WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: An Investigation to Identify Sources and Quantities of Modern Recharge to the Memphis Aquifer in the Sheahan Well field in Shelby County, Tennessee

Focus Categories: NPP, GW, HYDROL

Keywords: Groundwater Hydrology, Groundwater Movement, Age Dating, Groundwater Recharge, Groundwater Modeling, Groundwater Quality

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Statement of Critical Regional Water Problems

The Memphis aquifer is part of the much larger Northern Mississippi Embayment aquifer system composed of Tertiary and Cretaceous-age unconsolidated sand aquifers alternating with sand, silt, and clay confining units (Cushing et al., 1964; Grubb and Carillo, 1988). The Memphis aquifer is utilized as the primary drinking water source in the Memphis area and in practically all smaller urban areas in western Tennessee. The clay layers within the overlying upper Claiborne confining unit are known to be thin or absent in several areas of Shelby County. Absence of the clay and downward flux of surface waters and shallow groundwater are believed to contribute to water quality changes and possible contamination of the Memphis aquifer (Graham and Parks, 1986; Richardson, 1989; Parks, 1990; Parks and Mirecki, 1992; and Parks et al, 1995). The Memphis aquifer or similar unconsolidated sand aquifers are used throughout the Mississippi Embayment region for agricultural, domestic, and municipal water supplies. Post-depositional erosion and lateral heterogeneities in regional confining layers, such as those observed in the Memphis area, may provide avenues for contaminants in surface and shallow groundwater to enter "primary" regional aquifers. This problem is especially acute in areas where high groundwater use has substantially lowered potentiometric surfaces.

The research proposed herein addresses identification of the geologic mechanism providing modern recharge to the Memphis aquifer in the Sheahan well field in Shelby County, Tennessee (Figure 1 and Figure 2). Previous research indicates that a window in the upper Claiborne confining unit overlying the Memphis aquifer may be absent in this area (Kingsbury and Parks, 1993) and that modern recharge has entered some of the Sheahan wells (Graham and Parks, 1986). Recent studies of the deposits comprising the shallow aquifer in Shelby County show that a major paleovalley was cut into the confining unit in late Cenozoic time (McClure, 1999). The Sheahan well field provides an opportunity to study the mechanisms of interaquifer leakage by utilizing water chemistry and environmental tracers (tritium/^{3}Helium ($^3H/^3He$)) coupled with a shallow seismic investigation of the area to identify the lateral extent of the confining unit. This information is needed by municipal water suppliers in the Memphis area (Memphis Light, Gas, and Water, etc.) to assess vulnerability of well fields to contamination. The results should provide a conceptual model for the mechanism of interaquifer leakage that will be useful to the region.

Research Results, Benefits and/or Information

The results of the study will include, at a minimum, the following as they pertain to the Sheahan well field: (1) an estimate of the quantity and timing of modern recharge entering the Memphis aquifer from the shallow aquifer, (2) a better understanding of the hydrostratigraphic characteristics of the upper Claiborne confining unit, (3) a conceptual model for the distribution and characteristics of hydraulic pathways between the shallow aquifer and the Memphis aquifer, and (4) a better understanding of the potential of shallow seismic studies for defining hydrogeologic units. These results will clarify the potential for vertical leakage to the Memphis aquifer related to municipal pumping in the aquifer. Because of the similarities between the Memphis aquifer and other heavily utilized unconsolidated sand aquifers in the Mississippi Embayment, Gulf Coast, and Atlantic Coastal Plain, the results should provide important data and considerations for similar regional areas.

The information gathered in the study will aide in understanding the impacts of pumping-induced stresses and inter-aquifer hydraulic communication on water quality and quantity in aquifer systems of the northern Mississippi embayment. In addition, the study will provide an opportunity to evaluate the potential of using shallow seismic studies to clarify hydrostratigraphic relationships between aquifers and confining units. In concert with other studies supported by the Shelby County Health Department, this work will continue to refine the application, in the Mississippi embayment aquifer systems, of new age-dating technologies utilizing $^{3}H/^{3}He$ and ^{85}Kr techniques. This study and others pending funding support include a broad and diverse group of collaborators at the USGS, University of Utah, Millsaps College, and Institute for Rare Isotope Measurements and Department of Geological Sciences at the University of Tennessee, Knoxville. The increased understanding of the hydraulic dynamics of the aquifer system will result in more reliable numerical computer models that can be employed to explore the future impacts of water quantity and quality changes in the system. While this study will directly evaluate the Memphis aquifer, the degree to which confining layers "protect" underlying aquifers is a general issue of National concern. The results of the study in conjunction with the results of the other mentioned studies will be presented to the research community at national and regional conferences and in peer-reviewed journal articles.

Nature, Scope and Objectives of Research

GEOLOGIC BACKGROUND

Memphis and Shelby County lie in the center of the northern Mississippi embayment, a trough-shaped basin that plunges southward along an axis that approximates the trace of the Mississippi River. The stratigraphy of the upper Eocene through Holocene sedimentary fill of the Mississippi Embayment in the Memphis area is shown in Table 1. The early to mid-Tertiary-age geologic units beneath Shelby County dip gently to the west and include unconsolidated sand, silt, and clay with minor lignite. Pleistocene and Pliocene(?) fluvial terrace deposits unconformably overlie the mid-Tertiary units. Early workers (Fisk, 1944; Krinitsky, 1949) identified as many as three terrace levels, based on topography and limited borehole data. Recent work confirms the general observations of Fisk and Krinitsky and indicates that buried Pleistocene(?) paleovalleys (in excess of 45 ft deep) are concealed beneath the terrace surfaces (McClure, 1999; Larsen and McClure, 1999). Excluding the present-day tributary valleys, 10 to 65 feet of loess overlie the fluvial deposits and mantle the underlying topography. The loess is thickest near the Mississippi River bluff line (as much as 65 feet locally) and thins to the east. Present-day valleys of the Big and Nonconnah Creeks, and the Loosahatchie and Wolf Rivers contain as much as 60 feet of late Pleistocene and Holocene alluvium. The alluvium typically contains sand and gravel near the base and fines upward into sandy and clayey silt.

The geologic units beneath the Memphis and Shelby County area are divided into a series of hydrostratigraphic units, each with its own hydraulic characteristics. The loess and the upper part of the alluvium have similar grain-size and hydraulic properties (Robinson et al., 1997) and behave as a leaky, confining unit. The loess contains many vertical fractures and root pores that may dominate the hydraulic conductivity (Smith, 1997); thus, the loess-upper alluvium hydrostratigraphic unit may locally pose little resistance to downward percolation. The fluvial-terrace deposits and the sand and gravel in the lower part of the alluvium comprise the shallow aquifer. It locally includes Mid-Tertiary deposits in areas where sand-rich Eocene or Oligocene units directly underlie the fluvial-terrace deposits and alluvium. This unit is thought to be a water-table aquifer throughout much of the county, but is locally confined by loess along the Mississippi River bluffs and in the Millington area (Parks, 1990; Robinson et al., 1997). The shallow aquifer is used for domestic and farm water supplies in rural parts of Shelby County (Graham and Parks, 1986)

The Cockfield and Cook Mountain Formations comprise the lower confining unit for the shallow aquifer and upper confining unit for the Memphis aquifer; this unit is termed the upper Claiborne confining unit (Parks, 1990). The thickness of the upper Claiborne confining unit varies within Shelby County from about 375 feet to 0 feet in the eastern part of the county. The total thickness of clay beds in the confining unit varies from less than 10 to over 200 feet, suggesting that windows of hydrologic connectivity exist between the underlying Memphis aquifer and overlying shallow aquifer (Parks, 1990). The Memphis aquifer is unconfined in eastern Shelby County, but is generally confined beneath Memphis and throughout western Shelby County. The Memphis aquifer and the correlative Sparta aquifer in northern Mississippi and eastern Arkansas consitute an important agricultural, industrial, and municipal water source for the Mid-South region (Parks and Carmichael, 1990; Arthur and Taylor, 1990; Hays et al., 1998).

THE SHEAHAN WELL FIELD

The Sheahan well field is one of ten municipal well fields operated by Memphis Light, Gas, and Water in Shelby County, Tennessee (Figure 1). The Sheahan well field has been in operation since 1931 with a treatment capacity of 35 million gallons/day. The well field contains 24 wells distributed in a north to south band, approximately 1 mile across, extending north from Nonconnah Creek (Fig. 2). The potential for Nonconnah Creek to provide recharge to the Memphis aquifer near the Sheahan and Lichterman well fields was suggested by Criner et al. (1964), Moore (1965), and Nyman (1965). Graham and Parks (1986) present several lines of evidence for vertical leakage from the shallow aquifer to the Memphis aquifer. The lines of evidence most pertinent to the Sheahan well field include a cone of depression in the shallow aquifer and presence of high tritium concentrations in the southern part of the well field and distorted temperature logs throughout the well field. Tritium is a short-lived isotope of hydrogen; concentrations above approximately 0.5 tritium units in groundwater indicate the presence of some component of recharge less than 50 years old (“modern” recharge). Tritium and carbon-14 data from one sampling event of two wells (Sh:K-73 and -74) indicated a large component of modern recharge was present in the wells (Graham and Parks, 1986). Preliminary tritium results from 1999 sampling of production wells in the Sheahan well field by Ground Water Institute personnel indicates that tritium concentrations above detection limits are present in some wells (Table 2).

In a recent study of the distribution of Plio-Pleistocene fluvial-terrace deposits in Shelby County, McClure (1999) identified several buried paleovalleys (Figure 3). One of these paleovalleys appears to track along the southwestern boundary of the Sheahan well field and could be hydraulically connected to the Nonconnah Creek alluvial valley. Geologic data tends to be highly insular in the area west of the Sheahan well field, which is probably why the paleovalley feature is not apparent on maps of confining-clay thickness in Graham and Parks (1986) and Parks (1990).

SCOPE OF PROPOSED STUDY

The purpose of the proposed study is to better define the extent and geologic mechanism of modern recharge entering the Memphis aquifer near the Sheahan well field. The approach to be used will involve the following research objectives:

(1) Assembling all existing data pertinent to identifying the pathway for modern recharge to enter the Memphis aquifer near the Sheahan well field (driller’s logs, geophysical logs, aquifer test results, downhole temperature logs, water chemistry, etc.). The data will be entered and analyzed using geographic information system (GIS) software at the Ground Water Institute.

(2) Quarterly water sampling of production wells at the Sheahan well field and selected monitoring wells screened in the Memphis aquifer near the Sheahan well field. The samples will be analyzed for major and minor dissolved solutes and tritium.

(3) Sampling of selected production wells and monitoring wells for coupled tritium and helium-3. Helium-3 is the daughter product from the radioactive decay of tritium; the ratio of corrected helium-3 to tritium provides an apparent time since the water last equilibrated with the atmosphere (i.e., groundwater age).

(4) Data acquisition and calculation of 3 S-wave seismic profiles. The seismic profiles will be used to more clearly establish the extent and location of gaps in the upper Claiborne confining unit inferred from the chemistry and tritium data.

Compilation of the existing data will provide our initial conceptual model for the relationships between the aquifers and confining units in the Sheahan well field area. This will also include chemistry and tritium data from an initial round of production well sampling in the Sheahan well field completed in October through December, 1999. This data will help identify monitoring wells near the Sheahan well field that should be sampled during the study and probable recharge pathways that need to be evaluated.

The goal of the water chemistry and tritium data acquisition is to determine the distribution of modern recharge entering the Memphis aquifer in the Sheahan well field area. The water chemistry of the shallow and Memphis aquifers are different, especially with regard to total dissolved solids, alkalinity, and hardness (Brahana et al., 1987; Parks and Mirecki, 1992; Parks et al., 1995; Carmichael et al., 1997). Changes in these parameters as well as redox conditions and water temperature should reflect varying contributions of "old" Memphis aquifer water and "young" shallow aquifer water. Tritium is a radioactive tracer that is often used to identify the presence of post-1952 recharge in groundwater (Mazor, 1997). Water chemistry parameters and tritium values should vary coherently with increasing proportions of hard, higher-concentration, "young" waters from the shallow aquifer added to the softer, more dilute, "old" waters of the Memphis aquifer. The map distribution of waters containing a significant modern component should also closely reflect the geologic pathway by which modern recharge entered the Memphis aquifer.

The purpose of quarterly sampling of select production wells in the Sheahan well field is to determine whether the contributions of modern recharge are seasonal and affected by variable pumping stresses. Water levels in the Memphis aquifer in the Memphis area vary seasonally, in large part from increased pumping during the summer and fall (Parks, 1990). Precipitation also varies seasonally with greater precipitation during the winter and spring and lower precipitation during the late summer and fall. The contributions of modern recharge are thus expected to be greatest during the summer and late fall when pumping stresses are greatest. Two or three of the wells will be sampled multiple times through an individual pumping cycle to determine whether short-term pumping stresses significant affect water chemistry and tritium concentrations.

The purpose of the helium-3 analysis is to obtain apparent groundwater ages for water in the Memphis aquifer in the Sheahan well field area. Helium-3 is the daughter product from radioactive decay of tritium. When corrected for other sources of helium-3, the helium-3/tritium ratio can be used to calculate groundwater ages (Solomon et al., 1992; Ekwurzel et al., 1994). Using the water chemistry and tritium data as a guide, five wells (four production and one monitoring) will be sampled for helium-3 and tritium analysis. These wells will be chosen to sample the boundaries and interior of the region of the aquifer bearing significant quantities of modern recharge. The calculated groundwater age of the samples will be compared to the water chemistry to evaluate the proportion of "average" modern recharge mixed with "old" Memphis aquifer water.

The purpose of the shallow S-wave seismic profiles is to ground truth the recharge mechanisms inferred from chemistry and isotopic tracer results. The likely geologic pathways for recharge are paleovalleys eroded through the upper Claiborne confining unit and along faults that may offset Tertiary deposits (Kingsbury and Parks, 1993). Both of these types of geologic features are readily identified using reflection seismology. High-resolution P-wave (compressional wave) seismic reflection investigations targeting bedrock paleovalleys (i.e., Pullan and Hunter, 1990; Wolfe and Richard, 1996) and near-surface faults (i.e., Sexton and Jones, 1986) have been successful in areas where geological conditions are favorable for the collection of high-quality data (e.g., fine-grained material, shallow water table, and large seismic velocity contrasts). However, there are situations where shallow S-wave (shear wave) reflection methods are more effective. Unconsolidated, water-saturated sediment sequences are ideal for the use of S-waves. In such environments, P-waves travel with the velocity of the fluid and are often less sensitive to lithologic changes with depth. Because S-waves travel with the velocity of the sediment framework, they are not greatly influenced by the degree of saturation and often provide a more accurate image of the subsurface geology. For example, S-wave techniques have been used successfully for near-surface hydrogeologic (Langston et al., 1998; Miles et al., 2000) and earthquake hazard (Harris and Street, 1997; Harris et al., 1998; Woolery et al., 1999) studies in the Mississippi embayment.

The results of all components of the study will be compiled to clarify the extent of the "window" in the upper Claiborne confining unit and impact modern recharge is having on water pumped from the Sheahan well field. The results should allow Memphis Light, Gas, and Water to better manage pumping in the well field and guide future water development in the Memphis area. The results will also illustrate the degree that windows in the upper Claiborne confining unit can be identified using present-day technology.

Methods, Procedures and Facilities:

The various methodologies to be utilized for each component of the study are described in the sections below.

Water sampling— Water from production wells will be obtained from a sampling port located on the discharge main of a production well pump. For monitoring wells, standard low-flow groundwater sampling protocols will be used to obtain samples for conventional water chemistry and tritium analyses. Both filtered and unfiltered samples will be collected for major ions; the filtered samples will be preserved with concentrated nitric acid. ^{3}He is a dissolved gas which can easily be exchanged in a groundwater sample by exposure to the atmosphere or by diffusion through the walls of a plastic sample bottle. To control losses, the groundwater sample must be isolated from the atmosphere in a tightly-sealed glass container, or the dissolved gases can be stripped from the groundwater either as it is sampled or through an in-situ diffusion sampler. The researchers will coordinate with Dr. Kip Solomon to determine the needs and requirements for sampling from the Sheahan production wells. The methodology will include either an in-situ diffusion sampler or gas stripping of the water sample as it is collected. The observation wells will be sampled utilizing an in-situ diffusion sampler. The proposed program will use both the conventional water sampling and gas-stripping techniques to provide a quantitative comparison of values derived from the methods.

Chemical analyses– On-site chemical data determined by probes in a multiport sampling chamber will include pH, Eh, dissolved oxygen, and conductivity. In addition, on-site titrations for alkalinity and dissolved oxygen, and spectrophotometric analysis of nitrate, dissolved oxygen and sulfide will be conducted. Major anion and cation analyses will be conducted by ion chromatography and flame atomic absorption spectroscopy. Trace metal analysis will be performed using flame or graphite furnace atomic absorption spectroscopy, depending on the sensitivity required.

Standard ^3H measurement -- Tritium activity will be determined at the Center for Applied Isotopes Study, University of Georgia. Tritium enrichment will be utilized to obtain a detection limit of 0.1 tritium units (TU).

Enriched ^3H and ^3He -- Low-level ^3H measurements will be made at the University of Utah by Dr. Kip Solomon using the ^3He ingrowth method (Clarke et al., 1976). The practical detection limit for this method is approximately 0.05 TU when 250 ml samples are sealed for four months. Helium-3 will be measured using a combination of a quadrupole and sector-magnet mass spectrometers after cryogenic separation of non-reactive gases. The analytical precision is approximately ± 0.5% for He isotopes. The combined $^3H/^3He$ method has great advantages over conventional ^3H age dating methods. By measuring both ^3H and its daughter product ^3He, the ambiguity inherent in conventional ^3H age determinations (*e.g.* does a low ^3H level indicate pre-bomb or recent post-bomb water) may be removed.

S-wave Seismic Profiles -- The proposed S-wave reflection investigation (performed by personnel in the Department of Geology, Millsaps College) is a high-resolution, six-fold common-depth-point (CDP) survey. The recording system will be a 12-channel Bison 5012 signal enhancement seismograph. The 5012 has instantaneous floating point gain and records digital data on an internal storage board. Based on preliminary reflection tests in the area, the probable shotpoint and receiver spacings will be 3 m for the S-wave data collection. The available receivers include 4.5 Hz and 30 Hz horizontal geophones. In order to generate S-waves, a 10 kg steel I-beam will be oriented perpendicular to the geophone spread and impacted horizontally with a 4.5 kg sledge hammer. In our experience, 5-10 hammer blows are usually required to image the upper 100 m of the section. Because they are low-cost, durable, and portable, we have had good success with hammer and mass shear wave sources. Data processing will follow a standard sequence for shallow CDP reflection data, including trace editing, bandpass filtering, and automatic gain control.

Related Research

Much of the pertinent research regarding recharge to the Memphis aquifer was cited in section 11 above. The role of “windows” in confining units as avenues of recharge for major aquifers, especially with regard to a pumping well field, has been little studied. The most pertinent studies of recharge to the Memphis aquifer through a “window” in upper Claiborne confining unit are related to the Shelby County landfill (Bradley, 1991; Parks and Mirecki, 1992; Gentry, 1998; Gentry et al., in review) and the Davis well field (Richardson, 1989; Brown, 1993; Parks et al., 1995). Although water chemistry and environmental tracers were used in these studies, none of them utilized tritium to the extent currently proposed, none involved data manipulation and interpretation using GIS methods, and none have incorporated shallow seismic studies to verify trends inferred from chemical and isotopic data. The present study focuses on defining the geographic extent of and geologic mechanisms for modern recharge to the largely confined Memphis aquifer, with emphasis on how to best manage Memphis aquifer resources at the Sheahan well field.

The proposed study is an outgrowth of our current investigation of using water chemistry, tritium, and ^{85}Kr to identify the presence and quantity of modern recharge entering the Memphis aquifer. The work is supported by the Shelby County Health Department and Memphis, Light, Gas, and Water. The goal of this work is to identify, using water chemistry and tritium, areas of the largely confined Memphis aquifer that receive modern recharge and then use the ^{85}Kr method at selected sites to quantify the groundwater age. The ^{85}Kr method has many advantages over other common groundwater dating methods (tritium, chlorofluorocarbons, ^{14}C, etc) in that the source function is well known and simple; however, it is a technologically challenging procedure. The Memphis aquifer appears to be an ideal setting to apply age-dating technology, such as the ^{85}Kr method and ^{3}H/^{3}He method. Correlation of ^{85}Kr data with the data collected in this study should provide further data for interpreting age-dating results. The results of our current research should provide a regional framework for interpreting the results in the Sheahan well field and will complement the proposed study.

Another related project, for which funding is pending final approval, involves emplacement of three well clusters in the Memphis aquifer and overlying units within and adjacent to a window in the upper Claiborne confining unit. Following well construction, sediment core, water chemistry, and environmental tracer studies (helium-3/tritium and ^{85}Kr) will be used to better understand the overall role of windows in the confining unit for recharging the Memphis aquifer. The proposal was submitted to the American Water Works Research Foundation (AwwaRF) with Memphis Light, Gas, and Water. The results of the two studies should complement each other and reinforce our basic hydrologic understanding of windows in the confining unit.

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Table 1. Geologic units underlying the Shelby County Area

System	Series	Years before present	Group	Stratigraphic unit	Thickness (ft)	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene	11,000		Alluvium	0-175	Sand, gravel, silt, and clay. Underlies the Mississippi Alluvial Plain and alluvial plains of streams in the Gulf Coastal Plain. Thickest beneath the Alluvial Plain, where commonly between 100 and 150 feet thick; generally less than 50 feet thick elsewhere. Provides water to domestic, farm, industrial, and irrigation wells in the Mississippi Alluvial Plain.
	Pleistocene	500,000 to 2,000,000		Loess	0-65	Silt, silty clay, and minor sand. Principal unit at the surface in upland areas of the Gulf Coastal Plain. Thickest on the bluffs that border the Mississippi Alluvial Plain; thinner eastward from the bluffs. Tends to retard downward movement of water providing recharge to the fluvial deposits.
Quaternary and Tertiary (?)	Pleistocene and Pliocene (?)	13,000,000		Fluvial deposits (terrace deposits)	0-100	Sand, gravel, minor clay and ferruginous sandstone. Generally underlie the loess in upland areas, but are locally absent. Thickness varies greatly because of erosional surfaces at top and base. Provides water to many domestic and farm wells in rural areas.
Tertiary	Eocene	58,000,000	? Claiborne	Jackson Formation and upper part of Claiborne Group, includes Cockfield and Cook Mountain Formations (capping clay)	0-360	Clay, silt, sand, and lignite. Because of similarities in lithology, the Jackson Formation and upper part of the Claiborne Group cannot be reliable subdivided based on available information. Most of the preserved sequence is the Cockfield and Cook Mountain Formations undivided, but locally the Cockfield may be overlain by the Jackson Formation. Serves as the upper confining bed for the Memphis Sand.
				Memphis Sand ("500-foot" sand)	500-890	Sand, clay, and minor lignite. Thick body of sand with lenses of clay at various stratigraphic horizons and minor lignite. Thickest in the southwestern part of the Memphis area; thinnest in the northeastern part. Principal aquifer providing water for municipal and industrial supplies east of the Mississippi River; sole source of water for the City of Memphis.

	?			Flour Island Formation	160-310	Clay, silt, sand, and lignite. Consists primarily of silty clays and sandy silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining bed for the Memphis Sand and the upper confining bed for the Fort Pillow Sand.
				Fort Pillow Sand (“1400-foot” sand)	125-305	Sand with minor clay and lignite. Sand is fine to medium. Thickest in the southwestern part of the Memphis area; thinnest in the northern and northeastern parts. Once the second principal aquifer supplying the City of Memphis; still used by an industry. Principal aquifer providing water for municipal and industrial supplies west of the Mississippi River.
	Paleocene	63,000,000	Wilcox	Old Breastworks Formation	180-350	Clay, Silt, Sand, and lignite. Consists primarily of silty clays and clayey silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining bed for the Fort Pillow Sand, along with the underlying Porters Creek Clay and Clayton Formation of the Midway Group.

Adapted from Graham and Parks, 1986.

Table 2. Tritium Data from Select Production Wells in the Sheahan Well Field

Sample Location	Date Sampled	Well Depth (ft)	Concentration (TU)†
Well 97	9/23/99	574	4.01
Well 98	9/23/99	594	3.56
Well 99	9/23/99	459	9.31

†Tritium Units : 1 TU = 3.19 pCi/l

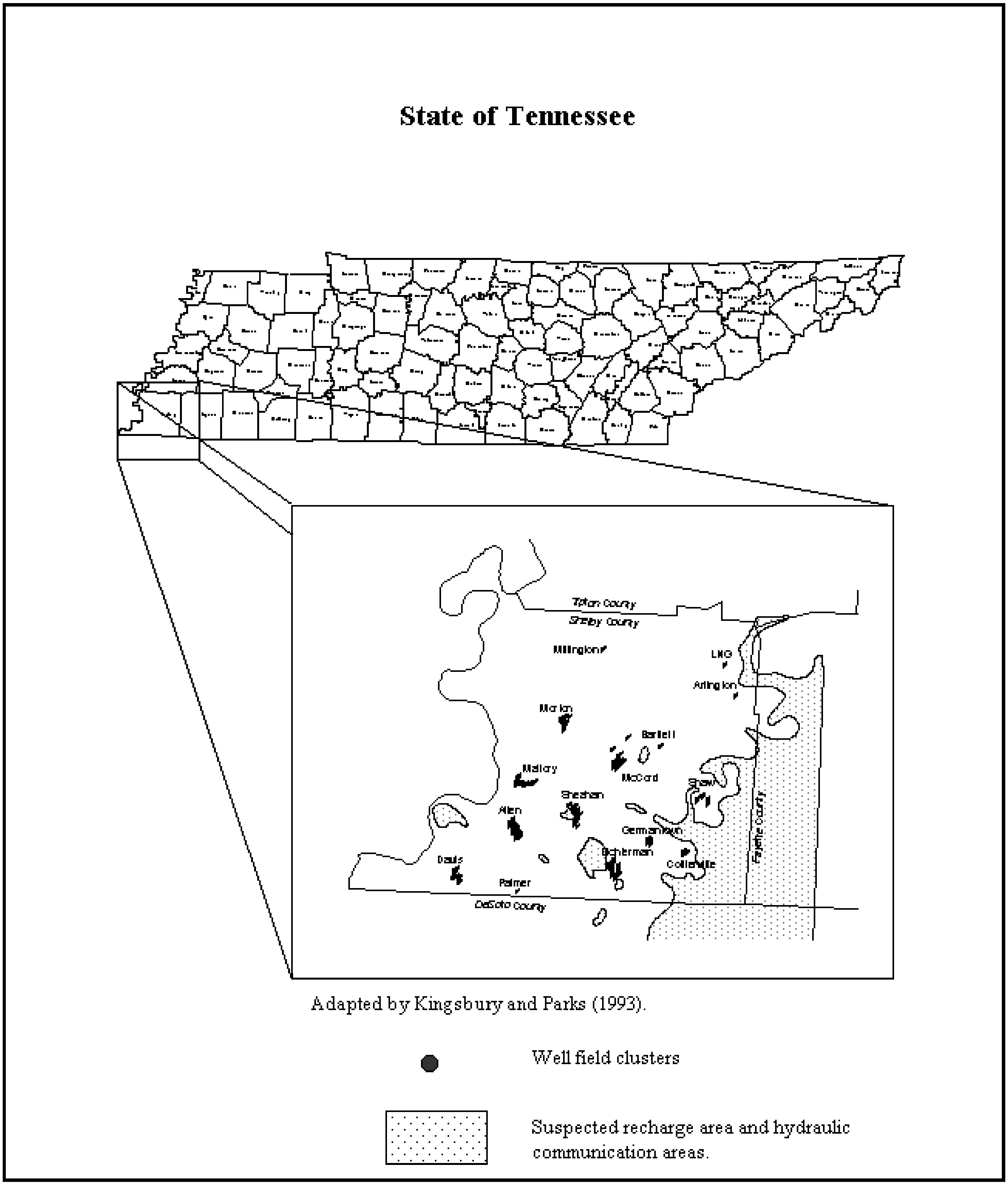

Figure 1. Geographical extent of Shelby County Tennessee with suspected areas of recharge and hydraulic communication windows in the confining clay layer of the Memphis aquifer.

Figure 1. Geographical extent of Shelby County Tennessee with suspected areas of recharge and hydraulic communication windows in the confining clay layer of the Memphis aquifer. Adapted by Kingsbury and Parks (1993). Well field clusters Suspected recharge area and hydraulic communication areas.

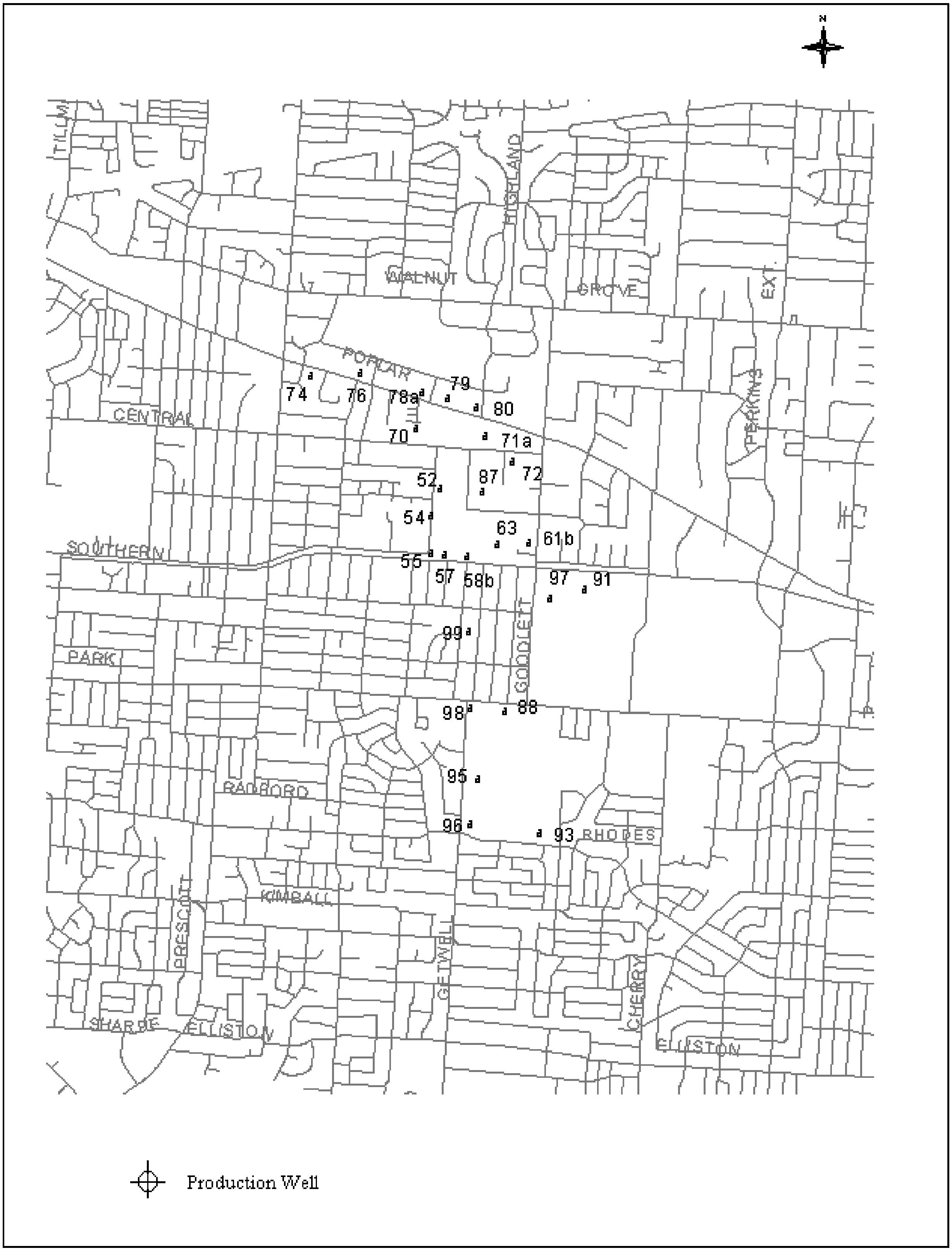

Figure 2. Layout of the Sheahan well field in Memphis, Tennessee.

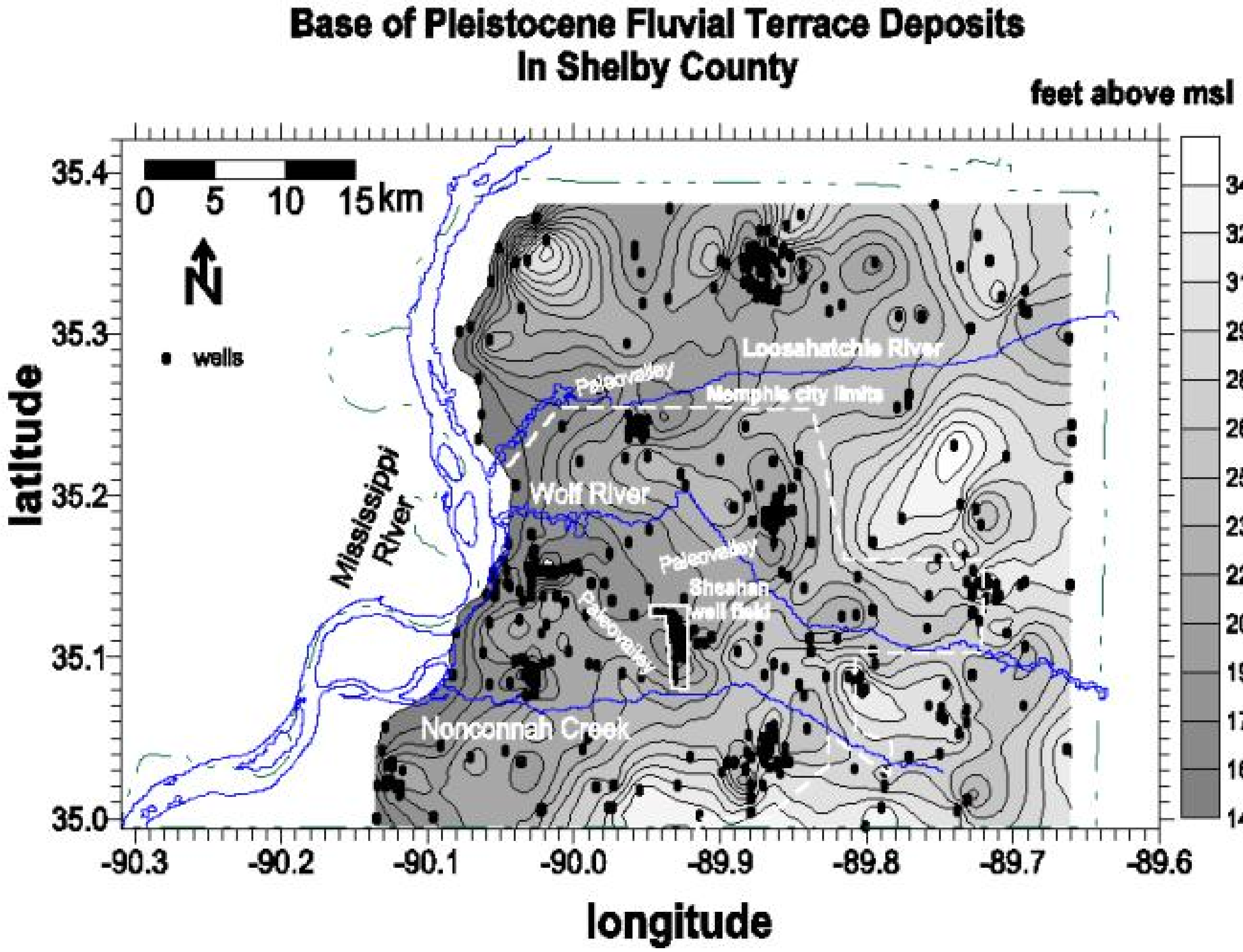

Figure 3. Structure contour map of the base of the Pleistocene fluvial terrace deposits in Shelby County. Note the position of paleovalley along western border of Sheahan well field.