Ground-water head distribution in the third dimension of the Pecos River basin, New Mexico

W. Kelly Summers

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Head distribution in ground-water basins

Prior to Hubbert's (1940) theoretical analysis of head and flow in a ground-water basin, most studies of head dealt with the average head in a specific lithologic or stratigraphic unit (aquifer). Later workers recognized that ground-water flow was not confined to specific rocks and that ground water flows updip, downdip, and across lithologic or stratigraphic boundaries. These studies have led to an understanding of the head distribution that one should expect in a ground-water basin in dynamic equilibrium.

The initial efforts were theoretical. Hubbert attempted to find an exact solution to the problem of the head distribution when the flow system is in dynamic equilibrium.

Tóth (1962, 1963) extended Hubbert's work through the formulation of flow patterns as analytic solutions to formal boundary-value problems. He dealt exclusively with a Laplacian solution over a homogeneous and isotropic medium. He also introduced the use of a sinusoidal representation of topographic effects on a regionally sloped water table. Tóth segregated ground-water flow into regional, intermediate, and local systems controlled by both topography and the basin height and width.

Freeze and Witherspoon (1966, 1967, 1968) critically reviewed Tóth's models and extended the theoretical simulation of head distribution with analytic and numerical models of multilayer (nonhomogeneous), anisotropic vertical sections with a general water-table configuration. Fig. 1 shows example illustrations of the theoretical development of head distributions by Hubbert, Tóth, and Freeze and Witherspoon. Table I defines some of the features labeled in Tóth's illustrations.

The theoretical models gave insight into expected head distributions within a ground-water basin and spurred geologists to develop methods to describe natural systems using extant data. Hitchon (1969a, b) developed one of the first empirical techniques for quantifying limited subsurface data into a coherent picture of basin-wide head distributions. He was interested in locating zones with high vertical hydraulic gradients in the western Canada sedimentary basin that could be explored for hydrocarbons. Hitchon examined the separate effects of topography and geology on the regional head pattern by looking at head data in discrete altitude intervals (slabs) and lithostratigraphic intervals (aquifers). He presented plan and cross-section views that demonstrate that topography exerts the dominant control on the head distribution. Later, Hitchon and Hays (1971) used slab maps to evaluate hydrocarbon potential in the Surat Basin, Australia, where very little deep subsurface information was available.

**FIGURE 2—Diagrammatic slab map and cross section showing the relations among well construction, water level, and head data.**

**FIGURE 1—Examples of ground-water flow systems.**

A. Simple single-layer example (after Hubbert, 1940)

B. Complex single-layer example (after Tóth, 1963)

C. Complex multiple-layer example (after Freeze and Witherspoon, 1968)
Several hydrogeologists studied relatively shallow ground-water flow systems and developed cross sections that describe ground-water flow in a vertical plane. For example, Nielsen (1971) characterized the hydrogeology of an irrigation study basin in the Oldman River drainage, Alberta, Canada, by comparing a vertical, two-dimensional, numerical, and electronic-analog models with b) empirical head distributions compiled from piezometer arrays. Table 2 is his comparison of these three approaches to basin-scale ground-water flow models. Nielsen recognized that piezometer arrays distributed over a basin would provide a three-dimensional picture of the head distribution in the basin.

More recently, hydrologists used slab maps to study ground water in other basins. Summers (1972) described the head distribution to an altitude of -6,000 ft in the Pecos River basin, New Mexico. Landers and Brimhall (1978) in an assessment of regional hydrology on the Navajo Indian Reservation used slab maps combined with stratigraphic and topographic data to picture the subsurface head distribution in part of the San Juan River basin, Arizona and New Mexico.

These theoretical analyses and basin studies support the following conclusions: 1) Ground water moves from recharge to discharge areas along flow paths governed by the potential-energy distribution provided by the topography; 2) The saturated rocks make up a flow continuum that governs the rates of flow and exerts only limited influence on the direction of flow; and 3) Because the saturated rocks form a flow continuum (albeit of diverse water-bearing and water-yielding characteristics), the head distribution can be mapped as an independent variable.

**Purpose and scope**

This article serves two purposes: first, it summarizes the procedure one must follow to develop slab-map data to generate cross sections that depict the variation of head in a vertical plane, and second, it presents two of my

### Table 1—Terminology of Flow-pattern Features (after Toth, 1970).

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<td>Pressure can be measured at every point on the profile, and equipotential lines can be constructed to almost any scale. Over a long period (several hours) there is drift in the electronic instrumentation, which is the main limitation on detail.</td>
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Pecos River basin cross sections and discusses their significance.

**Slab maps and cross sections**

Ground-water flow systems are three-dimensional, so any point in the system can be defined by Cartesian coordinates (x,y,z). If we take z as the altitude, then x and y become map coordinates and z becomes areographic data to picture the subsurface head distribution in part of the San Juan River basin, Arizona and New Mexico.

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table may be either higher or lower than the average head in a well.

In theory the differences between conceptualizing the iso-head contours as the average head and conceptualizing the iso-head contours as the head in the mid-plane are 1) the area mapped, and 2) the significance of a given well as a data point.

If we assume that the iso-head contours show the average head in the slab, then the resulting map is limited to the area where water table is higher than the lowest plane of the slab. The 400-ft plane (fig. 2) becomes the limit of the map. In the region where water table altitude is less than the upper limit of the slab (P to Q on the cross section of fig. 2), the average head in the saturated portion of the slab approximates the head at the water table.

Well G (fig. 2) depicts an ideal point for the slab map under the averaged-head assumptions. The well is open over the exact slab interval and no other. Other wells open in other slabs, such as wells A, B, C, and H (fig. 2), are also data points, but, because the water-level altitude observed in these wells averages head over a larger interval, the head determined by water-level altitude in the well may be different from the average head in the slab before the well was drilled. Conversely, wells open only partially in the slab, such as wells D, E, and F (fig. 2), do not necessarily give the average head, but rather some head that contributes to the average.

If we assume that the map depicts iso-head contours in the mid-plane, then the contours must be limited to that area where the water table has an altitude of 500 ft or higher. Well F (fig. 2) is an ideal data point under this assumption. It is open for practical purposes only in the mid-plane. The head in this piezometer is identical to the head in the plane. Most data points, however, are wells that are open over extended intervals. Clearly, the water levels in wells open at the mid-plane must be influenced by and exert an influence on the head in the mid-plane. Wells A, C, and G (fig. 2) are examples of such wells. Some data points are wells that are open over several intervals (well H, fig. 2), such that they are open both above and below the mid-plane, but not specifically at the mid-plane itself. Some wells, open near the mid-plane (well B, fig. 2), are not data points in themselves because their only open interval is above (or below) the mid-plane.
These wells may serve as auxiliary control if their upper or lower limit is near the mid-plane.

In practice the distinction between conceptualizing the iso-head contours as the average head and as the head in the mid-plane disappears. To have enough data in some areas, we must use data from all wells open in the slab and we draw slab maps as if they were average head maps, thereby optimizing the use of water-table contours. However, for the purposes of preparing cross sections, we treat the maps as if they show the head distribution in the mid-plane.

**Pecos River basin**

Figs. 3 and 4 are east-west geologic cross sections through the Pecos River drainage basin in New Mexico. These cross sections, first drawn in 1970, depict the following features: 1) stratigraphic relations, 2) lithology, 3) ground-water table, 4) head distribution, 5) ground-water flow paths, and 6) oil and gas fields.

The following paragraphs discuss how each feature was determined and reliability of the representation.

**STRATIGRAPHY**—The stratigraphic relations (figs. 3, 4) are based on contour maps of each stratigraphic unit depicted. To draw these maps, which are the same scale as the geologic map of New Mexico by Dane and Bachman (1965), I first plotted the altitude of the top of the unit using data from a variety of sources, including: 1) open-file data (scout tickets, lithologic logs, strip logs, drillers' logs, and electric logs) of the petroleum section, New Mexico Bureau of Mines and Mineral Resources, and 2) published documents and maps. Some maps had several hundred data points; others only a few. Then, I drew the contours on an appropriate contour interval (100, 200, 500, or 1,000 ft). In areas where data are numerous, conflicts occurred. The contours in these areas reflect the tenor of the data rather than the details of the numbers. In areas where data are sparse, the contours take into account the geometry of the underlying and overlying formations. In regions of outcrop the contours reflect both the state geologic map and the state topographic map. The maps on the whole represent the probable altitude of the stratigraphic unit to plus or minus one-half the contour interval.

To draw each cross section, I simply plotted the altitude of the top of the unit in the plane of the section. Fig. 3 was easy to draw; fig. 4 required some interpretation. In those areas of the reef complex where map units do not persist as easily recognized entities, the stratigraphic relations shown are realistic and conform within the limits of the art to cross sections of the area drawn by others.

**LITHOLOGY**—To depict the lithology on each cross section, logs of wells that were data are numerous, conflicts occurred. The contours in these areas reflect the tenor of the data rather than the details of the numbers. In areas where data are sparse, the contours take into account the geometry of the underlying and overlying formations. In regions of outcrop the contours reflect both the state geologic map and the state topographic map. The maps on the whole represent the probable altitude of the stratigraphic unit to plus or minus one-half the contour interval.

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FIGURE 4—East-West Hydrogeologic Cross Section of the Pecos River Basin through Carlsbad Caverns, New Mexico.
within one mile of the plane of the section were used. The lithologic pattern shown excludes many details, but is, nonetheless, basically correct. The region is one in which the lithology of some stratigraphic units changes markedly over relatively short distances, so the lithologies shown for these units are more diagrammatic than explicit.

**WATER TABLE**—The water table is the upper surface of the zone of saturation. Below the water table the rocks are entirely saturated.

To generate the water table shown on the cross sections, I drew a water-table map (scale 1:1,000,000). This map is based on 1) the water-level altitude of shallow wells, 2) the altitude of springs and perennial streams, 3) water-table maps prepared by others, and 4) the state topographic map. We may be sure that the water level in shallow wells approximates the water table. So, for the most part, the data from wells deeper than 100 ft were not used.

Springs and perennial streams are the outlets of the water table and so are shown on the water table map. Because the water table—by definition—must everywhere be below the land surface or be expressed as a lake, stream, spring, or bog, water-table contours were drawn so that they were indeed below the land-surface contour shown on the state topographic map.

The contour interval used reflected the reliability of the data and was 100, 200, or 500 ft. The water table shown on the cross sections is then a reasonable approximation of the water table to about ± 100 ft for the altitude interval 5,000–6,000 ft, and ± 250 ft for altitudes above 6,000 ft.

**HEAD DISTRIBUTION**—To determine the head distribution shown on the cross sections, I prepared slab maps as follows:

<table>
<thead>
<tr>
<th>Altitude Interval (ft)</th>
<th>Slab Interval (ft)</th>
<th>Contour Interval of map (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000 – 5,500</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1,000 – 1,500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>6,000 – 6,500</td>
<td>1,000</td>
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Data points were used 1) the altitude of water levels in wells that were published in reports or on file with the U.S. Geological Survey, the New Mexico Bureau of Mines and Mineral Resources, or the New Mexico State Engineer; 2) drill-stem test and bottom-hole pressure data from wells and test holes converted to the altitude of the water level in an equivalent fresh-water column; and 3) altitude of water levels reported by drillers when holes filled with water during drilling.

The 500-ft contour interval has two advantages: first, converting from pressure to fresh-water-level altitudes introduces error. Using a 500-ft contour interval more than offsets any error from this source; and second, in some areas the data were so sparse that only a 500-ft interval reflects the level of accuracy of the resulting contours.

In the region of the basin where irrigation has caused extensive water-level changes the 100-ft contour interval gives more detail. By resorting to 100-ft intervals, I hoped to foreSTALL the problem of water-level change as a result of intermittent pumping.

To draw each cross section, I treated a slab map as if it were a mid-plane map and entered the value of the contours on the mid-plane altitude where it crossed the section. A set of data points that fell on the mid-plane lines resulted for each cross section. The contours shown connect points of equal value.

Through observation the contour interval shown to 500 ft, the head distribution becomes general but also represents reality fairly well. That is, the cross sections predict the altitude of the water level in a well (or the equivalent bottom-hole or drill-stem test pressure) to an accuracy of ± 250 ft over most of the area depicted by the cross section.

**FLOW PATHS**—Flow paths depicted on the cross sections assume that fluid flow, and ground-water flow especially, is from areas of high head toward areas of low head. The flow presumably is more or less at right angles to the iso-head lines. The flow lines are shown for illustration purposes only; they neither constitute a flow grid nor reflect the volume of water flowing along paths.

**GAS AND OIL FIELDS**—The oil and gas fields shown on the cross section are those that occur within 1 mi of the plane of the section, and the shape reflects the producing intervals of the wells within 1 mi of the plane of the section.

**The natural system**

Fig. 5 shows diagrammatically in black the features of the natural system suggested by fig. 3.

The ground-water flow system that existed before irrigation and petroleum production was complex. Water flowed from recharge areas on both sides of the Pecos River. The recharge area that provides the ground water that reaches the Pecos River and which once fed the spring discharge at Roswell had its origin in a region west of Roswell, but not so far west that it reached to the surface-water or ground-water divide. Recharge from the west side flowed not only to the Pecos but also appears to have underflowed the river. McNeal (1965) drew some head-distribution maps that suggest movement toward the western or central Texas. Some underflow probably discharged downstream from the plane of the cross sections.

Water moving from the recharge area east of the river passes through the Rustler and Salado Formations dissolving gypsum and halite. Thus, water along the east side of the river has large concentrations of total dissolved solids.

The recharge area west of the river encompasses large areas of karst topography—a direct result of the solution of limestone and dolomite by the percolating recharge.

Shallow oil fields (for example, Bitter Lakes, Linda, and Pecos) occur along the east side of the Pecos River in stagnation zones where the local flow system east of the river conflicts with the regional system that underflowed the Pecos River.

The cross section through the southern part of the Pecos River drainage basin in New Mexico (continued on p. 12)
The modified system

Irrigation—Because irrigation using ground water has gone on for more than 40 yrs, the ground-water flow system has been modified extensively. The blue lines (fig. 5) show the changes that have taken place in the Roswell area that can be attributed to irrigation. The changes include 1) creation of new recharge areas, 2) the water that reaches the river from the east moves through the Rustler and Salado Formations to become highly charged with dissolved solids, 3) ground water from the west underflows the river, and 4) karst features occur in the recharge areas.

The cross section also shows the relation of ground-water flow to the evaporite series and impact of the reef complex on the ground-water flow. The evaporite series have low hydraulic conductivity so we expect very little ground-water flow through them. The cross section shows that ground water in the plane of the section does flow around, rather than through, the evaporites. The flow that does occur appears to be directed downward.

The rocks of the reef complex have relatively large hydraulic conductivities so more ground water moves through them. On the west side the flow toward the reef appears as flow to a sink. In this region the ground-water flow is perpendicular to the plane of the section. The flow is probably southerly, as underflow—that is, the reef complex carries a large part of the underflow that eventually discharges to the lower Pecos River or the Rio Grande. In the eastern part of the section the reef complex serves as a source, expelling water in the plane of the section. The water in all probability entered the reef to the north and west and discharges to west Texas rivers.

The cross sections through the Pecos River basin illustrating the method of developing a three-dimensional expression of head distribution are ten years old. These cross sections should be updated and extended to the Gulf Coast. Despite their age, the cross sections confirm (for those of us who believe) the dynamic behavior of ground water and illustrate the importance of topography.

The cross sections show that ground water flows across lithologies and that the flow direction is not dominated by the dip of the strata. They also use all available data to help explain phenomena such as salt-water encroachment.

If we could reconstruct the pre-pump flow system, we would, I believe, show that hydrocarbon occurrence depends on ground-water dynamics. Proof now is less than ideal, but hydrocarbons seem to occur in a ground-water system where the water provides the means of transport from source rock to reservoir and where ground water rises through low permeable rocks. The flow that has the oil strained from it or where changing pressure (not necessarily head) creates conditions in which soluble hydrocarbons become insoluble, exsolve, and begin to accumulate in structural, stratigraphic, and hydrodynamic traps.

Because karst solution features such as sink holes and caves occur in the recharge areas where CO₂-rich waters percolate through carbonates, we can expect that induced recharge may cause sink holes and caves to develop in the natural discharge area.

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Nielsen, G.L., 1971, Hydrogeology of the irrigation study basin, Oldman River drainage, Alberta, Canada: Brigham Young University, Geology Studies, v. 18, no. 1, 98 p.

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