W. Kelly Summers

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

by W. K. Summers, W. K. Summers and Associates, Inc., Socorro, NM

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 1 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.

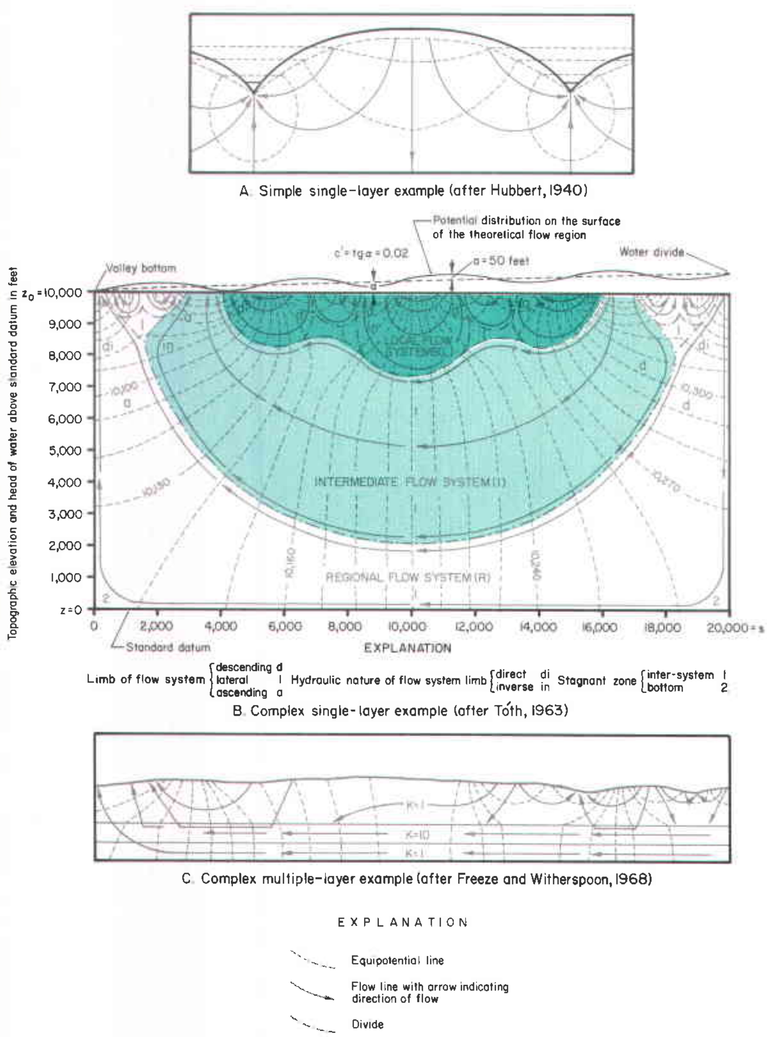

FIGURE 1—EXAMPLES OF GROUND-WATER FLOW SYSTEMS.

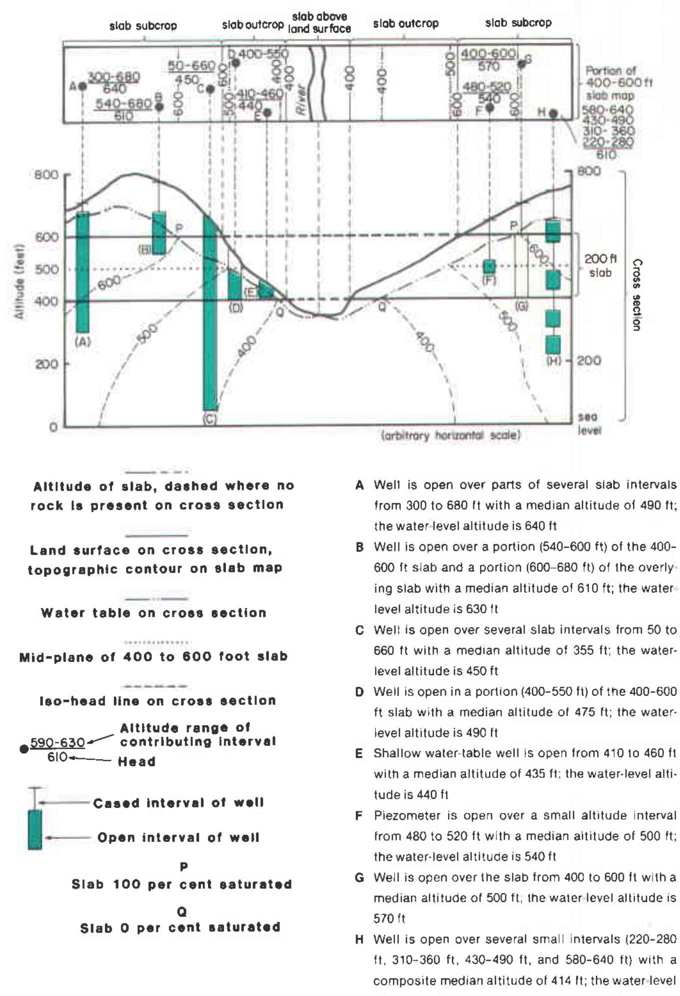

FIGURE 2—DIAGRAMMATIC SLAB MAP AND CROSS SECTION SHOWING THE RELATIONS AMONG WELL CONSTRUCTION, WATER LEVEL, AND HEAD DATA.

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 electric-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 Pecos River basin cross sections and discusses their significance.

TABLE 1—TERMINOLOGY OF FLOW-PATTERN FEATURES (after Toth, 1970).

Item	Type of item	Code of item	Characteristic hydraulic property
Flow system	Local	L	Recharge and discharge areas contiguous
	Intermediate	I	Recharge and discharge areas separated by those of one or more local systems
	Regional	R	Recharge and discharge areas separated by those of one or more local systems and occupying the main divide and main valley
Limb of flow system	Descending	d	Movement directed away from the water table
	Lateral	l	Movement subparallel with the water table
	Ascending	a	Movement directed toward the water table
Hydraulic nature of flow system termination	Direct	di	Sense of horizontal flow component unchanged in vicinity of stagnant zone
	Inverse	in	Sense of horizontal flow component reversed in vicinity of stagnant zone
Stagnant zone	Inter-system	1	Formed by three or four systems in the interior of the flow region
	Bottom	2	Formed by the descending or ascending limbs of two systems at lower boundary of the flow region

TABLE 2—RELATIVE MERITS OF GROUND-WATER FLOW MODELS (after Nielson, 1971).

Model	Reliability	Detail	Time	Cost*
Piezometer interpretation	Highest at piezometer tips, if all piezometers function properly; misleading if malfunctions are not recognized. Reliability between installations depends mainly on interpreter's skill.	Only a limited number of potentials can be measured, so much of the model must be interpreted.	About ⅔ day installation time per nest of deep piezometers; may require weeks or months to stabilize so that measurements may be used.	Cost rises very rapidly if piezometers are installed below 200 ft. Each new profile will require new installations.
Electrical analog	Excellent, providing that anisotropy is not a limiting factor; if the geology is highly anisotropic, the analog loses accuracy, mainly in predicting depths of flow. Distribution of recharge-discharge areas is less affected by anisotropy.	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.	About 9 hrs were required to set up and run this profile.	Once the instrumentation is available, the only cost is that of the operator's salary and the necessary silver paint and conductive paper.
Computer model	Excellent, particularly for anisotropic situations, provided that information fed in is reasonably accurate.	Detail obtained is a direct function of the number of nodes used; large number minimizes necessary approximations and increases detail. Potential is calculated for a network of points, the number of which is determined by the quantity of nodes used in the vertical and horizontal directions.	Once the program was debugged, each data deck took about ½ day to prepare, and 10 mins computer time to run without the plotter subroutine. The potential field was plotted manually requiring about ½ day; plotter would require ½ hr.	The commercial rate for necessary computer time was about $85, plus about another $40 for plotter time, if used.

*Inflation will increase these values dramatically.

Slab maps and cross sections

Ground-water flow systems are three-dimensional, so any point in the system may be defined by Cartesian coordinates (x,y,z). If we take z as the altitude, then x and y become map coordinates and $\alpha = f(x,y)$ and z become cross-section coordinates.

Slab maps are maps that show iso-head contours within a stated altitude interval (z_1 to z_2) called the slab interval. The iso-head contours represent either the head distribution in a plane midway between the upper and lower altitude limits of the slab (the plane we call the mid-plane) or the average head in the altitude interval considered.

Expressed mathematically, a slab map shows either

$$h^{-}(x,y) = \int_{z_1}^{z_2} f(x,y,z)dz \Big/ \int_{z_1}^{z_2} dz$$

or

$$h = f(x,y,\frac{z_1 + z_2}{2}).$$

Fig. 2 illustrates some basic features of slab maps by showing how we depict the features of a slab whose altitude interval is 400–600 ft on a cross section and on a map.

Although the definition of the slab is independent of lithology, topography, and water-table configuration, neither the topography nor the water-table configuration can be ignored. As the example cross section of fig. 2 shows, the 400–600-ft slab extends from an area where it is entirely above the land surface into areas where it is partly above and partly below the land surface into areas where it is entirely below the land surface. These areas are discriminated on the map by stippling the area between the 400- and 600-ft contours (the area where the slab crops out).

For hydrologic purposes we are concerned with the saturated part of the slab; that is, the part below the water table. Therefore, the map shows three water-table contours: 1) the 400-ft contour, which shows the limit of the area over which the water table is below 400 ft and so where no part of the 400- to 600- ft slab can be saturated; 2) the 500-ft contour, which defines the mid-plane of the slab; and 3) the 600-ft contour, which shows the limit of the area over which the water table is above 600 ft and, therefore, defines the area over which the slab is 100 percent saturated.

Fig. 2 also illustrates 1) the difference between water table, water level in a well, and head and 2) the relationship of wells constructed in a variety of ways to the 400- to 600-ft slab and how to depict these differences on preliminary maps. The water table marks the upper surface of the saturated rocks. The head at a point in the flow continuum is the altitude to which water of a specific density will rise in a piezometer at that point. The water level in a well is some average of the heads in the flow continuum that the well exposes. As a data point, the height to which water rises in the well departs from the ideal because this height depends upon head range in the contributing interval (interval of open hole, perforated casing, or screen). Thus, the head at the water 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 must 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-

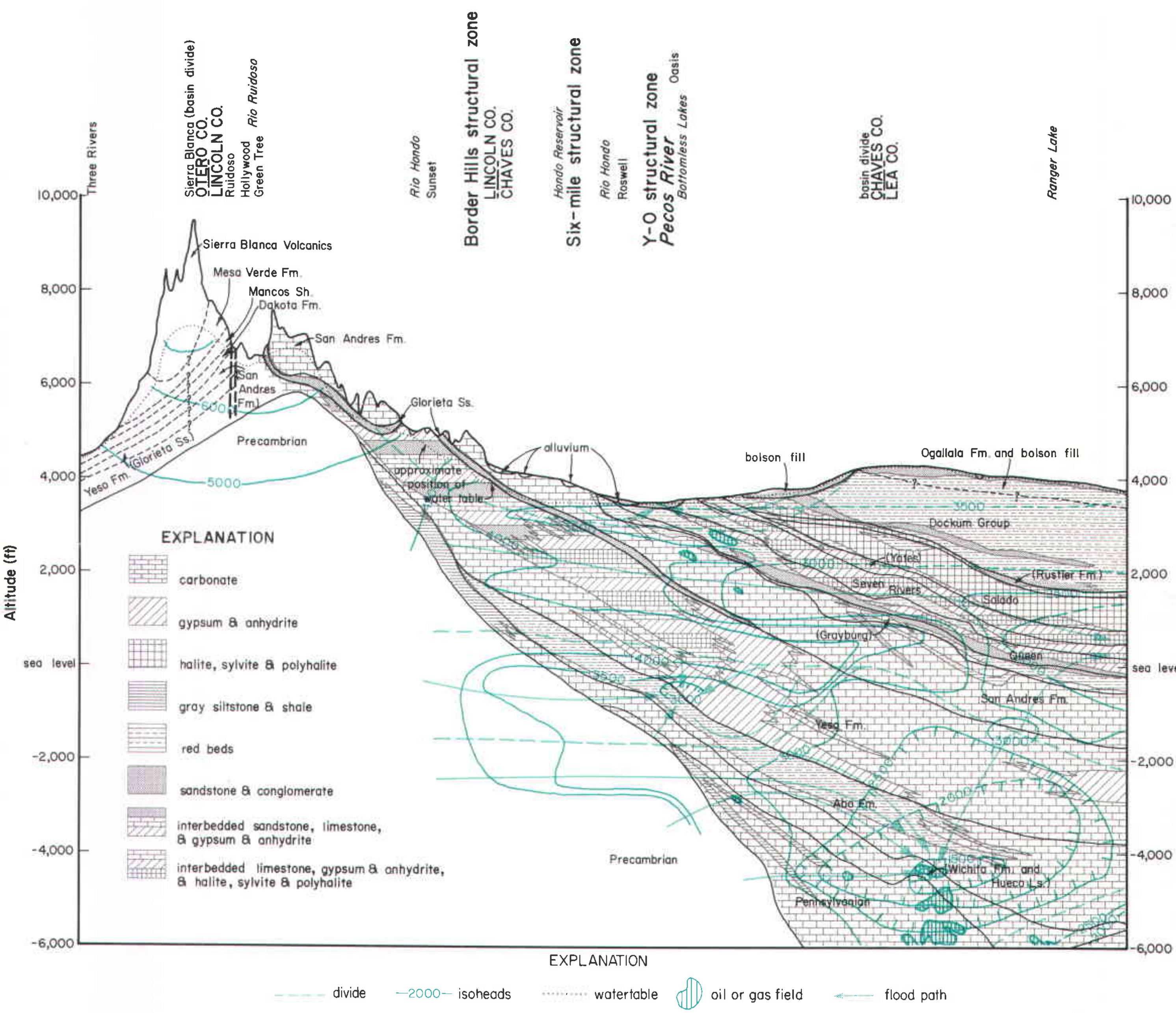

FIGURE 3—EAST-WEST HYDROGEOLOGIC CROSS SECTION OF THE PECOS RIVER BASIN THROUGH ROSWELL, NEW MEXICO.

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

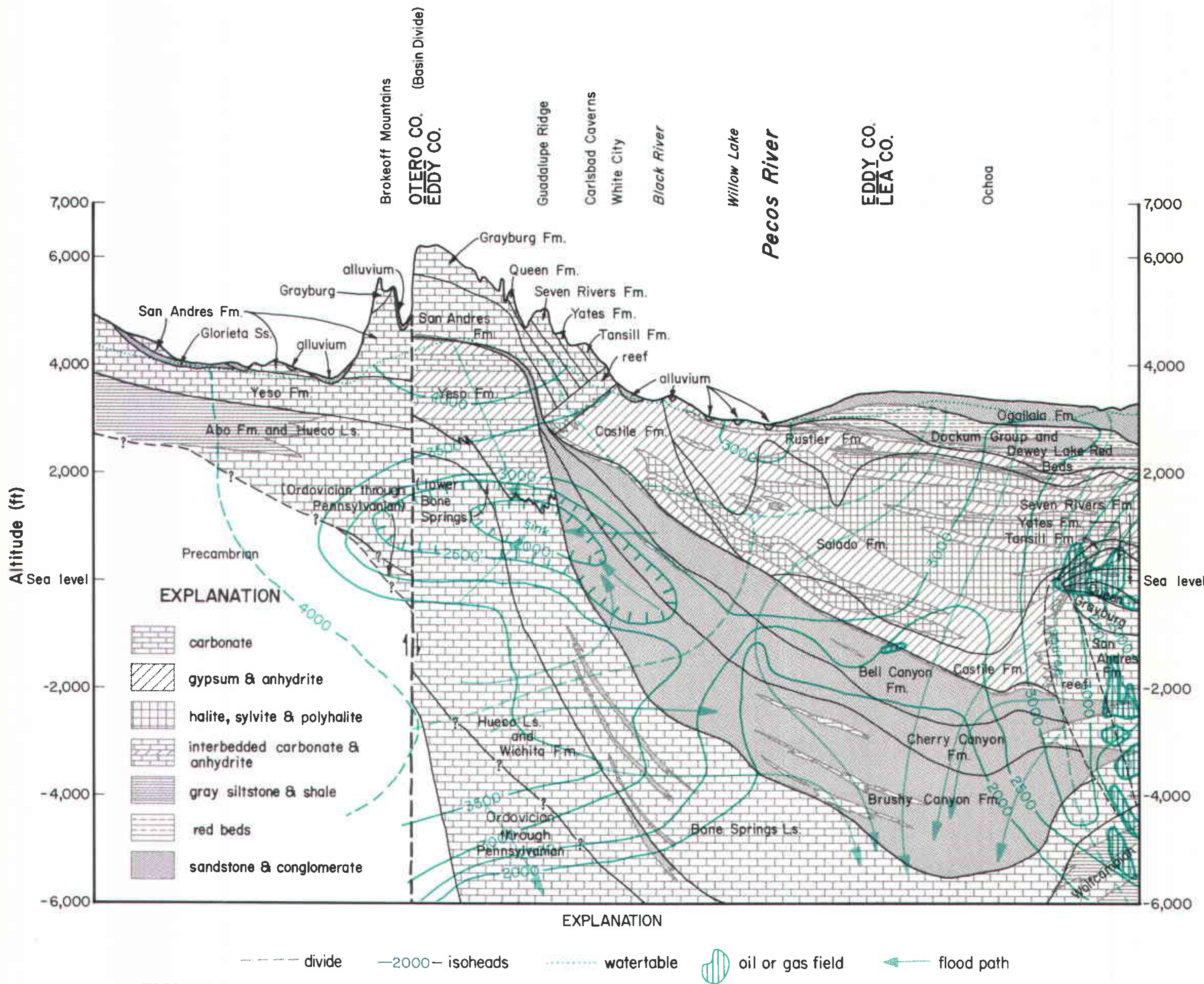

FIGURE 4—EAST-WEST HYDROGEOLOGIC CROSS SECTION OF THE PECOS RIVER BASIN THROUGH CARLSBAD CAVERNS, NEW MEXICO.

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 outcrop of the water table and so are appropriate data points. 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 as 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:

Altitude interval (ft) From	To	Slab interval (ft)	Contour interval of map (ft)
5,000	5,500	100	100
1,000	5,000	500	500
-6,000	1,000	1,000	500

Data points used were 1) the altitude of water levels in wells that were published in reports of 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 of 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 restriction of 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 accurancy 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 the path.

OIL AND GAS 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 rivers of west 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 Mex-

(continued on p. 12)

Satellite photomap of New Mexico →

This map is a product of the latest remote-sensing technology used in the Landsat satellites of the National Aeronautics and Space Administration. Other available editions, published as *Resource Map 12* by the New Mexico Bureau of Mines & Mineral Resources, are listed on p. 5. The mosaic was compiled by the Agricultural Stabilization and Conservation Service of the U.S. Department of Agriculture with funds provided by the Bureau.

Since 1972, three Landsats orbiting the Earth 14 times every day at an altitude of 570 mi have gathered a storehouse of scientific data relating to the Earth's surface. These satellites make available for the first time extremely accurate imagery of large areas.

The Landsat's detecting instrument is not a camera but rather a sensor capable of scanning an area 115 mi × 115 mi, called a *scene,* every 25 seconds. The scan lines are closely spaced and at right angles to the line of flight. Because the satellite is in approximate polar orbit, the scan lines on the imagery are roughly east-west (actually N.80°W.-S.80°E.). On the small-scale mosaic, the scan lines are barely visible except across the southernmost region.

The new mosaic of New Mexico was compiled from portions of 33 separate pictures (scenes) selected from the Landsat 2 and Landsat 3 orbits of October 1977 and 1978. In preparing a mosaic, every effort is made to fit adjoining, overlapping pictures so that the match lines resulting from differences in shading are subdued. Only a few match lines are obvious on this small-scale mosaic. The most prominent one courses generally north-south as an irregular line in the east-central region about 100 mi west of the eastern boundary line.

Finding scenes that are relatively free of cloud cover is another concern. In this mosaic the only clouds are a few scattered patches in the vicinity of the Alamo Hueco Mts. in the southwest corner of the state, a small group over the Mimbres Mts., and three small patches over the Sacramento Mts. in the south-central region. Every cloud has a black shadow to the northwest, as do prominent ridges and escarpments. During the summer, profuse vegetation can mask terrane; October is the optimum month for selecting imagery for terrane maps.

The multispectral sensor in the satellite intercepts the total range of radiation from each scene and then separates components of the spectrum into several different bands (wavelengths). The bands used in compiling the New Mexico mosaic are: band 4—visible reflected *green* light; band 5—visible reflected *red* light; and band 7—invisible *near infrared* radiation. The visible green and red bands are best suited for delineating terrane, surface water, and many cultural features; band 7 detects the invisible infrared radiation emitted by growing plants and therefore is ideally suited for delineating vegetational cover. After the bands have been sorted out in the sensor, they are digitized and beamed back to receiving stations on Earth. The total stream of data is stored on magnetic tapes.

When the tapes are inserted in a laser-beam recorder, a scene becomes a black and white picture of the imagery on photographic film—a separate film for each band. The film images are then projected through color filters to form a composite color negative of the scene. Final prints are then processed in the "false" colors seen on the mosaic.

The unconventional colors help identify features that could not be detected in natural color. *Red* indicates active vegetation; the lusher the growth the brighter the tint. Principal mountain ranges are characterized in dark red because of an "evergreen" forest cover. *Black* indicates recent lava flows, deep ico (fig. 4) cuts the Capitan reef (twice) and the evaporites of the Delaware Basin (Ochoan). The ground-water flow in this section is similar to the flow shown in fig. 3 in that 1) the water that reaches the river from the west derives from a relatively small part of the recharge area, 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 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 flow systems maintained by pumping wells, and 2) natural discharge areas becoming induced recharge areas.

Pumping wells have generated two flow systems—the shallow system (I) and the artesian system of the Roswell Basin (II). The shallow system has reversed the hydraulic gradient in the vicinity of the river so that precipitation in the discharge area, which in the past would have run off or been lost to evapotranspiration, now may infiltrate to become ground water. Water in the river may now percolate to the pumping wells of the shallow system.

The quality of the water in the shallow system is decaying because water that flows through the Salado Formation and used to discharge to the river is now moving to the shallow wells, thereby causing the dissolved solids in the easternmost wells to increase.

The artesian system intercepts flow that once underflowed the basin. Because this water flows through evaporites, it is saline, containing more dissolved solids than the water that flows only through carbonates.

The saline water has the long underflow path and so appears in wells on the east side of the Roswell Basin, giving the appearance of water moving upward from the east in the San Andres Formation.

HYDROCARBONS—Hydrocarbon production in the Permian Basin has gone on for more than 40 yrs. The wells have discharged oil, gas, and ground water—albeit, brackish to saline ground water. On the Roswell cross section (fig. 3) these pumping centers appear as closed, hachured contours.

On the Carlsbad Cavern cross section (fig. 4) the effects of pumping are less obvious. The large region of head below 2,000 ft is probably a direct result of hydrocarbon production in the Delaware Basin. The 2,000- and 2,500-ft contours along the east ends of the section will probably close around producing fields.

Discussion

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.

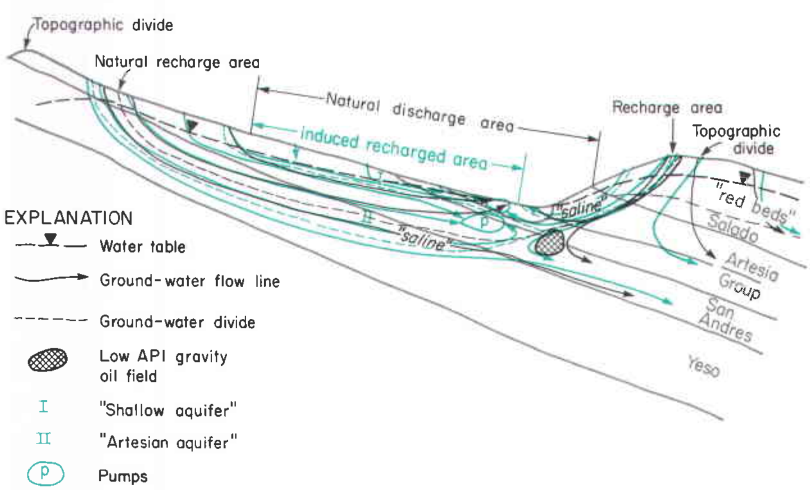

FIGURE 5—DIAGRAMMATIC EAST-WEST CROSS SECTION THROUGH ROSWELL, NEW MEXICO, ILLUSTRATING THE PROBABLE CHANGES IN THE GROUND-WATER FLOW SYSTEM THAT HAVE COME ABOUT BECAUSE OF PUMPING.

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 rising through low permeability rocks 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 CO_2-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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