GROUNDWATER MONITORING

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Keywords: drilling, groundwater, groundwater quality, groundwater sampling, filter design, water level, monitoring program, network design, well development

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Summary

Groundwater monitoring networks are constructed to meet regulatory requirements, perform site monitoring, ambient groundwater quality monitoring, and to collect data to develop groundwater aquifers or initiate site remediation. The design of monitoring networks is complex and expensive, and their construction can pose risks to health and safety of site personnel.

The design of groundwater monitoring networks must consider the objectives of the monitoring program, materials for well construction, drilling and installing wells, well

development, maintenance and rehabilitation of installed wells, and data collection and interpretation. There are a number of factors that affect each of the above activities. Additionally, the activities can be completed using a number of available techniques. An understanding of the relative strengths, weaknesses, and factors affecting their performance is important for designing effective monitoring networks.

This paper presents an overview of the purpose for undertaking groundwater monitoring, network design process, drilling techniques, well design and development, well maintenance and rehabilitation, sampling, and data analysis to enable better groundwater monitoring decisions.

1. Philosophy and Purpose of Groundwater Investigations

Groundwater aquifers are valuable sources of water supply for various purposes including domestic, commercial, and industrial use. Additionally, dewatering of groundwater aquifers is sometimes necessary to alleviate flooding or enable quarrying. Lastly, groundwater monitoring for contamination by processes, such as leaking underground fuel tanks, accidental spills, industrial discharges, leaking landfills and sewer systems, and land use activities, may be required.

The primary purpose of groundwater monitoring systems is to monitor the flow characteristics and/or the quality of groundwater. Periodic water level measurements at various locations are essential for assessing the flow characteristics. Information on flow direction, flow velocity, and temporal water table fluctuation is necessary for groundwater modeling. Similarly, water quality monitoring is performed to assess the magnitude of contamination or the rate of contaminant migration in groundwater.

The planning, design, and installation of groundwater monitoring systems plays an important role in groundwater engineering.

2. Health and Safety Considerations

Hazard recognition is an important consideration when conducting groundwater monitoring and leads to safety in the field and minimizes environmental contamination. A review of the monitoring program and site characteristics must be performed to identify existing and potential sources of physical, chemical, drilling, and sampling hazards.

Key aspects of the safety plan include a list of the known or anticipated site hazards, personal protection equipment requirements, standard operating safety procedures, work practices and engineering controls, personal hygiene and decontamination procedures, emergency equipment, and medical emergency procedures. The site safety plan must address all potential sources of hazards and anticipated emergencies. It should be issued to all on-site workers to minimize potential problems and misunderstandings. Personnel working on-site must be adequately trained, physically fit, and possess a positive attitude toward safety.

Potential electrical, physical, noise, and biological hazards and ways to minimize them are discussed briefly below. Electrical hazards may include electrical wires and buried cables. To minimize these hazards, low-voltage equipment should be used wherever possible and information on buried cables should be collected from local utilities before earthworks are performed. Physical hazards may result from unstable slopes, slippery and mud covered surfaces, etc. These hazards can be minimized by good housekeeping on the site. High-intensity noise on-site can interfere with normal communication between workers and damage the ear causing pain and temporary or permanent hearing loss. In such situations, hearing protectors should be worn to reduce the sound entering the ear. Biological agents, such as living organisms or their products, can cause illness or death of the individuals exposed. The risks may be minimized at locations where exposure to potentially harmful biological agents or hazardous substances can occur by wearing protective clothing such as, gloves, safety shoes, goggles, overalls, and dust mask.

3. Groundwater Monitoring Networks

Monitoring networks are necessary for development of groundwater resources, controlling groundwater hazards (e.g., pollution, saltwater intrusion, etc.), and remediation of contaminated subsurface. A properly designed monitoring network is necessary to obtain the required information in a timely and cost-effective manner. The most important aspects of the design of a monitoring network include:

- Network density: The number of observation wells and their location (in three dimensions) based on hydrogeological information available, required information and the objectives of monitoring.
- Sampling frequency: the number of observations or samples per unit time.

A modern network design incorporates the following elements:

- Spatial and temporal coverage of the sampling sites.
- Objectives of the monitoring program.
- The complex nature of geologic, hydrologic, and other environmental factors.
- Uncertainty in the geologic, hydrologic, and environmental parameters needed in the design process.

To illustrate the application of these principles in practice selected characteristics of the guidelines on design of monitoring networks commonly applied in the United Kingdom and the United States are presented below.

The United Kingdom guidelines in BS 10175:2001 categorize water monitoring into three phases:

- Exploratory investigation: Construction of a limited number of installations within and around the site based on preliminary investigation data (hydraulic gradient and direction of flow) and an initial conceptual model. Information is collected on water level and preliminary water quality in this phase.

- Main investigation: Installation of additional monitoring wells to give broad cover across the area of interest. Testing *in situ* may be performed to determine aquifer properties and additional water level and aquifer quality information.
- Supplementary investigation: Further adjustment of monitoring network, where appropriate, based on previous findings. Testing *in situ* may be performed to further define aquifer characteristics, water level, and water quality in specific areas.

In the United States, monitoring systems for hazardous waste and solid waste sites are expected to meet the following requirements:

- Consist of a sufficient number of wells installed at appropriate locations and depths to represent the groundwater quality for the background (upgradient) and at the compliance point downgradient of facility. At least one upgradient and three downgradient monitoring wells must be installed at the periphery of the waste management area.
- Wells are screened in the same stratigraphic horizons as the downgradient wells to ensure comparability of data.
- A sufficient number of wells are placed to account for site heterogeneity and its effect on background groundwater quality.

3.1. Monitoring System Design

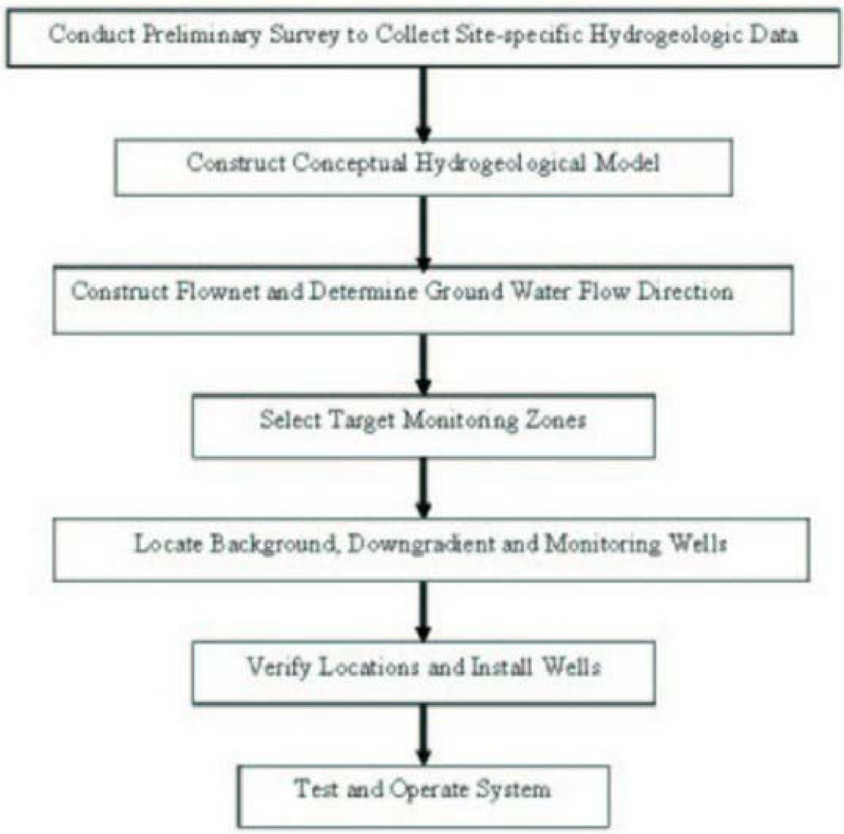

Figure 1. Procedure for designing a groundwater monitoring system

The typical steps involved in the design of a groundwater monitoring system are shown on Figure 1 and discussed in the sections below.

Geologic and hydrogeologic data are required to design a monitoring system. Geologic data provide information on the types of rock and soil formations and their water-bearing properties. Hydrogeologic data provide information on the movement of water in the formations. These data normally are obtained from field investigations or from published surveys. Preliminary site investigations consisting of geophysical surveys and groundwater quality, and subsequent data analysis can provide information on:

- Lithologic characteristics: texture, structure, mineralogy, vertical, and horizontal stratification of natural and manmade layers beneath the site, and strata variability (occurrence and thickness).
- Hydrogeologic characteristics: hydraulic conductivity, porosity, hydraulic gradient, specific yield, and potential migration routes.
- Aquifer characteristics: boundaries, type of aquifer, saturated/unsaturated conditions, and occurrence and distribution of multiple aquifers.
- Characteristics of contaminants present at the site and their distribution.
- Biological, chemical, or physical processes affecting contaminant concentration and migration.
- Presence of surface water bodies on, or adjacent to, the site.

Using the above data, an initial conceptual model is formulated to describe the geologic material, stratification, distribution of hydraulic conductivity, and the groundwater flow paths. If required, further investigations may be carried out to collect additional information to refine the conceptual model.

The conceptual model is used to construct flow nets. The gradient, flow direction, and the groundwater flow rates are calculated from the information provided by the flow net. Also, a comparison of the relative vertical heads between layers can reveal interconnections and the hydraulic conductivity between aquifers.

Selection of monitoring zones and up-/downgradient wells involves considering the size of facility, location of recharge/discharge areas (i.e., streams, wetlands, or other surface-water bodies), groundwater movement, groundwater quality, objectives, ease of access, and flexibility in monitoring seasonal changes. Improperly located wells can lead to erroneous conclusions regarding groundwater quality. Placing wells too close (where they are susceptible to contamination) or too far (where they are influenced by other geochemical processes) from the facility, can lead to errors.

3.1.1. Designs for Selected Hydrogeologic Settings

Design of monitoring systems can be complicated by complex hydrogeologic characteristics. For example, proper well placement in areas with steep gradients or sites with both confined and unconfined aquifers can be difficult. In areas with low hydraulic conductivity, steep gradients are present and there is little potential for reverse flow. Target zones at such sites are narrower than those at flat gradient sites and there is little margin for error. At sites with confined and unconfined aquifers, differences in the hydraulic conductivity of the aquifers and the intervening layers separating the aquifers can result in complex flow patterns. The flow lines will refract at the geologic interfaces and flow can be largely horizontal in high-conductivity soils and vertical in low-conductivity soils. The selection of target monitoring zone will need to consider such complications and monitoring may need to be expanded to greater depths. The following section briefly presents important considerations during the design of monitoring systems in soils with a few selected hydrogeologic characteristics or constraints.

Alluvial sites: These deposits have high-permeability, shallow, sandy zones combined with low-permeability sediments, thus making it difficult to identify the target zone(s). Such sites generally lack significant horizontal gradients and experience a predominance of vertical gradients. The monitoring program must be based on the delineation of site geology, regions of different hydraulic conductivity, flow direction in different regions, and site stratigraphy.

Single homogeneous aquifer: The process of designing a monitoring system for a single homogeneous aquifer with simple boundary conditions may involve determining the aquifer geometry, thickness, and hydraulic conductivity (both vertical and horizontal), constructing flow nets, preparing a conceptual geologic and hydrogeologic model, identifying potential target monitoring zones, and installing monitoring wells.

Single heterogeneous aquifer: When the hydraulic conductivity varies spatially, the monitoring system design must consider the areal extent, thickness, hydraulic conductivity of individual geologic layers, and potential off-site migration. As an example consider a site with a layer of silty sand overlying a gravel layer. If the silty sand layer is discontinuous, the gravel layer will be the primary monitoring target zone. However, if the silty sand layer extends beyond the site boundary, both of the silty sand and gravel layers would be target zones.

Multiple aquifers: A multiple-aquifer system may require more complex three-dimensional hydrogeological characterization. The monitoring program will need to consider installing multiple borings to characterize the site areally and with depth, and determine the vertical and horizontal hydraulic gradients, in addition to the factors specified in the previous paragraph. The objective can also influence the selection of the target zone. If the goal is to detect contaminant release from a source, the monitoring zone may be limited to the unconfined uppermost aquifer. However, if the aim were to assess the extent of contaminant movement, it would require monitoring of the upper and lower aquifers.

Structurally controlled sites: Geologic structures such as dipping beds, faults, and cross-bedding can affect the rate and direction of groundwater movement by creating preferential flow paths in high porosity cross-bedded sands and fractures, or introducing barriers to groundwater flow in fault zones containing finely ground rock and clay. At such sites, the monitoring system design may based on the location and characteristics of springs, vegetation, surface geology, stream alignments, and geologic structures. Also, the design should allow for installation of additional borings to further define the hydrogeological characteristics.

Karst aquifers: Karst aquifers are those occurring in limestone, dolomite, gypsum salt, carbonate-cemented clastic rock, or their combination, and characterized by features (such as, underground caverns and enlarged fractures) created by mineral dissolution. Water flow is primarily through conduits (caves) and along bedding planes and fractures. In such settings, wells must be located in springs, caves, streams, or in fractured zones, and the monitoring program should consider using dye tracers to establish flow paths, prove connections between facility and monitoring wells, and locate background/sampling wells.

4. Monitoring Wells

4.1. Drilling Methods

Some of the commonly used drilling methods for monitoring wells are discussed below.

Percussion drilling: This method of drilling involves hammering to break the formation. The method does not require a compressor or mud pump, nor generate large amounts of cutting or require drilling fluids. Although the rate of drilling can be slow, ranging from 5 to 8 meters per day in average soils, the technique is flexible and can be used in a variety of settings. Additionally, the drilling rig is comparatively small and does not require large space to operate. On the other hand, soils are disturbed during hammering and undisturbed soil samples cannot be collected. Cable tool drilling is one of the common percussion drilling methods in use.

Displacement boring: In this method, a probe, such as a steel rod with a T-handle, is advanced into soil to force the soil out of its path and make the bore. A common modification to the T-shape probe is a probe with a piston type sampler. The piston is kept closed until it reaches a desired level, then opened and advanced to collect the soil.

Auger drilling: Auger drilling uses a spiral tool that brings excavated soil to the surface while drilling. In addition to all the advantages of percussion drilling, it can be used to collect soil samples accurately, is a fast drilling method, and can be used for monitoring well installation in urban areas. Its primary disadvantage is that it cannot be used to drill in rocks.

Rotary drilling: In this method, drilling is accomplished using a continuously rotating tool bit in a circulating fluid that flushes out the cuttings. In some cases, air is used instead of fluid and the method is then referred to as air rotary drilling. The disadvantages of rotary drilling are that the circulating fluid may cause cross-contamination and the drill mud may affect water quality by invading water-bearing formations.

4.1.1. Selection Procedure

The following factors should be considered in the selection of the appropriate drilling method.

Purpose of well: Monitoring wells are typically used for water-quality testing or water-level monitoring, and occasionally for collecting soil samples during drilling. Some drilling techniques, such as percussion drilling, disturb soils samples and are not appropriate if undisturbed soil samples are needed; others, such as rotary drilling, can cross-contaminate the soil and must be used with caution.

Size, depth of drilling, and aquifer properties: Aquifer properties can greatly affect the selection of a suitable drilling method. Auger drilling, for example, is very effective in unconsolidated soils but not suitable for use in hard rocks. Also, auger drilling is not recommended for more than 100 m depth because of high friction between auger and soil. Rotary and cable-tool methods are suitable for drilling wells more than 500 m deep. Use of circulating fluid drilling methods in fractured material is not advisable due to the large loss of drilling fluids in fractures. The water level can also affect method selection, as methods involving fluid circulation may not be effective beyond the water table.

Land availability and site access: Selection of an appropriate drilling method must consider the availability of land for construction and site accessibility, especially in urban areas. Clearance requirements for the drilling rig and support vehicles may need to be checked against available space.

Disposal of cutting and drilling fluids: Disposal requirements for the excavated material and drilling fluids may affect method selection. At contaminated sites, the excavated soils and drilling fluids may need to be treated as hazardous and require costly disposal. Techniques that minimize the amount of waste material produced would be preferred due to their cost effectiveness.

Noise and safety: In urban residential areas, noise generated by drilling equipment, such as hammers and compressors, may exceed acceptable levels and disfavor the use of some techniques. However, methods for controlling noise may reduce the efficiency of the equipment or increase the cost of operation. Additionally, in some cases, concerns over noise emissions may lead to placement of restrictions, such as no night time operations.

Public safety is a high priority consideration, especially in populated areas. Special precautions are required to ensure public safety during drilling operations. This may add an extra cost to drilling operations.

Regulatory requirements: In certain settings, the disposal of drilling fluids and extracted soil and water may require approval from regulatory authorities. While this may not add to the cost of drilling, delays can result if timely approval cannot be obtained. These issues must be considered in the selection of drilling method.

Cost and time: The cost and time taken for drilling should be considered together with all other factors in selecting an appropriate drilling method.

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Biographical Sketches

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