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PUBLIC DATASETS INTEGRATED WITH GIS AND 3-D VISUALIZATION HELP EXPAND SUBSURFACE CONCEPTUAL MODEL

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Public domain water well drilling logs were used to construct a 3-D visualization of the subsurface in a karst terrain. Subsurface displacements seen in the 3-D visualization model were shown to correlate with surface topography in the Digital Elevation Model (DEM). This methodology could improve the effectiveness of limited funding by using public datasets to contribute to conceptual hydrogeologic models. It could also identify areas that merit additional investigation which might have gone unnoticed otherwise.

Physical characteristics of the surface and subsurface environment typically affect water movement, levels, and quality. Regional population and development continue to increase in northwest Arkansas, causing changes in landuse practices. The unconfined carbonate units near the surface are subject to potential sources of pollution of groundwater caused by landuse changes. Complexities of surface-to-groundwater transport and groundwater movement are increased in karst terrain. For example, sinkholes funnel water into subsurface flow systems, while faults act as barriers or conduits for water movement. Carbonate lithologies dissolve along bedding planes, fractures, and other paths of least resistance, affecting routes of movement and development of secondary permeability. However, it has also been shown that water movement may be independent of the regional structure, and movement from an area of recharge splay laterally in all directions (Stringfield *et al.* 1979). LeGrand (1979) asserted that increased understanding of a fractured-rock system such as carbonate aquifers that are within several hundred meters of the surface is accomplished by continual data collection, observations of the system, and by making hydrogeologic inferences that lead to the development of conceptual models. Geologic structure is one factor that strongly influences carbonate rock hydrogeology. When this study began, the Arkansas Geological Commission (AGC) file contained ~2100 wells for Washington County and ~3100 for Benton County. Water well users included private rural residents, confined animal operations, RV parks, small communities, and businesses and industry. A cost-effective methodology for modeling subsurface structure using these wells could greatly contribute to the conceptual understanding of local and regional groundwater pathways by increasing the database of information within the framework of limited funding resources and manpower.

GIS facilitates data management, access, and analysis (Star & Estes 1990; Tsihrintzis *et al.* 1996). These abilities extend the research knowledge-base by allowing for the continued acquisition of data to be built on what was previously acquired, thereby improving understanding (Waite & Thomson 1993). Since earth-system processes can be exceedingly complex when trying to solve environment-related questions, spatial representation of them is critical for clarity (Parks 1993). The communication of information can be accomplished in a variety of ways, but visualization provides the most effective manner for conveying complex spatial relationships to the human brain (Bonham-Carter 1996). Additionally, when trying to model land-surface and subsurface hydrogeologic linkages, the inherent complexity of environmental processes is compounded by the fact that they are hidden from view and are,

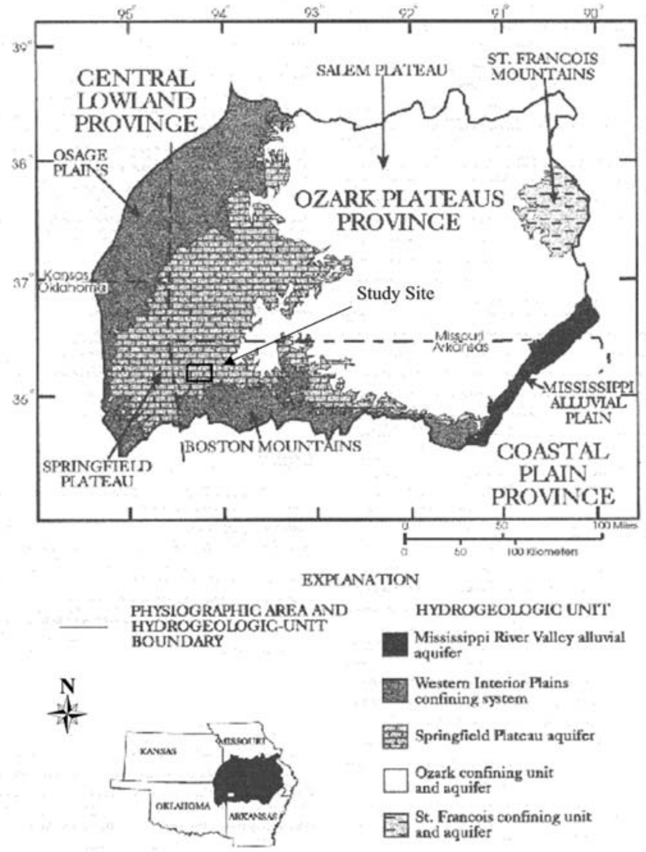

Figure 1. Regional physiographic area and hydrogeologic environment surrounding the study site (modified after Adamski 1997).

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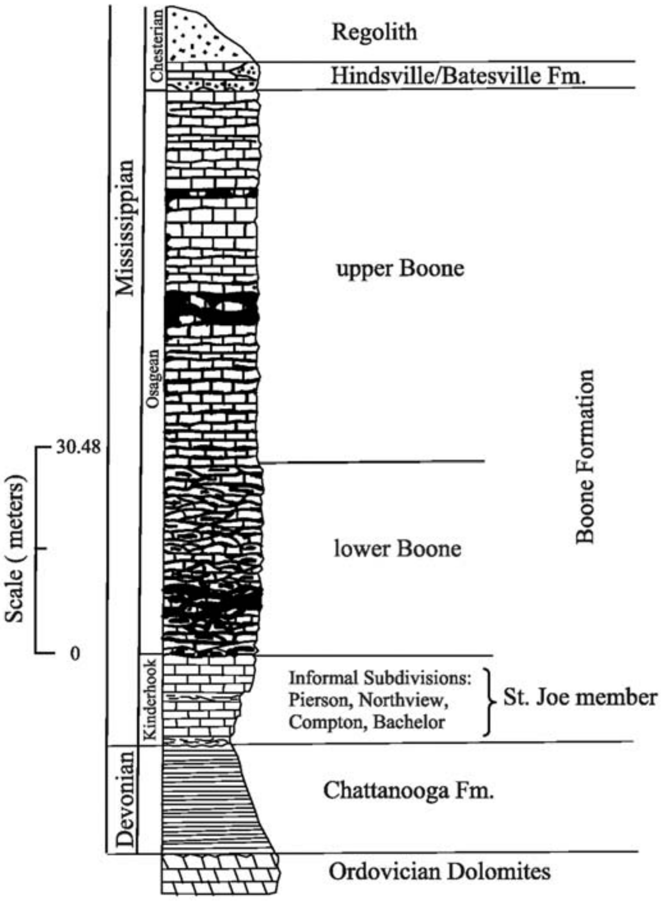

Figure 2. Generalized stratigraphic column for northwest Arkansas (modified after Bartholmey 2001).

thus, more difficult to comprehend or verify. Development of a conceptual model can reveal spatial patterns which might not otherwise be apparent (Bonham-Carter 1996). Furthermore, 2-D models have a limited functionality when attempting to convey location relationships (x and y) in space (z); thus, 3-D models are preferred. Kolm & Downey (1993) and Turner & Kolm (1991) assert that the inability to visualize in three dimensions greatly impairs interpretation of the systems. Maidment (1993) reminds us that coupling both surface and subsurface models provides a more complete understanding of the hydrosphere.

Camp *et al.* (1994) assert that the best information on the subsurface comes from wells. However, hydrogeologic investigations are typically costly and time consuming (Smith & Paradis 1989; Brahana 1997). For example, northwest Arkansas drillers charged ~$5.00/ ft for drilling (with an additional charge of $1.00/100 ft when the depth passed 800 ft), $5.50 per casing, and $200 as the accessory fee (i.e., cost of cement, well cap, and drive shoe) at the time this study was concluded (1999).

Interactive viewing of complex problems is one of the most powerful capabilities of 3-D modeling (Smith & Paradis 1989). As exact subsurface representation is not possible, the ability to identify geologic conditions and their parameters is the most important constraint in 3-D representation of the hydrogeology of the subsurface (Turner 1989). One of the major processes in characterizing the subsurface is the development of conceptual models from typically sparse datasets. When employing computerized methodologies, the ease of combining various data types is enhanced, and 3-D visualization allows interaction with the datasets so that their spatial relationships are maintained (Turner 1992). This increases the geoscientists' ability to analyze the data.

GEOLOGIC SETTING

The study area is located on the Springfield Plateau of the Ozark Plateaus Province (Fig. 1) in northwest Arkansas and covers portions of southwest Benton County and northwest Washington County. The regional stratigraphy is nearly horizontal but dips slightly (<1º) to the south (Howard 1989) and drainage patterns are dendritic. Strata include the Upper Devonian Chattanooga Shale, which acts as the regional confining unit (USGS 1998), and Lower Mississippian St. Joe Member of the Boone Formation (Barlow & Ogden 1982) (Fig. 2). Chattanooga Shale crops out at the surface along streambeds. Limestones dominate 96% of study area surface exposures (Phelan 1999). The area is highly fractured and subject to solutional enlargement of joints and fractures (Renken 1998).

METHODOLOGY

Water well log data for March 1973 to August 1997 were obtained from the Arkansas Geological Commission (AGC) in Little Rock, Arkansas. Two basic assumptions were made from the beginning: 1) the drillers were able to differentiate between the major geologic units; and 2) the wells were basically vertical and did not drift significantly. Well log data and locations were entered into a spreadsheet and sorted by geologic unit.

The dataset for this study contained all formats of location description but latitude/longitude was required for use in a GIS. Wells without a provided latitude/longitude had their location field-verified and coordinates were determined with a Trimble GPS Pathfinder Pro-XL™ global positioning system (GPS). GPS measurements could not be performed on some well locations because of restricted access at confined animal operations. When locations were confirmed for these wells, they were placed as accurately as possible on a standard USGS 7.5-minute topographic quadrangle map (datum NAD27) and later digitized.

Geologic units above and below the Chattanooga Shale unit were correlated with the driller's descriptions, and an evaluation was made as to whether or not geologic formations were correctly identified based on the descriptions and thicknesses reported on the log sheet. Each well location was required to contain a depth to the base of the shale. This was

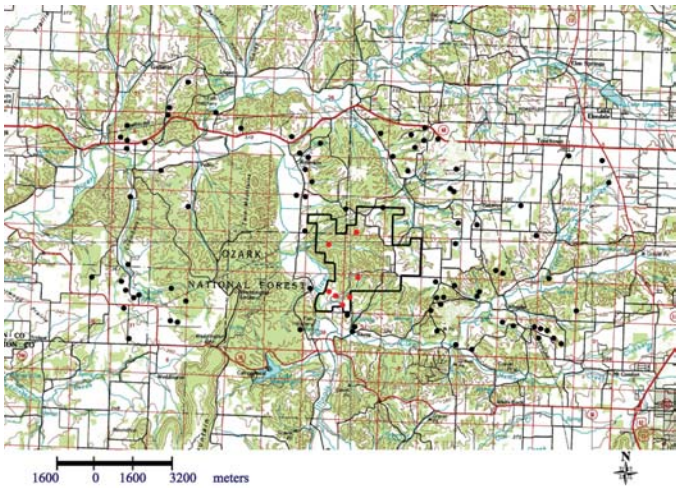

Figure 3. Study area showing water well (black dots) and control well (red dots) locations. Savoy Experimental Watershed property boundary is shown in black outline (modified after Phelan 1999).

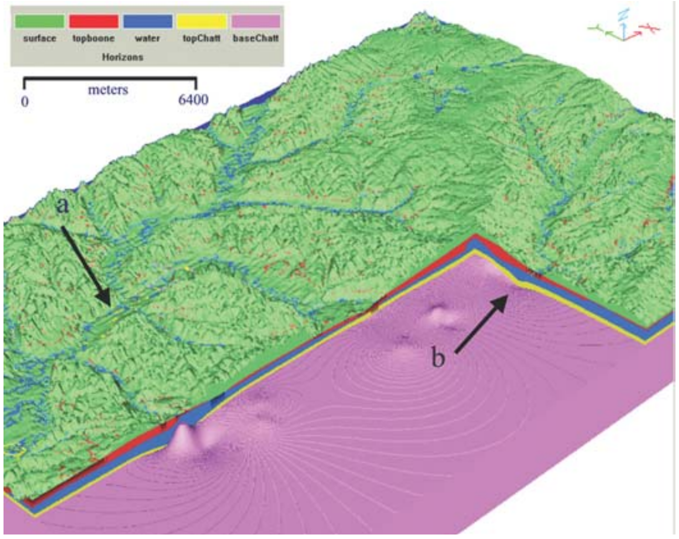

Figure 4. Chair graphic perspective viewed from azimuth 226, declination 55, Z exaggeration = 3. Arrow "a" points to where shale outcrops in the bed of the Illinois River and "b" points to apparent lineament alignment. Note that "Y" axis always points north, corresponds to latitude or northing, "X" corresponds to longitude or easting, and "Z" represents the vertical direction (elevation).

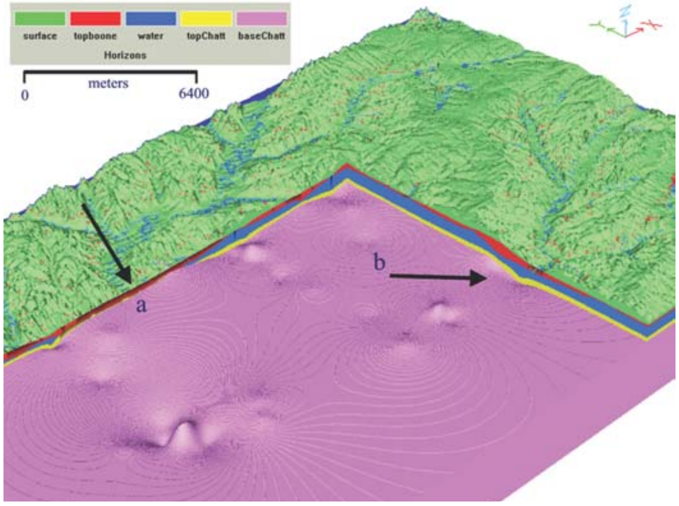

Figure 5. Chair graphic perspective viewed from azimuth 225, declination 55, Z exaggeration = 3. Arrow "a" points to where the Boone unit pinches out and shale surfaces in the bed of the Illinois River and "b" points to apparent lineament alignment. Note that "Y" axis always points north, corresponds to latitude or northing, "X" corresponds to longitude or easting, and "Z" represents the vertical direction (elevation).

necessary for two reasons: (1) to correctly distinguish by visual means alone the specific positions of the carbonate units above and below the Chattanooga Shale; and (2) to maximize the data points obtained with respect to necessary time for field verification of each well location. The initial number of log sheets for the study area totaled 174 records. After evaluating the log records, and after the field verification process eliminated additional wells, the final dataset for the study totaled to 83 water wells (Fig. 3). They were irregularly spaced, clustered, and biased according to anthropogenic uses. The well depths represented in the dataset are as follows:

Number of wells	Range of depth, m
14	<91
15	91 - 122
16	123 - 152
18	153 - 183
10	184 – 213
10	>213

While the log sheet format has changed over time, the necessary basic information needed for this study — location data, date well was drilled, owner's name at the time of drilling, driller's name, total well depth, depth to top and base of carbonate and shale units, depth to water — has remained constant over time and appeared on all forms.

Arkansas climatic division 0301 precipitation records were utilized to determine if the well was drilled in a high-flow or low-flow season. Division data were used instead of individual recording station data because they were considered to be more representative of the nature of the areal distribution of precipitation and groundwater recharge for the study area. Climatic divisions are defined as relatively homogenous areas within a state. Each reporting station within a division is equally weighted with the others in the same division, and their precipitation measurements are totaled and averaged for that division. While the reporting stations within a division vary in number and location, this method of calculating precipitation more accurately reflects the precipitation received in a physically homogenous area than relying on the nearest gauging station, which may or may not be working properly or be truly representative (Karl *et al*. 1983).

To determine if a well was completed in a low-flow or high-flow time of year, the date of completion was compared to the median statistics of the amount of rainfall for that month and year. If the amount of rainfall for the month was below the monthly median, then the well was considered to be completed in a low-flow time period. Using only low-flow completed wells as representative of base groundwater flow, an xyz point file for each geologic unit was created. Subsurface elevations for the top of the limestone unit (Boone Formation) and top and base of shale (Chattanooga Formation) for each well site were calculated from the surface elevation DEM and the reported depths to formation tops and base as indicated on the well log sheets. Subsurface elevations at each well location were then separated and grouped according to geologic unit.

A raster surface representing the top and base of the geologic units was then created using thin-plate splining. Additionally, a water surface was generated based on the recorded depth to water in the well at the time of well completion and based on the elevation of surface water features (derived from vector stream and spring files and a DEM).

Mitasova and Mitas (1993) have shown that interpolation of surfaces using bivariate and trivariate completely regularized splines with tension works well with geoscientific and scattered data. This method is a multi-grid, radial approach with global interpolation that can be segmented for large datasets. The interpolated surfaces can be "tuned" by adjusting the tension parameter which then compensates for overshoots of the data points. An increase in tension causes the data points to have influence over a shorter distance resulting in a surface that acts like a rubber sheet. A decrease in tension causes the data points to have influence over a farther distance resulting in a surface that acts like a steel plate. The change in tension allows data points to be honored. Smoothing of the data can be incorporated if desired. Whereas the data points will create peaks and dips, the interpolated surface will eventually go back to trend. Trend is a constant, is a horizontal surface, and is derived from the dataset.

The tension value was chosen so that the interpolated surface would pass through the data points or as close as possible. In order to preserve abrupt changes in elevation that could be indicators of faults, no smoothing was used.

The interpolated raster surfaces were converted to grid-format, and used to construct a 2-D geometry viewable in 3-D perspective. Geologic horizons could then be viewed interactively with cutting planes, fence diagrams, and chair graphics chosen to visually evaluate the relation of the units to one another and to the surface topography. It should be noted that these surfaces are sampling-limited, so they will become more accurately defined as more samples are input into the model (Fisher 1993).

Seven instrumented wells located at the Savoy Experimental Watershed (SEW) were used as control wells when evaluating the interpolated surfaces. SEW is centrally located to the area chosen as the study site (Fig. 3).

RESULTS AND DISCUSSION

The ability to use water well driller's logs was based on the geology of the study area being visibly discernible from one unit to another. It is doubtful that areas with less visually identifiable geologic units would be able to rely on data provided by non-geologists. Also, public domain water well log use produces data points that are irregularly spaced, clustered, and biased according to anthropogenic uses.

There were 77 points used for the Boone limestone interpolation, 79 points for the top of shale surface, and 81 points to model the base of the shale unit. The logging length represented in this study totaled 12,964 m, including: 1104 m to the top of Boone limestone; 4804 m to the top of shale; and 5914 m to the base of shale. This dataset represents an overall aggregate cost savings of ~$229,300 (based on the cost of drilling in northwest Arkansas in May 1999). Comparison of interpolated surfaces with the 7 control well formation elevations showed differences in elevation of -18 to 15 m for top of Boone limestone, -29 to 9 m for top of Chattanooga Shale, and -12 to -2 m for base of Chattanooga Shale.

Interactive exploratory viewing of the interpolated geologic and water surfaces with and without the DEM is one main element of this study. Figures 4 through 7 demonstrate a few of the 3-D perspective views possible when visually comparing the interpolated surfaces to one another and to the surface topography. Dips and rises in the modeled surfaces can be seen to align with lineaments expressed in the surface topography. Arrows in Figures 4 and 5 point to where the top of the shale surface outcrops in the bed of the Illinois River (as confirmed in the field).

CONCLUSIONS

Free data on the subsurface in the form of water well drilling logs were successfully used to model geologic surfaces in a nearly horizontal karst environment. Additional data points are needed to continue testing the methodology. How successful this methodology would be in other geologic settings remains to be investigated.

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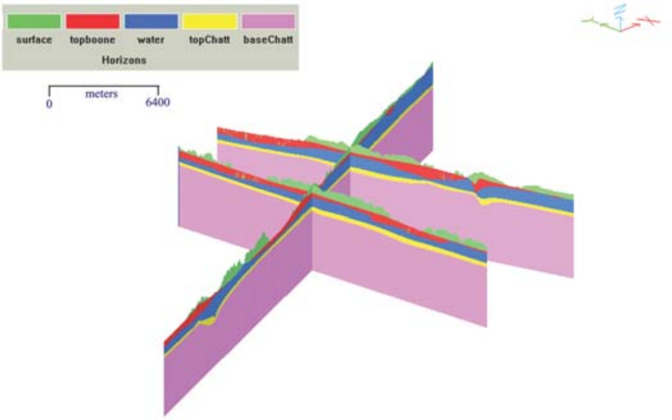

Figure 6. Iso-parametric perspective along axes. Note that "Y" axis always points north, corresponds to latitude or northing, "X" corresponds to longitude or easting, and "Z" represents the vertical direction (elevation).

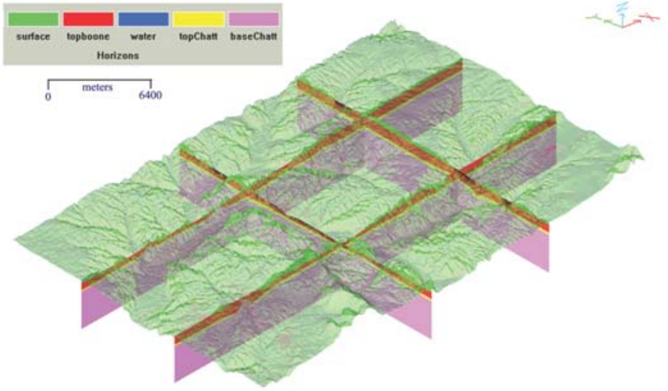

Figure 7. Iso-parametric perspective along axes with a 55% transparent surface layer. Note that "Y" axis always points north, corresponds to latitude or northing, "X" corresponds to longitude or easting, and "Z" represents the vertical direction (elevation).

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