New insights into the hydrostratigraphy of the High Plains aquifer from three-dimensional visualizations based on well records

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ABSTRACT

Regional aquifers in thick sequences of continentally derived heterolithic deposits, such as the High Plains of the North American Great Plains, are difficult to characterize hydrostratigraphically because of their framework complexity and the lack of high-quality subsurface information from drill cores and geophysical logs. However, using a database of carefully evaluated drillers’ and sample logs and commercially available visualization software, it is possible to qualitatively characterize these complex frameworks based on the concept of relative permeability. Relative permeability is the permeable fraction of a deposit expressed as a percentage of its total thickness. In this methodology, un cemented coarse and fine sediments are arbitrarily set at relative permeabilities of 100% and 0%, respectively, with allowances made for log entries containing descriptions of mixed lithologies, heterolithic strata, and cementation. To better understand the arrangement of high- and low-permeability domains within the High Plains aquifer, a pilot study was undertaken in southwest Kansas to create three-dimensional visualizations of relative permeability using a database of >3000 logs. Aggregate relative permeability ranges up to 99% with a mean of 51%. Laterally traceable, thick domains of >80% relative permeability embedded within a lower relative permeability matrix strongly suggest that preferred pathways for lateral and vertical water transmission exist within the aquifer. Similarly, domains with relative permeabilities of <45% are traceable laterally over appreciable distances in the subsurface and probably act as leaky confining layers. This study shows that the aquifer does not consist solely of local, randomly distributed, hydrostratigraphic units, as suggested by previous studies.

INTRODUCTION

Aquifers in thick sequences of continentally derived heterolithic deposits are the dominant source of groundwater in many areas of the world. Many of these sources are under intense development pressure and require management plans that are effective across a variety of temporal and spatial scales to ensure continued availability of water into the future. This goal is most efficiently achieved using numerical models to synoptically assess availability of water, evaluate the effectiveness of alternative management strategies, and set management goals. The ability to accurately simulate aquifer response to development is contingent in part on how well the hydrostratigraphic framework is known and subsequently represented in the model (Anderson and Woessner, 1992). Hydrostratigraphic characterization of these deposits is challenging because they typically consist of complex sequences of permeable zones separated by low-permeability barriers to flow. A more serious problem for characterization is the lack of high-quality subsurface geologic information, such as from drilled cores and geophysical logs, for defining the subsurface relationships between these features in three dimensions.

Lacking the ability to define these relationships, one approach to hydrostratigraphic delineation is to mine the information contained in drillers’ and sample logs of borings, typically the most abundant source of subsurface information available for a project area. The information contained within these logs is of variable quality and must be carefully evaluated prior to use. However, considering the number of test holes typically drilled to site a single production well, this data source has the potential for providing hydrogeologists with a wealth of local details on the distribution of and relationships between permeable and low-permeability zones within the aquifer.

In this pilot project, we used the thousands of drillers’ logs available from production well and test-hole drilling to create three-dimensional (3-D) visualizations of the aquifer from the land surface down to the underlying bedrock in a 13,600 km² area of the High Plains aquifer in southwest Kansas (Fig. 1). The visualizations were produced using commercially available software and examined to identify and relate relative permeability patterns to the aquifer’s sedimentary architecture.

The High Plains aquifer is the primary source of water for the production of food and fiber in the Great Plains area, central United States, and drives much of the economy of this region. However, the saturated thickness of the central and southern portions of the aquifer has diminished since the early 1970s because of an imbalance between pumping and recharge (McGuire, 2006; Sophocleous, 1998; Gutentag et al., 1984). Some of the highest water-level decline rates range from 0.2 to >1 m/yr where the aquifer is intensively pumped (McGuire, 2006; Wilson, 2007). Wilson (2007) projected that in some areas of western Kansas the usable lifetime of the aquifer for irrigation is <25 yr based on decline rates over the past decade. Work is currently under way to develop a numerical groundwater flow model of the aquifer in southwest Kansas for management purposes.

The aquifer framework consists primarily of Neogene (Miocene–Pliocene and Quaternary) alluvial gravel, sand, silt, clay, lime stone, marl, and eolian fine sand, silt, and clay (Gutentag et al., 1981). Discontinuous layers of groundwater-calcite–cemented sand and gravel and pedogenic carbonate nodules are abundant throughout the sequence. Almost half of the predevelopment thickness in southwest Kansas includes saturated sediments that do not contribute significantly to bulk aquifer transmissivity (Macfarlane and Schneider, 2007). The observed complexity in the distribution of Neogene lithologies has been attributed to a
variety of causes, including Miocene–Pliocene episodes of uplift of the central Rocky Mountains and adjacent piedmont, climate change, late Cenozoic volcanism, and local subsidence of the bedrock surface due to evaporite dissolution (Leonard, 2002; Molnar, 2004; Wisniewski and Pazzaglia, 2002; Pazzaglia and Hawley, 2004).

**METHODOLOGY**

The project database contains 3,031 logs that extend through the entire High Plains aquifer thickness and into the underlying bedrock (Fig. 1). Drillers’ logs from the water-well records archived since 1975 at the Kansas Geological Survey account for >80% of the database, with test-hole logs from local water-well drilling contractors, and the Kansas Geological Survey publications making up the remainder.

Logs added to the database were first evaluated to ensure that the driller accurately located the well described and produced a reasonably detailed description of the lithologies penetrated by the borehole. Locations of wells and...
test holes are recorded on the logs using public land survey notation with the accuracy of the location dependent on the finest subdivision of an ≈2.56 km² section specified in the notation, typically down to a 0.16 km² area (a quarter of a quarter section). Reported locations were verified using other location information provided by the driller on the well record. Point-based well and test-hole locations were converted into a geographic information system data layer based on geographic coordinates (public land survey or latitude-longitude) for each well location. The U.S. Geological Survey National Elevation Data set (NED: http://erg.usgs.gov/isb/pubs/factsheets/fs14899.html) 30 m × 30 m grid was used to estimate a surface elevation for each well location.

Log descriptions are typically a mix of geologic and drillers’ terms. Another potential drawback is the uneven level of recorded detail between logs. To overcome these hurdles an approach was developed and consistently applied to: (1) translate driller’s descriptions into lithologic terminology; (2) quantify the relative proportions of each lithology where heterolithic strata are mentioned in log entries; and (3) assign estimates of relative permeability fractions expressed as percentage (Table 1). Determination of relative permeability from the log description is arbitrary, but based on drilling contractor interviews, comparison of drillers’ logs with unpublished and published sample logs from Kansas Geological Survey publications, and on the deposits that most hydrogeologists would consider to be aquifer materials. Relative permeability is the fraction of a deposit considered to be permeable expressed as a percentage of its total thickness. At one end of the relative permeability spectrum, a unit consisting of unconsolidated sand and gravel is considered to be 100%, whereas one consisting of clay, silt, caliche, calcere, or cemented sand and gravel is considered to be 0%. Clayey or silty sand is considered to be 70% and sandy clay or silt is considered to be 30%. Processing of each driller’s log produces a vertical profile of relative permeability through the High Plains aquifer expressed as a percentage of each described interval (Fig. 2). All location, surface elevation, and interval permeability data were entered into an Excel spreadsheet for input into RockWorks v. 2006 (RockWare, 2006).

To generate visualizations, RockWorks v. 2006 (RockWare, 2006) first establishes a 3-D lattice of points within a user-defined domain based on the borehole distribution and user-selected easting, northing, and vertical dimensions. The lattice points define a 3-D array of unit volumes within the visualization, referred to as voxels, within which a value of the mapped parameter is assigned by the software based on the control points. In the pilot area visualizations, voxel dimensions were set at 229 m in the northing and easting dimension and 3 m in the vertical dimension. Top and bottom model boundaries were constrained by the land surface and the bedrock surface beneath the succession.

The closest point algorithm was used to create smoothed and unsmoothed 3-D visualizations to identify larger-scale trends and features and examine local variability of the relative permeability distribution. The algorithm sets the parameter value of a voxel equal to the value of the nearest data point (RockWare, 2006). This algorithm was selected because field data are not available to characterize the lateral and vertical dimensions of the lenticular bodies of sediment that form the Cenozoic succession. Smoothing was done by assigning to each voxel the arithmetic average value of relative permeability for the surrounding voxels in the visualization. The high-fidelity option was selected to better honor the control point data used to generate both visualizations. This option uses a recursive algorithm that repeatedly grids the residuals from modeling and adds them back into the smoothed and unsmoothed models until the cumulative error is less than a threshold value hard-wired into the program (RockWare, 2006). Fence diagrams consisting of a box work of 4 north-south- and 3 east-west-oriented panels were generated from smoothed and unsmoothed visualizations to examine large-scale trends and local variability in relative permeability, respectively.

**SETTING**

The pilot study area is 80 km × 170 km and elongated parallel to the eastward slope of the surface topography and bedrock surface beneath the High Plains aquifer and the assumed direction of sediment transport by the ancestral Cimarron and Arkansas Rivers. The bedrock surface rises steeply in the western third of the area on the eastern flank of the Sierra Grande uplift (Fig. 3; Robson and Banta, 1987). Permian, Triassic, and Cretaceous bedrock units underlie

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**TABLE 1. RULES USED TO ESTIMATE RELATIVE PERMEABILITY FROM DRILLERS’ LOGS DESCRIPTIONS**

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Percentage of the interval that is permeable/quantitative interpretation of lithology proportions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lithology</td>
<td></td>
</tr>
<tr>
<td>Clayey sand</td>
<td>70% contributing</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>30% contributing</td>
</tr>
<tr>
<td>Sand or sand and gravel</td>
<td>100% contributing</td>
</tr>
<tr>
<td>All other lithologies</td>
<td>Noncontributing</td>
</tr>
<tr>
<td>Multiple lithologies*</td>
<td></td>
</tr>
<tr>
<td>A with a lens, streak or thin strips of B</td>
<td>80% A and 20% B</td>
</tr>
<tr>
<td>A with B</td>
<td>90% A and 10% B</td>
</tr>
<tr>
<td>A and B or A, B (as a list)</td>
<td>60% A and 40% B</td>
</tr>
<tr>
<td>A, B, C (as a list)</td>
<td>50% A, 30% B, and 20% C</td>
</tr>
<tr>
<td>A, B, C, D, ... (as a list)</td>
<td>40% A, 25% B, 20% C, and 15% D</td>
</tr>
</tbody>
</table>

*A, B, C, and D are individual lithologies mentioned within the single entry of a drillers’ log that applies to a depth interval of the borehole.

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![Figure 2. Relative permeability profile and major Neogene lithic units encountered in the Haskell County boring.](image-url)
the Neogene sequence, dip in a northern direction, and have been beveled and deeply incised by streams (Fig. 3; Macfarlane et al., 1993). In the southeast part, dissolution of evaporites in the Permian bedrock occurred along a front and created a northeast-southwest–trending line of coalesced sinkholes, and farther west a series of enclosed basins in the bedrock surface along the southern edge of the area (Macfarlane and Wilson, 2006). Neogene sediment thickness ranges to 217 m along the south-central part of the study area and is <100 m along the western edges of the area due to Quaternary fluvial and eolian processes (Fig. 4; Osterkamp et al., 1987). Sediment thickness is greater in the central and southern parts because of the additional accommodation space created by subsidence and incision of the bedrock.

### RELATIVE PERMEABILITY DISTRIBUTION AND SEDIMENTARY ARCHITECTURE

Aggregate relative permeability in the pilot study area ranges to 99% with a distribution mean value of 51% and standard deviation of 17%. Mean aggregate relative permeability is generally higher and the distribution of values displays less variability where Neogene sediment thickness is greater (Fig. 5A). In map view, the relative permeability distribution displays a pronounced northwest-southeast grain across much of the area (Fig. 5B). A wide north-south band of aggregate relative permeability >50% covers much of the central and eastern parts and joins a narrow, northwest-southeast–trending, >50% band near the south border of the pilot study area. Following Gustavson’s (1996) depositional model of the Ogallala Formation, these bands would represent coarse sediments in the channel belts of paleovalley systems. Elsewhere, areas with aggregate relative permeabilities of <40% would represent the interfl uves where fine sediment was deposited.

Comparison of the map in Figure 5B with the unsmoothed and smoothed visualization fence diagrams of relative permeability indicates a much more complex distribution of relative permeability in three dimensions (Fig. 6). Variability in the unsmoothed visualization arises primarily from local relative permeability variations within the Neogene sediment sequence, influenced by the manner in which drillers’ logs were recorded. Driller’s log descriptions of the High Plains succession are based on depth

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Figure 3. Elevation of the bedrock surface beneath the Neogene sequence. The white dashed line is the subcrop of the northward-dipping Mesozoic–Permian bedrock boundary beneath the Neogene in the study area.

Figure 4. Neogene sediment thickness in the pilot study area and the location of the Haskell County boring.
intervals along the boring, in some cases 10 m or longer. Also, the top and bottom of each described interval may or may not correspond to changes in sediment type and may or may not correlate to the described intervals in the drillers’ logs of other nearby boreholes. Pit exposures in the pilot study area reveal considerable vertical lithic variability in the Neogene succession, with bed thicknesses from <1 m to >10 m. Thus, the true variability of relative permeability within the sequence may be poorly reflected in the resulting visualization, if the described intervals in the log are too long. To mitigate this impact, logs were not included in the database where it was evident that most of the log consisted of descriptions of thick intervals of heterolithic strata.

Visual inspection of the fence diagram panels from the smoothed visualization (Figs. 6A, 6C) suggests a three-way classification of the Neogene sedimentary framework based on relative permeability: (1) intervals consisting of strata with >80% relative permeability (red and yellow-green), (2) intervals consisting of heterolithic strata with 45%–80% relative permeability (yellow-green to blue-green), and (3) intervals consisting of strata with <45% relative permeability (blue-green to purple).

An upper discontinuous zone of relative permeability >80% in the Neogene sequence (I, Fig. 6) is traceable laterally across most of the eastern and central parts of the smoothed and unsmoothed visualizations. The zone is continuous across the north-central part of the project area in panel 1 and also in the northern part of panel 6, but discontinuous in the other panels of the fence diagram. This unit was encountered in a recent boring in northeast Haskell County described as a 48.8-m-thick sand and gravel interval (Fig. 2; Macfarlane and Schneider, 2007). Recovered gravels consist of up to 4-cm-diameter subrounded clasts of quartz of multiple origins, and granitic and metamorphic rocks, with minor amounts of cemented sandstone, pedogenic carbonates, and basalt. Sand grains are fine to coarse and dominantly arkosic with traces of muscovite, biotite, and magnetite. Frye and Leonard (1952) believed that this sheet-like body of coarse sediment was deposited in an alluvial braid plain of a major early Pleistocene, southward-flowing drainage that predated the Arkansas and Cimarron river drainages. However, the recovery of basalt clasts from this interval in Haskell County boring suggests that sediments were also contributed from the 3–9 Ma flows of the Raton-Clayton volcanic field of northeastern New Mexico and southeastern Colorado (Stroud, 1997). In panel 3 of the fence diagram, incised valleys are filled with >80% relative permeability sediment and tend to be elongated vertically, which suggests stacking of multistory channels filled with permeable sediment in paleovalley systems (II, Fig. 6).

Most of the Neogene succession is 45%–80% relative permeability in the smoothed visualization (Fig. 6). In the unsmoothed visualization...
Figure 6. Fence diagrams derived from the smoothed (A, C) and unsmoothed (B, D) three-dimensional visualizations of the percent relative permeability in Neogene sediments. I—upper sheet sand and gravel; II—incised valley fill (>80% relative permeability); III, IV, and V—silty clay (<45% relative permeability). The index map shows the counties included in the study area; the Arabic numerals identify each fence diagram panel.
these domains typically consist of thin, discontinuous intervals of varying relative permeability (Figs. 6B, 6D). In recorded drillers’ logs, these intervals consist of thin layers of fine to coarse sediment, pedogenic carbonates, cemented sand, or all three interbedded with sand or sand and gravel. The fence diagram panels also reveal that sediments in this relative permeability category are as likely to fill incised paleovalleys as high or low relative permeability sediments.

Domains of sediment with a <45% relative permeability occur in the upper and middle part of the Neogene sequence and are sinuous to tabular in vertical profile (III, Fig. 6). Several zones are easily traceable from panel to panel in the smoothed fence diagram. In the lower part of the sediment sequence, test-hole drilling reveals that a 27.5-m-thick, brown, silty clay in the northeast Haskell County boring grades laterally and vertically into a stiff, plastic, blue clay to the north of the pilot study area in southern Finney County (Macfarlane and Schneider, 2007; McMahon et al., 2003). Drill cuttings from the upper part of this interval (Fig. 2) contain manganese-oxide-stained surfaces that could be interpreted as mangans (Buol et al., 1973) preserved in one or more paleosols. This zone of low relative-permeability sediment is portrayed in hues of dark blue and violet in fence diagram panels 1 and 6 (IV, Fig. 6). In southeastern Grant County, a patch of less permeable sediment shown in blue and purple is present in the middle part of the sequence in panel 2 (V, Fig. 6). Drillers’ logs of wells in the vicinity indicate that a thick section of gray-tan to blue-gray clayey silt and fine sand bearing fragments of lignite and mollusk shells occurs in the middle of the Neogene succession (Fader et al., 1964). In the eastern part of the visualization, zones of low relative-permeability sediment occur in the upper part of the section and may represent loess and fine-grained flood plain deposits containing volcanic ashes (Frye, 1942; Izett and Honey, 1995).

CONCLUSION

The deposits that form the High Plains hydrostratigraphic framework are usually characterized as being extremely heterogeneous. For example, Frye et al. (1956, p. 8) stated, “Throughout this heterogeneous assortment of sediments there is virtually no distinctive bed that can be traced appreciable distances in the field.” Based on a statistical analysis of a random sample of drillers’ logs of borings from across the High Plains aquifer extent, Ashworth (1980) and Gutentag at al. (1984) concluded that the distribution of sediment types within the subsurface sequence is random. These and other early research efforts to characterize the lithologic and hydrostratigraphic variability of the Neogene sequence did not have access to the wealth of data provided by the drillers’ and sample logs that are now available or the software to process them.

The unsmoothed visualization captures what appears to be the extreme local variability in the distribution of permeable strata and is influenced by the level of detail in the drillers’ logs expressed in the interval input data and the amount of well control. In those areas of the visualization where the well control and/or level of detail in the log descriptions are low, details of the relative permeability distribution cannot be portrayed. It is also important to note that use of the closest-point algorithm to create the visualizations was expedient and justified by the lack of geologic information on the lateral extent of the relative permeability features being portrayed. Thus, the unsmoothed visualization is a representation of the aquifer framework that is not conditioned on the characteristics of and relationships between the lithotypes that form the aquifer framework. Instead, the smoothed and unsmoothed visualizations show that there are discontinuous but widespread hydrostratigraphic units that can be traced over significant distances in the subsurface. Lithologically, these are traceable intervals of sand and gravel and silt and/or clay and groundwater-calcite-cemented units set within a heterolithic assemblage of moderate relative permeability strata. The existence of these persistent stratigraphic zones of dominantly high and low relative permeability strongly suggests that there are preferred pathways for lateral and vertical water transmission within the saturated and unsaturated portions of the aquifer at least at the subregional scale and in many areas at more than one depth level. These results are consistent with earlier work in the Texas panhandle region on the Neogene deposits that form the High Plains aquifer. Gustavson (1996) related the occurrence of basal sands and gravels in outcrops of the sequence to the paleovalley system incised into the underlying bedrock beneath it. Dutton et al. (2001) demonstrated the hydraulic continuity of high-permeability sand and gravel deposits in the High Plains aquifer using geologic models and a regional groundwater flow model.

The project results demonstrate that using the procedures outlined in this paper, it is possible to use drillers’ logs to qualitatively establish in three dimensions the hydraulic continuity of permeable and low-permeability zones within thick heterolithic sequences of continentally derived deposits. More important, it is possible to use this approach to more accurately simulate changes in the elevation of the water table over time locally and regionally, because of the added dimensionality. Work is currently under way at the Kansas Geological Survey to develop an electronic drillers’ log database of the High Plains aquifer in Kansas. In concert with the database development, there are plans to develop tools that will allow efficient manipulation of the log information as users see fit. The results of these efforts will provide an efficient means of using the logs to quantify the hydraulic properties used in modeling based on the lithotypes that form the aquifer framework.

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