

Groundwater Levels, Mapping

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INTRODUCTION

Maps of groundwater levels are used to estimate groundwater flow direction and velocity, to assess groundwater vulnerability, to locate landfills and wastewater disposal sites, and as input to hydrologic and pollutant transport models. Because groundwater is hidden from view beneath the land surface, groundwater can only be directly observed through monitoring wells. However, because these observations are limited to specific points, mapping groundwater levels requires hydrogeologically appropriate techniques to generalize the point measurements. Rules or models for spatially and temporally generalizing monitoring (sample) data across the groundwater system are inherent and essential to hydrogeologic science. Our understanding of ground water is the product of a long history of hypothesis and model development, testing, and refinement.^[1]

The position of the water table is the product of a wide range of static and dynamic environmental conditions and processes affecting the rate at which water enters and leaves the saturated zone of the aquifer. The water table rises if the rate of water added (recharge) exceeds the rate of water leaving (discharge); conversely, the water table falls if discharge exceeds recharge. The water-table surface is therefore not static, nor flat (as the name implies), but responsive to climatic, vegetative, geomorphic, and geologic conditions.

As Matson and Fels^[1] also pointed out, traditional water-table mapping uses graphical methods to interpolate between water-table measurements and hydrogeologic boundaries, with professional judgment and experience filling the gaps in sampling. Computer assisted approaches may incorporate surface mapping methods such as trend surface interpolation and *kriging*;^[2] many of these tools are currently provided in Geographic Information Systems (GIS) software. Other methods employ mathematical modeling to predict water-table elevation from hydrogeologic conditions and processes.

DESIGNING A MONITORING SYSTEM

Setting up a monitoring system requires careful consideration of both the hydrogeologic setting and the data

needed. It is premature and wasteful to locate monitoring wells without first synthesizing what is known about the setting—in other words, without formulating a sound conceptual model of the system under study. For example, water-supply wells drilled without understanding area hydrogeology may be placed where 1) the aquifer is thin or missing altogether, 2) the aquifer is present but not very productive, or 3) the aquifer contains water of poor quality.^[3]

Areas in which the geology is highly variable require more extensive (and costly) water-level monitoring systems than comparatively more homogeneous areas. The degree of geologic complexity is often not known or appreciated during the early phases of a testing program, and it may require several stages of drilling, well installation, water-level measurement, and analysis of hydrogeologic data before the required understanding is achieved. Due to space limitations, the design for an optimal spacing of groundwater-level monitoring wells cannot be covered in this article; however, the reader is referred to Refs. [4,5] for examples of such an observation well network design.

NATURAL PROCESSES CAUSING GROUNDWATER-LEVEL FLUCTUATIONS

To interpret the monitored water levels, one needs to understand the various processes causing fluctuations in groundwater level. These are the effects of hydrologic processes active in the atmosphere, land surface, and subsurface, the groundwater movement in hydrodynamic flow systems, groundwater recharge and discharge processes, atmospheric pressure changes, plant transpiration, aquifer compression and dilation, and others.

In addition to natural processes, human activities also cause groundwater-level fluctuations. Major among them are: 1) groundwater withdrawals from wells; 2) artificial recharge; 3) irrigation; 4) land clearing; 5) pumping of hydrocarbons and brine from reservoirs; 6) construction of water reservoirs; 7) mining; and 8) loading and unloading by heavy equipment, such as freight trains.



ANALYSIS, INTERPRETATION, AND PRESENTATION OF WATER-LEVEL DATA

Primary uses of groundwater-level data are to understand and predict water-level changes and to assess the direction of flow beneath an area. The usual procedure is to plot the location of wells on a base map, convert the depth-to-water measurements to elevations, plot the water-level elevations on the base map, and then construct a groundwater elevation contour map. Constructing a water-level change map, as will be explained later on (see section on “Examples of Groundwater-level Data Interpretation”), will indicate the extent and severity of water-level declines resulting from a variety of factors, including human development and droughts. The direction of ground-water flow is estimated by drawing groundwater flow lines perpendicular to the ground-water elevation contours (Figs. 1 and 2) if the aquifer can be considered *homogeneous* and *isotropic*.

The relatively simple approach to estimating groundwater flow directions described above is suitable where wells are screened in the same zone and the flow of groundwater is predominantly horizontal. However, as attention has focused on detecting the subsurface position of contaminant plumes or predicting possible contaminant migration pathways, this simple approach has been shown to be not always valid.^[6] Increasingly, flow lines shown on vertical sections are required to complement the planar maps showing horizontal flow directions to illustrate how groundwater is flowing either upward or downward beneath a site.

Groundwater flows in three dimensions, and as such can have both horizontal and vertical (either upward or downward) flow components. The magnitude of either the horizontal or the vertical flow component and the direction of groundwater flow are dependent on several factors: recharge and discharge conditions, aquifer heterogeneity, and aquifer anisotropy. Dalton et al.^[6] summarized these factors, and the following draws on their summary.

In recharge areas, groundwater flows downward (or away from the water table), whereas in discharge areas groundwater flows upward (or toward the water table). Groundwater migrates nearly horizontally in areas where neither recharge nor discharge conditions prevail. For example, in Fig. 1 well cluster A is located in a recharge area, well cluster B is located in an area where flow is predominantly lateral, and well cluster C is located in a discharge area.^[7] Note in Fig. 1 that wells located adjacent to one another, but finished at different depths, may display different water-level elevations.

In a heterogeneous aquifer, hydrogeologic properties are dependent on position within a geologic formation,^[8] and thus the geology needs to be considered in evaluating water-level data. While recharge or discharge may cause vertical gradients to be present within a discrete geologic zone, vertical gradients may also be caused by the contrast in hydraulic conductivity between aquifer zones. This is especially evident where a deposit of low hydraulic conductivity overlies a deposit of relatively higher hydraulic conductivity.

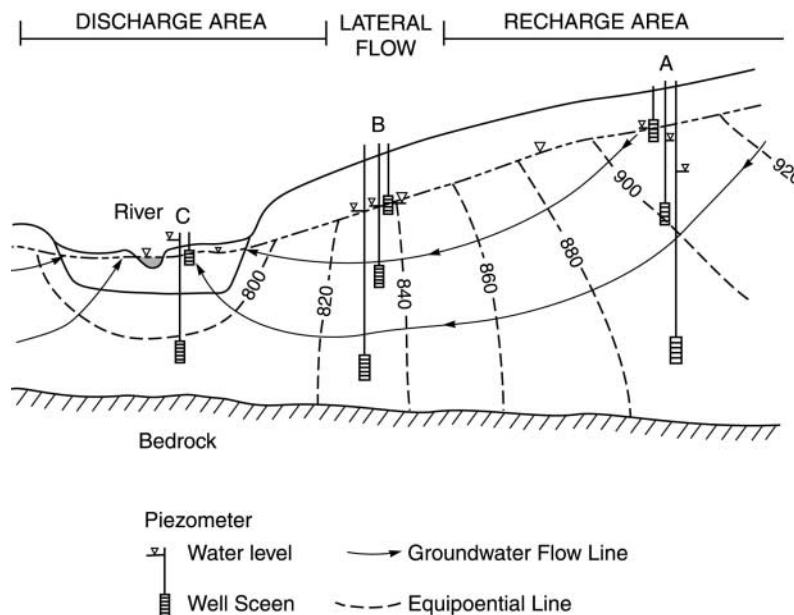


Fig. 1 Ideal flow system showing recharge and discharge relationships (adapted from Saines, 1981^[7]).



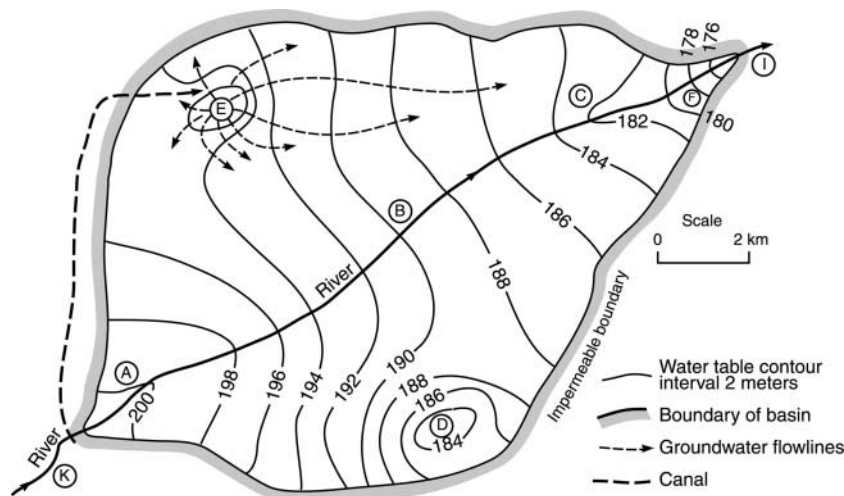


Fig. 2 Contour map of the water table in a small hypothetical groundwater basin. If the aquifer is homogeneous and isotropic and if the slope of the water table is not large, the map can be used to construct a flow net. A small number of flowlines (shown as dash lines) have been drawn on the map. Excessive convergence of the flow lines suggests a changing transmissivity of the aquifer (from Ref. [9]).

Aquifer anisotropy refers to an aquifer condition in which aquifer properties vary with direction at a point within a geologic formation.^[8] For example, many aquifer zones were deposited in more or less horizontal layers, causing the horizontal hydraulic conductivity to be greater than the vertical hydraulic conductivity. In anisotropic zones, where the horizontal component of hydraulic conductivity is higher than the vertical one, flow will be restricted to higher elevations compared to an equivalent flow system in isotropic zones showing the same water-level conditions.

The practical significance of the three factors discussed earlier is that groundwater levels can be a function of either well-screen depth or of well position along a groundwater flow line or, more commonly, a combination of the two.^[6] For these reasons, considerable care needs to be taken in evaluating water-level data.

Interpreting Water-Level Data

Dalton et al.^[6] also summarized the various steps in groundwater-level data interpretation. The first step in interpreting groundwater-level data is to make a thorough assessment of the site geology. The vertical and horizontal extent and relative positions of aquifer zones and the hydrologic properties of each zone should be determined to the fullest extent possible. It is extremely important to have as detailed an understanding of the site geology as possible. Detailed surficial geologic maps and geologic sections should be constructed to provide the framework to interpret data on groundwater levels.

The next step in interpreting these data is to review monitoring wells with respect to screen elevations and

the various zones in which the screens are situated. The objective of this review is to identify whether vertical hydraulic gradients are present beneath the site and to determine the probable cause of the gradients.

Once the presence and magnitude of vertical gradients and the distribution of data with respect to each zone are established, the direction of groundwater flow can be assessed. If the geologic system is relatively simple and substantial vertical gradients are not present, a planar groundwater elevation contour map can be prepared which shows the direction of groundwater flow. However, if multiple zones of differing hydraulic conductivity are present beneath the site, several planar maps may be required to show the horizontal component of flow within each zone (typically the zones of relatively higher hydraulic conductivity) and vertical sections are required to illustrate how groundwater flows between each zone.^[6] The presence of vertical gradients can be anticipated in areas where sites are underlain by a layered (heterogeneous) geologic sequence, especially where deposits of lower hydraulic conductivity overlie deposits of substantially higher hydraulic conductivity; or are located within recharge or discharge areas.

Site activities can modify local conditions to such an extent that groundwater flows in directions contrary to what would be expected for “natural” conditions. For example, drainage ditches can modify flow within near-surface deposits, and facility-induced recharge can create local downward gradients in regional discharge areas.^[6]

As mentioned previously, groundwater flow directions and water levels are not static and can change in response to a variety of factors, such as seasonal precipitation, irrigation, well pumping, changing river stage, and fluctuations caused



by tides. Fluctuations caused by these factors can modify, or even reverse, horizontal and vertical flow gradients and thus alter groundwater flow directions.

Contouring of Water-Level Elevation Data

Typically, as Dalton et al.^[6] also outlined, groundwater flow directions are assessed by preparing groundwater elevation contour maps. Water-level elevations are plotted on base maps and linear interpolations of data between measuring points are made to construct contours of equal elevation (Fig. 2). These maps should be prepared using data from wells screened in the same zone, where the horizontal component of the groundwater flow gradient is greater than the vertical gradient. The greatest amount of interpretation is typically required at the periphery of the data set. A reliable interpretation requires that at least a conceptual analysis of the hydrogeologic system be made. The probable effects of aquifer boundaries, such as valley walls or drainage features, need to be considered.

Computer contouring and statistical analysis (such as kriging) of water-level elevation data are becoming more popular. These tools offer several advantages, especially for large data sets. However, the approach and assumptions that underlie these methods should be thoroughly understood before they are applied, and the computer output should be critically reviewed. The most desirable approach would be to interpret the water-level data using both manual and computer techniques.^[6] If different interpretations result, then the discrepancy between the interpretations should be resolved by further analysis of the geologic and water-level data.

Examples of Groundwater-Level Data Interpretation

Several common errors in interpreting and contouring groundwater-level data are summarized by Davis and DeWiest.^[9] Fig. 2 presents a number of water-table configurations related to common geologic or hydrologic causes. Area A is an area of recharge within an alluvial fan where the surface is 24 m above the water table. Here the stream continually loses water to the permeable substrata. Streams with this relationship to the water table are called *influent* or *losing* streams. In such cases, ground-water contours form a V, pointing downstream when they cross a losing stream. At point B, the water in the stream is at the same elevation as the water table. The water-table contour is normal to the stream at this point because there is no flow from the stream and groundwater flowlines are therefore tangent to the direction of the stream. At C the surface of the stream is below the water table, and the stream receives groundwater discharge. At C the stream is called an *effluent* or *gaining* stream. Groundwater contours

bend upstream when they cross a gaining stream. At F the stream is still an effluent stream, but most of the groundwater has already been discharged into the stream so the contours no longer bend sharply upstream.^[9] Point D is an area of heavy pumping in which the water has been lowered to 6 m below the stream level at B. After a short period, the pumping at D should make the contours shift so the river will be influent at B. Area E is an area of recharge in which surplus irrigation water has produced a groundwater mound 3 m above the stream surface at B. The stream at K and I is flowing in an impervious channel. The difference between the discharges at K and I is equal to the water lost or gained within the ground-water basin.

Common mistakes in mapping groundwater levels are a failure to distinguish between the water levels of different aquifers and to identify wells that have contact with more than one aquifer (Fig. 3). If the area is one of complex stratigraphy or structure, the data should be interpreted with maximum use of geologic information. Similar problems occur if observation wells completed at different depths in recharge and/or discharge areas are all combined to produce a groundwater elevation contour map. In such areas, vertical flow components are significant (Fig. 1) and water levels in wells completed at different depths will be at different elevations. In such cases, only shallow wells screened at or near the water table should be used for constructing water-table maps.

Surface-water features such as springs, ponds, lakes, streams, and rivers can interact with the water table. In addition, the water table is often a subdued reflection of the surface topography. All this must be taken into account when preparing a water-table map.^[10] A base map showing the surface topography and the locations of surface-water features should be prepared. The elevations of lakes and ponds can be helpful information. The locations of the wells are then plotted on the base map, and the water-level elevations are noted. The datum for the water level in wells should be the same as the datum for the surface topography. Interpolation of contours between data points is strongly influenced by the surface topography and surface-water features. For example, groundwater contours cannot be higher than the surface topography. The depth to groundwater will typically be greater beneath hills than beneath valleys. If a lake is present, the lake surface is flat and the water table beneath it is also flat.^[10] Hence, groundwater contours must go around it (Fig. 4a). The only exception to this rule is when the lake is perched on low-permeability sediments and has a surface elevation above the main water table.^[10] Mistakes in constructing water-table maps are often associated with purely mechanical extrapolation of contours between measured water levels. The water table thus can be placed mistakenly above the land surface



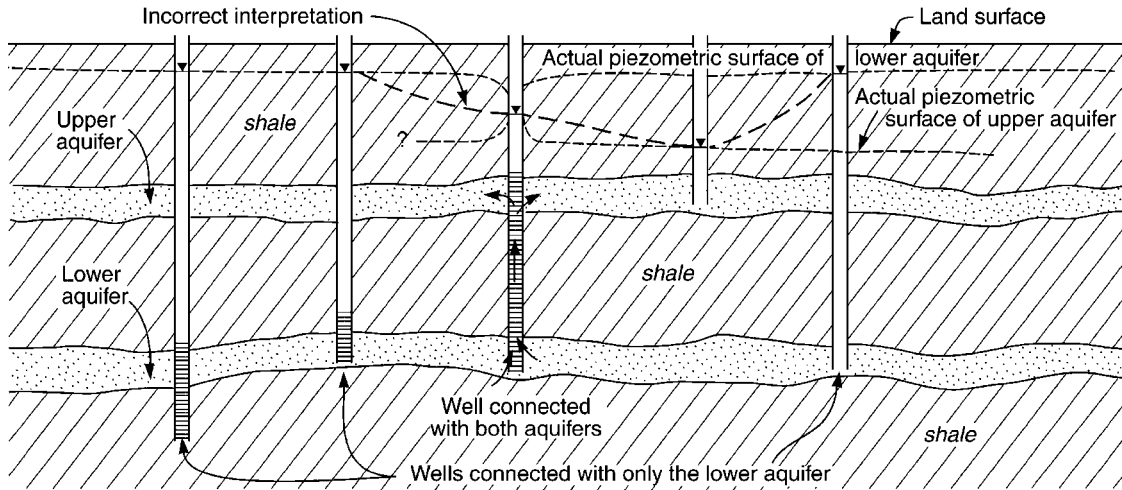


Fig. 3 Observation wells in a region having two confined aquifers under separate pressures. Correct interpretation of water levels is almost impossible unless details of well construction are known (from Ref. [9]).

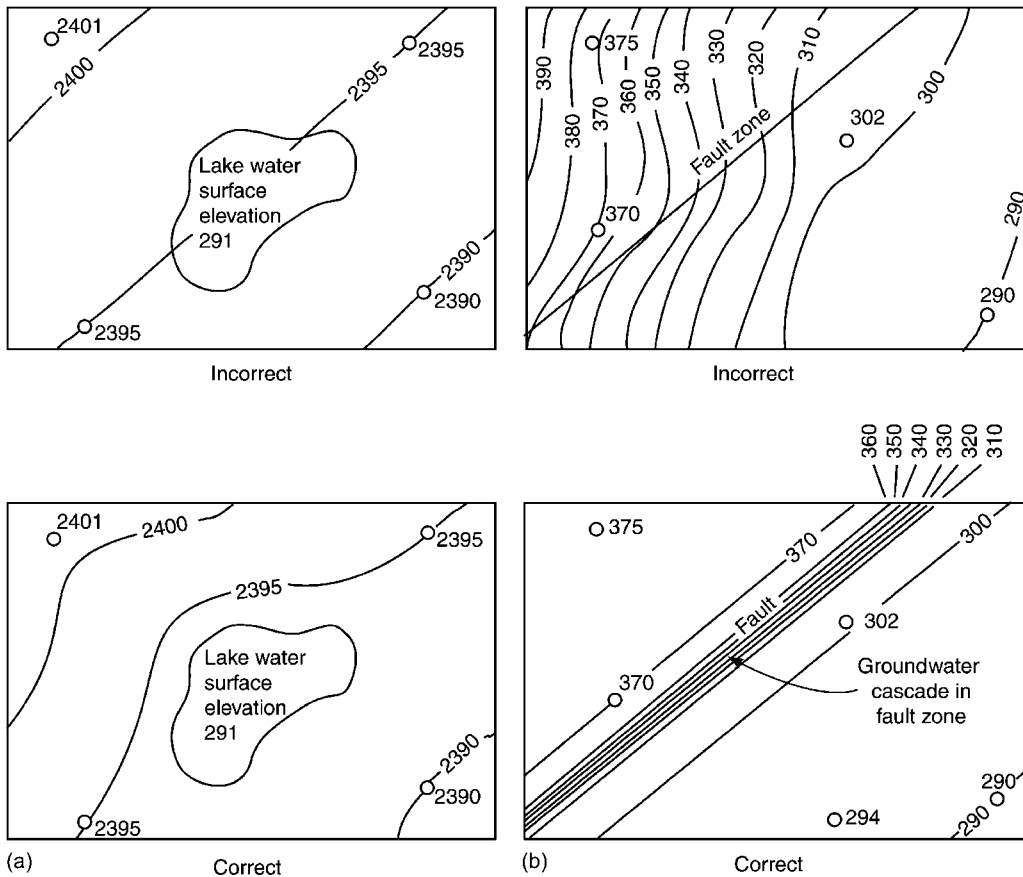


Fig. 4 Common errors encountered in contouring water-table maps in areas of (a) topographic depressions occupied by lakes, and (b) fault zones (from Ref. [9]).



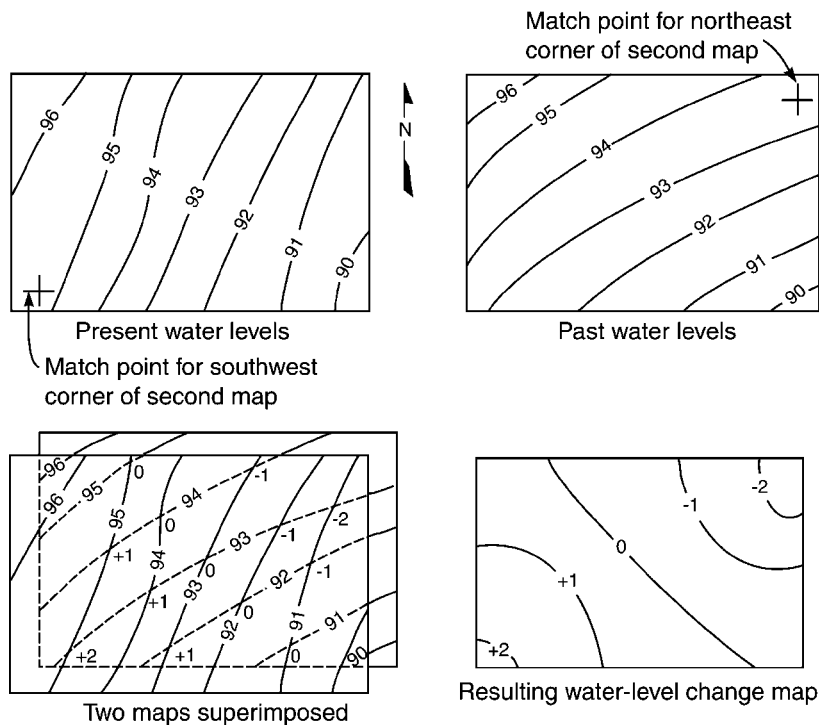


Fig. 5 Construction of a water-level change map by superimposing water-level contour maps (from Ref. [9]).

(Fig. 4a), or obvious geologic structures are ignored (Fig. 4b; Ref. [9]).

In areas where the groundwater levels exhibit a gentle gradient, the groundwater contours will be spaced well apart. If the gradient is steep, the groundwater contours will be closer together. Groundwater will flow in the general direction that the water-level surface is sloping.

Water-level change maps are constructed by plotting the change of water levels in wells during a given span of time. If the study is of a short span of time, data from the same wells can be used. If, however, the time span is long (of the order of 50 yr or more), it is impossible in some areas to measure the same wells, owing to their rather rapid destruction or failure. The best procedure in this case is to draw two water-table maps of the years of interest.^[9] The maps are then superimposed and the water-level changes at contour intersections are recorded. The values can then be transferred to a separate map and lines of equal water-level change can be drawn (Fig. 5). Modern technology, especially the use of GIS, has made such procedures much easier and faster.

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