STATE OF ARKANSAS

Arkansas Geological Commission
Mac B. Woodward, State Geologist

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Abstract

The municipal wells of the City of Dardanelle tap the alluvial aquifer of the Arkansas River in an area where the alluvial plain is about 1.4 mi (2.3 km) wide and 68 ft (21 m) thick, flanked by areas of Paleozoic shale bedrock outcrop. The city planners were concerned about potential contamination of their water-supply system if the river were to be polluted. We conducted a study of the local hydrology in order to construct a MODFLOW groundwater model of the alluvial aquifer. Based on available driller's logs from the city's wells and from U.S. Geological Survey (USGS) exploration wells, which show an upper interval of silty and clayey fine sand and a lower interval of coarse sand and gravel, a two-layer model was developed. Hydraulic conductivity, K, of the upper layer was estimated from grain-size analysis of soil auger samples taken at 5 ft (1.5 m) depths, with comparison to estimated permeability published in a county soil survey. A range of K values for the model's lower layer were used, based on aquifer tests published in a USGS report from a reconnaissance study (Bedinger and others, 1963). Aerial recharge for the model was based on an estimate given in the same report. MODFLOW's stream package was applied to model the involvement of Smiley Bayou in the system, using a stream discharge based on flow measurements made in the field. The Arkansas River was modeled as a constant head boundary based on an average low-flow condition. Areas of bedrock outcrop form a no-flow boundary almost parallel to the Arkansas River, and groundwater flow lines form no-flow lateral boundaries. Steady state models of both the natural condition (no pumping wells) and a pumping condition using annual pumping rates of the city's wells were run. The natural condition model shows a system in which the groundwater head gradient is toward the Arkansas River, indicating that in the absence of pumping wells flow through the alluvium discharges into

the Arkansas River. In the pumping condition model, the head gradient is reversed in the area between the river and the wells nearest to the river, indicating that some of the municipal wells are being significantly recharged by inflow from the Arkansas River. The conclusion is the same for any reasonable K value picked for the lower part of the aquifer, where the city wells are screened. Model heads reasonably match water levels indicated on well-drilling records and in existing wells accessible to measuring devices. Water quality analyses of raw water from wells in the Dardanelle well field compared to analyses of water from the Arkansas River and water from the aquifer in areas remote from Dardanelle indicate a mixing of the aquifer water with water from the river, corroborating the conclusions drawn from the flow model.

Introduction

In December, 2001 a study was initiated to determine the characteristics of flow in the alluvial aquifer flanking the Arkansas River at Dardanelle, Arkansas. The study was initiated to address concerns of the city officials of Dardanelle regarding water quality in their municipal supply wells. A neighboring city, Russellville, was considering a new waste-water discharge site into the Arkansas River just upstream from Dardanelle. Members of the Dardanelle City Council were concerned that water from the Arkansas River might move in the subsurface to their well system, and if by any reason an inadequately treated discharge were to be released by Russellville, then Dardanelle's water quality could be compromised. The study presented in this report was conducted to evaluate the possibility that water from the Arkansas River is actually making its way to the Dardanelle water-supply wells.

At first we thought the problem could be easily solved by locating a number of domestic wells in the area, measuring and mapping the elevation of water levels in the wells, and seeing if the gradient was toward the river, or away from it, toward the municipal wells. We assumed that because the town was in a rural setting and had been there for a long time that there would be plenty of such wells, even if not in use. However, Dardanelle has had a water management system in place for many years and has banned domestic wells; only one well was found that is still open. Therefore a more comprehensive approach to the problem was taken. We endeavored to quantify all the components to the hydrologic system of the Dardanelle area and to use this data to construct a MODFLOW groundwater model of the aquifer. This model was then used to characterize the dynamics of groundwater flow in the aquifer, particularly with regard to the relationship between the Arkansas River and the municipal supply wells.

Area Geology

The City of Dardanelle lies on a narrow strip of alluvial sediment on the southwest side of the Arkansas River in Yell County. Figure 1 shows the boundary between alluvial sediment and bedrock outcrop based on the Arkansas Geological Commission's "Geologic Worksheet" for the Dardanelle quadrangle (USGS 7.5 minute series). The distribution of alluvium and bedrock is not shown on the east side (the Russellville side) of the Arkansas River, because the river forms a hydrologic boundary, and therefore groundwater and surface water flow on that side is irrelevant to the situation on the Dardanelle side of the river.

The bedrock in the Dardanelle area consists of the Atoka Formation, which is almost entirely shale in this vicinity, with only very minor thin sandstone and siltstone intervals. On the north end of town, Dardanelle Mountain is a hogback ridge underlain by a thick occurrence of the Hartshorne Sandstone, which is inclined northeastward at a moderate angle along the south limb of a large syncline. The river has eroded through this ridge, and the ridge's extension on the east side of the Arkansas River can be seen as a small, linear topographic high running approximately east-west. Upstream of the ridge, the gravel and sand of the Arkansas River's bottom lies on horizontal Hartshorne Sandstone in the hinge area of the syncline; downstream of the ridge, shale of the Atoka Formation underlies the river. The alluvial plain on which the City of Dardanelle is located is also underlain by the Atoka Formation shales.

Information regarding the thickness and character of the alluvial sediments is available from driller's logs that were filed with the completion of most of the municipal wells. Records of a few USGS exploratory wells are also on file with the Arkansas Geological Commission. The Arkansas Department of Environmental Quality (ADEQ) Underground Storage Tank Division has drilling records from a site investigation at the corner of Union and Second Streets. Most depth-to-bedrock measurements are 66-73 ft (20-22 m) and thus the elevation of the floor of the aquifer based on drilling depths is also fairly consistent in the area where the production wells are. Two exploratory boreholes, designated here as the Rock Street well and USGS well #1,

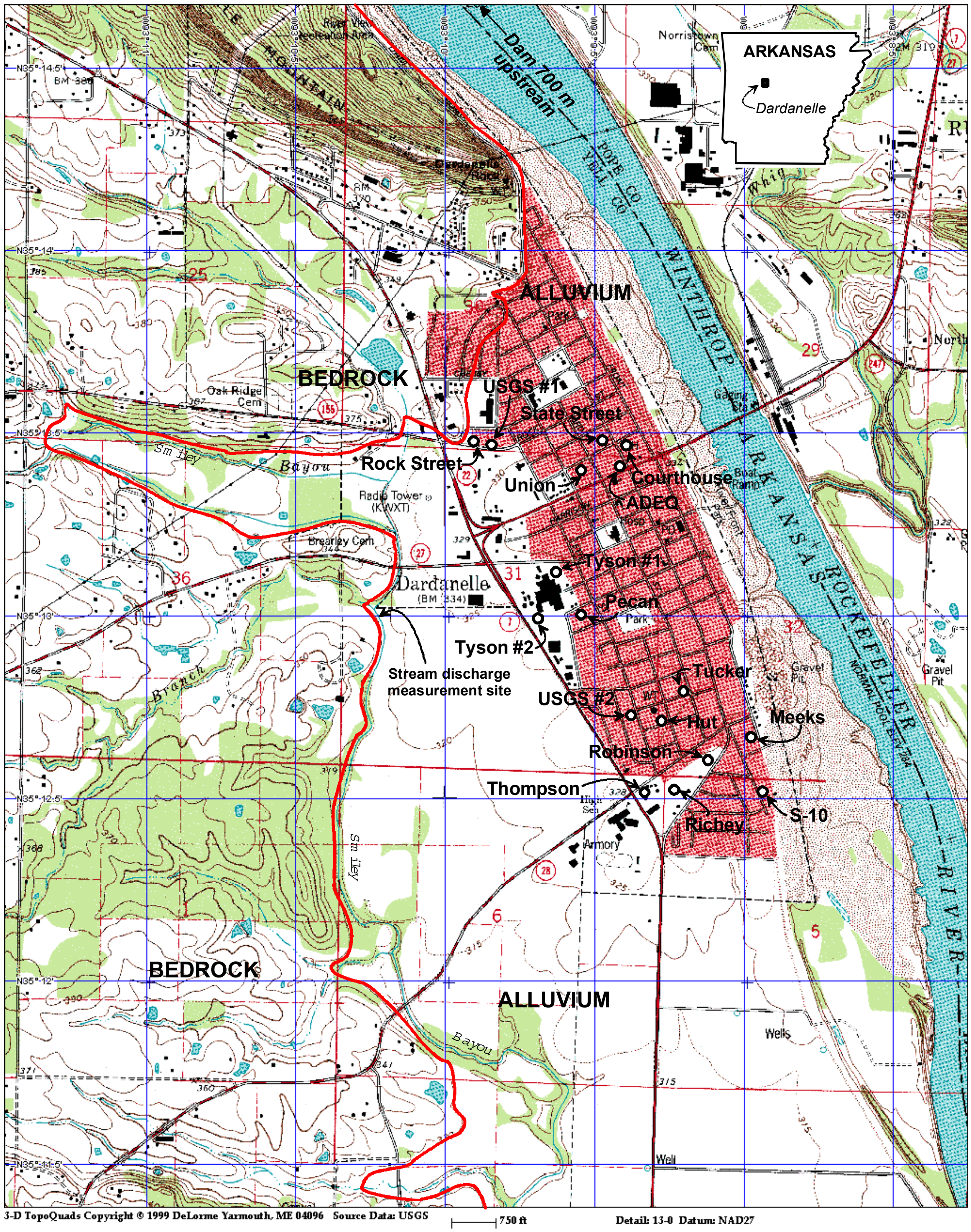

Figure 1. Map of the Dardanelle area. Base map is the Dardanelle 7.5 minute quadrangle (USGS topographic series); the boundary between the alluvium and the area of bedrock outcrop is drawn based on the Arkansas Geological Commission Geologic Worksheet for the Dardanelle quadrangle. Locations of municipal wells and other wells referenced in the text are shown with circles labeled according to well names. The site where the discharge of Smiley Bayou was measured is also indicated.

cannot be located in the field, but from location descriptions they must have been very close to each other near the edge of the alluvial plain. Figure 1 shows their estimated positions. At the Rock Street well site, the alluvium is only 35 ft (10.7 m) thick, while at the nearby USGS well #1, it is 53.5 ft (16.3 m) thick. Based on the drilling depths, therefore, it is thought that the elevation of the bottom of the alluvium (top of bedrock) throughout most of the area covered by the alluvial plain is fairly constant, that is, a fairly flat basin bottom, with a rather abrupt, steep margin along its western edge. The general arcuate shape of the alluvium's western edge is probably a former cut bank of a meander bend of the Arkansas River's past configuration. The lateral migration of the river with the erosive action of the river channel most likely planed off the area where it migrated and left the steep lateral margin.

Understanding of the stratigraphy of the alluvium is also based on the drilling logs. However, logs written by most well drillers must be interpreted with caution because most drillers are not schooled in standardized methods of sediment description, so their designations are rather subjective. The most reliable are the USGS and ADEQ logs. All of the logs document a coarse section of sediment at the bottom, designated by such terms as "gravel", "sand and gravel", or "gravelly sand". Based on the USGS and ADEQ descriptions and eye witness of the ADEQ drilling by the first author of this report, this coarse lower section is probably mostly very coarse sand with dispersed gravel clasts.

The USGS and ADEQ logs, recorded by trained geologists, show an upper section that has layers with varying proportions of very fine sand, silt, and clay. Most of the simpler logs, those from the municipal well drillers, describe the entire upper section as simply "sand" or "sand and clay", though one (the Tucker well) says "clay" and another (the Richey well) says "coarse sand and gravel". At four of the municipal well sites, including the Richey and Tucker sites, we sampled to 5 ft (1.5 m) deep with a manual soil auger and found nearly identical material in all four, mostly very fine sand and coarse silt with some clay. We believe that the description for the Richey well is in error, and that throughout the area the alluvium has a fairly consistent basic stratigraphy of an upper section of very fine materials with a rapid transition to a lower section of very coarse sand with dispersed gravel clasts. Based on the available drilling logs, the upper section is an average of 42 ft (12.8 m) thick, with a range of 35-50 ft (10.7-15.2 m). The thickness of the lower section averages 22 ft (6.7 m), with a range of 9.5-33 ft (3-10 m).

Flow in the Arkansas River is now controlled by the Dardanelle hydroelectric dam. Even so, flow on the river is not constant. Typically due to power needs there are daily cycles of rise and fall of water surface elevation. Climatological events produce longer-period fluctuations. Downstream at Morrilton, another dam exists. This dam, in conjunction with a very gentle downstream natural gradient, makes the surface of the river between the two dams nearly horizontal. The topographic map (Fig. 1) indicates a normal pool elevation of 284 ft (86.6 m) for the river in the vicinity of Dardanelle (considered also as part of Winthrop Rockefeller Lake, formed by the dam at Morrilton). According to hourly measurements made at the dam site, during the winter months of December, 2001 and January, 2002, when most of the data for this study was collected, the elevation of the river surface deviated from this indicated elevation. Generally the river elevation was in the range of a little over 284 ft (86.6 m) to about 288 ft (87.8 m) for daily fluctuations during a period of low flow, and was up to a range of 302-308 ft (92-93.9 m) during a period of high flow due to a major rain storm in the region. According to employees at the dam, the low-flow conditions described here are rather typical of the low-flow conditions during most other times of the year. Water depth in the river varies due to shifting sand, but a channel is maintained by dredge for navigation. Considering the elevation trend of the boundary between the coarse and fine sections of the alluvial sediment, the channel no doubt intersects the coarse section of the river sediment.

Along the west side of the alluvial plain is a stream called Smiley Bayou. Smiley Bayou flows in from an area of higher elevations to the west, flowing nearly due east until it reaches the edge of the alluvial plain (Fig. 1). The stream valley there is filled with alluvial sediment, making an arm of alluvium that projects westward off of the main section of the Arkansas River alluvial plain. From there Smiley Bayou turns south. Where it turns south there is also another tributary that joins it from the northwest. There are also several small tributaries that join the bayou south of that area. The stream flows for the most part right along the border between the bedrock area and the alluvial plain, but flows on alluvial sediments. Several of the tributaries are intermittent streams that flow constantly during the winter and spring when the water table is generally higher, but dry up during the summer and early fall. Smiley Bayou itself, however, is a perennial stream, flowing year round, although it flows with lower discharges during the summer and early fall.

Data for the Model

Aquifer Boundaries

Figure 2 shows the portion of the Dardanelle area modeled in this study with the model boundaries, which are discussed below, indicated on the map. The map is oriented with north toward the left for convenience in working with the numerical modeling software. The model cells are 200 ft X 200 ft (61 m X 61 m) in dimension.

Rivers, such as the Arkansas River, always play a significant role in the distribution and movement of groundwater in the area surrounding the river. A river can act as a groundwater discharge point or as a source of recharge to the groundwater system depending on various other hydrologic factors in the area. How a river will affect the surrounding groundwater system is mainly dependent on its head, expressed by the elevation of the water surface of the river, relative to head in the surrounding aquifer. For the groundwater model of the Dardanelle area it was decided to simulate the Arkansas River as a constant head boundary. An unlimited amount of water can flow into or out of a constant head boundary, flowing in or out depending on the head specified for the river relative to the head in the adjacent area. Large rivers, such as the Arkansas River, have a very large water supply relative to adjacent aquifers and are suitably modeled as constant head boundaries (Anderson and Woessner, 1992). Although the river level on the downstream side of the dam fluctuates by several feet on a daily basis and can fluctuate over 20 feet (6 meters) due to climatic factors, for a conservative model of the steady-state condition a typical level of the river during relatively low-flow conditions, 285 ft (86.9 m), was chosen. We chose the low flow condition because if the model shows a head gradient from the river toward the municipal wells for a low flow condition, then certainly the gradient would be in that direction during periods of higher flow in the river.

As discussed in the section on geology above, the bedrock in this area consists predominantly of shales of the Atoka Formation. Consolidated shales have essentially only fracture porosity and permeability, and normally their hydraulic conductivities are quite low, on the order of 3 X 10^{-4} ft/d (1 X 10^{-4} m/d) or less (Heath, 1989, p. 13). If a material has a hydraulic conductivity (K) over two orders of magnitude lower than an adjacent material, it can be modeled effectively as a no-flow boundary (Anderson and Woessner, 1992). Because of

Boundary Conditions

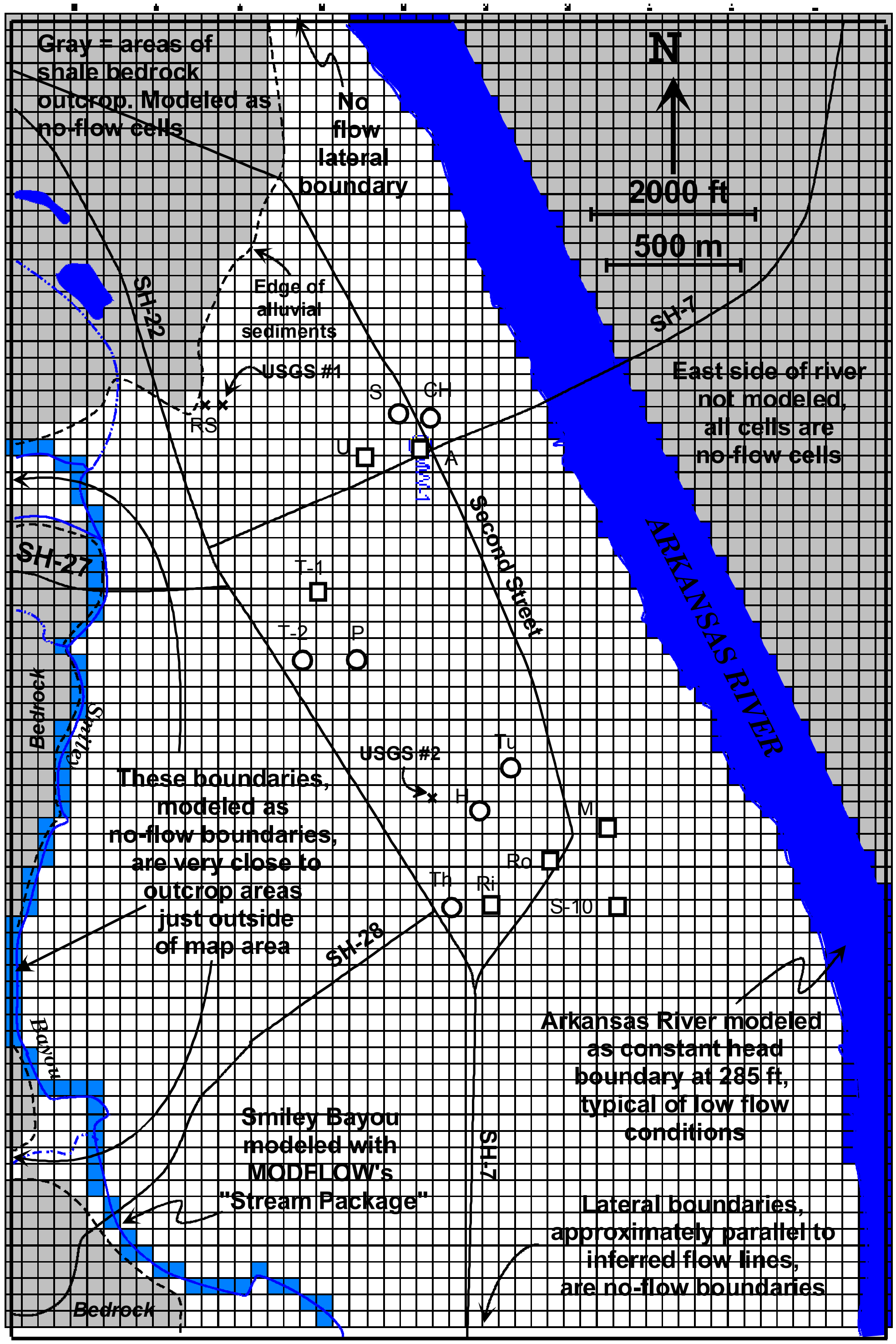

Figure 2. Map of area covered in the groundwater model, showing hydrologic boundaries of the aquifer. Model grid pattern also shown, cells 200 ft X 200 ft (61 m X 61 m). Same wells as shown in Figure 1, but with names abbreviated: A = ADEQ well, CH = Courthouse well, H = Hut, M = Meeks, Ri = Richey, Ro = Robinson, RS = Rock Street, S = State Street, T-1 & T-2 = Tysons #1 & #2, Th = Thompson, Tu = Tucker, U = Union. Those wells modeled as pumping wells are shown as circles, those not pumping as squares, filled-in wells as X's. The major streets outlining Dardanelle are shown.

significant differences in hydraulic conductivity, areas of bedrock outcrop adjacent to alluvial aquifers are commonly modeled as no-flow boundaries. The hydraulic conductivity in the Dardanelle alluvial aquifer (discussed below) is significantly greater than what is likely in the Atoka Formation. Therefore, we model the edge of the outcrop areas and the bedrock below the aquifer as no-flow boundaries. No doubt those areas contribute groundwater to the system, but the quantities would not make significant changes in the general hydrology of the alluvial aquifer, justifying their being modeled in this way. The outlay of the base of the alluvial aquifer, as interpreted from available well logs and geomorphological reasoning, is portrayed in Figure 3. Figure 3 shows the interpreted elevation variation in the way that it was eventually put into the groundwater model, that is, on a cell by cell basis. The stair-step fashion that is produced is an artifact of dividing the area into discreet cells.

Flow lines can also constitute no-flow boundaries in a numerical model (Anderson and Woessner, 1992). Those areas of outcrop outside the map area to the west of the map generally rise in elevation westward (toward the lower border on Figure 2). Thus the natural regional groundwater flow direction should be from the west toward the river. Therefore, the left and right borders (north and south borders) of the map, where they are not already covered by a no-flow outcrop area, are also modeled as no-flow boundaries, because they are roughly parallel to flow lines of the regional flow pattern.

The east side of the Arkansas River (the upper left corner of Figure 2) is also blocked off as a no-flow area. There actually are alluvial sediments there, as well as an area of bedrock outcrop, but the hydrology there has no impact on the hydrology of the Dardanelle side of the river. It is modeled as a no-flow area so that mass balance calculations will entirely reflect the hydrology of the Dardanelle area.

Aquifer Stratigraphy

As discussed above, driller's logs indicate that the alluvium consists of a fine-grained upper section and a coarse-grained lower section. Based on this, the model was designed as a two-layer model, the upper layer being designated as Layer 1. Figure 4 is the interpreted boundary between the two layers, based on the driller's logs and geological reasoning. The upper surface of Layer 1 (Fig. 5), the model top, was constructed according to the topography shown

Layer 2 Bottom Elevation (Bottom of Alluvial Aquifer)

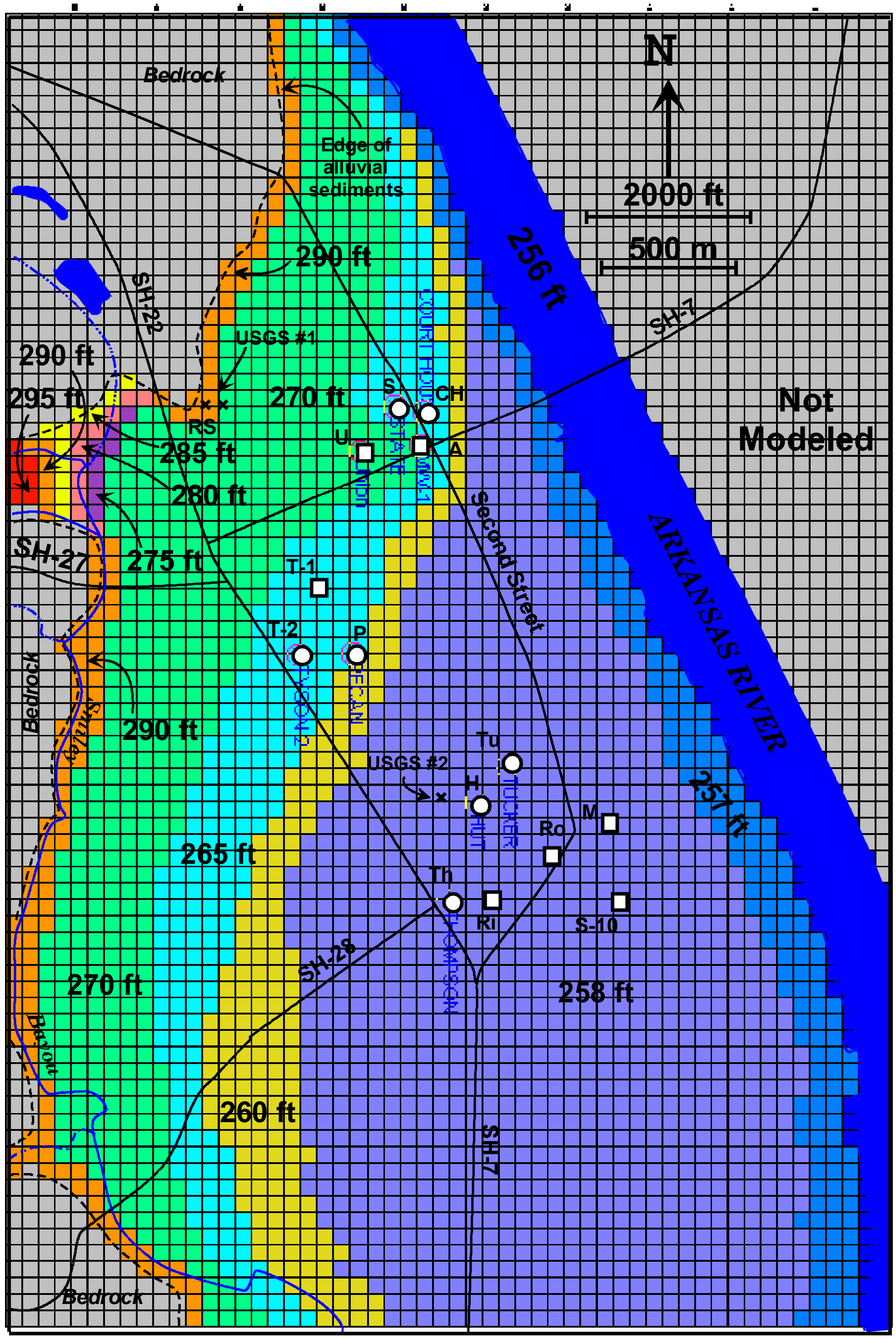

Figure 3. Model area showing the elevation of the bottom of Layer 2, the base of the alluvial aquifer. Layer 2 bottom shown as cells shaded according to the elevations used in the model. Elevations estimated from well logs with extrapolation beyond well area based on geological reasoning. Wells as in Figure 2. Note that the number labeled in the Arkansas River is not the water level, but the estimated elevation of the base of the aquifer in that area.

Layer 1 Bottom / Layer 2 Top Elevation

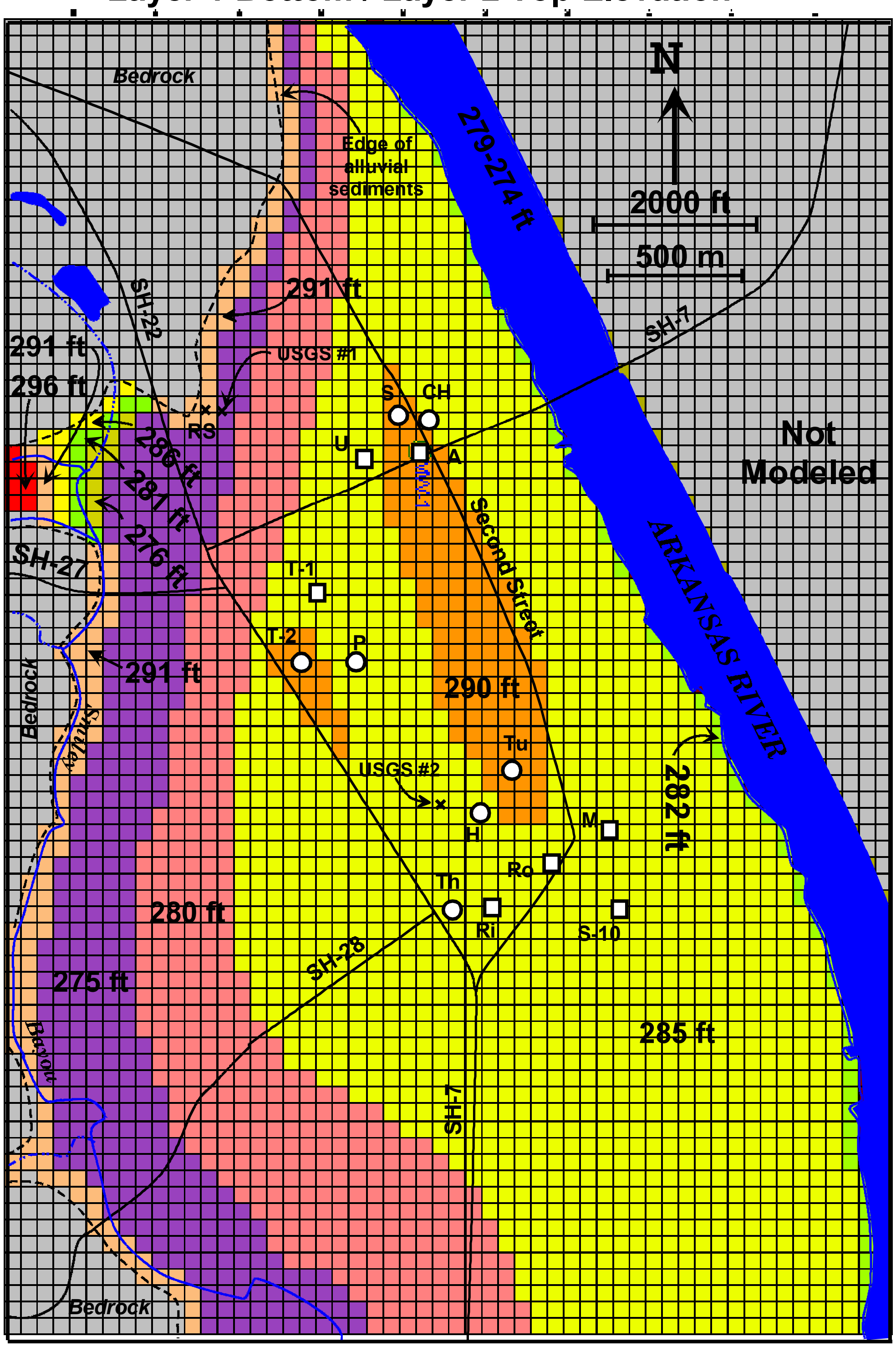

Figure 4. Model area showing the elevation of the bottom of Layer 1, which is the top of Layer 2. Layer 1 bottom shown as cells shaded according to the elevations used in the model. Elevations estimated from well logs based on where the change from fine to coarse sediment takes place. Extrapolation beyond well area based on geological reasoning. Wells as in Figure 2. Note that the number labeled in the Arkansas River is not the water level, but the estimated elevation of the base of Layer 1 in that area.

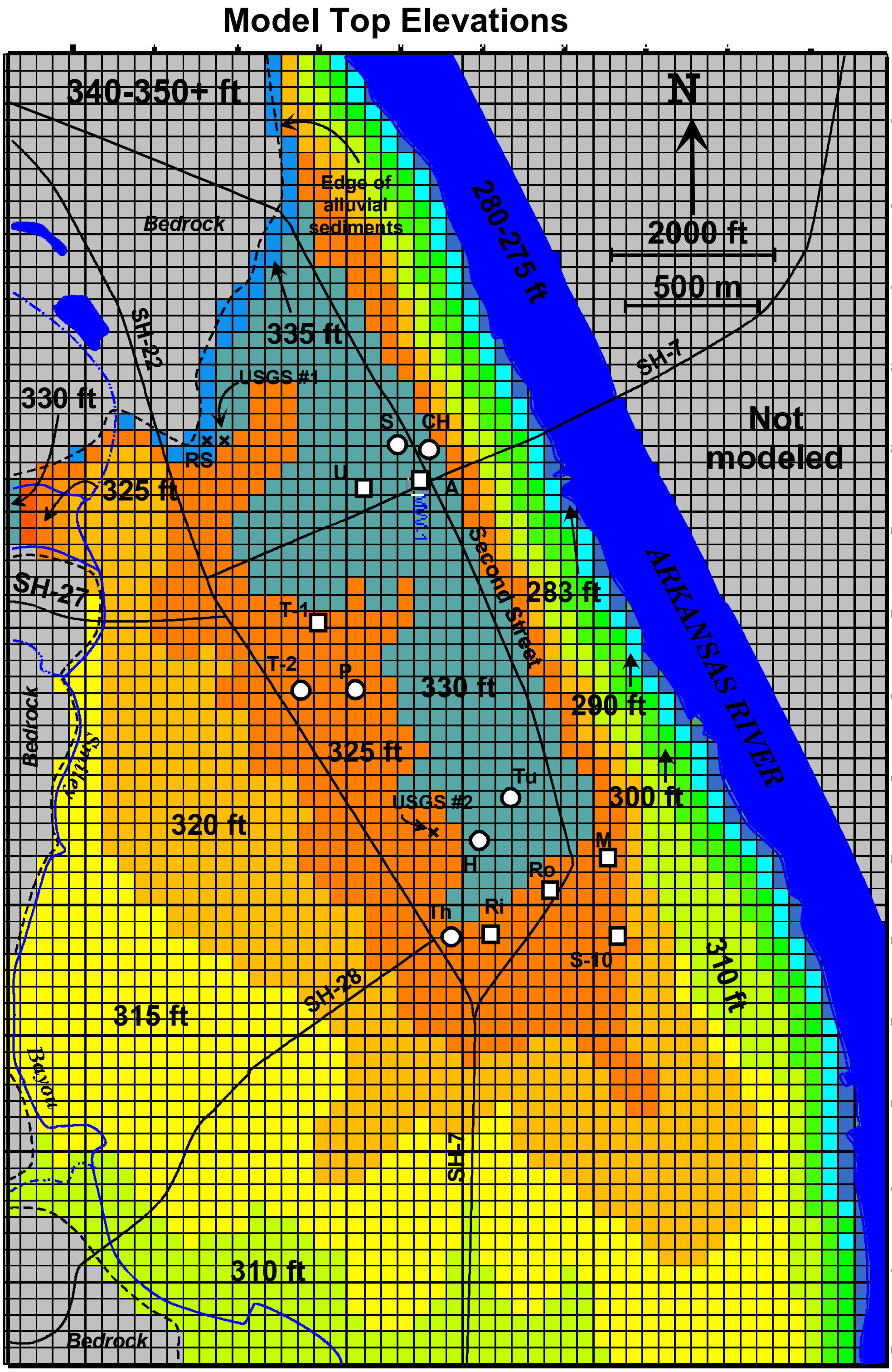

Figure 5. Model area showing the top of Layer 1, which is the top of the entire model. Distribution of cell elevations based on contours on the Dardanelle 7.5-minute quadrangle. Wells as in Figure 2. Note that the number labeled in the Arkansas River is not the water level, but the estimated elevation of the land surface in that area, that is, the bottom of the river. The 275 ft cells are toward the center of the river and toward the eastern side, where the deeper channel is.

on the Dardanelle 7.5 minute quadrangle. The distribution of the thickness of Layer 1 is represented by the elevation differences in corresponding cells between Figures 4 and 5. Layer 2 thickness is gauged by comparing elevation differences between Figures 3 and 4.

Hydraulic Conductivity in the Aquifer

The distinctly different grain sizes of the two sections of the aquifer necessitate determining different hydraulic conductivities to apply to the two layers of the groundwater model. We chose a hydraulic conductivity of 2 ft/d (0.6 m/d) for the upper layer (Layer 1) based on published information and on interpretation of grain size analyses. For the lower layer (Layer 2), we considered a range of hydraulic conductivities from 175-400 ft/d (53-122 m/d) based on published data. The reasoning behind these choices for hydraulic conductivity are discussed below.

There are at least two methods that have been developed to estimate hydraulic conductivity from grain-size analyses, Hazen (1911) and Shepherd (1989). Each of these employs a grain-size distribution curve derived from the analysis, with empirical formulas based on certain parameters read from the curve, and coefficients estimated based on other factors interpreted from the curve. As mentioned above, we sampled the upper sediment at four of the well sites using a soil auger. Grain-size distribution analysis was performed on these samples using a wet sieving technique to prevent loss of the finest particles to the air. A hydrometer test was also used to determine the percent clay in each sample. Results of these analyses are given in Table 1. Figure 6 is an example of one of the grain-size distribution curves, the one generated from the analysis of sediment at the Meeks well site. The other curves are similar. Hydraulic conductivities estimated from the two methods applied to the grain-size curves for each of the four samples are also given in Table 1. Note that both of these estimation methods involve empirical equations that require choosing coefficients that are not precisely defined, imparting a degree of uncertainty regarding the hydraulic conductivity that is estimated.

Hydraulic conductivity estimates are given for the soils of the Dardanelle area in the Yell County Soil Survey (Vodrazka and others, 1988). These soils are in essence the sediment in the uppermost horizons of the alluvium. The soil in nearly the entire City of Dardanelle is classified as Roxana silt loam. The Roxana silt loam is given a permeability rating (in terms of hydraulic

Table 1. Grain size analyses and hydraulic conductivity based on graphs of analyses

Tucker well site

Mesh #	Size (mm)	Weight caught (g)	% finer than
10	2	0.6896	99.3104
16	1.18	0.154	99.1564
35	0.5	0.3954	98.761
50	0.3	0.3206	98.4404
100	0.15	1.726	96.7144
140	0.106	17.269	79.4454
200	0.075	39.1173	40.3281
270	0.053	18.1038	22.2243
400	0.037	8.5588	13.6655
finer		13.6655	
clay (hydrom)	0.004		0

Hydraulic conductivity(K) based on analysis
K = 1.2 ft/d (0.37 m/d) -- Hazen (1911) method
K = 7.4 ft/d (2.26 m/d) -- Shepherd (1989) method

Richey well site

Mesh #	Size (mm)	Weight caught (g)	% finer than
10	2	0	100
16	1.18	0	100
35	0.5	0.2099	99.7901
50	0.3	1.3293	98.4608
100	0.15	3.0506	95.4102
140	0.106	6.007	89.4032
200	0.075	17.0977	72.3055
270	0.053	14.1172	58.1883
400	0.037	21.7159	36.4724
finer		36.4724	
clay (hydrom)	0.004		0

Hydraulic conductivity(K) based on analysis
K = 0.09 ft/d (0.027 m/d) -- Hazen (1911) method
K = 2.8 ft/d (0.85 m/d) -- Shepherd (1989) method

Thompson well site

Mesh #	Size (mm)	Weight caught (g)	% finer than
10	2	0.3742	99.6258
16	1.18	0	99.6258
35	0.5	1.0463	98.5795
50	0.3	1.8977	96.6818
100	0.15	2.3538	94.328
140	0.106	2.7367	91.5913
200	0.075	11.4519	80.1394
270	0.053	20.6867	59.4527
400	0.037	26.1802	33.2725
finer		33.2725	
clay (hydrom)	0.004		2

Hydraulic conductivity(K) based on analysis
K = 0.09 ft/d (0.027 m/d) -- Hazen (1911) method
K = 3.0 ft/d (0.91 m/d) -- Shepherd (1989) method

Meeks well site

Mesh #	Size (mm)	Weight caught (g)	% finer than
10	2	0	100
16	1.18	0	100
35	0.5	0.3672	99.6328
50	0.3	0.8488	98.784
100	0.15	2.6671	96.1169
140	0.106	5.75	90.3669
200	0.075	15.453	74.9139
270	0.053	16.0845	58.8294
400	0.037	21.3178	37.5116
finer		37.5116	
clay (hydrom)	0.004		2

Hydraulic conductivity(K) based on analysis
K = 0.074 ft/d (0.023 m/d) -- Hazen (1911) method
K = 2.8 ft/d (0.85 m/d) -- Shepherd (1989) method

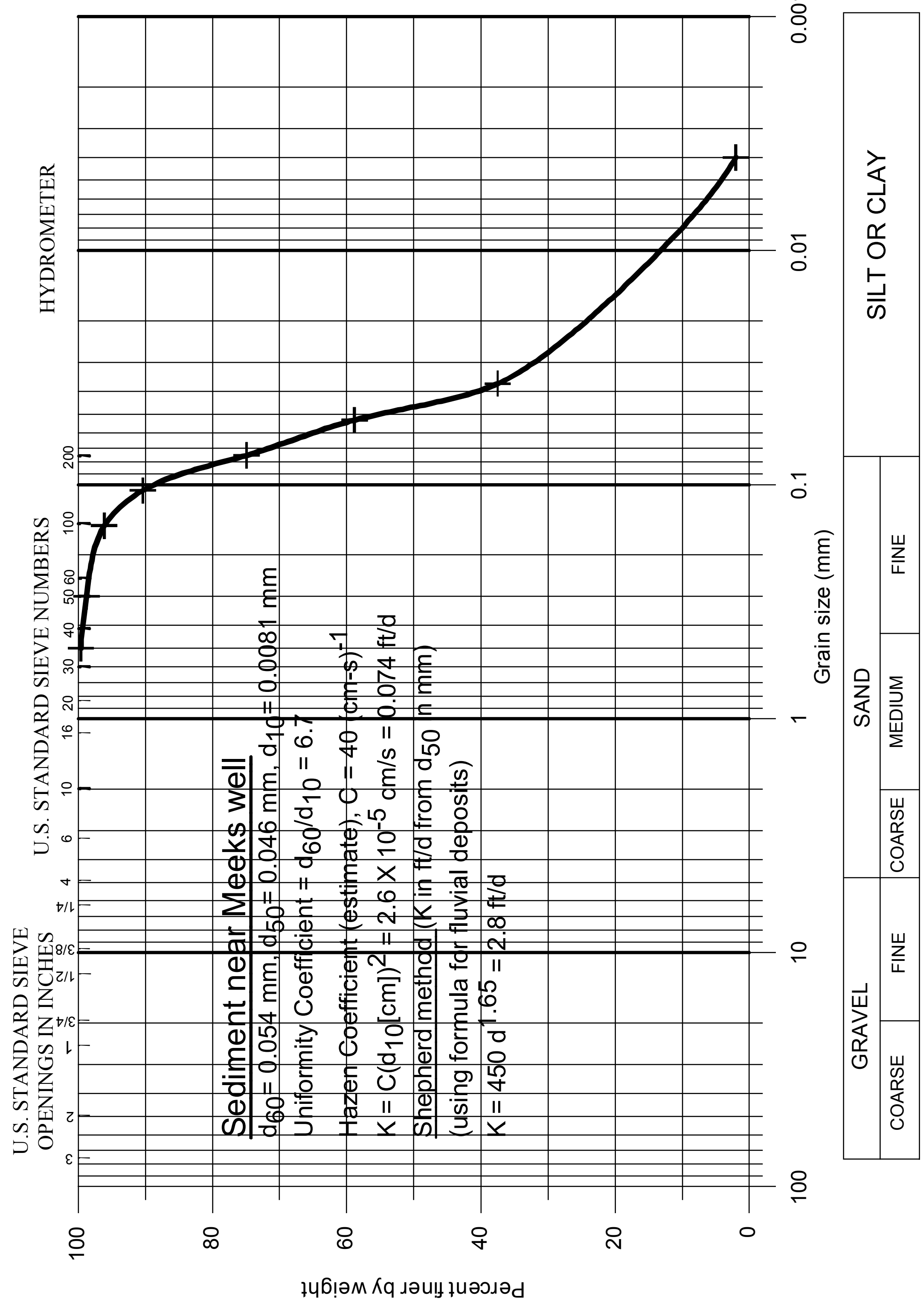

Figure 6. Grain-size distribution curve for sediment taken from 5 ft (1.5 m) depth at the Meeks well site. Curves for the other three near-surface samples are similar. Calculation of hydraulic conductivity (K) by two empirical methods (Hazen, 1911, and Shepherd, 1989) based on this curve is also shown.

conductivity) of 0.6 to 2 in/hr (equivalent to 1.2 to 4 ft/d or 0.37 to 1.22 m/d). Other areas within the alluvial plain in the vicinity of Dardanelle include Dardanelle silt loam in the area west of town and south of town, Barling silt loam in the area where Smiley Bayou flows onto the alluvial plain, and Roellen silty clay in the western part of the alluvial plain south of Highway 28. The Soil Survey gives the Dardanelle and Barling silt loam soils the same permeability rating as the Roxana soil. The Roellen silty clay is indicated as having a hydraulic conductivity in the 0.06-0.2 in/hr (0.12-0.4 ft/d or 0.037-0.0122 m/d) range.

There is overlap in the hydraulic conductivities estimated from the grain-size distribution curves and the conductivities presented in the soil survey. Considering the range of values, we chose a hydraulic conductivity of 2 ft/d (0.6 m/d) as a reasonable value to ascribe to the upper section of sediment in the area for modeling the hydrologic system. When the models are run with other values that lie within the range of values estimated from the grain size analyses or published values the model results are not significantly changed, probably because most of the water in the system lies within the lower part of the aquifer.

Regarding the lower part of the aquifer (Layer 2) we relied on published data. Bedinger and others (1963) presented results of a reconnaissance study of the alluvial aquifer along the Arkansas River from Little Rock to Fort Smith. They calculated aquifer transmissivity based upon pumping aquifer tests conducted at six sites within their study area (although none at Dardanelle). The stratigraphy at each site is similar to the general stratigraphy at Dardanelle, in that there is a section of fine sediment overlying coarse. Based on saturated thicknesses of the aquifer at the sites where the tests were conducted and the transmissivities they determined, the hydraulic conductivities range from 175 to 400 ft/d (53 to 122 m/d). At these test sites and at Dardanelle most of the groundwater is within the coarse, lower section of the aquifer, so groundwater flow is primarily controlled by properties of this section of the aquifer. To model flow in the aquifer at Dardanelle we constructed two models based on this range of likely hydraulic conductivity in Layer 2, the lower part of the aquifer.

Porosity in the Aquifer

Because the groundwater model is for steady state conditions, the porosity does not enter into any of the calculations. Nevertheless, we input a porosity of 0.15 for the upper layer based on ratings given by the Yell County Soil Survey, and we estimated 0.20 for the porosity of the lower layer because it has far fewer fines. These values would be useful for a transient run of the model.

Groundwater Recharge

Bedinger and others (1963) evaluated recharge to the alluvial aquifer at two places. Based on these calculations they considered that on the average the aquifer receives about 10 in/yr of aerial recharge. This value converts to about 0.002 ft/d (0.00061 m/d), which is the value included in the groundwater model. Within the town of Dardanelle itself there are some parking lots, a greater number of streets, and driveways that promote more runoff. Within that area we lowered the recharge value by 20% to 0.0016 ft/d (0.00049 m/d).

Smiley Bayou

The Dardanelle quadrangle shows Smiley Bayou as a perennial stream. The stream flows on alluvial sediments along the western border of the aerial extent of the aquifer in question. Perennial streams in most places in the eastern United States are gaining streams, although some perennial streams can have loosing reaches, sections of the stream where the level of the water table is below the bottom of the stream and therefore water seeps from the stream into the groundwater system. It is not uncommon in areas where pumping wells disturb the natural condition, for streams to be converted from gaining streams to losing streams, because water tables are lowered below stream level in the cone of depression around the wells. It is clear that if Smiley Bayou is being tapped due to drawdown from the municipal wells of Dardanelle, it is not loosing enough water to dry up the stream, because local residents say that although the stream does flow with less water during dry summer months, it does not dry up.

For including the stream in the groundwater model, measurement of the stream discharge was taken at the point indicated on Figure 1. The measurement site is just downstream of a tributary that joins Smiley Bayou. The discharge was determined by extending a tape measure across the stream and taking depth and flow rate measurements at one foot increments following the procedure outlined in Rantz and others (1982). Flow rate was measured using a USGS style

Pygmy current meter. The measured flow rates were integrated with the cross-sectional areas represented by each measurement site and summed across the entire stream. The total discharge determined in this way was 256,800 ft^3/d (7,273 m^3/d). This value, measured during a time of base flow, on 1/10/02 would not be expected to hold constant year round. As the winter progresses the base flow discharge should increase, because that is a time of regional groundwater recharge. During the summer months the discharge should fall lower than the measured amount. Although the actual discharge of the stream varies, we believe the measured discharge is a reasonable representation of the stream for modeling the aquifer.

City Wells

Another component to the hydrologic system is the withdrawal of water from the aquifer by the municipal water-supply wells. There are nine city wells (Fig. 1 and Table 2), of which three (the Richey, Robinson, and Meeks wells) are inactive until a water treatment plant is built. On a week-by-week basis a consistent pattern is followed for pumping and non-pumping time periods. The primary controlling factor is usage of water at a Tyson's poultry processing facility that uses large quantities of the city's water in its process. When Tyson's starts up on Sunday evenings, the rapid draw of water from the municipal water tank triggers startup of the municipal water wells, all of which run at full capacity. Tyson's slows its water consumption Friday evening around 6-7:00 pm, followed by a major reduction in water use around 6-7:00 am Saturday morning, at which time the city wells automatically shut down. Sunday evening begins the cycle again. Over a weekend, a couple of municipal pumps may turn on automatically for 1-3 hours occasionally to replenish water drained by normal usage in the city. There are also two wells at the Tyson's plant, one of which is inactive, and the other of which ("Tyson's #2") runs continuously to supply water for cooling towers.

Because the wells run the majority of the week throughout the year, a steady-state model was used. Table 2 is a production summary for the wells for the year 2001 obtained from the Dardanelle Water Department. The Tyson well production is based on the regular discharge rate quoted by a Tyson's plant manager. In the Courthouse and Thompson wells production was greatly reduced or was altogether shut down in some months, due to technical problems. Therefore in order to obtain average well discharge for a normal year, estimates were used for

Table 2. Dardanelle Well Production Summary, Year 2001. Pumpage quantities in thousands of gallons.

	HUT	TUCKER	PECAN	STATE	COURT HOUSE	THOMPSON	RICHEY	ROBINSON	MEEKS	TYSON	**TOTAL WELL**
January	8,633	6,226	8,812	10,922	10,023	8,071				6,570	59,257
February	6,668	5,002	6,855	9,004	9,153	6,812				6,570	50,064
March	7,941	5,774	7,873	11,203	8,970	8,153				6,570	56,484
April	9,234	6,649	9,068	10,274	11,310	9,234				6,570	62,339
May	9,304	6,462	9,295	11,513	10,233	8,075				6,570	61,452
June	8,619	5,552	9,226	10,367	10,414	5,752				6,570	56,500
July	10,069	6,359	10,473	11,826	11,356	3,994				6,570	60,647
August	9,363	6,361	9,859	12,049	10,388	0			5,944	6,570	60,534
September	8,972	6,351	8,065	10,343	0	2,102	3,045	7,425	4,958	6,570	57,831
October	10,069	6,637	11,850	6,899	0	8,672	94	5,056	3,238	6,570	59,085
November	8,552	5,699	9,423	9,656	0	7,617	0	2,538	0	6,570	50,055
December	8,472	5,057	9,625	9,070	1,449	7,039	0	0	0	6,570	47,282
TOTAL	105,896	72,129	110,424	123,126	83,296	75,521	3,139	15,019	14,140	78,840	681,530
*avg-ft^3/d	38,787	26,419	40,445	45,098	45,497	33,904				28,877	
(avg-m^3/d)	1,098	748	1,145	1,277	1,288	960				818	

*Average production per day calculated based upon dividing the total yearly pumpage by 365 days, then converting to ft3/d and m3/d.

In the Courthouse and Thompson wells, due to technical malfunctions in the wells, the production was reduced greatly or was shut down altogether in some months. Therefore in order to obtain average per day production during a normal year, estimates were used for these months that corresponded with the production of normal months.

these wells that corresponded with the production of normal months. The average daily discharge for each well was obtained for the steady-state model by dividing the total pumpage by 365 days.

Water Levels in the Wells

For a few of the municipal wells and for the USGS exploratory wells water levels at the time of drilling were recorded. Also a few of the wells have openings in the well head and are therefore accessible for measuring present water levels. Well water levels can be used to compare with the head distribution in a groundwater model to see if the model reasonably matches reality. In order to compare water levels in the wells to each other, to the model, or to compare with water level in the Arkansas River, an accurate elevation of each well is needed. Well head elevations were surveyed using a Lietz automatic level. The survey was conducted by beginning from the 333.95 ft bench mark at the corner of Cedar Street and Second Street, near the north end of town, and measuring elevations in steps along the way between the wells. After the farthest well was reached, the survey was worked back to the bench mark to close the loop. The final measurement was only 0.04 ft (0.012 m) different from the starting elevation, implying that the surveyed well elevations are probably accurate. Water levels in the Arkansas River are constantly monitored by instruments at the dam.

Results of Groundwater Modeling

A two-layer MODFLOW numerical model was produced using Groundwater Vistas (Environmental Simulations, Inc.) pre-processing and post-processing software. For the model a portion of the aquifer surrounding the City of Dardanelle was selected and divided into 200 ft X 200 ft (61 m X 61 m) cells, each of which was assigned hydraulic properties according to the parameters discussed above. The model boundaries, model bottom elevation, model top elevation, and the elevation of the contact between Layer 1 and Layer 2 are shown in Figures 2-5. The hydraulic conductivity distribution is not shown here, but is basically the hydraulic conductivities discussed above assigned to the two layers of the model. Likewise the aerial recharge is assigned to the model's top layer as discussed above. The municipal wells are distributed in the model according to the distribution shown in Figure 1. All of them have screen positions in the lower layer, with pumping rates according to Table 2. Smiley Bayou is included in the model using the MODFLOW Stream Package. This package allows water from the stream to either flow into the model or out of the model depending on the position of the calculated water table relative to the designated elevation of the bottom of the stream. The Stream Package also calculates the stream's discharge and head along its course, given a starting discharge and head value. With the Stream Package, if a stream looses too much water, it will "dry up". It is useful to have this function in the model as a kind of calibration tool, because if the model stream dries up when the actual stream does not, then something is not right in the model (likewise if the model stream gains an unreasonable amount of water, that also would be a "red flag"). In the case here, the stream was simplified by leaving off the tributaries and applying the measured stream discharge to the point where the stream enters the map on the west side (bottom of Figure 2) just north (left) of Highway 27. Simplifying in this way does not affect the basic impact of the stream on the hydrologic system.

Two models were constructed based on the range of likely hydraulic conductivity in the lower layer (Layer 2). Each model was first run without the effect of pumping wells to see if the model reasonably represents what might be expected in the natural condition. Then each was run with the wells pumping. Figures 7 and 8 show the result of simulating the natural condition and the pumping condition respectively for the model with the hydraulic conductivity of the lower layer at 175 ft/d (53 m/d). Figures 9 and 10 show the same for the model with K = 400 ft/d (122 m/d) in the lower layer.

To consider the reasonableness of the models we compared head distribution in the models with some water-level measurements in wells and the Arkansas River. Figure 11 shows water levels given in the original drilling records for some of the area wells, and representative water-level measurements taken in a few wells during December 2001. Considering the historical record of water levels at the times wells were drilled one can see a wide variation of water levels. The meaning of the historical data is obscured by unknown factors affecting the water levels in wells at the time of each measurement, such as the stage of the Arkansas River, climatic effects on the water table, and withdrawal schedules of any nearby wells existing at the time. Note that the Dardanelle Lock and Dam was completed in 1966. Before that time the river's water level would fluctuate even more widely than now. With these variations in mind, it seems that either of the two natural condition models (Figures 7 and 9) could be possible. The

Water Table Elevation Distribution
Steady-State Condition, No Pumping, K = 175 ft/d in Layer 2

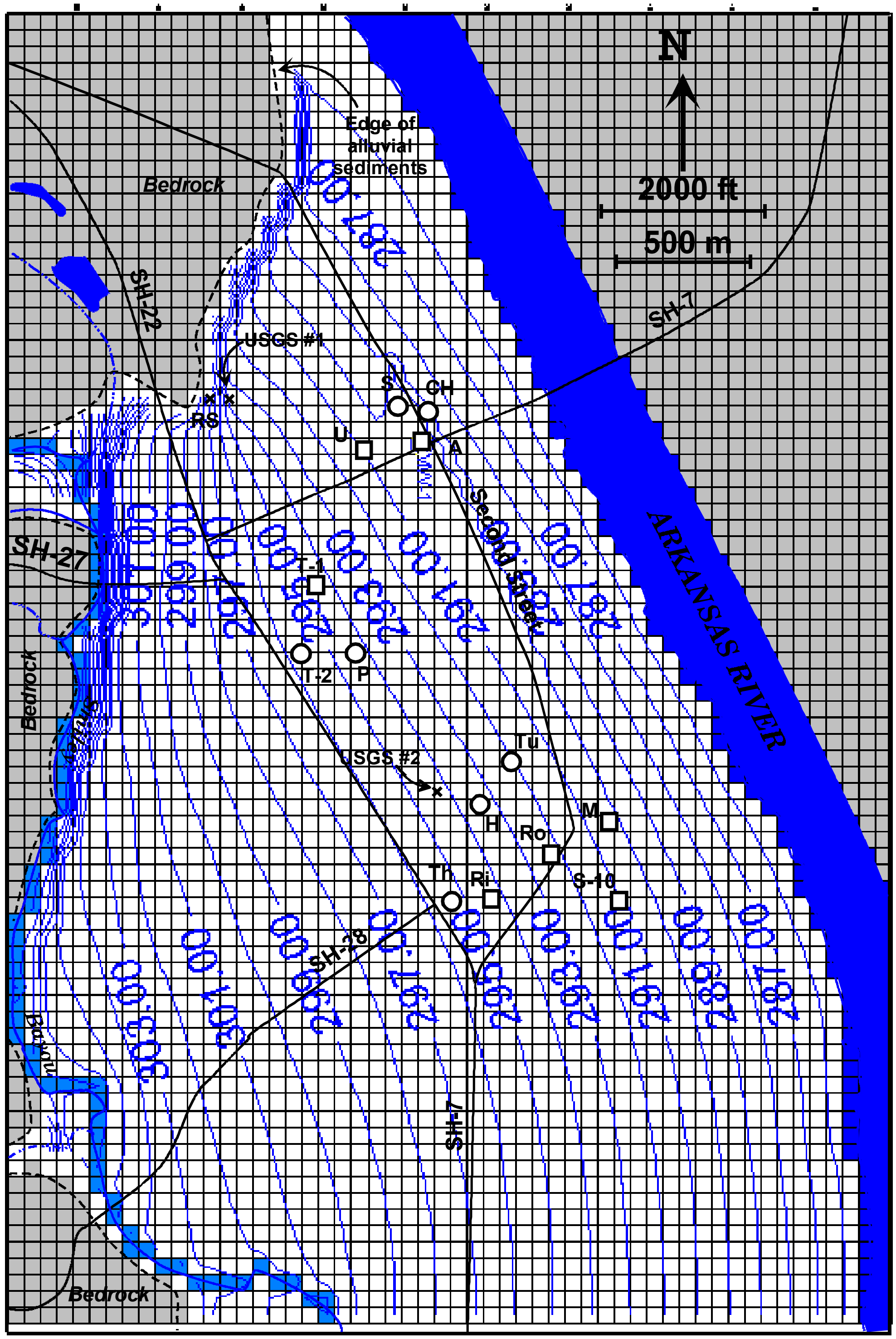

Figure 7. Potentiometric surface map generated by the steady-state groundwater model employing K = 175 ft/d (53 m/d) in Layer 2. Contours are in feet above MSL; contour interval is 1 ft. Head in the Arkansas River is 285 ft (87 m). This map shows the natural condition, no extraction wells.

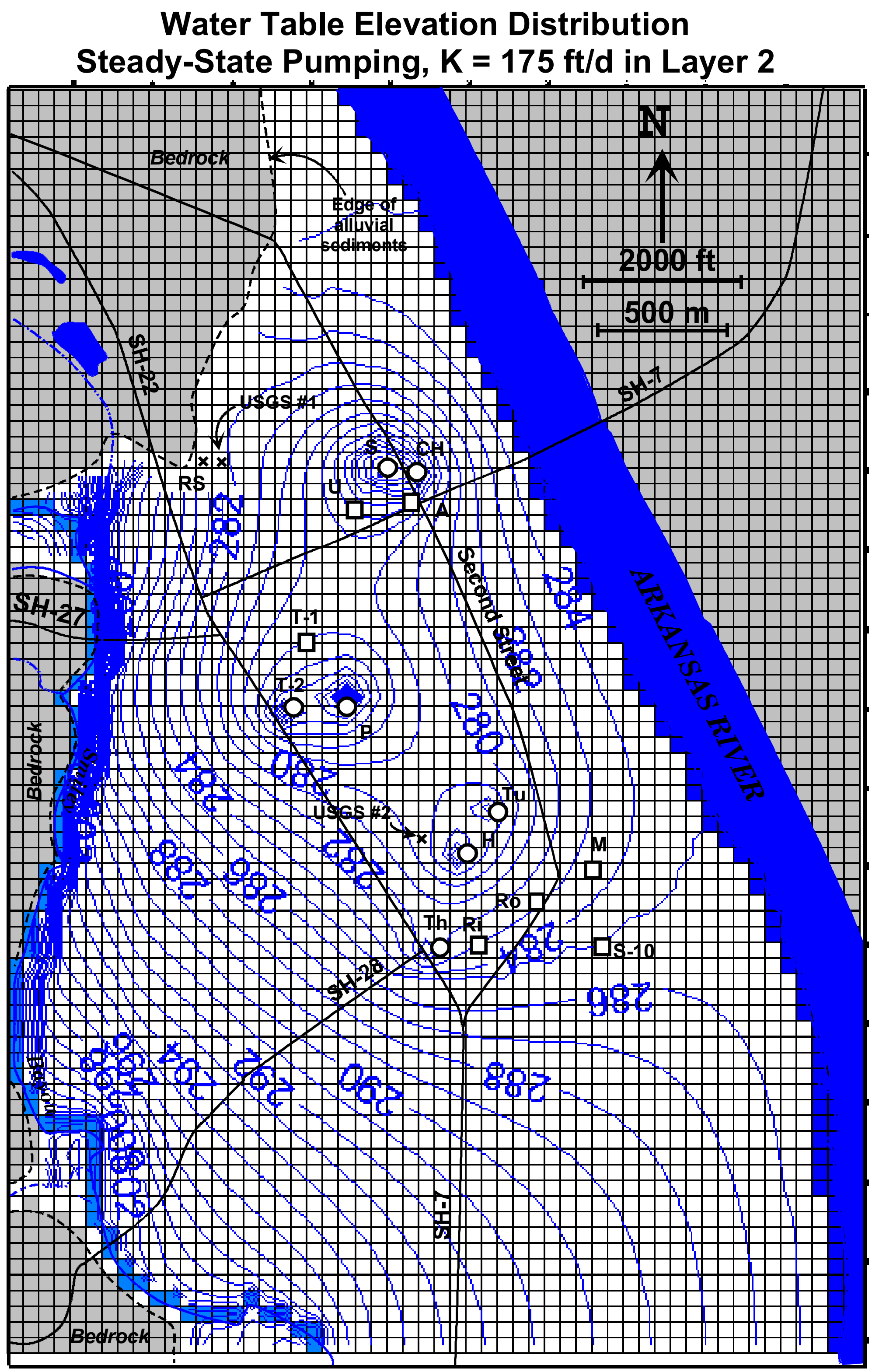

Figure 8. Potentiometric surface map generated by the steady-state groundwater model employing K = 175 ft/d (53 m/d) in Layer 2. Contours are in feet above MSL; contour interval is 1 ft. Head in the Arkansas River is 285 ft (87 m). This map shows the condition when the wells are operating.

Water Table Elevation Distribution
Steady-State Condition, No Pumping, K = 400 ft/d in Layer 2

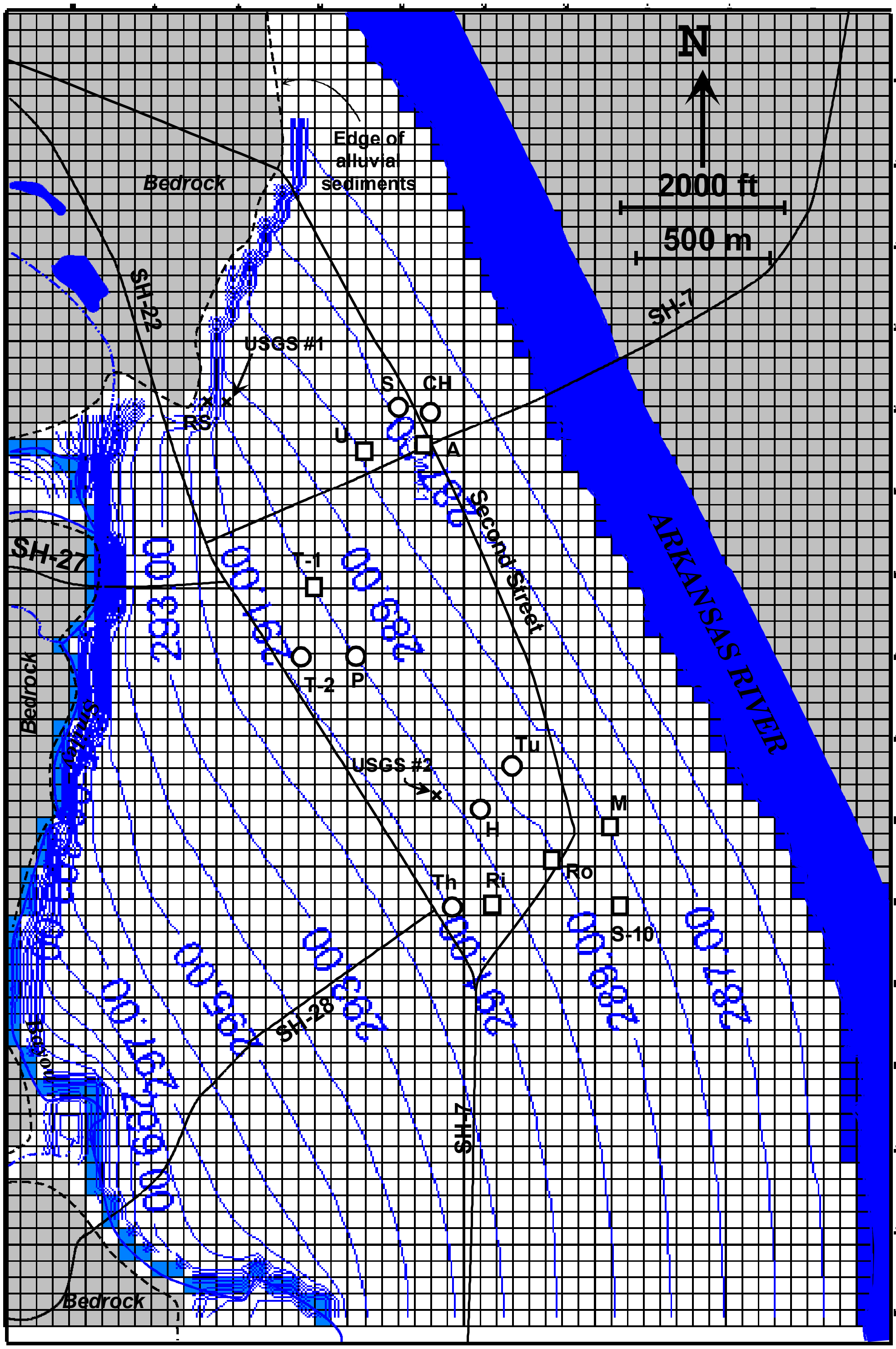

Figure 9. Potentiometric surface map generated by the steady-state groundwater model employing K = 400 ft/d (122 m/d) in Layer 2. Contours are in feet above MSL; contour interval is 1 ft. Head in the Arkansas River is 285 ft (87 m). This map shows the natural condition, no extraction wells.

Water Table Elevation Distribution
Steady-State Pumping, with K = 400 ft/d in Layer 2

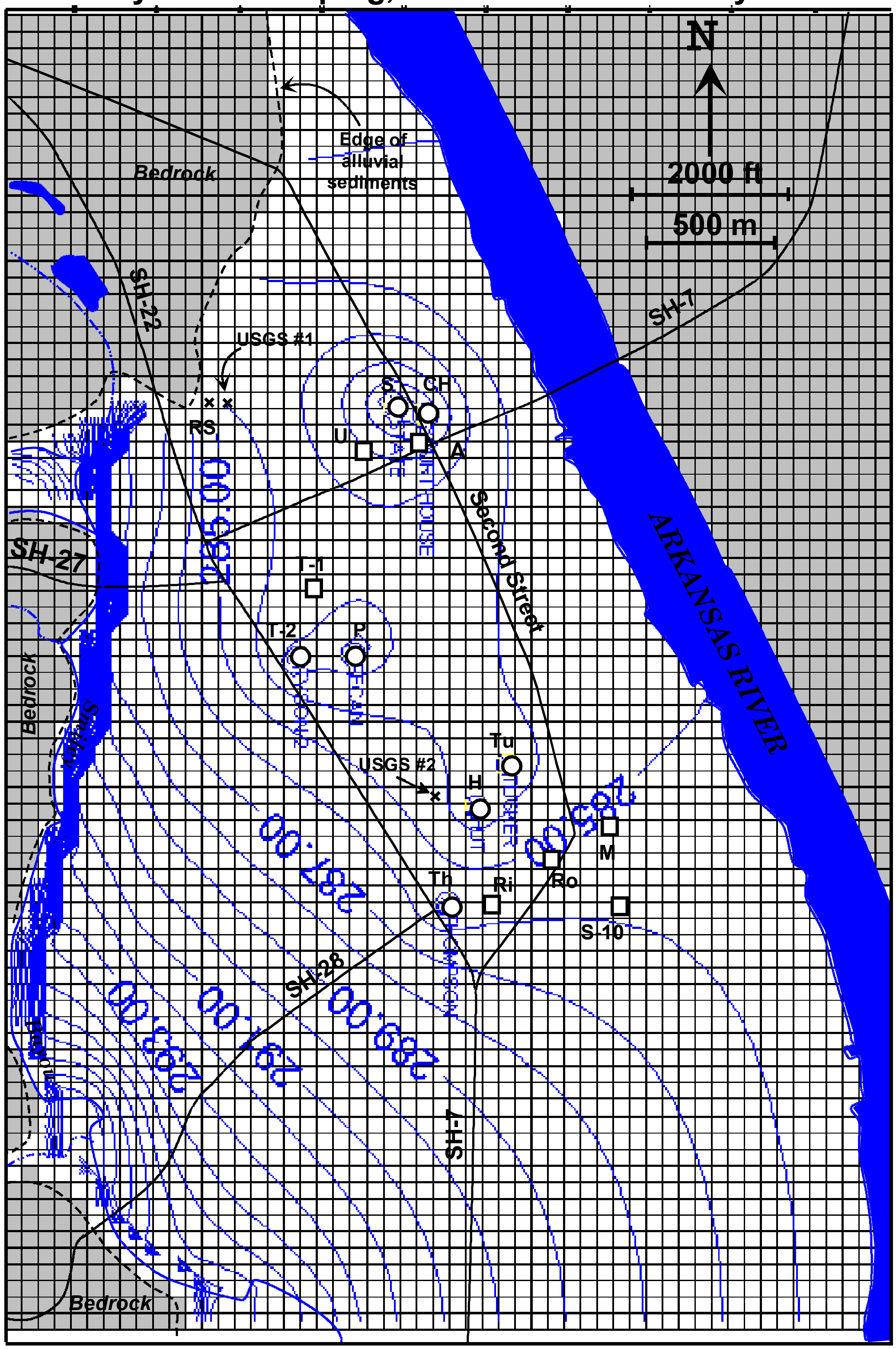

Figure 10. Potentiometric surface map generated by the steady-state groundwater model employing K = 400 ft/d (122 m/d) in Layer 2. Contours are in feet above MSL; contour interval is 1 ft. Head in the Arkansas River is 285 ft (87 m). This map shows the condition when the wells are operating.

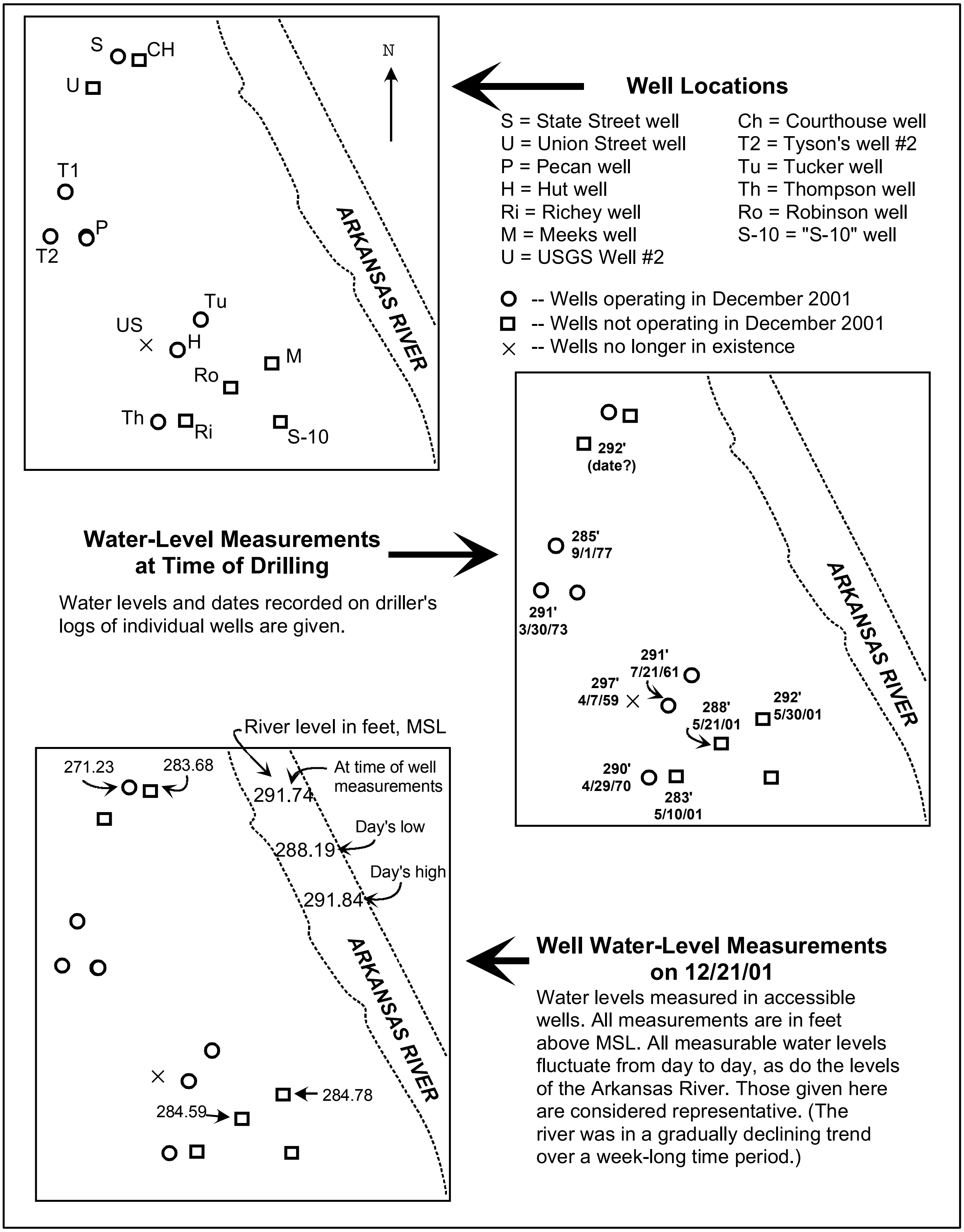

Figure 11. Maps for comparing model head distribution with water level measurements in wells and the Arkansas River.

model heads are reasonably close to measured water levels. Keep in mind that only a generalized approximation can be made of the hydrology of the aquifer anyway, because with the limited data it is impossible to know all the details of the aquifer's stratigraphy and other factors affecting the hydrology.

Also the behavior of Smiley Bayou is reasonable in each of the natural condition models. In each case the model stream is a losing stream, but the discharge stays within the same order of magnitude over its model length. In the lower K model the discharge drops from 256,800 ft^3/d (7,273 m^3/d) at the beginning to 245,000 ft^3/d (6,938 m/d) at the end; in the higher K model it drops to 198,000 ft^3/d (5,607 m/d). It is not known if Smiley Bayou is actually a loosing stream or not. We attempted a downstream discharge measurement for comparison, but the water there is in a deeper channel and moves too slowly for detection with our instrument. As stated above, the area immediately west of Smiley Bayou is modeled as a no-flow boundary. However, there actually is water flowing into the alluvial aquifer there, perhaps enough to make up for the stream discharge losses shown in the model. Regardless, as stated above, a perfect model of the aquifer is impossible, and the water loss to Smiley Bayou in the model is not extreme.

Considering the comparison of the pumping condition (Figs. 8 and 10) with the recently measured water levels (Fig. 11), the data for comparison are few. This is because few of the Dardanelle wells have access ports available for lowering measuring devices into the wells, and among those that have them measurement is often hindered by entanglement with cables and other obstacles in the well. Furthermore, we found that water levels in the wells fluctuate from day to day probably from effects of the river's constant state of flux and effects from the municipal well system being turned on and off every week. However, no obvious pattern of water level variation was recognizable. So although the water levels shown in Figure 11 are representative of recent water levels, they are not a static representation.

The December 2001 water levels in the Meeks and Robinson wells (Fig. 11) are reasonably close to the head distribution in both the pumping condition models, considering the possible variation of conditions discussed above. Regarding the comparison of the models to the water levels of the State Street and Courthouse wells, there is an important difference between the situation on the measurement date and the situation of the models (Figs. 8 and 10). The Courthouse well was shut down during the time that water levels were being monitored, but the models were constructed to depict the normal situation when the Courthouse well is in operation.

Comparing the December 21, 2001 measurements (Fig. 11) in the active State Street well and the inactive Courthouse well, it appears that there was a steep gradient between the two wells, which are only 367 ft (112 m) apart. This gradient is more nearly matched by the closely spaced head contours in the model with the lower hydraulic conductivity in Layer 2 (Fig. 8). In fact the gradient represented in Figure 8 is not as steep as the gradient interpreted from Figure 11, suggesting that the hydraulic conductivity of Layer 2 is even lower than the 175 ft/d (53 m/d) used in the model. However, monitoring of the State Street well's recovery when turned off for a weekend during the summer of 2002 indicated that the well operates with a high degree of inefficiency. The result of this inefficiency is that the water level in the well itself probably falls to nearly 8 ft (2.4 m) lower than the water level in the aquifer immediately adjacent to the well during times when the pump is running. So on December 21, 2001 the actual water level in the aquifer adjacent to the State Street well was probably above 279 ft (85 m) elevation at the time when the water level in the Courthouse well was 283.68 ft (86.466 m). This gradient is more consistent with the head contours in Figure 10. This makes us think that the hydraulic conductivity in the lower part of the aquifer is probably closer to 400 ft/d (122 m/d) than to 175 ft/d (53 m/d).

In both the pumping condition models Smiley Bayou looses more water than in the corresponding natural condition models. The lower K model drops to 213,000 ft^3/d at the end, and the higher K model drops to 178,800 ft^3/d (m^3/d). Loosing more water is to be expected because of the withdrawal of water from the aquifer due to the pumping wells. The amount of total loss is not unreasonable, especially considering the water actually coming from the area of outcrop not figured into the model.

Regardless of which hydraulic conductivity better represents the actual conditions of the aquifer, the models both indicate that the composite cone of depression produced by the municipal well system at Dardanelle intersects the Arkansas River. In each case, the head gradient progressively falls from the Arkansas River toward the pumping wells. The head distribution in each of Figures 8 and 10 indicates flow of Arkansas River water to the Courthouse, State Street, Pecan, and Tucker wells. The gradient from the river to the wells is steeper for the lower conductivity model (Fig. 8), so if the material in Layer 2 actually has a lower hydraulic conductivity than what was modeled, still the river water would recharge the wells. Considering what would be the case if the hydraulic conductivity is actually higher than what was modeled, we ran the model with conductivity ranging up to 1750 ft/d (533 m/d). All of these runs still showed gradients from the river toward the wells. Changing the hydraulic conductivity of the upper layer only affects how much water Smiley Bayou will gain or loose; the cone of depression still intersects the Arkansas River. So for essentially any reasonable hydraulic conductivity that could occur in a coarse sand and gravel deposit, one would have to conclude that the river must contribute water to some of the wells in the Dardanelle well system.

Water Quality

A comparison of available chemical data for the Arkansas River and the alluvial aquifer at Dardanelle supports the indication from the groundwater flow model that water from the river provides recharge to the aquifer and makes its way to the Dardanelle municipal well system. This data will be shown and discussed below after a brief comment about general water quality conditions in the Arkansas River and in the aquifer.

ADEQ regularly monitors the quality of water in the State's rivers, including the Arkansas River, and there is a sampling site at Dardanelle, at the Highway 7 bridge over the Arkansas River. According to mandates of Section 303(d) of the Clean Water Act, states are required to identify impaired waters not meeting applicable water quality standards. A two mile (3.2 km) segment of the Arkansas River on the downstream side of the dam at Dardanelle is on Arkansas' "303(d) list" because during occasional periods in summers it has below-standard dissolved oxygen content (ADEQ, 2002). This segment extends approximately to the Highway 7 bridge and therefore includes part of the section of the river that is indicated by the flow model as contributing water to the aquifer. The low dissolved oxygen in the river here is a result of occasional hypoxic conditions in bottom strata of the Dardanelle Reservoir that are tapped by releases through the hydroelectric dam. However, with regard to the threat to public health and the environment, this water quality condition only affects aquatic life in this segment; all other assessed uses, including water supply for raw drinking water, are considered "supported" by the water in this segment (ADEQ, 2002). Furthermore, studies of pesticide concentrations in the water and toxic trace elements have not found any of these potential pollutants in concentrations above the Safe Drinking Water Act's maximum contaminant levels (MCL). Therefore there is no significant threat to the Dardanelle water supply posed by the present water quality conditions of the Arkansas River. The concern that the Dardanelle City Council members had was not with present conditions in the river, but with potential conditions if something happened to pollute the river.

Bedinger and others (1963) included a discussion of water quality in the alluvial aquifer between Little Rock and Fort Smith. They indicated that at the time of their study (most sampling in the early 1950s) water in the aquifer throughout the region was suitable for irrigation, municipal water supply (with some treatment), and some industrial uses. For irrigation most water in the alluvium rated excellent to good, with about 10% of water samples tested rating good to permissible. Industries requiring water for boilers and steam turbines would not find the aquifer water suitable because of high hardness (median hardness for the entire aquifer was 253 ppm), high iron (median 1.4 ppm), and high silica (a range of 5.8 to 35 ppm). However, these parameters are no problem to some industries, such as the Tyson's chicken processing plant mentioned above, which has been using water from the aquifer for many years in cooling towers for its refrigeration system. The high hardness and iron (in some places very high iron) make the aquifer water not altogether satisfactory for domestic use (household wells) when untreated, but at the time of the Bedinger and others (1963) publication four municipalities (Atkins, Dardanelle, Morrilton, and Ozark) were using treated water from the aquifer for public supply. Today Dardanelle and Maumelle use the aquifer.

In their report, Bedinger and others (1963) pointed out that municipal wells in both Ozark and Dardanelle occasionally tapped water from the Arkansas River, as indicated by chloride contents in samples from their water systems. The data for that study were gathered through the 1950's. The wells that supplied Dardanelle during that time period pre-date the wells that exist today. There were two wells located very near the river at the corner of Hickory and Front Street, one on Hickory Street frontage and one on Front Street frontage (in Fig. 1, the closest street parallel to the river is Front Street, and Hickory is the 6th street north of the Courthouse well). So the conclusion drawn in that report, that Arkansas River water occasionally entered the Dardanelle well system, was based on data from different wells than those in existence today. Therefore the conclusion could not necessarily be assumed to be true of the present well field, which is farther from the river. However, the groundwater flow model presented in the present report, indicates that their conclusion is indeed valid for today's well system. Furthermore, chemical data from the individual monitoring wells that formed the basis of the Bedinger and others (1963) report are now available on line, and a comparison of those data with water analysis data from the river and today's municipal wells strengthens the case for river water intrusion.

Table 3 presents a comparison of water analyses from the Arkansas River at Dardanelle, the Dardanelle well field, and USGS monitoring wells used in the Beddinger and others (1963) study. The data from the Dardanelle wells were obtained from the Arkansas Department of Health (ADH), from raw water samples taken from test wells that were drilled for the Richey, Meeks, and Robinson wells. No other untreated water analyses are available from the ADH. The Arkansas River water analyses are from the ADEQ, from a sampling site at the Highway 7 bridge. The sample dates that were chosen for Table 3 are ones that were near the time period in which the Dardanelle well samples were taken. With regard to the USGS monitoring well data, a great many samples were taken from wells in the alluvium, terraces, and nearby bedrock areas throughout the section along the southwest side of the Arkansas River from Dardanelle southeastward to Petit Jean Mountain. Data from those wells that were sampled for chemical analysis are available on line (URL given with Table 3). We downloaded 63 analyses from nearly as many wells in that section of the alluvium. Of those analyses, four had all the parameters that we chose to compare. These are the ones presented in Table 3. The locations of those wells are also given with Table 3. To further aid in the comparison of the waters, the analyses in Table 3 are also presented on a Piper diagram (Figure 12).

Considering Table 3 and Figure 12, the greatest differences in water chemistry are between the Arkansas River samples and the USGS samples that were from wells outside of the vicinity of the Dardanelle well field. One of the USGS wells ("USGS 4") was in the City of Dardanelle close to the Arkansas River and in the vicinity of the municipal wells of that time. (The latitude/longitude position of that well plots at the intersection of Front Street and Maple, the next street north from Hickory. It may be that the well was not a monitoring well drilled by the USGS, but actually the city's municipal well itself.) The sample from that well plots with the Arkansas River analyses on the Piper diagram (Fig. 12) and has a TDS value that is more akin to the river samples than to the other USGS wells (Table 3). However, another USGS well ("USGS 3") was also located very close to the Arkansas River, but far from the Dardanelle well field. That sample shows many dissimilarities in comparison to the Arkansas River samples and is more similar to the USGS samples that are from wells far from the river. The character of the "USGS 3" sample corroborates the indications on Figures 8 and 10 that southeast from the

Table 3. Water quality data from the Arkansas River, Dardanelle municipal wells, and USGS monitoring wells

Sample #	Date	[1]TDS mg/L	Hardness mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Fe mg/L	[2]HCO_3 mg/L	Cl mg/L	SO_4 mg/L	F mg/L
River 1	7/27/98	566	226	59.2	18.9	117.9	4.6	0.02	254	118	122	0.293
River 2	9/28/98	346	181	52.2	12.4	59.8	4.2	0.02	138	83.2	66.3	0.219
River 3	11/9/98	366	142	39.7	10.5	71.8	3.6	0.02	166	98.8	59.5	0.264
River 4	1/11/99	229	102	29.1	7.2	34.6	4.8	0.10	150	46.6	32.6	0.148
Dard 1	1/28/98	405	266	87.1	10.0	55.0	2.7	2.68	237	72.7	57.6	0.20
Dard 2	2/4/98	439	31.3	103	13.0	47.7	2.7	0.40	299	69.7	55.5	<0.2
Dard 3	1/11/99	209	172	49.1	11.8	14.9	<2	0.11	165	23.7	28.1	<0.2
Dard 4	2/5/98	312	135	44.4	5.9	68.6	2.9	0.03	120	84.7	46.6	0.24
USGS 1	7/25/50	153	120	36	8.4	12	3.9	---	110	20	18	0.2
USGS 2	2/17/59	168	120	40	4.6	16	1.1	0	130	8.8	34	---
USGS 3	7/19/50	46	35	9	3	6.2	0.9	0.05	38	1.8	6.2	0.1
USGS 4	2/25/50	267	140	39	11	49	4.7	---	110	80	29	0.1

[1]Total Dissolved Solids. For Dardanelle well data, this was calculated from the total of the major ions according to method in Hem (1985).

[2]HCO_3 in the samples from the river was calculated from reported TDS and the other major ions. In the Dardanelle wells HCO_3 was calculated from reported alkalinity. Both calculations according to methods in Hem (1985).

Arkansas River analyses were taken from data for ADEQ sampling site ARK0032 (at the Highway 7 bridge at Dardanelle). The data are given on the ADEQ web site: www.adeq.state.ar.us/techsvs/water_quality/monitors.asp.

Dardanelle well analyses were obtained from the Arkansas Department of Health, based on raw water samples taken when test wells were drilled which later became municipal wells: Dard 1 = Richey well, Dard 2 & 3 = Robinson well, Dard 4 = Meeks well.

Data for USGS monitoring wells obtained from NWIS data base on the web at: http://waterdata.usgs.gov/ar/nwis/qw/. The site numbers for the wells that were chosen are given below. The first part of the site number is a designation of the latitude and longitude in DMS, with the last two digits indicating well number at that site; the second part is a designation for the U.S. Land Office grid system, with the last digit for the well number at that site. Note that the designations “USGS 1” etc here do not correspond to the USGS sites given on Figure 1.

“USGS 1” = # 350735093054001—06N20W35DBB1. This well was SW of Holla Bend, 7.4 mi (11.9 km) SE of the Highway 7 bridge at Dardanelle and 2.6 mi (4.2 km) from the Arkansas River.

“USGS 2” = #350758093061002—06N20W35BBC2. This well was west of Holla Bend, 6.9 mi (11.1 km) SE of the Highway 7 bridge and 2.4 mi (3.9 km) from the river.

“USGS 3” = #351110093081501—06N20W09CBC1. This well was just SE of the Dardanelle wastewater treatment plant, 2.74 mi (4.41 km) SE of the Highway 7 bridge (0.26 mi [0.42 km] from the SE corner of Figure 1) and was only 0.1 mi (0.16 km) from the Arkansas River.

“USGS 4” = #351352093093503—07N20W30DBA3. This well was in Dardanelle on Front Street (the street adjacent to the Arkansas River [see Figure 1]) at the intersection of the 7th street NW of the Courthouse well and was 0.23 mi (0.37 km) from the river.

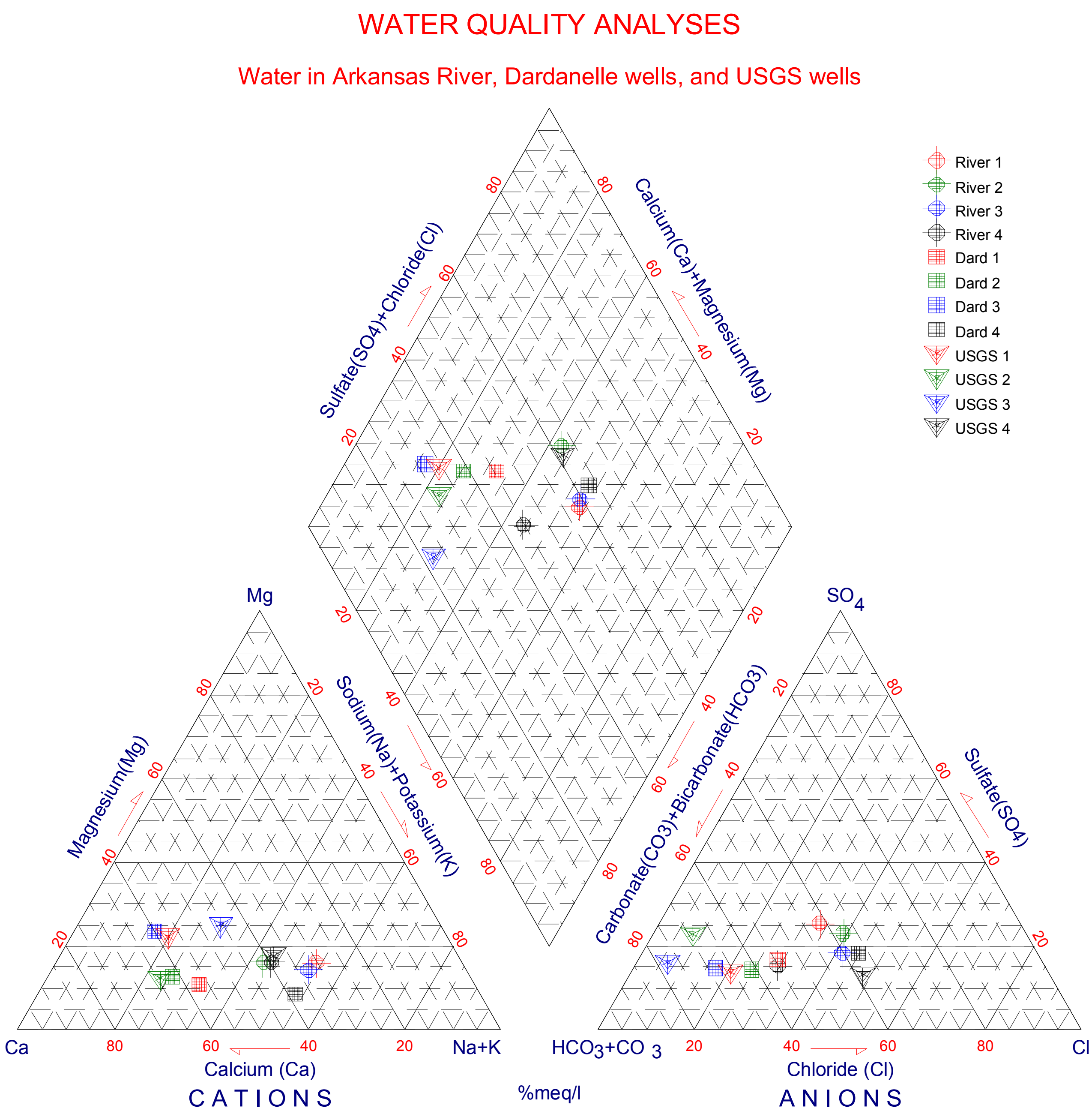

Figure 12. Piper diagram comparing relative concentrations of major ions in waters from the Arkansas River, Dardanelle wells, and USGS exploration wells. Samples are those listed in Table 3.

vicinity of the Dardanelle well field the aquifer's gradient slopes constantly toward the river, so that groundwater flows from the aquifer into the river there, rather than the other way. The samples from the Dardanelle municipal wells have varying similarities to the river water and to the water from wells isolated from the river. The water table contours generated by the flow models indicate that these wells are in an area that would likely receive contribution from both the river and the aquifer. This is evident especially when one takes into account that the river level is not static as in the models but rather often rises to levels well above the constant head chosen for the models. The samples from these wells are probably a complex mixture of both sources. Note, however, that the sample from the Meeks well, the one closest to the river, is essentially indistinguishable from the Arkansas River.

Conclusions

The numerical flow models based on hydrologic conditions of the alluvial aquifer at Dardanelle indicate that a significant portion of the water drawn from the aquifer into the Dardanelle city well system is coming from infiltration from the Arkansas River. The models are based on a low-flow condition in the Arkansas River, the condition least favorable for generating a head gradient from the river to the wells. If the river's low-flow condition indicates a groundwater head gradient from the river to the wells, certainly the gradient is in that direction when the river flows at higher stages. Chemical analyses of raw water from wells in the Dardanelle well field compared to analyses of water from the Arkansas River and water from the aquifer in areas remote from Dardanelle indicate a mixing of the aquifer water with water from the river, corroborating the conclusions drawn from the flow model.

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