the casing should preferably be the end of a casing length fitted with threads to allow extension or adaptation at a later date (this may be significant where a borehole has the potential to become artesian). The top of the casing should be as high as possible within the headworks design to minimise the risk of inundation of the GQMP.

4.5 On-site decision making

Some decisions regarding the design may need to be made on-site at the time of drilling and installation, as a result of additional information collected on the geological and hydrogeological conditions at the borehole. This information may require the user to re-locate the response zone and seals, due to changes in the depth of the water table or the location of permeable and impermeable horizons. Alternatively, the user may need to re-design the filter pack.

Users may also encounter difficulties during drilling or installation. Sometimes the ground conditions mean that the desired borehole depth cannot be achieved - for example, the borehole will not stand open. For reasons of time and cost, users may choose to complete the GQMP despite this set-back and adopt a ‘least-worst’ contingency.

Decisions on site should be made in the context of the monitoring objectives and should be communicated to site supervisors with the underlying logic clearly stated.

To aid on-site decision-making, the designer should give consideration to a number of contingency plans for any foreseeable issues or difficulties. These plans may include:

- alternative response zone location;
- alternative drilling techniques;
- alternative headworks design;
- an action plan or method for abandonment.

4.6 Borehole development

4.6.1 Introduction

Borehole development is a frequently neglected but vital step in the commissioning of a GQMP. Development is the process of returning the conditions around the GQMP to as close to those prior to drilling as possible. This involves pumping and cleaning to remove any fluids added to the formation during drilling, and the removal of fine material from the borehole and surroundings.

In water wells, flocculants may be added to remove mud caked on the borehole sidewalls and acid may be added to improve hydraulic performance, although these practices are unlikely to be acceptable in a water quality monitoring borehole.

4.6.2 Pre-installation

It is good practice to clean out the borehole prior to the installation of the well screen and casing. However, the extent to which this can be done will depend upon the stability of the borehole sidewalls. In stable formations, much of the development can be undertaken in the unsupported holes, but in unstable formations, minimal cleaning of the borehole, if any, will be undertaken.

For holes drilled using rotary methods, cleaning may be achieved by continuing the flushing until further recovery of cuttings is no longer possible. For cable percussive drilling, cleaning is likely to be limited to the bailing of the temporarily-cased or open borehole to remove loose material and sediment-laden water.

4.6.3 Post-installation

Post-installation development is required to ensure the hydraulic functioning of the GQMP. Borehole development can be carried out with chemical or mechanical methods. Chemical development will not generally be suitable for GQMPs and should be avoided.

Development should be undertaken as soon as possible after drilling and installation, although time will be required to allow bentonite seals to fully hydrate and cement grouts to cure. The use of an improper technique can introduce the risk of collapse/failure of the screen or casing and therefore development must be planned and undertaken carefully.

The following mechanical techniques are available for borehole development: surging, pumping, back-washing, bailing, air-lifting and jetting.

Surging involves the vertical movement of a surge block within the installation, which alternatively forces water in to,and out of the screen and filter pack, mobilising fine particles and foreign materials introduced during drilling. The surging is combined with abstraction to remove the mobilised material. Surging must be carried out using a suitably sized surge block and must be done at a rate that will not damage the casing or the screen through which it travels. Damage can occur if surging creates strong suction.

For pumping, abstraction using a submersible pump will mobilise water, any dissolved materials introduced during drilling and some of the finer sediment particles, and will draw them towards and through the screen. The pump must be capable of dealing with sediment-laden water or can be used in conjunction with a bailer. Since flow is always towards the screen, it is possible that material will become clogged around the screen. Development by pumping may not be practicable in narrow diameter GQMPs or in low permeability deposits.

Back-washing involves adding water to a GQMP to produce an outward flow that can dislodge sediment in the screen and filter pack. Back-washing, which employs a pump, will, however, force material introduced by drilling further into the aquifer. The pump is used to release a column of water back into the borehole when switched off, to create a surge that will cause mixing in the borehole and displacement of water out of the casing into the surrounding filter pack. Back-washing will only mobilise sediment and will not remove materials introduced during drilling. It is therefore not practical for development of GQMPs.

Bottom-loading bailers can be used for the gentle removal of water and debris from the GQMP. Movement of the bailer within the water column will have a similar effect to a surge block and will mobilise fine particles into suspension. Bailing can be slow in deep boreholes and will not be effective in pulling material into the borehole for recovery from the filter pack or surrounding aquifer. Bailing is suitable in low permeability deposits where only limited volumes of water are removed.

In air–lifting, the release of compressed air within the water column will cause a pressure imbalance and the discharge of water at the surface. This discharge can be difficult to collect, which may be an issue when contaminated groundwater is present. Compressors must be oil-free and the air must be filtered as compressors can introduce hydrocarbons into the flow. Aggressive release of air can cause a pressure gradient that leads to damage or failure of the GQMP screen or casing. Air-lifting has the disadvantage of introducing air into the filter pack and the aquifer, where it can temporarily affect groundwater chemistry. Where volatiles are present in groundwater (or as free-phase), air-lifting can pose a significant health and safety risk.

The technique of jetting uses high velocity water jets which act horizontally through the screen from a sonde lowered into the GQMP. Jetting introduces additional water and fine particles into the aquifer and is therefore unsuitable for most GQMPs. In addition, the sonde requires boreholes of greater than 100 mm diameter. Jetting is also much less effective where slotted casing is used and is more applicable to the cleaning of continuous wire-wound screens.

Prior to or during development, the well casing (and headworks) above ground should be cleaned to remove any residual drilling fluids, grout or other debris. This may be done with water from development provided it is of suitable quality.

Development should continue until a defined end point has been reached, such as:

- chemical indicator stability - using field measuring techniques for pH, EC and dissolved oxygen, development is continued until these parameters stabilise in abstracted water;
- reduced turbidity, where development is continued until the abstracted water is reasonably free of suspended solids;
- volumetric - if a flush was used to aid drilling, the volume of flush lost in the borehole can be determined and development should aim to remove a multiple of this volume;
- hydraulic performance, where development is continued until there are no further improvements in borehole transmissivity.

Where the borehole fails to reach its development end point, an upper limit in terms of the time and effort expended may be set.

4.7 Completion

Following development and installation of headworks (if not undertaken before development), the GQMP is complete. The drilling site must be left in a clean and tidy condition and all materials and spoil removed.

5. Post construction activities

5.1 Introduction

Following development and headworks installation, the GQMP is complete. However, there are a number of post-construction activities that can help to maintain the performance of a GQMP and these are explained below.

5.2 Sampling

Groundwater sampling is discussed in detail in a number of other references (such as Environment Agency 2003b) and is not covered in this report. Following drilling and installation, there is a need to allow the GQMP to equilibrate before sampling commences. A rule of thumb (US Army 1998) is that 14 days should be allowed for the stabilisation of the groundwater and its equilibrium with the casing and backfill materials, although this has no substantive scientific basis. The duration of any stabilisation period should be based on the hydrogeological conditions and the nature of the materials introduced during the drilling and installation process.

As part of a groundwater monitoring programme, records should be kept on borehole performance over time. Such records should include the following during each sampling event:

- plumbed depth of the borehole;
- rest water level;
- identify if the equipment snags on the sides of the casing;
- volume of water purged from the installation prior to sampling;
- response to pumping (pumping rate, drawdown at end of pumping);
- turbidity and colour of pumped water for comparison between sampling events. An increase in turbidity or a change in colour may indicate collapse of the borehole or damage to the screen intake. Visual assessment of turbidity and colour should be made against a white background;
- time for indicators (EC, pH, dissolved oxygen) to stabilise where measured during purging;
- water quality issues which may have resulted from poor installation, such as high pH or potassium concentrations due to grout contamination;
- condition of headworks – cracks or damage to the headworks, presence of water or flooding around borehole.

Any problems with the installation that are observed on-site should always be reported immediately.

It is also necessary to keep a record of post-installation activities, such as rehabilitation works or changes to the headworks that could affect the datum.

5.3 Routine inspections and maintenance

In the context of this report, maintenance refers to routine activities and is distinguished from rehabilitation which is an infrequent activity undertaken to restore borehole performance. Where a borehole is sampled infrequently, regular inspection visits should be considered to assess its condition.

Correctly installed GQMPs should not, in general, need much maintenance. Maintenance is most likely needed for headworks, particularly in areas with heavy traffic. These may become damaged as a result of trafficking, ground movement (such as shrinkage or swelling of clays) or from sampling use (for example, where sampling devices are clamped to the headworks). Maintenance may also be needed to remove accumulated silt by pumping (usually undertaken during sampling).

Regular maintenance may also be required to maintain access to a GQMP, for example, where it is in an area of thick vegetation or at risk of burial or inundation by sediments. Such maintenance may form a requirement under a site working plan or agreement that includes maintenance responsibilities and contingency plans.

5.4 Rehabilitation

GQMP function may deteriorate over time for a number of reasons including:

- fouling by chemical, biochemical or biological material;
- silting due to invasion of the filter pack, screen and casing by fine materials;
- mechanical failure of casing due to ground movement;
- corrosion or degradation of GQMP materials;
- accidental or deliberate damage.

Where the deterioration can be reversed, some rehabilitation may be desirable or necessary. Primarily this will involve addressing problems of deteriorating hydraulic performance which have occurred as a result of fouling or silting. The need for rehabilitation can often be reduced or eliminated through good design, installation, development and sampling practices. In this sense rehabilitation uses the techniques described in Section 4.6 (borehole development) to clean out the borehole. For older installations, greater care may be required as materials may have lost strength following prolonged exposure to the environment.

Rehabilitation options are limited by the original construction, including its diameter, strength and screen length. In addition, the use of chemical treatments to undertake such work will need to be carefully considered to determine whether such an approach is compatible with the monitoring objectives.

The time and effort spent on rehabilitation will be a function of the value of the GQMP and the difficulty in replacing it. It should be noted, however, that constructing a new borehole may lead to changes in key parameters due to natural variability or use of different materials and a new borehole may take some time to acclimatise. It is therefore better, where possible, to retain an existing borehole.

5.5 Decommissioning

5.5.1 Introduction

In some situations, boreholes will require decommissioning at the end of a project to ensure that they do not form preferential pathways for contaminant migration. In situations were decommissioning is identified at the start of the project as likely to be required, it should be included in the capital costs for the project. Decommissioning is a potentially expensive and time-consuming operation.

Additional advice on decommissioning is given in *Decommissioning abandoned boreholes and wells*, an Environment Agency information pamphlet available on its website (www.environment-agency.gov.uk) .

5.5.2 Objectives

The objectives of decommissioning may include:

- removal of a safety hazard;
- preventing a GQMP acting as a pathway for contaminant migration;
- preventing mixing of contaminated and uncontaminated groundwater, for example fresh water entering a contaminated aquifer and becoming contaminated via a GQMP;
- preventing vertical flows within a GQMP;
- sealing overflowing artesian boreholes.

5.5.3 Considerations

Selection of the most appropriate method for decommissioning a borehole will require detailed knowledge of the GQMP design, including:

- GQMP construction details (depth, borehole diameter, casing materials and diameter, depth and length of screened section, backfill type and thickness, age of construction);
- GQMP condition (whether the annulus seal is intact, whether the casing has suffered corrosion or degradation);
- sub-surface environment (location of aquifers and aquitards, standing water level, zones and types of contamination).

5.5.4 Pre-works site inspection

A site inspection visit should always be conducted prior to undertaking decommissioning works, to determine or verify construction details and to ensure that the GQMP can be found and is accessible. In addition to the visit objectives listed in Section 3.7, the inspection visit should include plumbing of the borehole to confirm its depth and measurement of the groundwater level.

If a borehole cannot be located, but is believed to be causing or is potentially at risk of causing contaminant migration, then additional measures may be necessary to locate it. Such measures may include stripping of vegetation, accurate surveying of known positions or geophysical techniques.

For deep boreholes, the borehole may require a closed-circuit television inspection to determine its condition, particularly with respect to whether the casing is intact.

5.5.5 Approach

Any equipment within the borehole should be removed along with the headworks prior to decommissioning. The approach to decommissioning will be determined by the considerations outlined above. The options are to:

- remove the GQMP completely by pulling and/or drilling out;
- partially remove the GQMP to break the pathway;
- seal the intact GQMP including the filter pack to prevent it from forming a preferential pathway.

The preferred option is complete removal of the borehole where possible. Sealing-only techniques offer less assurance that all potential pathways have been closed. However, unsuccessful removal operations carry the risk of leaving an unsealed section of the borehole in the ground and hence a contaminant pathway. The decision to undertake complete removal or to seal the borehole will depend upon the condition of the casing and the risks posed by the GQMP.

5.5.5.1 Decommissioning by casing removal

Casing can be removed from the GQMP either by pulling it out or by over-drilling the borehole. Pulling with hydraulic jacks or other devices may be appropriate where the GQMP is not particularly deep, the casing is not well cemented, the GQMP may not have been grouted or where the grout has shrunk away from the casing during curing. Direct pulling will not work for deep installations or those that are tightly held by grout.

Following successful removal of the casing, the borehole should be over-drilled to remove any remaining installation materials.

Over-drilling is commonly undertaken using a hollow stem auger which is 50 to 100 mm larger than the external casing diameter. The auger is placed over the casing so that the backfill materials are drilled out, leaving the unsupported casing in the hollow stem from where it can be removed. The borehole is backfilled via the hollow stem as the auger is removed.

Over-drilling can also be undertaken using rotary techniques by first drilling out the casing materials and then reaming out the backfill materials. Similarly, cable tool methods can also be used to over-drill the borehole.

Hollow stem auger techniques are preferable because they do not require the borehole to stand open during backfilling operations.

5.5.5.2 Backfill

The borehole should be backfilled in one of two ways: in a way that mimics the natural conditions in the ground – in other words, high permeability backfill should be used in high permeability zones and low permeability material placed against low permeability zones; or by sealing with low permeability materials (grout).

Backfill materials should be used in accordance with the guidance in Section 4.4.

In high-permeability and fissured strata, grout may travel away from the borehole. In this situation, the use of a granular backfill is likely to be more appropriate.

The final 2 m to ground surface should be filled with a concrete cap that extends to 1 m around the site of the borehole and is of suitable strength for the proposed land use.

5.5.5.3 Decommissioning without casing removal

Where casing removal is only partially successful, or where it is not possible to remove the casing and it is known or suspected that there is a contamination migration route via the backfill, then the casing should be perforated using casing cutters and the installation pressure grouted to seal these potential pathways. Advice on the number and spacing of perforations is contained in ASTM (1992).

Where the borehole casing and grout seal is intact, then the casing can be grouted or sealed using bentonite.

5.5.6 Documentation of decommissioning

The decommissioning process should be fully documented to demonstrate that it has been undertaken. Records should include:

- the reason for abandonment;
- groundwater level prior to decommissioning
- any removal of casing or attempts to remove the casing;
- the depth, position and nature of backfill materials;
- problems encountered during decommissioning.

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Appendix A

Information questionnaire and checklists

5 Pages

Initial Design

Monitoring Objectives:

Define primary and secondary objectives: ☐

……….

……….

……….

……….

……….

Site Data: ☐

Potential of surface/near surface contamination ……………………………………………………….

Difficult ground conditions ………………………………………………………………………………….

Potential flood risk ………………………………………………………………………………….

Geology:

Source of geological data ………………………………………………………………………………….

Drift and Made Ground - ☐

Type ………………………………………………………………………………….

Thickness ………………………………………………………………………………….

Strength ………………………………………………………………………………….

Stability ………………………………………………………………………………….

Solid strata - ☐

Type ……………………………………………………………………………………….

Strength ……………………………………………………………………………………….

Thickness ……………………………………………………………………………………….

Stability ……………………………………………………………………………………….

Gather additional information if required.

Hydrogeology:

Source of hydrogeological data ………………………………………………………………………….

Flow regime (hydraulic conductivity, flow type (intergranular / fissure), location of different layers, direction of groundwater flow) ☐

…….

…….

…….

…….

…….

Depth to water table - (artesian conditions) ☐

……………………………………………………………….

Background groundwater quality - (acidic, alkaline, reducing, oxygenated, saline, mineralised etc) ☐

…….

…….

…….

……………………………………………………………………………………
…………………………….

Potential or known groundwater contaminants (substances, concentration, phase) ☐

……………………………………………………………………………………
…………………………….

……………………………………………………………………………………
…………………………….

Gather additional information if required.

Establish Conceptual Model ☐

Initial Design

Identify appropriate: ☐

Screen length
……………………………………………………………………………
Screen / casing diameter
……………………………………………………………………………
Depth
……………………………………………………………………………
Diameter
……………………………………………………………………………

Identify borehole numbering system ☐

Identify and consult stakeholders - ☐

-Environment Agency -Landowners -Coal Authority

-English Nature -BGS

Drilling:

Select suitable drilling methodology ☐
……………………………………………………………………………

Identify precautions/contingencies against: ☐

Cross contamination

Artesian conditions

……………………………………………………………………………………
…………………………….

……………………………………………………………………………………
…………………………….

…………………………………………………………………………………………
……………………………….

Initial Cost Estimate

Undertake initial cost estimate ☐

………………………………………………………………………….

Detailed Design

Drilling

Confirm drilling choice ☐

……………………………………………………………………………….

Drilling company

……………………………………………………………………………….

Drilling rig type and number

……………………………………………………………………………….

Drilling crew

……………………………………………………………………………….

Confirm drilling location NGR: ☐

…………………………………………………………………….

Materials

Select casing and screen material based on: ☐

Slot size

…………………………………………………………………………………….

Depth

…………………………………………………………………………………….

Contaminants and phases present

……………………………………………………….

Primary filter pack materials: ☐

Grain size

……………………………………………………………………………….

Chemical composition

……………………………………………………………………………….

Secondary filter pack materials: ☐

Grain size

……………………………………………………………………………….

Chemical composition

……………………………………………………………………………….

Geo-textile wrap (if applicable) ☐

……………………………………………………………………………….

Development

Type of development ☐

Duration of development ☐

Developed well head parameters: ☐

……

……

……

……

Headworks

Select and design headworks based on ☐
Type (above/below ground)
Size (to accommodate equipment)
Security requirements (padlock, lifting device)
Select colour scheme/headworks size (for visibility and storage)
Drainage provision
Labelling considerations

Write specification and bill of quantities ☐

Confirm costs ☐

Borehole Construction Checklist

General issues/requirements

Health and safety plan ☐

Services plans and installation location maps/diagrams ☐

Method statements ☐

Contingency plan ☐

Written instructions ☐

Mobilisation

Check equipment suitability and completeness (rig stability etc) ☐

Check calibration (dippers, EC, pH meters etc) ☐

Cleaning of drilling rig and materials ☐

Storage and disposal of wastes ☐

Check sources of water / flush medium ☐

Drilling and Testing

Monitor progress ☐

Log borehole geology and water strikes ☐

Identify quantities of water / flush used

Undertake testing ☐

Clean-out borehole (pre-installation development) ☐

Installation

Clean work area ☐

Clean screen and casing ☐

Assemble and place ☐

Install filter pack ☐

Install sand bridge (if appropriate) ☐

Install seal ☐

Grout backfill ☐

Headworks ☐

Development

Type of development ☐

Time allocated for development ☐

Stabilisation criteria ☐

Check storage and disposal of water ☐

Record keeping

Location of borehole / sketch plans ☐

Depth of drilling, screen, backfill materials ☐

Construction notes ☐

Observations during drilling ☐

Observations during installation ☐

Observations during development ☐

Appendix B

Drilling techniques

5 Pages

Table B1 Summary of common drilling techniques

Description	Advantages	Limitations
Cable tool		
A rig with a winch is used to repeatedly drop a weighted tool. A number of tools are available which can chisel, cut, crush and remove material Due to the action of the tool there is a risk of instability and temporary casing is often advanced as the hole deepens Installation of the casing and backfill materials takes place within the string of temporary casing (where this is used) which is removed in stages Drilling depths are limited by rig size (commonly depths of <50 m in the UK) and diameters are a minimum of 150 mm	Widely available Suitable for all soil and some rock types Good sample return Rapid and relatively inexpensive set up Temporary casing prevents collapse of loose strata and reduces risk of cross contamination	Progress will be slow in most consolidated deposits Difficult to penetrate cobbles and boulders Many downhole geophysical methods will not work inside temporary casing Water is often required to aid drilling in unsaturated strata Installation and removal of the temporary casing can cause smearing of borehole walls
Rotary - general		

A cutting bit is mounted on a rotating drill pipe with a circulating flushing fluid to remove debris and cool the bit. The fluid and bit have a number of variants and there is a wide range of rig sizes In unstable formations a flush can be chosen that invades the borehole wall and provides temporary stability Drill-bit and flush choice depend upon the expected strata and the borehole depth. A range of borehole diameters can be drilled In conventional drilling, the flush is injected into the hole through the drilling string, and discharges from the vicinity of the drill bit. The returning fluid and drill cuttings are forced upwards within the annulus of the hole to the surface where they are collected. The flush may be re-circulated	Drilling rates can be very rapid (even in strong rock) and can reach to considerable depths Cores can provide excellent strata information Boreholes can be left open in stable deposits to facilitate geophysics and other downhole testing methods (e.g. packer testing) The addition of specialist equipment to the rig can allow drilling in strongly artesian conditions	Fissured strata has the potential to slip into the borehole and trap the drill bit Loss of flush (into fissures/ voids) can slow drilling rates and compromise subsequent samples Initial set up and mobilisation can be expensive Sample recovery can be poor If liquids are used as the flush there is a need for storage and re-circulation on site. This may be significant if contaminated groundwater is present or space is limited A long section of open hole may lead to contaminant mobilisation from one aquifer system to another
In the reverse circulation method, the drilling fluid is injected down the annulus, outside of the drill string and abstracted though the drill stem. This method lowers the pressure on the formation and significantly reduces the invasion of the drilling fluid into the aquifer. In general only water is used as a flush	Advantages, in addition to those for standard rotary drilling are principally the minimisation of invasion of the formation by the drilling fluid	More expensive than conventional rotary drilling. Requires specialist equipment.

Table B1 (continued) Summary of common drilling techniques

Description	Advantages	Limitations
Rotary (air flush)		
Air flush can be used as a drilling fluid to aid the return of drill cuttings to the surface. The addition of small amounts of water to an air flush provides a mist flush. Reverse circulation using air can be used	Air flush can be used in fractured strata Readily available. Flush does not require treatment or disposal	Introduction of large quantities of air to groundwater may produce significant changes in chemistry In unstable strata temporary casing will need to be used May mobilise VOCs
Rotary (percussive)		
The addition of a hammer bit powered by compressed air allows a much more rapid rate of penetration when rotary drilling. Reverse circulation can not be used when using percussive drilling	Rapid penetration	Poor sample returns Introduction of large volumes of air into the aquifer
Rotary (water flush)		
Water is used in place of air to lubricate the drill bit and return cuttings to the surface. This requires the provision of circulation tanks or pits on site and a suitable water source Reverse circulation drilling is commonly undertaken using a water flush	Reduces the generation of dust Readily available	The addition of water will affect groundwater chemistry in the immediate vicinity of the borehole In unstable strata temporary casing will need to be used
Rotary (mud flush)		
Mud is a drilling fluid comprising water with an additive to provide additional viscosity and density. Mineral (such as bentonite) and chemical (e.g. guar gum) muds are available	Loose borehole walls can be stabilised The use of 'heavy' muds can aid drilling in artesian conditions Restricts fluid invasion of the formation	The addition of mud (and any degradation products) will affect the hydraulics of the borehole wall and the aquifer and groundwater chemistry

Table B1 (continued) Summary of common drilling techniques

Description	Advantages	Limitations
Unusual/Uncommon techniques		
Sonic drilling		
Based on a rotary rig, sonic drilling adds a high frequency vibration to the rotating bit. This vibration increases penetration speed in unconsolidated granular deposits Although relatively uncommon in the UK this method is well established in the US	Sample recovery can be excellent (using cores) Drilling fluids are not needed when drilling soils. Drilling speed can be very rapid in 'suitable deposits' The amount of waste spoil generated can be less than conventional drilling as aquifer material can be displaced into the borehole walls	Current availability is limited in the UK and restricted to small rigs, which have restricted depth capabilities and cannot penetrate strong materials Vibration of the drill bit can cause heating of the drill bit leading to volatilisation of volatile organics
Direct push		

A narrow diameter well point (<50 mm) attached to the bottom of a casing length is driven by hand or machinery Alternatively, a length of temporary casing can be driven into the ground and the inside cleared by bailing. Installation can then be undertaken within this casing which is then withdrawn Cone penetrometer (CPT) equipment can also be used to drive monitoring installations into the ground	Inexpensive Rapid Minimal aquifer disruption in fine granular deposits	No sample recovery or geological information Unable to penetrate dense materials or deposits containing cobbles or boulders Limited depth of penetration Risk of smearing clays Unable to seal off discrete layers Steel drive tube or casing (used for strength) can interfere with groundwater chemistry No filter pack installation possible

Table B1 (continued) Summary of common drilling techniques

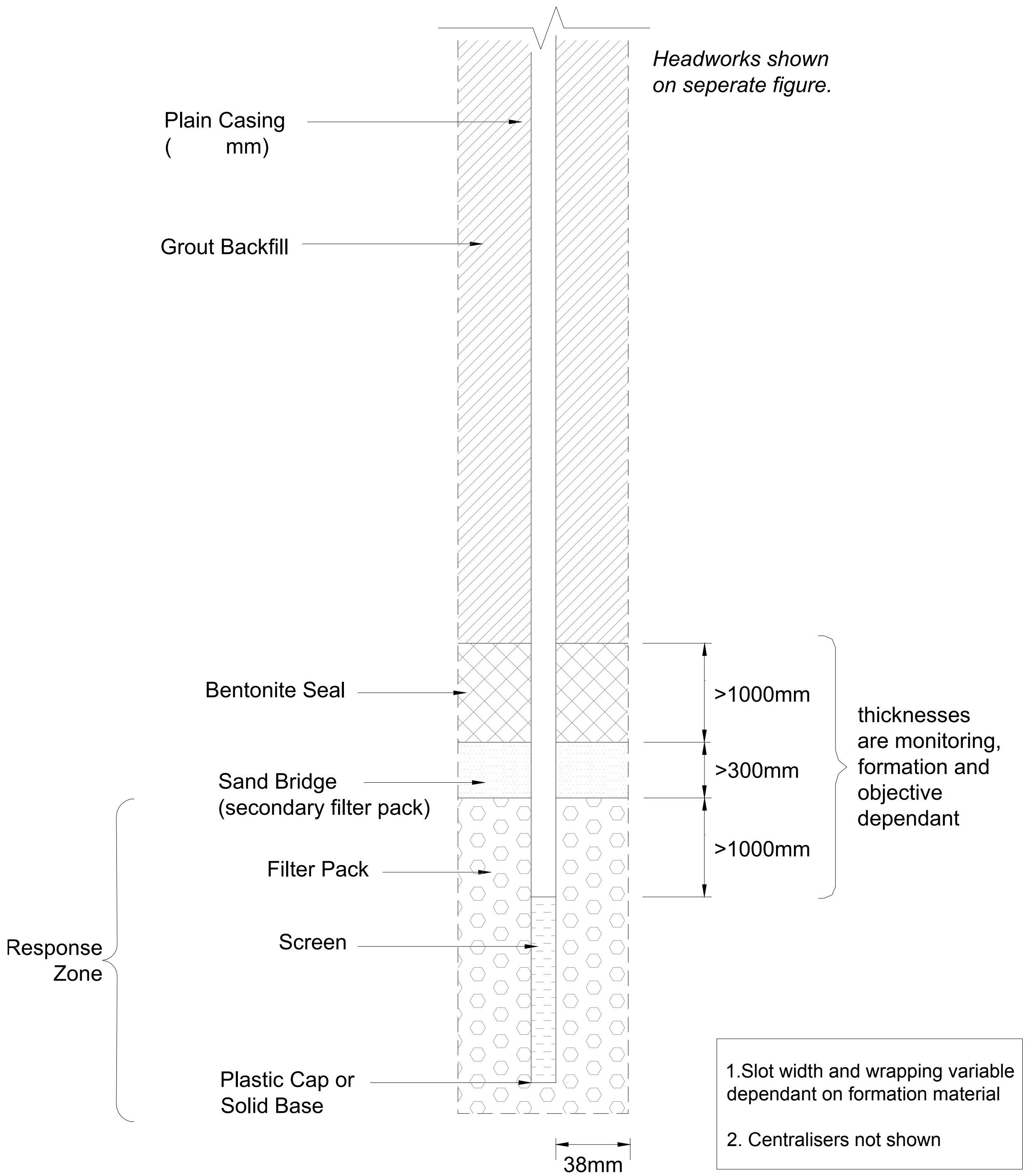
Rig type	Method	Benefits	Limitations
Jetting			
	As a modification to the direct push this technique uses a jet of water emanating from the tip of the casing	Inexpensive Rapid	No sample recovery Limited to sands Limited depth of penetration Requires clean and plentiful water supply
Directional drilling			
	Directional drilling is a variant of rotary drilling where the rig has the ability to angle the mast and as such, dictate the direction of the drill bits progress	Possible to drill boreholes under structures or features of interest Possible to intercept vertical fractures Possible to monitor surface/groundwater interfaces with a longer screen section	Support of borehole walls required Installation of casing and monitoring equipment can be difficult Expensive
Augering - (Solid auger, hollow stem auger and hand auger)			

Rotation of a helix with vertical pressure will allow penetration of loose or weak strata. Auguring can be undertaken by hand to shallow depths and at narrow diameters. Motorised equipment can drill deeper and at a greater diameter	Hand auguring is inexpensive and rapid Drilling fluids are not required Hollow stem augers provide an open void for installation materials	Auger drilling equipment is relatively uncommon in the UK Unable to penetrate strong rock Hollow stem auger is unable to progress in presence of cobbles or boulders Installations in unstable ground are not possible using solid stem augers Smearing of clays may occur

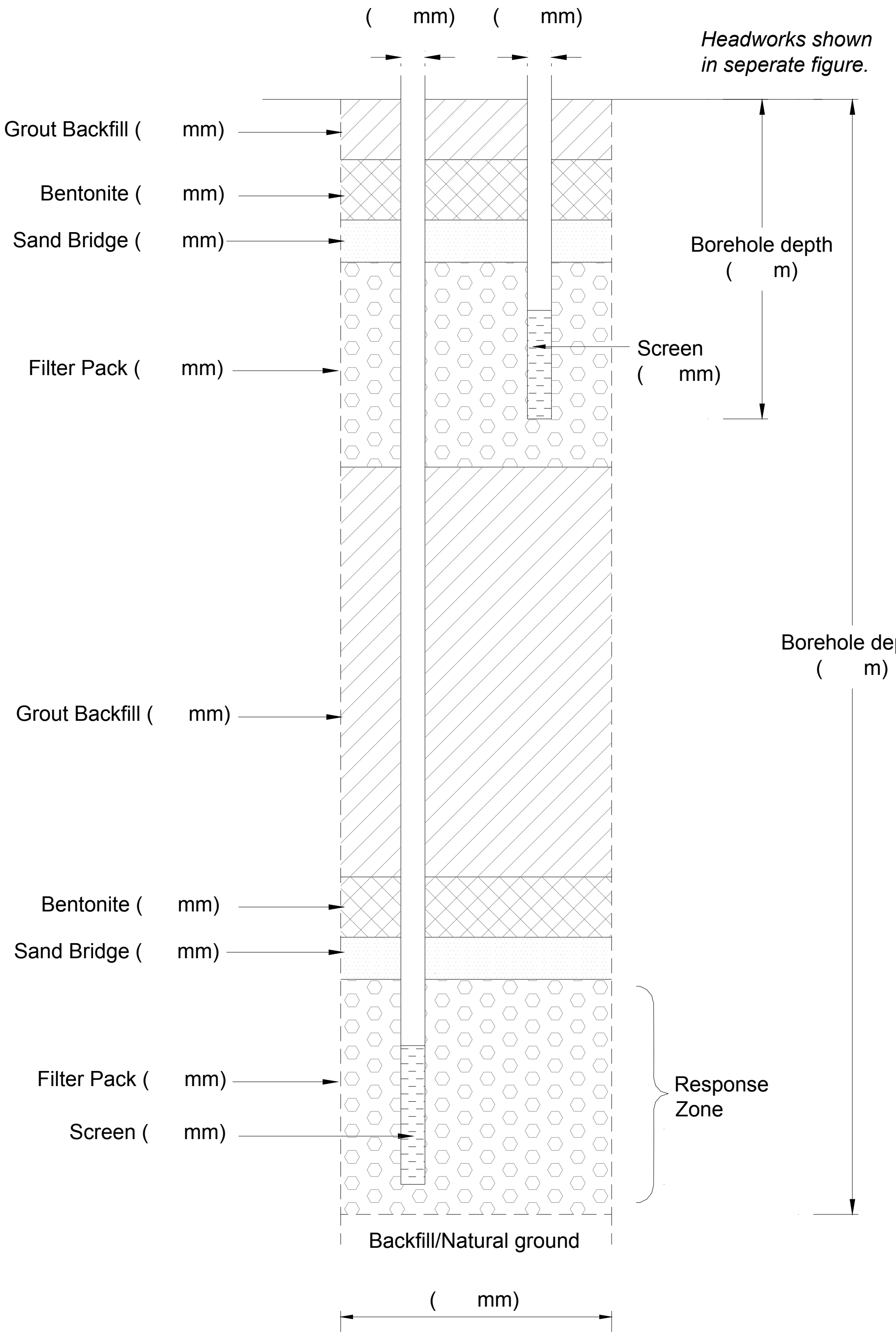
Appendix C

Borehole schematics

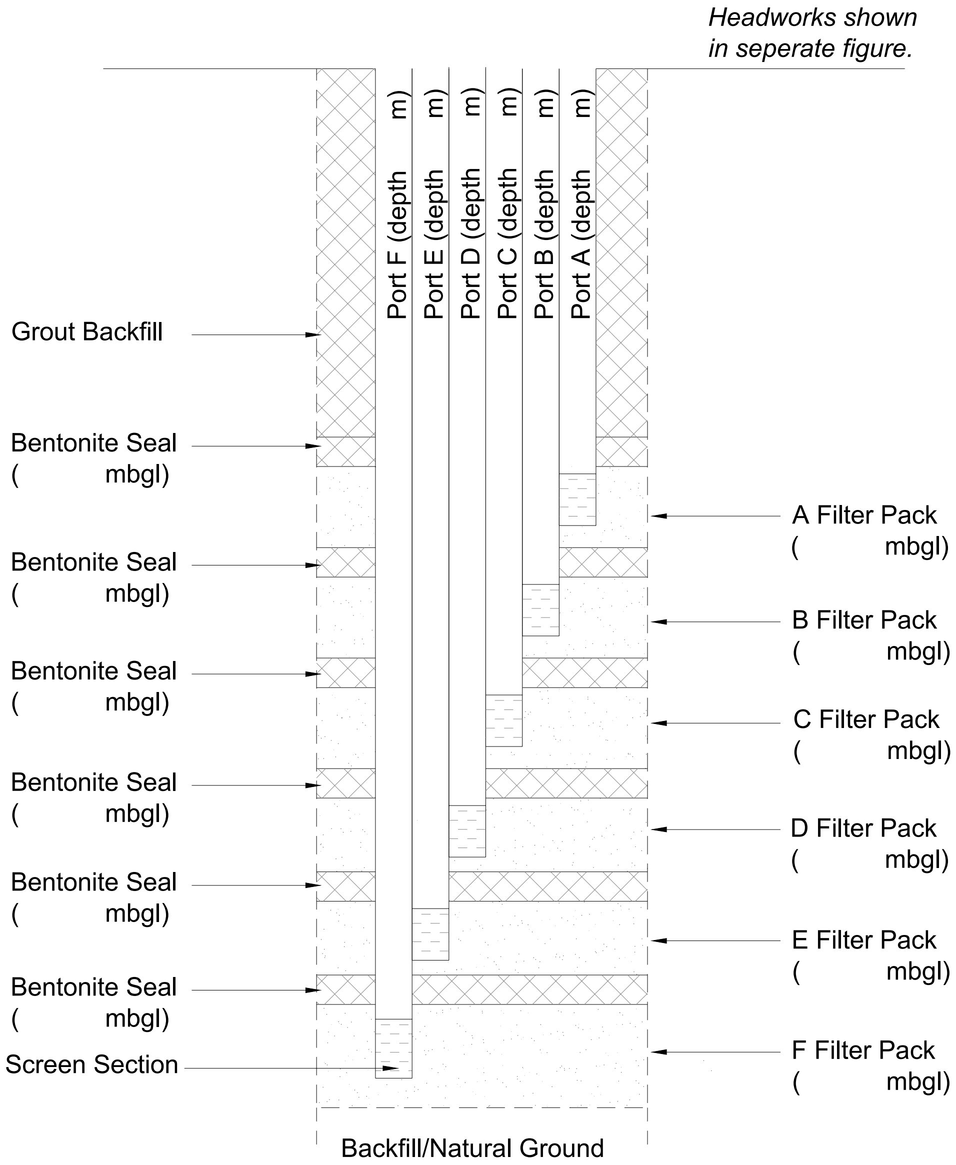
6 Pages



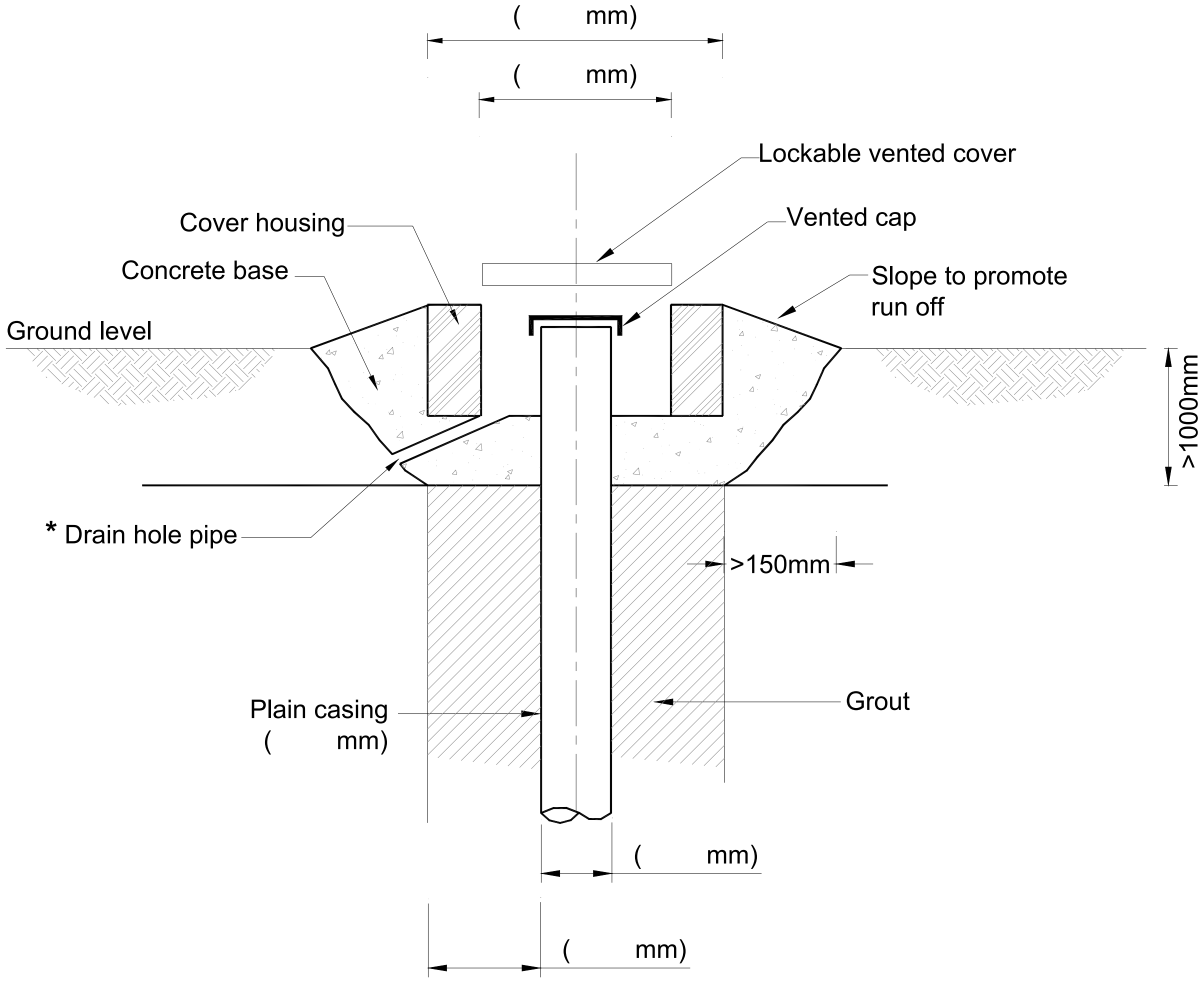
Drawing 1. Typical GQMP installation



Drawing 2. Typical nested GQMP installation

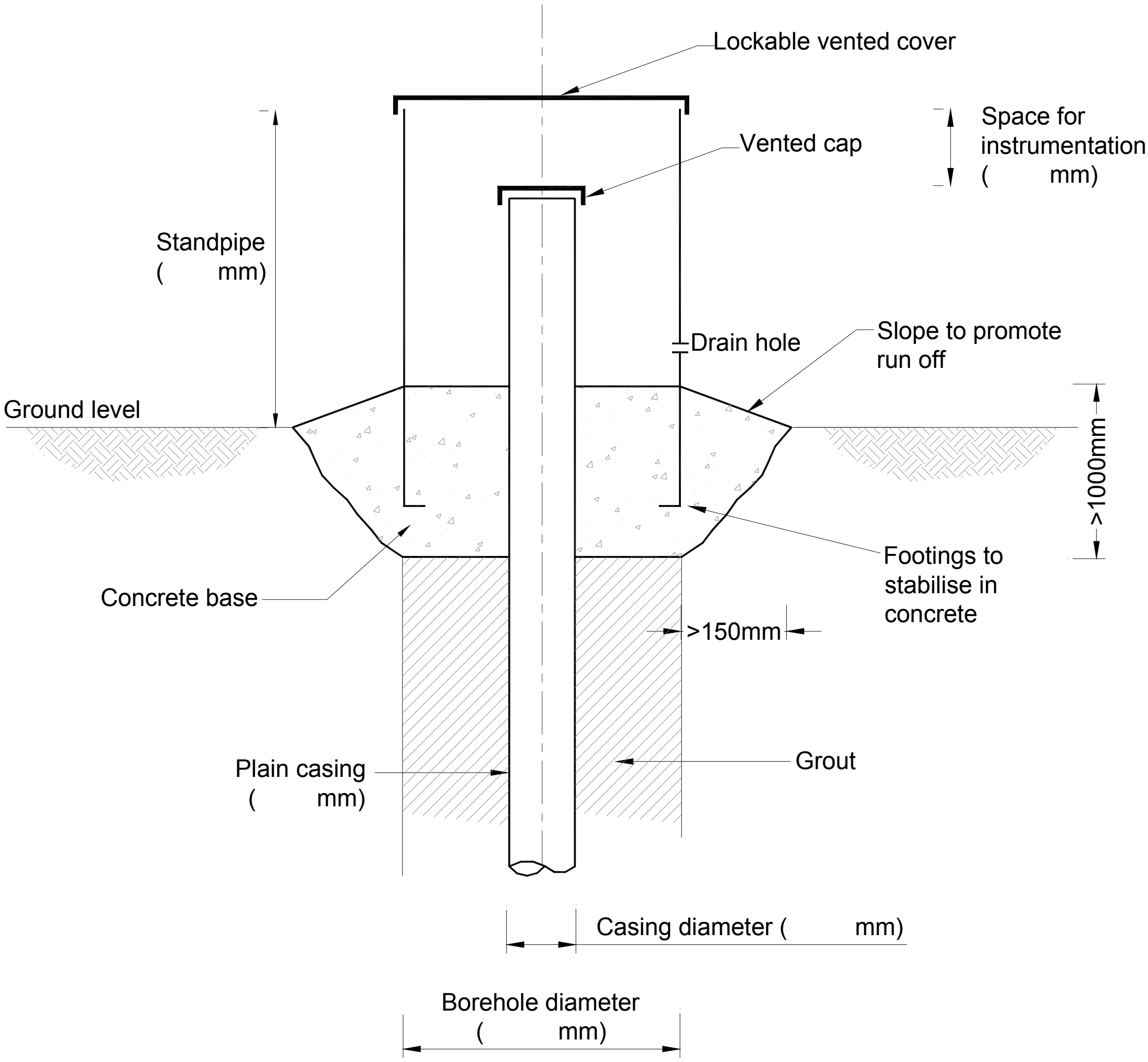


Drawing 3. Schematic of a multi-level GQMP installation

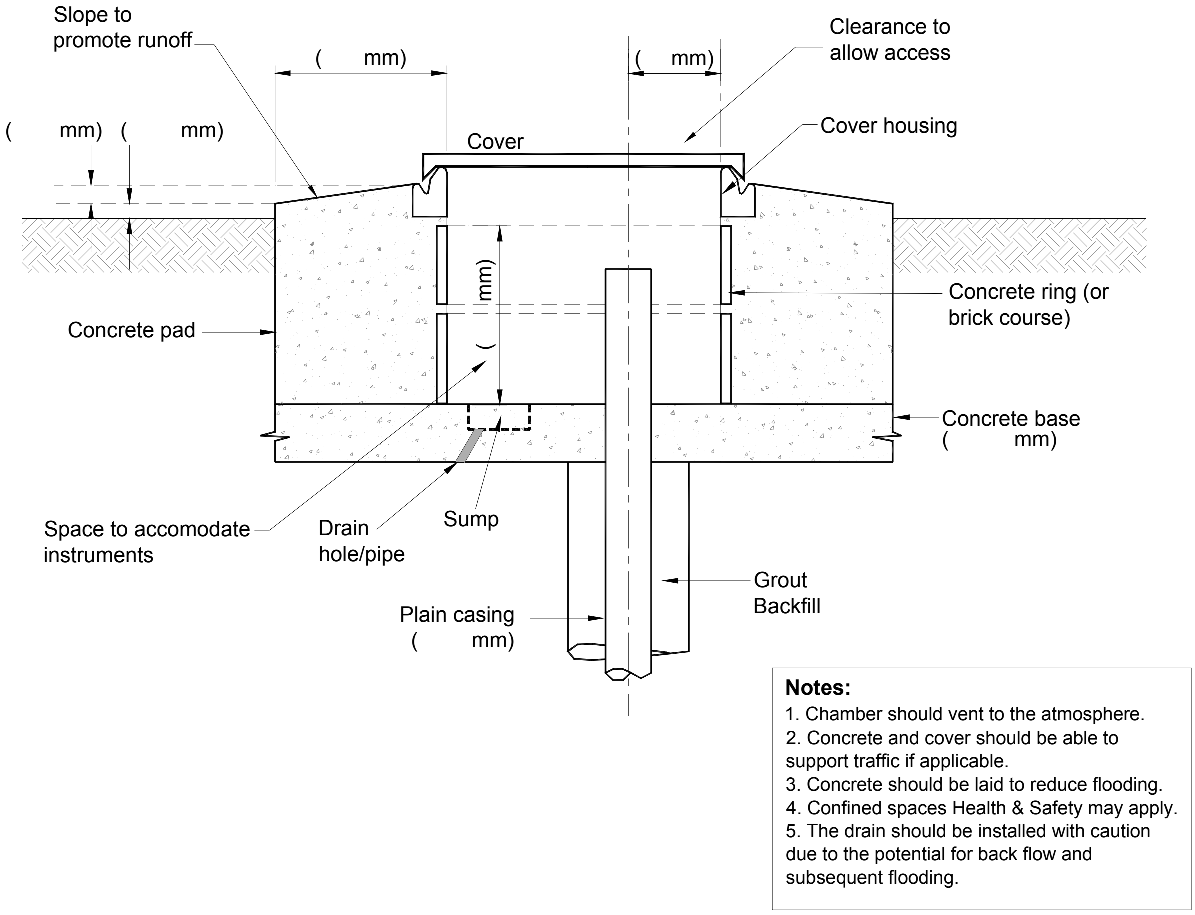


Notes
* The drain should be installed with caution due to the potential for back flow and subsequent flooding.

Drawing 4. Headworks: Stopcock cover completion



Drawing 5. Headworks: Standpipe completion



Drawing 6. Headworks: Below-ground chamber completion

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