GROUNDWATER MONITORING NETWORKS

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Contents

Summary

Groundwater monitoring programs are generally designed to measure changes in groundwater quality or changes in groundwater level over time, in either single or multiple aquifers. Some monitoring programs attempt to do both, but usually have to compromise some of the needs of each program. The efficient design of a groundwater monitoring network depends on a number of factors including its budget, the hydrogeology and geology of the aquifer, the size of the monitoring network, and incorporation of any regulatory requirements that may be needed into the design.

Networks can be designed by using statistical methods for optimizing well placement and sampling frequencies, by using detailed hydrogeological information and local knowledge to place wells, or by a combination of both methods. The scale of the monitoring program may dictate which method is used. Small-scale monitoring networks lend themselves to statistical approaches, whereas large (national-scale) networks are more likely to rely on detailed hydrogeological information. Regional-scale models are likely to use a combination of the two methods.

Groundwater quality networks can be designed to monitor point-source or diffuse-source pollution, and the design of each type of network will be different. Networks will differ in design depending on whether they are measuring small-scale issues such as interference from pumping wells, or large-scale issues such as defining recharge areas or groundwater decline from aquifer-wide pumping.

The best network designs will be achieved if:

- the goals of the monitoring program are well developed,
- the budgetary constraints are taken into consideration, and
- the hydrogeology of the area to be monitored is well understood and incorporated into the design.

Statistical methodologies will help optimize a groundwater monitoring network, but they cannot take the place of sound hydrogeological evaluation of the area to be monitored.

1. Introduction

Groundwater monitoring networks can serve many different purposes and be constructed on varying scales and extents. For example, the design of a monitoring network to determine the extent of pollution from a point source will be different from one designed to monitor diffuse pollution sources. In addition, the design of networks to monitor groundwater *quality* may call for different locations, scales, or sampling intervals than those of groundwater *resource* networks. However, designing groundwater monitoring networks can be complicated when networks are to be used for multiple purposes (that is, both quality and resource evaluation).

The optimal design of groundwater monitoring networks is limited by a number of factors, including the geography and geology of the network area, the scale of the network, budgetary constraints on the network, and potential sources and location of contaminants or aquifers. Several statistical and modeling techniques have been developed to optimize the design of groundwater monitoring networks. These include kriging, Monte Carlo, Kalman filtering, and Student's *t* test techniques, which are used for different types of network design (that is, sampling frequency, well placement, water quality analysis, and so on). There is no single correct way to design monitoring networks; all of the factors listed above (and others) must be taken into consideration, and in many cases judgments should be based on the geologic and hydrologic expertise of the personnel designing the network rather than relying solely on statistical or modeling results.

In this article, the three basic types of groundwater monitoring networks—first, diffuse-source water quality networks, second, point-source (contaminated site) water quality networks, and third, groundwater resource (groundwater level) networks—are discussed to illustrate the scales and fundamental components that are needed to construct a well-designed groundwater monitoring network. Other types of groundwater monitoring networks exist, including ones for predicting earthquake movement, but these are relatively rare and their designs are related to the three main types of networks that will be discussed. Of fundamental importance in designing a groundwater monitoring network is the scale and objectives of the network. These topics form the basics of this article.

2. Types of Groundwater Monitoring Networks

Groundwater monitoring networks are generally designed to answer one or more of the following questions:

- What is the status of water quality in a basin?
- What are the contributing sources of diffuse or regional groundwater contamination?
- Where is point-source contamination going and how quickly?
- What are the long-term trends in groundwater quality?
- In what direction is groundwater flowing?
- Is groundwater abstraction sustainable?
- How do seasonal and climatic variations in recharge affect water use in a basin?
- Where is recharge coming from in a basin?

All of these questions can be answered using one or more of the following three types of groundwater monitoring networks at the appropriate scale, coupled with land use information and geological data:

- Diffuse-source water quality networks—usually regional to national scale.
- Point-source (contaminated site) water quality networks—usually local scale.
- Groundwater resource (groundwater level) networks—both local and regional scale.

The following sections will discuss each of these types of networks in some detail.

2.1. Diffuse-source Water Quality Networks

Diffuse-source groundwater quality networks are used to evaluate the effects of contamination from land use activities that spread contaminants relatively uniformly over the land surface, usually (but not always) in rural agricultural areas. In this way, leaching of these contaminants down to the groundwater table can occur wherever recharge to the aquifer is possible. Typical contaminant sources could be nutrients from urine or feces from grazing animals such as cattle, sheep, deer, or pigs; application of pesticides and fertilizers to crops and trees; application of road salt in winter months; and human waste from multiple point-source discharges from housing developments that rely on septic tanks systems for sewage disposal.

One of the key questions that needs to be answered is: when does a point source of pollution become a diffuse source? This may seem a semantic question, but there are many cases where multiple point sources may need to be monitored as a diffuse-source system. For example, in the city of Auckland (New Zealand), soak-holes drilled into the top of a porous fractured-rock aquifer are used to disperse storm water runoff. There are hundreds or thousands of these individual point sources that add water and contaminants to the aquifer over an extensive geographic area. For monitoring purposes, these point sources are evaluated using a diffuse-source monitoring program. Rural areas with multiple septic tank disposal systems are another example of point sources that need to be monitored using a more regional network.

The answer to the question is generally defined as a matter of scale and number of sources. If the scale is small, less than 1 km^2, and there is one source of contamination, then the monitoring network should be designed to be a point-source network. If the scale is small, but there are multiple sources (or suspected sources) of contamination, then aspects of both types of network should be used.

Diffuse-source monitoring networks are generally designed on a regional scale, or at least incorporate a significantly large local area. Most diffuse-source monitoring networks are limited by budgetary constraints on either the installation costs of monitoring well or the costs of analyzing the samples collected; as a result, the optimal network size is rarely reached. One significant exception is the Dutch groundwater sampling network that included 350 well sites that collect water quality information on deep and shallow wells at each site.

Diffuse-source monitoring networks may have multiple goals and purposes. It is important to determine all of the goals of the network before monitoring sites are chosen. For example goals such as determining, on the one hand, the long-term trends in water quality, and on the other hand, the spatial distribution of contaminants in a basin may require different monitoring strategies based on the hydrogeology of the basin and budget constraints. In addition, the direction of groundwater flow needs to be determined in order to site potential monitoring wells. This means that some water-level monitoring network will need to be established or utilized before the water quality network can be established.

If the monitoring network focuses on a single basin or part of a basin then it is important that all wells are screened in the same aquifer. In this way pathways of contaminant sources can be followed and their impacts can be more efficiently addressed. However, if groundwater head data indicate that flow is between multiple aquifers, then monitoring may need to include multiple aquifers and several depths.

The minimum requirement for the depth of monitoring wells is that they must be below the lowest groundwater level in any given year. Generally, 3 to 5 meters below the water table is sufficient to meet this requirement. However, the vertical distribution of potential contaminants may be important, because of multiple aquifers, the three-dimensional aspects of groundwater flow, or because a potential contaminant is heavier than water. In these cases, wells at the same location drilled to different depths may be necessary. Installing wells that sample the entire thickness of the aquifer may not be a good plan, because having such a broad sampling point may make it difficult to detect the source of contamination. However, wells that penetrate the entire aquifer may be essential for groundwater resource monitoring networks. Therefore, it is important to determine what the most important aspects of the monitoring will be before designing monitoring wells.

2.2. Point-Source (Contaminated Site) Water Quality Networks

Point-source monitoring is generally undertaken to determine whether a possible contaminant source is leaking into the groundwater. The problem can be as small in scale as a broken pipe, or as big as a landfill site or land treatment facility. However, most point-source water quality networks are not larger than 1 km^2. Many point-source monitoring networks are required for legal reasons and design elements (such as the number of wells, sampling frequency, constituents to sample for, and so on), of many of these types of networks is stipulated by regulatory authorities. Therefore, the optimal monitoring network may not always be achieved in a regulatory framework.

For example, it is possible to use only one groundwater well to monitor a point source of contamination, if the well is located within the contamination plume and no other possible sources of contamination are present. However, accurately assessing the fate and transport of contamination from a point source cannot be accomplished with only one monitoring site. In addition, it is essential to have a reference-monitoring site that is outside the expected contamination plume in order to determine that the measured concentrations in the plume are greater than any background contamination from natural or anthropogenic sources.

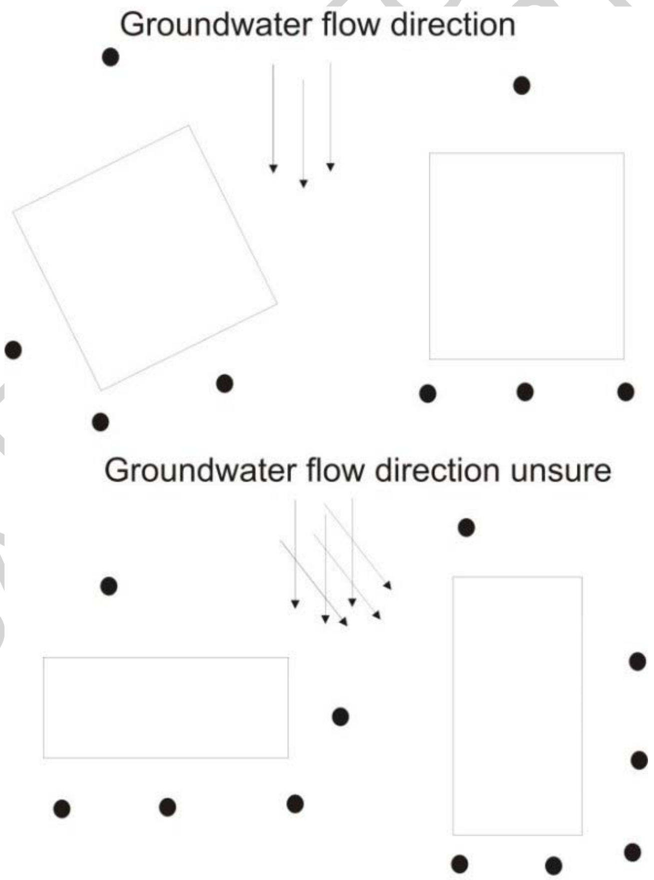

Figure 1. Typical patterns of monitoring well emplacements using the minimum number of monitoring sites possible. Monitoring sites are represented by black dots; the box represents the point source of contamination. At least one up-gradient monitoring site is included.

Figure 1 shows some minimal network configurations for monitoring a point source of contamination from a block of land depending on how well the groundwater flow direction is known. When the groundwater flow direction is less constrained, more monitoring wells are needed. Other factors that could influence the placement and number of monitoring wells needed include:

- the geology of the aquifer (fractures, preferred flow zones);
- interfering water sources (rivers, drainage ditches, pumping wells, wetlands); and
- other sources of contamination (both point and diffuse-source contamination).

Placement of wells in urban areas can also be influenced by the availability of sites.

In general, a complete monitoring network for a point source of contamination will have at least one reference well (up-gradient of the contamination source) and enough wells within and outside the contamination plume to define the extent of contamination. The number of wells needed depends on the size of the contamination source, the amount of dispersion that is encountered in the aquifer, the rate of groundwater flow, and the degree to which degradation of the contaminant source occurs within the aquifer (Figure 2).

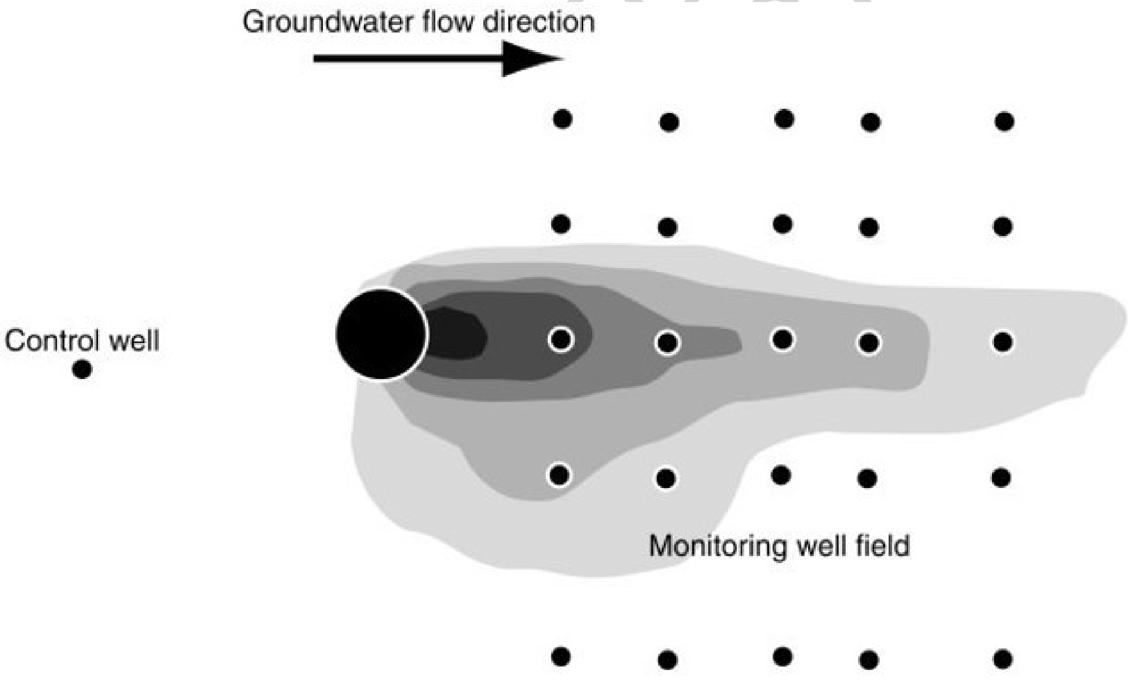

Figure 2. Diagram of a typical monitoring array for defining a point source of contamination. Wells at multiple depths at the same site may be required to define the vertical position of a plume in the aquifer.

It is important to know or have some general knowledge of the types of contaminant that may be encountered when designing a point-source monitoring program. This is because the type of contaminant may affect the materials used to construct the wells. In addition, if the contaminant is denser than water, as is the case with dense non-aqueous phase liquids (DNAPLs), the direction of movement of the contaminant may not coincide with the direction of groundwater flow. In this case it is necessary to know the hydrogeology of the aquifer very well and plan to place monitoring wells in positions that are downslope (rather than down groundwater gradient) of the contaminant source.

2.3. Groundwater Resource (Groundwater Level) Networks

Groundwater resource networks or groundwater level networks are constructed for both local and regional purposes. They are rarely constructed on a national scale, because to be useful they must measure only one set of interacting aquifers, which is difficult to achieve on a national scale. Local groundwater level networks may attempt to measure the effects of pumping on neighboring wells, monitor the effects of saltwater intrusion in coastal areas, or help to define contaminant pathways for point sources of contamination. Regional-scale networks are usually concerned with determining the draw-down of a particular aquifer due to overexploitation, or with defining seasonal variability in water levels caused by changes in recharge patterns.

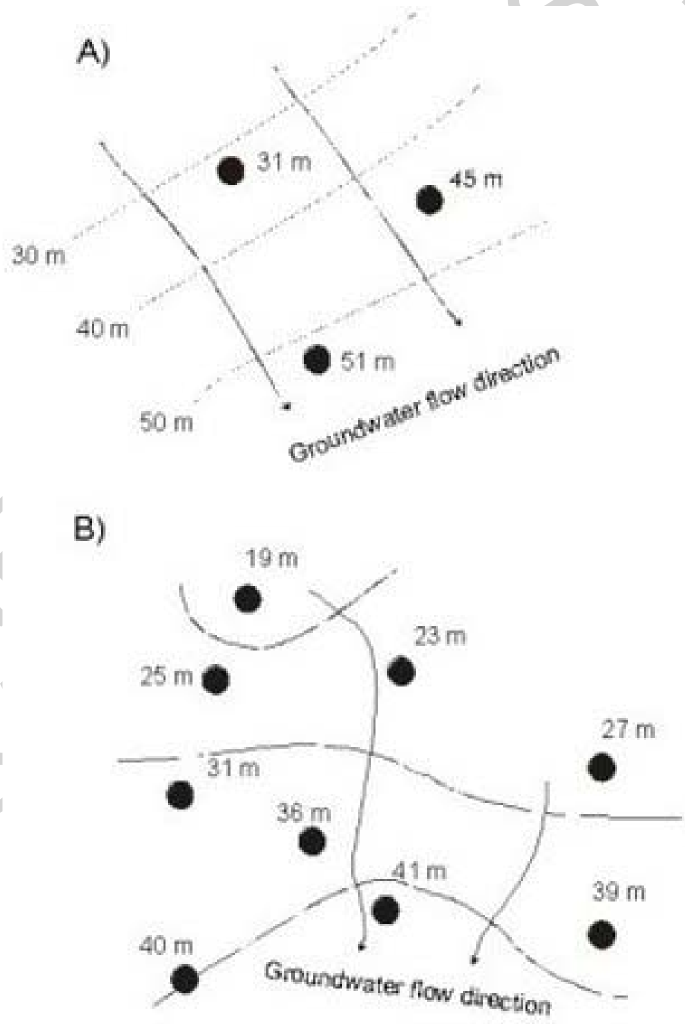

Figure 3. A) Equipotential lines showing groundwater flow directions using minimum data (3 points). Depths are meters below ground surface. B) Equipotential lines showing groundwater flow directions using a network of wells. Depths are meters below ground surface.

A general flow direction can be determined with just three points as long as they are not located in a line. The use of existing water supply wells or irrigation wells can provide the points necessary for determining the slope of the water table. However, it is necessary to know that all the points used to construct the flow diagram come from the same aquifer (this highlights the importance of obtaining well logs before selecting the well to monitor). The elevation of the wells must be accurately determined either by surveying techniques or by Global Positioning Satellite (GPS) units and tied to a consistent datum (either mean sea level or some other fixed datum). In this way the relative height of the water in each well can be determined without the influence of the changes in height of the land surface between wells. Flow directions can be estimated by contouring the map in a similar manner to topographic contours. Lines of equal groundwater height (equipotential lines) are constructed, and groundwater will flow perpendicularly to these contours (Figure 3).

Streams may also give some indication of groundwater levels, because during low flow conditions many stream levels represent the top of the water table in that area. However, caution should be exercised because many rivers act as recharge areas rather than discharge areas. This means that the groundwater flow direction could be away from the river rather than towards it. A good way to test this is to locate (or construct) a well about 20 to 50 meters away from a river. If the water level in the well is below the base river level, the groundwater is flowing away from the river. If the water level in the well is above the base level of the river the groundwater is flowing towards the river. If the groundwater level and the river level are equal, it may be that on some occasions groundwater is flowing towards the river (e.g. after heavy rainfall), but on other occasions it may be flowing away from the river (e.g. during drought conditions).

Once a general groundwater flow direction has been determined, monitoring wells can be added to the network to define the groundwater flow accurately and/or to capture any flow of contaminants that enter the groundwater (if a multipurpose network is being constructed).

Depending on the location of available wells, additional monitoring wells should be constructed so that they increase the ability of the network to define flow paths and, most importantly, are placed so that they can answer the questions that need to be addressed. This can be difficult to determine if only limited data are available on flow directions. Regional groundwater flow may be different from local groundwater flow, and in the case of point-source contamination, it is the local flow that may be more important.

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Biographical Sketch

Dr. Michael R. Rosen is currently the Nevada Basin and Range (NVBR) Study Unit Chief for the National Water Quality Assessment (NAWQA) program at the US Geological Survey, based in Carson City, Nevada. He joined the USGS in May 2001 to take up this position. Before working with the USGS he was employed for almost eight years at the Institute of Geological and Nuclear Sciences Ltd in Taupo, New Zealand as the Groundwater Programme Leader. He also worked in the Division of Water Resources (now call Land and Water), CSIRO in Perth, Western Australia (two years), Curtin University of Technology (one year), Perth, Western Australia, and at the Limnological Research Center at the

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