No. 143, Original

IN THE
Supreme Court of the United States

STATE OF MISSISSIPPI,

Plaintiff,

v.

STATE OF TENNESSEE, CITY OF MEMPHIS, TENNESSEE AND MEMPHIS LIGHT, GAS & WATER DIVISION,

Defendants.

On Bill of Complaint
Before the Special Master, Hon. Eugene E. Siler, Jr.

PLAINTIFF'S RESPONSE TO DEFENDANTS' JOINT MOTION IN LIMINE TO PRECLUDE MISSISSIPPI FROM ARGUING THAT THERE ARE TWO AQUIFERS AT ISSUE

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I. Introduction

Defendants' Joint Motion in Limine to Preclude Mississippi from Arguing That There Are Two Aquifers at Issue (Dkt. No. 78; "Motion") requests that the Special Master "prohibit Plaintiff, State of Mississippi, Plaintiff's witnesses, and Plaintiff's counsel from testifying, introducing evidence, inquiring on cross-examination, or otherwise arguing that there are two aquifers at issue in this case, rather than one." Motion at 1. Defendants' Motion seeks to avoid development of an accurate, complete, and detailed scientific record relevant to this original action on a matter of first impression.

As the United States Geological Survey ("USGS") has acknowledged, the complexity of naturally created groundwater systems often makes clear articulation of the key hydrogeologic concepts difficult and confusing. *See generally* Exhibit 1 (R. L. Laney and C. B. Davidson, USGS Open-File Report 86-534, *Aquifer-Nomenclature Guidelines* (1986)). This is certainly the case when the relevant geographic area hosts the interface of two separate geologic formations with different hydrogeologic constituents formed millions of years ago.

Mississippi has not "reversed course" as Defendants assert. Instead, Mississippi simply believes the Special Master should hear *scientific evidence* relating to *all* of the formations that are present in the areas of southwestern Tennessee and northwestern Mississippi. And most importantly, the outcome of this case should focus on the *groundwater* at issue, regardless of the aquifer(s) in which that water has resided within Mississippi's borders for thousands of years.

II. Argument

There is no doubt that the groundwater terminology used in this case has not always been as precise and consistent as it could have been. The problem arises from the fact that "[a]quifers do not lend themselves to brief, neat, simple definitions." Ex. 1, p. 3. In fact, "[t]he term aquifer probably has more shades of meaning than any other term in hydrology. It can mean different things to different people and different things to the same person at different times." *Id*. at 4-5. Beyond this, "[t]he variety of ways in which aquifers have been named is one of the causes of confusion associated with aquifer nomenclature," and this confusion has been further "compounded by the various scales or hydrologic investigations." *Id.* at 17.

In this case, the parties have stipulated that "aquifer" means "a formation, a group of formations or part of a formation that contains sufficient saturated, permeable material to yield usable quantities of water to wells and springs." Plaintiff's and Defendants' Joint Statement of Stipulated and Contested Facts (Dkt. No. 64) at S-17 (page 102). Based on this definition, "aquifer" is a term that can be used to refer to a single formation/aquifer; *or* used to refer to a group of formations/aquifers.

Defendants assert that there is a single aquifer at issue, encompassing the entirety of the Mississippi Embayment, but Mississippi simply wants the record to be clear that the "Aquifer" to which Defendants refer is made up of a *group* of different formations and aquifers, including the "Sparta Sand" and the "Memphis Sand."

The Sparta Sand is recognized in scientific literature as an aquifer; and the Memphis Sand is recognized in scientific literature as an aquifer. They are aquifers (or sub-units) within the Middle Claiborne aquifer system, and are sometimes referred to *collectively* as the "Memphis Sand Aquifer," the "Sparta Sand Aquifer," the "Memphis Sparta Aquifer," and the "Middle Claiborne Aquifer."

By way of example, attached as Exhibit "2" is United States Geological Survey ("USGS") Scientific Investigations Map 314 (Schrader, T. P. 2007) ("Map 314"), entitled "Potentiometric Surface in the Sparta-Memphis Aquifer of the Mississippi Embayment." This document—which has been identified by both Plaintiff and Defendants as a hearing exhibit—explains that what it refers to as "the Sparta-Memphis Aquifer" is actually two aquifers: the "Sparta aquifer" and the "Memphis aquifer." *Id*. ("Herein, the sand layers within the Sparta Sand and Memphis Sand that comprise *the Sparta aquifer* and *the Memphis aquifer* will be referred to as the Sparta-Memphis aquifer.") (footnote omitted; emphasis added).

In the upper left-hand portion of Map 314 is “Table 1. Hydrogeologic units and their correlation across the states within the Mississippi Embayment,” which reflects that the “Memphis Sand” is present in Tennessee (and not in Mississippi) and that the “Sparta Sand” is present in Mississippi (and not in Tennessee). Map 314 explains that near the Tennessee-Mississippi border there is a “facies” change in the Middle Claiborne geological formations. Map 314 describes this as follows:

> In the southern part of the Mississippi embayment (south of about 35 degrees north latitude), the Sparta Sand of Claiborne Group (herein referred to as the Sparta Sand) is composed of a sequence of alternating sand and clay beds between the massive clays of the confining units of the overlying Cook Mountain Formation of Claiborne Group and the underlying Tallahatta Formation of Claiborne Group in Alabama, Cane River Formation of Claiborne Group in Arkansas and Louisiana, and the Zilpha Clay of Claiborne Group in Mississippi (table 1). In Alabama, the Lisbon Formation of Claiborne Group is equivalent to the Sparta Sand. In the northern Mississippi embayment (north of about 35 degrees north latitude), the Memphis Sand of Claiborne Group (herein referred to as the Memphis Sand) (Sparta Sand equivalent) is between the confining units of the overlying Cook Mountain Formation of Claiborne Group and the underlying Flour Island Formation of Wilcox Group in Arkansas, Missouri, and Tennessee and the Tallahatta Formation of Claiborne Group in Kentucky. At about 35 degrees north latitude, there is a transition zone where the Cane River Formation of Claiborne Group in Arkansas and the Zilpha Clay of Claiborne Group in Mississippi have a facies change or pinch out. The sequence of the Sparta Sand, Cane River Formation or Zilpha Clay, and the Carizzo Sand of Claiborne Group merges into the Memphis Sand at approximately 35 degrees north latitude.

Id.

Similarly, Exhibit 3 is a 2016 USGS report[1] that contains a table identifying the "Middle Claiborne aquifer" as a "Regional hydrogeologic unit" that includes the "Sparta aquifer" in Northern Mississippi and the "Memphis aquifer" in West Tennessee.

The varying labels applied to these formations separately and/or collectively have led to confusion, both in scientific publications and, unfortunately, in this proceeding, where the parties and various witnesses and counsel have, at times, referred to the Sparta aquifer and the Memphis aquifer separately and sometimes collectively, using a hodge-podge of terms. Inconsistencies and/or confusion even exist currently among Defendants' experts in this proceeding. MLGW's expert David E. Langseth states that the aquifer at issue is the "Memphis/Sparta Sand Aquifer (MSSA)," which Langseth defines as "[t]he aquifers of the Middle Claiborne, Lower Claiborne, and Upper Wilcox units, represented by layers 5-10 in the US Geological Survey (USGS) Mississippi Embayment Regional Aquifer Study (MERAS) model . . . ." Ex. 4 (excerpts from the June 27, 2017, report of David E. Langseth) at 4. Tennessee's experts, however, state that the aquifer at issue is the "Middle Claiborne aquifer." *See, e.g.*, Ex. 5 (excerpts from the June 30, 2017, report

[1] C. J. Haugh, USGS Scientific Investigations Report 2016-5072, *Evaluation of Effects of Groundwater Withdrawals at the Proposed Allen Combined-Cycle Combustion Turbine Plant, Shelby County, Tennessee* (2016).

of Brian Waldron) at 2 ("The Middle Claiborne aquifer will be the geologic name applied in this report to represent the Memphis aquifer and the Sparta aquifer.")

In the June 30, 2017, Report of Richard Spruill, one of Mississippi's experts, Dr. Spruill framed his report around what he called the "Sparta-Memphis Sand, also known as the Middle Claiborne Aquifer or the Memphis Aquifer," but identified the Sparta Sand in Mississippi as a separate formation within the larger Middle Claiborne geological formation, and acknowledged its hydrogeological connection with the upper part of the separate Memphis Sand. Ex. 6 (excerpts from June 30, 2017, Report of Richard K. Spruill) at 1-2, 14-16. Dr. Spruill addressed this further in his deposition, including during the following exchange with defense counsel:

> Q. Do you understand the names "Memphis Sand" and "Sparta Sand" as used at various times in this case are both referring to the same aquifer?
>
> A. I think the "Memphis Sand" and "Sparta Sand" are often used interchangeably, but there are regional differences in the two.…
>
> …
>
> A. They are part of a single geological formation. The Sparta Sand is not the same unit as the Memphis Sand in terms of its thickness and its areal distribution. They are the part of the same hydrostratographic unit.
>
> Q. If I talk about the "Middle Claiborne," you'll understand that name is referring to the entire geologic formation that encompasses what you are referring to, both the Sparta Sand and the Memphis Sand, correct?
>
> A. I think it is really important to say which geographic area we are talking about and make that distinction. Generally I would agree with what you said.

Ex. 7 (excerpts from the September 28, 2017, deposition of Richard K. Spruill) at 8-11.

Notably, Defendants do not suggest that the distinctions between the Sparta Sand and Memphis Sand are not scientifically accurate. Instead, Defendants rely entirely on an alleged admission by Mississippi in response to a request for admissions served early in the discovery in this original proceeding. While this response is the basis for Defendants' arguments that Mississippi should be barred from offering genuine scientific evidence, Defendants' Motion recites only a portion of it. Mississippi's actual response (with the only language quoted by Defendants in their Motion in **bold underlined font**) is set forth below:

> **REQUEST NO. 1:** The Aquifer underlies several states including Mississippi, Tennessee, and Arkansas.
>
> **RESPONSE:** Mississippi objects to Request No. 1 because it improperly defines the "Aquifer" as "the underground hydrogeologic units identified in paragraphs 15 and 41 of the Complaint," and conflates the natural groundwater movement and storage in a deep confined geological formation within each state's borders with generalized geology to erase state boundaries and sovereignty to natural resources residing within their territory under natural conditions. (See Defendants' "Definitions and Instructions," at paragraph 14.) Mississippi's claims relate solely to groundwater collected and stored in the Sparta Sand within Mississippi and its specific hydrogeology, not in multiple "hydrogeologic units." Further, the proposed definition and Request No. 1 are built on a false premise, as they fail to distinguish between (1) the sandstone geological formation known as the "Sparta Sand within Mississippi territory," and (2) the water naturally collected and stored in Mississippi in the Sparta Sand formation. Mississippi, therefore, denies Request No. 1.

> Without waiving its objection, Mississippi states **<u>that the general geologic formation known as the Sparta Sand underlies several states, including Mississippi, Tennessee, and Arkansas</u>**; and avers that the groundwater at issue in this case underlies and is confined in Mississippi only under natural conditions, and is an intrastate natural resource.

Obviously, this response does not constitute an agreement to Defendants' definition of the "Aquifer at issue" in this original proceeding. Mississippi did not waive its objection to Defendants' definition, and following the Federal Rules of Civil Procedure, it acknowledged some undefined existence of the broadly-defined Sparta Sand formation in the three listed states, wholly reaffirming its position that the issue is the groundwater itself.

In any event, Mississippi does not deny that its pleadings, briefs, and experts have frequently referred to the Memphis Sand and the Sparta Sand collectively, but the Court must be made aware of the existence of and differences between the Sparta Sand and Memphis Sand through the presentation of scientific evidence. Defendants will certainly not be surprised or prejudiced, given that their own exhibits recognize distinctions between the two formations. The Special Master may eventually conclude that the Memphis Sand and the Sparta Sand should be considered a single aquifer (e.g., the Middle Claiborne aquifer system), but the Special Master's decision should be a fully informed one. And regardless, it is imperative that the threshold legal issue remain focused on the *groundwater* at issue.

III. Conclusion

For the foregoing reasons, Plaintiff requests that Defendants' Motion (Dkt. No. 78) be denied.

Dated: November 20, 2018

Respectfully submitted,

THE STATE OF MISSISSIPPI

/s/ *C. Michael Ellingburg*
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CERTIFICATE OF SERVICE

Pursuant to Paragraph 3 of the Special Master's Case Management Plan (Dkt. No. 57), I hereby certify that all parties on the Special Master's approved service list (Dkt. No. 26) have been served by electronic mail, this the 20th day of November, 2018.

/s/ C. Michael Ellingburg
C. Michael Ellingburg

Counsel for Plaintiff

AQUIFER-NOMENCLATURE GUIDELINES

U.S. GEOLOGICAL SURVEY
Open-File Report 86–534

AQUIFER-NOMENCLATURE GUIDELINES

By Robert L. Laney and Claire B. Davidson

U.S. GEOLOGICAL SURVEY
Open-File Report 86–534

Reston, Virginia
November 1986

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

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PREFACE

With the advent of the Regional Aquifer-System Analysis (RASA) Program in the late 1970's, flow systems were studied over much larger areas than typically had been done in previous investigations. Procedures for naming aquifers that were used at the local level without difficulty were not applicable in some of the RASA studies covering several states. Discussions involving these problems of nomenclature made more apparent than ever, the need for guidelines in designating and naming aquifers. The development of the guidelines in this report provides an opportunity not only to consider the nomenclature problems that have been raised by the RASA studies, but also to provide more uniform procedures to designate and name aquifers at all levels and scales of investigations. The discussions, suggestions, criticisms, and encouragement of many hydrologists in the Water Resources Division were essential ingredients in the preparation of the guidelines. In weighing these various--and sometimes strongly differing--opinions, we attempted to write guidelines that are definitive, that cover a broad spectrum of concerns of hydrologists in the Division, and that remain flexible enough to address nomenclature problems in various hydrogeological settings throughout the country. The guidelines should be considered subject to modification as use and future needs dictate. Written suggestions for such modifications are welcome.

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CBD

TABLE OF CONTENTS

ILLUSTRATIONS

Page

AQUIFER-NOMENCLATURE GUIDELINES

By

Robert L. Laney and Claire B. Davidson

ABSTRACT

This report contains guidelines and recommendations for naming aquifers to assist authors of hydrogeological reports in the United States Geological Survey, Water Resources Division. The heirarchy of terms that is used for water-yielding rocks from largest to smallest is aquifer system, aquifer, and zone. If aquifers are named, the names should be derived from lithologic terms, rock-stratigraphic units, or geographic names. The following items are not recommended as sources of aquifer names: time-stratigraphic names, relative position, alphanumeric designations, depositional environment, depth of occurence, acronyms, and hydrologic conditions. Confining units should not be named unless doing so clearly promotes understanding of a particular aquifer system. Sources of names for confining units are similar to those for aquifer names, i.e., lithologic terms, rock-stratigraphic units or geographic names. The report contains examples of comparison charts and tables that are used to define the hydrogeologic framework. Aquifers are defined in 11 hypothetical examples that characterize hydrogeologic settings throughout the country.

INTRODUCTION

An essential requirement of hydrologists in evaluating the hydrologic properties of a segment of earth materials is to define and map hydrogeologic units--aquifers and confining units--which are determined on the basis of relative permeability. Discussion of the hydrogeologic units is facilitated by individual designations. Determinations of hydrogeologic units are based on indirect methods--knowledge of the geologic materials (geologic mapping, surface geophysical surveys, borehole geophysical logs, drill-cuttings and core descriptions, and so forth) and hydrologic testing (aquifer tests, laboratory permeability tests on core samples, and so forth). The physical properties of all rock units will change if traced laterally and vertically. The rock units are broken by unconformities and faults, which may or may not affect the flow of ground water. Therefore, the process of designating and naming aquifers and confining units is a somewhat subjective undertaking, and if not thoroughly documented, can lead to confusion. Guidelines for naming aquifers can help avoid some of the confusion and problems associated with hydrogeologic studies if the guidelines are straight forward to apply, flexible, and applicable to studies of a variety of scales from site-specific to regional. The guidelines that follow include discussions of the terminology of aquifer nomenclature, the definition of the hydrogeologic framework, the recommended procedures for naming aquifers, and examples of naming aquifers.

These guidelines have resulted from numerous discussions on the subject of aquifer nomenclature among hydrologists in the Water Resources Division of the U.S. Geological Survey. Although many hydrologists in the Division have

contributed to the discussions of the problems of aquifer nomenclature, a few have presented their ideas in writing for colleagues to read and criticize. In this regard, we wish to thank Hayes Grubb, Richard Johnston, Donald Jorgensen, James Miller, and Paul Seaber. Although unanimous agreement on these proposals was not achieved, the exercises provided an extremely useful purpose in creating additional thought and discussion. Without these exchanges of ideas, the writing of these guidelines would have been a much more difficult task.

TERMINOLOGY OF AQUIFER NOMENCLATURE

Aquifers do not lend themselves to brief, neat, and simple definintions; therefore, a flexible heirarchy of terms is used in these guidelines. The terms that are used for water-yielding rocks from largest to smallest are

aquifer system (Poland and others, 1972),

aquifer (Lohman and others, 1972), and

zone (R. H. Johnston, written commun; 1985, Miller, 1986).

Parallelism between the heirarchy of terms for water-yielding rocks and rock-stratigraphic terms--aquifer system (group), aquifer (formation), and zone (member)--should be avoided because water-yielding rocks can cross the boundaries of geologic units, or constitute only part of a geologic unit. The scale of the study also may determine the best usage. For example, at the local scale an aquifer system could be defined totally within a single formation, and at the regional scale a formation or group could be totally within and only a part of a single aquifer or an aquifer system. Again, the guidelines for aquifer nomenclature must remain flexible to meet a variety of hydrogeologic scales and settings.

A brief discussion of the terms aquifer, aquifer system, zone, and confining unit is provided here to give authors a common reference base. Although complete agreement on these definitions has not been achieved, the terms are adequate to transfer knowledge from authors to readers of reports. It is not the purpose of these guidelines to formally redefine the terms or to define new terms to take their place.

Aquifer

The term "aquifer" probably has more shades of meaning than any other term in hydrology (Freeze and Cherry, 1979, p. 47). It can mean different things to different people and different things to the same person at different times. Meinzer (1923) defined an aquifer as:

> "A rock formation or stratum that will yield water in sufficient quantity to be of consequence as a source of supply is called an 'aquifer,' or simply a 'water-bearing formation,' 'water-bearing stratum,' or 'water-bearer'........It is water-bearing not in the sense of holding water but in the sense of carrying or conveying water."

Lohman and others (1972) refined Meinzer's definition of an aquifer as:

> "A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs."

Both of these definitions imply that the aquifer is bounded by or is included within the formation(s) (or stratum), but the concept of the aquifer extending across formational boundaries is not indicated explicitly. In many local studies covering a few ten's to a few hundred square miles, the aquifer and the formation may be the same. In these studies, few problems may exist in defining the aquifer. However, since the late 1970's, studies of regional aquifers that may cover hundreds of thousands of square miles have been made under the Regional Aquifer-System Analysis (RASA) Program. Results from several of the RASA studies have shown that regional aquifers may include numerous formations and rock types and that the aquifers cut across formational and lithologic boundaries so that no one formation is completely representative of the aquifer. In studies of regional scope, the shape and the boundaries of the permeable rocks that form the aquifer have greater importance to understanding the flow system than do the individual formational boundaries. A definition that places less emphasis on the formal term "formation" (see North American Commission on Stratigraphic Nomenclature, 1983) and more on "permeable rocks" has merit. For example, aquifer is defined in the Glossary of Geology (Bates and

Jackson, 1980) as:

> "A body of rock that is sufficiently permeable to conduct ground water and to yield economically significant quantities of water to wells and springs."

Regardless of the fine points in any definition, delineating permeable rocks should be the major goal of hydrologists in mapping and describing an aquifer. By the same token, detailed knowledge of the stratigraphic units and post-depositional processes, such as solution, cementation, folding, and faulting, are essential in determining where the boundaries of the aquifer are located and in understanding the flow system. In addition, hydraulic properties (hydraulic conductivity and storage coefficient) throughout the aquifer usually are not determined directly but are estimated by indirect means, such as aquifer tests, analyses of drill cuttings and cores, borehole geophysical logging, and surface geophysical surveys. In many situations, hydrologic estimates and extrapolations can be made on the basis of rock type alone without any determination of hydrologic properties. For example, a wide-spread, thick clay separating two sand units tentatively could be designated as a confining unit on the basis of geologists' logs and borehole geophysical logs alone without any hydrologic data.

Aquifer System

Poland and others (1972) defined aquifer system as:

> "A heterogeneous body of intercalated permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more permeable beds (aquifers) separated at least locally by aquitards (confining units) that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system."

The definition could be more general if the term "aquifers" were used in place of "permeable beds." "Bed" implies a single stratigraphic unit, whereas, the individual aquifer could include or cross many "beds". "Confining unit" should be used instead of "aquitard" because the definition of confining unit is broad enough to include varying degrees of "leakiness."

The heirarchy of aquifer and aquifer-system names may not always be consistent in practice. Because of differences in scales of investigations, individual aquifers may be combined into a single aquifer system, which may be only a part of another aquifer system over a larger area. Authors have the responsibility to explain these relationships clearly with comparison charts and descriptions in the text.

Zone

The term zone may be used to subdivide an aquifer for the purpose of delineating a particular hydrologic characteristic that is not typical of the entire aquifer. For example, the "Fernandina permeable zone" is a high-permeability subunit of the Lower Floridan aquifer (Miller, 1986, p. B70). The zone consists of vuggy, locally cavernous limestone and is traceable for as much as 100 miles in coastal Georgia and Florida. The permeability of the zone greatly exceeds that of most of the Lower Floridan aquifer.

Confining unit

Confining bed was defined by Lohman and others (1972, p. 5) as:

> " . . . . a term which will now supplant the terms "aquiclude," "aquitard," and "aquifuge" in reports of the Geological Survey and is defined as a body of "impermeable" material stratigraphically adjacent to one or more aquifers. In nature, however, its hydraulic conductivity may range from nearly zero to some value distinctly lower

than that of the aquifer. Its conductivity relative to that of the aquifer it confines should be specified or indicated by a suitable modifier such as slightly permeable or moderately permeable."

Although the Lohman and others (1972) definition of "confining bed" is descriptive and should be used, the term "confining unit" is more general and appropriate than "confining bed" especially where more than a single bed makes up the confining unit. The term "bed" is not correct usage for a thick sequence of stratigraphic units that could be of member or formation rank. Bed is particularly inappropriate when used for intrusive igneous rocks beneath an aquifer. The term "bed" has a formal definition in the 1983 North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983; see article 26) and should not be used in definitions of aquifer nomenclature.

Many confining units are leaky and in some areas may, under natural conditions, contribute significant amounts of water to the aquifers they confine, and even larger quantities of water as heads are lowered in the aquifer by pumping. In areas where withdrawals from aquifers have caused large declines in head, considerable amounts of water may be derived from water stored in the confining unit. Poland and others (1972, p. 2) retained the terms "aquiclude" and "aquitard" in their definitions related to studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal. An aquiclude was defined as a body of saturated but relatively impermeable material that is characterized by very low values of "leakance" (the ratio of vertical hydraulic conductivity to thickness) and transmits negligible inter-aquifer flow. An aquitard is a saturated poorly permeable bed that has values of leakance that range from relatively low to relatively high. Where an aquitard is sufficiently thick, it may form an important ground-water storage unit.

In reports of the Geological Survey, the general term "confining unit" is preferable to aquitard, aquiclude, and aquifuge, as was recommended by Lohman and others (1972). Estimation of the "leakiness" of the confining unit should be discussed if this hydrologic information is available.

Terms to be avoided

The use of terms that are intended to be synonomous with "aquifer" or "aquifer system" should be avoided. Terms such as "hydrofer" or "aquiformation" should not be used in lieu of aquifer; "aquigroup" should not be used in place aquifer system. The term "aquifer" may be less precise than we would like, but it has been widely used and accepted in the hydrologic literature since it was originally defined. Coining new terms for aquifer and aquifer system that either are synonyms or defined with slightly different meaning is not an advancement--it only creates confusion especially among nonhydrologists. Use of the term "aquiformation" also infers an equivalence between aquifer and formation that is not always correct.

DEFINITION OF THE HYDROGEOLOGIC FRAMEWORK

In hydrogeologic studies, as in purely geologic investigations, the orderly, consistent designations of pertinent parts of the geologic framework is essential to a clear reporting and understanding of the study results. In ground-water studies, this involves definition and correlation of water-yielding rock materials, and relating those rock materials to established rock-stratigraphic units. Geological Survey authors of reports on ground-water resources are required to follow the same rules and guidelines for designating rock-stratigraphic units as are authors of purely geologic reports, that is, they must follow the guidelines and rules in the North

American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). The authors of ground-water reports, however, have an additional requirement to identify significant water-yielding parts of the geologic framework. Commonly, the water-yielding parts do not correspond exactly to named geologic units and, therefore, present additional nomenclatural problems. Although exhaustive systematic guidelines for the complex task of naming geologic units have been developed over several decades (North American Commission on Stratigraphic Nomenclature, 1983), there are no comparable guidelines for naming water-yielding units. [See, for example, the 5th edition of "Suggestions to authors of the reports of the U.S. Geological Survey" (U.S. Geological Survey, 1958), which devoted 6 lines to the subject (p. 87); the 6th edition (U.S. Geological Survey, 1958), 21 lines (p. 156); and the "Water-Resources Division Publications Guide" (Finch and Aronson, 1982, p. 211-213.] The proper designation of hydrogeologic units involves the consistent use of ground-water terms as well as actual naming of the units.

One of the first considerations in describing an aquifer in a report is mappability. The aquifer should be mappable at map scale used in the report of the study area. Exceptions to this rule may occur in areas where thin, highly transmissive aquifers could not be easily mapped at the principal map scale of the study but would still be important hydrologically. The report must contain comparison charts, maps of the top, thickness, and geographic extent of the aquifers, and hydrogeologic cross sections. Hydraulic characteristics should be discussed to show how the aquifer differs from the underlying and overlying confining units.

If the author believes that additional information on the hydrologic characteristics of the aquifer in the third dimension is necessary a "type area" or "type locality" and (or) a "type well" can be described. Several surface exposures and wells may be required to describe the characteristics of the aquifer if the hydrologic properties of the aquifer change greatly vertically and laterally. In this case, selected surface exposures and wells can be used to illustrate important hydrologic aspects of the aquifer. For example, the surface exposures can show effects of fracturing or solution, grain size, bedding thickness, faulting, folding, and so forth, all of which may affect movement and storage of ground water. Borehole geophysical logs, cuttings and core descriptions, driller's and geologist's logs for wells can be used to illustrate hydrologic properties in the subsurface.

A comparison chart is one of the most essential parts of a report that involves a description of a ground-water flow system and aquifer names. The comparison charts consist of three major components:

(1) A correlation chart that shows rock- and time-stratigraphic (geologic) units for the water-bearing materials described in the report.

(2) A comparison of hydrogeologic units to layers used in digital flow model (if one is used).

(3) A comparison of hydrogeologic units of the report with those in previous reports.

The amount of detail in the comparison chart will be determined by the scale and complexity of the investigation. If the report contains only a few geologic and hydrogeologic units, all of the comparisons may be shown in one illustration. For complicated investigations that involve many geologic and hydrogeologic units, two or three illustrations may be required to show the comparisons.

An example of a comparison chart that shows the relation of geologic units, hydrogeologic units and model layers is shown in figure 1. Figure 2 shows a comparison of geologic and hydrologic units with those in previous reports. A chart like that in figure 2 is especially important in reports where aquifers are redefined and renamed. Figure 3 shows an example of a correlation chart where the hydrogeologic units are made up of many rock-stratigraphic units. Unlike the chart shown in figure 1, the hydrogeologic units are on the left side and the rock-stratigraphic units are combined on the right side of the chart. This chart emphasizes primarily hydrogeologic units and secondarily rock-stratigraphic-units, although considerable analysis of rock-stratigraphic data from throughout the study area was required to develop the chart. This analysis of time-stratigraphic units and rock-stratigraphic units in a correlation chart should be shown as a separate illustration because of the great number of rock-stratigraphic units to be considered. The comparison chart should make completely clear to the reader the relationships of the hydrogeologic units to the geologic units (and to equivalent layers in the computer flow models (if one is included in the report).

GEOLOGIC UNIT

Erathem	System	Series	Stratigraphic unit	Thickness (feet)	Lithology	Aquifer
CENOZOIC	QUATERNARY	Holocene	Unnamed alluvial lake and windblown deposits	0-75	Alluvium, freshwater marl, peats and muds in stream and lake bottoms. Also, some dunes and other windblown sand	Shallow aquifer
					unconformity	
		Pleistocene	Pamlico Formation and marine and estuarine terrace deposits	0-75	Mostly marine quartz sand, unconsolidated, and generally well graded. Also, some fluviatile and lacuatrine sand, clay, marl, and peat deposits.	
					unconformity	
	TERTIARY — UPPER	Pilocene	Jackson Bluff Formation	0-75	Marine sands, argillaceous, carbonaceous, and sandy shell marl. Some phosphatic limestone.	
			Alachua Formation	0-100	Nonmarine interbedded deposits of clay, sand, and sandy clay, much of unit is phosphatic, *base characterized by rubble of phosphate rock and silicified limestone residum in a gray and green phosphatic clay matrix*	
		Miocene	Fort[1] Preston Formation	0-100	Nonmarine fluviatile sand, white to gray variegated orange, purple and red in upper part, fine- to coarse-grained to pebbly, clayey, crossbedded	
			Hawthorn Formation	0-300	Marine interbedded sand, cream, white and gray, phosphatic, often clayey, clay, green to gray and white, phosphatic, often sandy, dolomite cream to white and gray, phosphatic, sandy, clayey, and some limestone, hard, dense, in part sandy and phosphatic. Tends to be sandy in upper part and dolomitic and limey in lower part	
					unconformity	
		Oligocene	Suwanee Limestone	0-150	Marine limestone, very pale orange, finely crystalline, small amounts of silt and clay	Floridan aquifer system
					unconformity	
	TERTIARY — LOWER	Eocene — Upper	Ocala Ls[2] — Upper[3] member	0-325	Marine limestone, cream to white, soft, granular, highly porous, coquinal, often consists almost entirely of tests of formanifers, cherty in places	
			Ocala Ls[2] — Lower[4] member		Marine limestone, cream to tan and brown, granular, soft to firm, porous, highly fossiliferous; lower part at places is dolomite, gray and brown, crystalline, sacchoroidal porous	
					unconformity	
		Eocene — Middle	Avon Park Formation	600-1600	Marine limestone, light to brown to brown, finely fragmental, poor to good porosity, highly fossiliferous (mostly foraminifers), and dolomite brown to dark brown, slightly porous to good porosity, crystalline, saccharoidal, both limestone and dolomite are carbonaceous or peaty, gypsum is present in small amounts	
		Eocene — Lower	Oldsmar Formation	300-1350	Marine limestone, light brown to chalky, white, porous, fossiliferous, with interbedded brown, porous, crystalline dolomite, minor amounts of anhydrite and gypsum	
		Paleocene	Cedar Keys Formation	500-2200	Marine dolomite, light gray, hard, slightly porous to porous, crystalline, in part fossiliferous, with considerable anhydrite and gypsum, some limestone	
					unconformity	
MESOZOIC	CRETACEOUS		Upper and Lower Createaceous rocks	1500-?	Mostly marine Upper Cretaceous carbonate and evaporate rocks, sands and shales, thin Lower Cretaceous clastic section in some of area	
					Coastal Plain bedrock	
PALEOZOIC and PRECAMBRIAN			Devonian to Precambrian (?) rocks	Basement rocks	Marine Devonian, Silurian, and Ordovician quartose sandstone and dark shale, lower Paleozoic (?) or Precambrian (?) rhyolite, tuff, and agglomerate	

[1]Usage of Bureau of Geology, Florida Department of Natural Resources
[2]Ocala Group of Bureau of Geology, Florida Department of Natural Resources
[3]Crystal River Formation of Ocala Group
[4]Inglis Formation and Williston Formation (older to younger) of Ocala Group

Figure 1.--Example of a chart showing comparison of geologic units, hydrogeologic units, and equivalent units in a digital ground-water flow model (from Tibbals, in press).

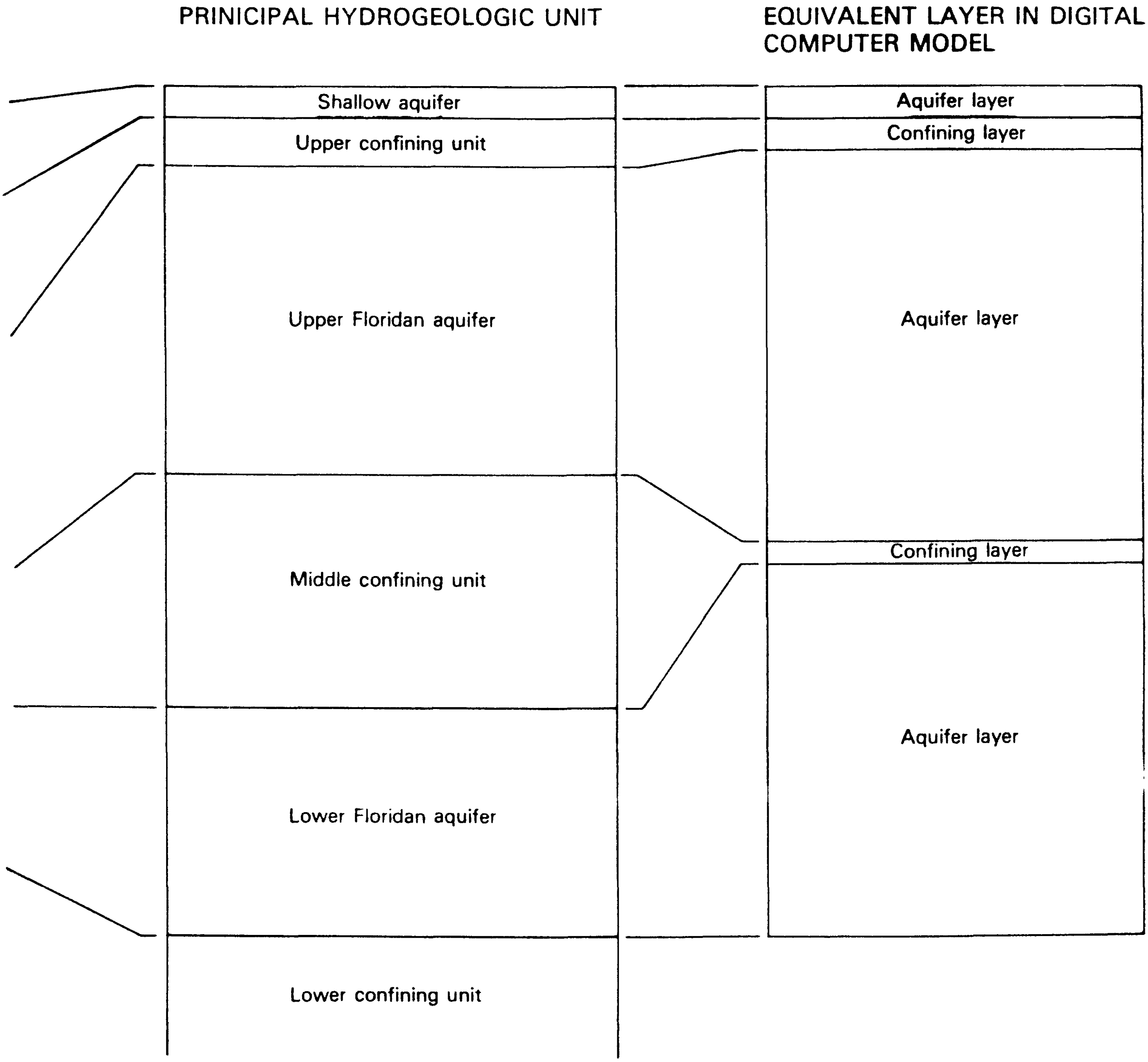


Figure 1.--Continued

EPOCH		Stringfield (1936)		Parker & others (1955)		Stringfield (1966)		Miller, in Franks (1982)		Miller (1982 a,c)		This Report	
		Formation	Aquifer	Formation	Aquifer	Formation	Aqaifer	Formation	Aquifer	Formation	Aquifer System	Formation	Aquifer System
MIOCENE	Middle	Hawthorn Formation		Hawthorn Formation	Where Permeable	Hawthorn Formation		Hawthorn Formation		Hawthorn Formation		Hawthorn Formation	
	Early	Tampa Limestone	Principal artesian formations	Tampa Limestone	Floridan aquifer	Tampa Limestone	Principal artesian aquifer	Tampa Limestone	Where Permeable	Tampa Limestone	Where Permeable	Tampa Limestone	Where Permeable
OLIGOCENE		Oligocene Limestone		Suwannee Limestone		Suwannee Limestone		Suwannee Limestone	Floridan aquifer	Suwannee Limestone	Tertiary limestone aquifer system	Suwnnnee Limestone	Floridan aquifer system
EOCENE	Late	Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone	
	Middle			Avon Park Limestone		Avon Park Limestone		Avon Park - Lake City Limestone		Avon Park - Lake City Limestone		Avon Park - Formation	
				Lake City Limestone		Lake City Limestone							
	Early					Oldsmnr Limestone		Oldsmar Limestone		Oldsmar Limestone		Oldsmar Limestone	
PALEOCENE								Cedar Keys Limestone		Cedar Kays Limestone		Cedar Keys Limestone	

Figure 2.--Example of chart showing comparisons of geologic and hydrogeologic units with those in previous reports (from Miller, 1986).

	GEOHYDROLOGIC UNIT	THICKNESS, IN FEET	LITHOLOGY AND HYDROLOGIC CHARACTERISTICS
	Western Interior Plains confining unit	0 to 6,000	Layer of very low permeability shales separated by layers of permeable limestones and sandstones. Leakage through layers of shales is low.
Ozark Plateaus aquifer system	Springfield Plateau aquifer	0 to 1,500	Permeable limestone, fractured and solutioned locally. Well yields range from 1 to 300 gallons per minute, but typical yields are of 5 to 10 gallons per minute.
Ozark Plateaus aquifer system	Ozark confining unit	0 to 1,500	Shale layers are very low permeability; however, at most locations thickness of shale layers is less than 20 feet. Thus, unit is moderately leaky.
Ozark Plateaus aquifer system	Ozark aquifer	0 to 4,000	Mostly dolostone with limestone and sandstone layers. Dolostone well fractured with very permeable zones of fractured and solutioned dolostone. Well yields range from 2 to 2000 gallons per minute, but typical yields are 200 to 400 gallons per minute.
Ozark Plateaus aquifer system	St. Francois confining unit	0 to 730	Shale, siltstone, dolostone and limestone are all of low permeability. Unit is leaky to slightly leaky.
Ozark Plateaus aquifer system	St. Francois aquifer	0 to 500	Fractured and permeable dolostone and sandstone. Well yields range from 1 to 500 gallons per minute, but typical yields are 50 to 200 gallons per minute.
	Basement confining unit		Mostly igneous and metamorphic rocks. Rocks are fractured and locally will yield small quantities of water to wells. No known aquifers beneath these rocks, thus it is the basal confining unit.

Figure 3.--Example of a chart showing comparison of geohydrologic units, rock-stratigraphic units, and time-stratigraphic units (modified from Jorgensen, written commun., 1986, and Jorgensen and others, in press).

ROCK-STRATIGRAPHIC UNIT	TIME-STRATIGRAPHIC UNIT
Marmaton Group, Cherokee Group Atokan rocks, Bloyd Shale, Hale Formation, Morrowan rocks, Pitkin Limestone, Fayetteville Shale, and Batesville Sandstone	Middle Pennsylvanian through Upper Mississippian (Chesterian)
Moorefield Formation, St. Louis Limestone, Salem Limestone, Warsaw Limestone, Boone Formation, (St. Joe Limestone Member), Keokuk Limestone, Burlington Limestone, and Fern Glen Limestone	Upper Mississippian and Lower Mississippian
Chouteau Group (Limestone) and Chattanooga Shale	Lower Mississippian and Upper Devonian
Clifty Limestone, Penters Chert, Lafferty Limestone, St. Clair Limestone, Brassfield Limestone, Cason Shale, Fernvale Limestone, Kimmswick Limestone, Plattin Limestone, Joachim Dolomite, St. Peter Sandstone, Everton Formation, Smithville Formation, Powell Dolomite, Cotter Dolomite, Jefferson City Dolomite, Roubidoux Formation, Gasconade Dolomite, (Gunter Sandstone Member), Eminence Dolomite, and Potosi Dolomite	Middle Devonian through uppermost Cambrian
Elvins Group Doe Run Dolomite, Derby Dolomite, Davis Formation	Upper Cambrian
Bonneterre Dolomite and Lamotte Sandstone	Upper Cambrian
Mostly igneous and metamorphic rocks	Precambrian

Figure 3.--Continued

Preparation of a comprehensive comparison chart requires a thorough search of the literature for all previous studies in the project area that contain rock-stratigraphic names and aquifer names. The comparison chart must contain the following items:

1) Headings entitled: Erathem, system, series, rock-stratigraphic unit, thickness, lithology, hydrogeologic unit, and hydrologic characteristics.
2) The geologic units that are pertinent to the hydrology under study.
3) The hydrogeologic units that the author is using and how they relate to geologic units and previously named hydrogeologic units.
4) A column that shows relations of hydrogeologic units to layers in the flow model, if one is included in the study.

Only the part of the geologic column that pertains to the hydrology under study should be discussed and shown in detail. The amount of discussion of the geology should be limited mainly to those aspects that affect the movement and storage of ground water. An exception would be a situation where the details of the stratigraphy were not well known prior to the hydrologic study, and as a result of determining the hydrogeologic units a clearer understanding of the stratigraphy was achieved.

Differences in opinions between hydrologists as to what should constitute the aquifer(s) and confining units(s) may still exist after the report is published. However, no uncertainty should exist as to what the author included in the definition of the aquifer(s) and confining unit(s) and the relationships to geologic units and hydrogeologic units in previous investigations.

NAMING AQUIFERS

Currently, within the Water Resources Division, aquifer names are derived from a variety of sources:

- o Rock-stratigraphic terms (Sparta aquifer).
- o Geographic features (High Plains aquifer; Floridan aquifer).
- o Time-stratigraphic terms (Cambrian-Ordovician aquifer).
- o Lithology (limestone aquifer).
- o Depth of occurrence ("500-foot" sand in the Memphis area).
- o Depositional environment (shallow marine aquifer, glacial aquifer).
- o Alphanumeric designations for model layers (A1 aquifer layer, C1 confining layer, etc.).
- o Relative position (upper carbonate aquifer).
- o Unusual locations (Clinton Street-Ballpark aquifer).
- o Unusual geologic features of rock exposures (bird's-nest aquifer).

The variety of ways in which aquifers have been named is one of the causes of the confusion associated with aquifer nomenclature. The problem is compounded by the various scales of hydrologic investigations. Until the advent of the RASA program, few ground-water studies were areally large enough to encounter the problems that arise when one attempts to extend local aquifer and stratigraphic nomenclature to a regional scale. The gradational changes that are commonplace in geologic materials complicate the work of hydrologists who are trying to define aquifers and related confining units. At the scale of a study concerning a few ten's to a few hundred square miles, gradations in the physical properities of the rocks are often not obvious. Generally, it is straightforward to apply names of rock-stratigraphic units to aquifers because of the relative uniformity of the rocks within the study area where a stratigraphic unit may make up the entire aquifer. At the scale of many of the RASA studies, the problem is that of differentiating regionally extensive units of relatively high or relatively low permeability within a group of rock units whose relations and variability are frequently complex, and whose names may change at political boundaries.

It is recommended that in reports of the Water Resources Division that involve hydrogeology, the author should consider first not naming aquifers. If aquifers are already named in the area and (or) if the extent of the aquifer is reasonably well known, aquifer names should be derived from the following sources:

1) Lithologic terms (sand and gravel aquifer).
2) Rock-stratigraphic names (Sparta aquifer after the Sparta Sand).
3) Geographic names (High Plains aquifer for the permeable parts of the Ogallala Formation and overlying and underlying hydrologically continuous deposits in parts of eight states; Floridan aquifer system for permeable parts of several Tertiary carbonate formations in the Southeastern United States).

It is further recommended that aquifer or aquifer-system names not be derived from the following sources:

1) Time-stratigraphic names (Cretaceous aquifer).
2) Relative position names (upper carbonate aquifer).
3) Alphanumeric designations for model layers (A1 aquifer layer, C1 confining layer, etc.).
4) Depositional environment (shallow marine aquifer, glacial aquifer, etc.).
5) Depth of occurrence ("500-foot" sand).
6) Acronyms (The first letter of each formation in a multiaquifer system).
7) Hydrologic condition ("principal artesian aquifer").

Each of these sources of aquifer names is discussed in the following sections.

Recommended Sources for Aquifer Names

Authors of reports on hydrogeology have the following options in dealing with aquifer nomenclature: (1) do not name the aquifers or (2) name the aquifers using lithologic, rock-stratigraphic, or geographic names. The water-bearing properties of rocks can be described in many investigations without naming aquifers. Each rock unit and its water-bearing properties can be described in comparison charts and tables. The principal difference between a report of this kind and one describing named aquifers would be in phraseology. Although this approach could be used in studies involving both formal and informal rock-stratigraphic names, it would have particular application in areas where no formal rock-stratigraphic-units had been designated and/or where both the stratigraphy and hydrology of the particular rocks are poorly known. There is an advantage to not cluttering up the literature with aquifer names in areas where the hydrogeology as not been studied in great detail, where the present study describes the area in only a cursory or reconnaissance fashion, or where the size of the study area is so small that only a small part of the aquifer is investigated. This option should be considered to avoid the unnecessary coining of new aquifer names.

If aquifers are to be named, lithologic names and (or) rock-stratigraphic names should be used to the extent that permeability distribution and hydrologic continuity permit. If in a larger area these terms are inappropriate, geographic names should be used. For example, in a local study where the aquifer consists of a single rock-stratigraphic unit, the name of the rock-stratigraphic unit may be used for the aquifer name. If, at a later time, another study was done that included a larger area than the first, a judgment would have to be made to determine if the rock-stratigraphic name was still appropriate. If the aquifer in the larger area still consisted of the same rock-stratigraphic unit, its name could be retained as the aquifer name. However, if the aquifer was made up of several units, none of which would be appropriate to name the aquifer, or if the aquifer extended across rock-unit boundaries, a name based on a geographic feature should be used. These relations should be shown clearly in the comparison charts of the report.

If an aquifer is named after a rock-stratigraphic unit or geographic feature, rules of priority should be followed. A thorough literature search should be made to avoid duplication of aquifer names. The name should be cleared through the Reston Geologic Names Unit, and the name should not be preempted by a rock-stratigraphic name.

Lithologic Names

Lithology-derived aquifer names are useful in some investigations to define water-bearing materials where formal rock-stratigraphic units do not exist. The adjectives for lithologic aquifer names may be based on lithologic terms--sand and gravel aquifer, granite aquifer, limestone aquifer, etc. If uncertainty exists about a lithologic term being consistent throughout the extent of the aquifer, a geographic name could be used. Lithologic names are especially useful for naming aquifers in glacial deposits. If several aquifers are discussed in a report describing ground water in glacial deposits, lithologic terms might be similar. In these situations, local geographic names may be more appropriate.

Rock-Stratigraphic Names

Rock-stratigraphic names may be used as the basis for aquifer names for studies that generally cover a state, or parts of a state and an adjacent state. At the scale of these studies, the rock-stratigraphic unit and the aquifer commonly are equivalent. In addition to the criteria for defining the hydrologic framework the following guidelines should be used, as appropriate, for assigning names and using or modifying existing aquifer names that are based on rock-stratigraphic names:

1) Through the use of comparison charts, maps, and cross sections, it must be shown clearly how much of the rock-stratigraphic unit is included in the aquifer. In some areas, aquifers have been named for, but consist of only a part of, the rock-stratigraphic unit. Geologic units in the coastal plain of Atlantic and Gulf coasts generally thicken in an oceanward direction, and the units may become less permeable in the same direction because of an increase in fine-grained materials in the sediments. Thus, the aquifer may thin as the formation thickens [the Tuscaloosa Formation (Group) and the Tuscaloosa aquifer of Alabama, for example]. Similar problems of the aquifer not corresponding with the rock-stratigraphic unit of the same name can exist at any scale when the formation name is automatically used for the aquifer name and little consideration is given to how much of the formation actually constitutes the aquifer.

2) The binomial name of the rock-stratigraphic unit should be shortened for use as the aquifer name:
   a) Madison aquifer, after the Madison Group
   b) Edwards aquifer, after the Edwards Limestone
   c) Sparta aquifer, after the Sparta Sand.

   The argument is made that including the full rock-stratigraphic name provides additional information (e.g., Edwards Limestone aquifer). If the aquifer is adequately described in the comparison table, the text, maps, and so forth, then it is redundant--and in many situations incorrect where additional rock types are included in the aquifer--to have the modifier in the aquifer name. In addition, including all the modifiers in some rock-stratigraphic names can result in long, awkward aquifer names. Lithologic modifiers for existing entrenched aquifer names should not be capitalized, e.g., Burnam limestone aquifer not Burnam Limestone aquifer.

3) Do not use the name of a rock-stratigraphic unit for an aquifer name unless the unit is part of the aquifer.

4) Aquifer names based on multiple stratigraphic units:

a) If an aquifer includes all or part of two superimposed rock-stratigraphic units, the aquifer name is hyphenated with the younger unit first; for example, the lower Hell Creek-Fox Hills aquifer consists of the lower part of the Upper Cretaceous Hell Creek Formation and underlying Fox Hills Sandstone. This usage conforms to map explanations, tables, sections, and the computerized Water Data and Storage Retrieval System (WATSTORE), which all show units in chronologic sequence youngest to oldest. However, an aquifer name consisting of units in order of decreasing age may be used if its use is entrenched in an area or has been used in legal terminology. For example, the oldest to youngest named Potomac-Raritan-Magothy aquifer in the Cretaceous Potomac Group and overlying Raritan and Magothy Formations is of longtime usage in New Jersey.

b) If an aquifer includes three or more superimposed rock-stratrigraphic units, the aquifer name may include all units youngest to oldest (hyphenated), or only the youngest and oldest units. For example, the Galena-Platteville aquifer that is used locally in Wisconsin is in the Galena Dolomite (youngest), Decorah Formation, and Platteville Formation. Giving an aquifer an appropriate geographic name would be a desirable alternative to a cumbersome hyphenated rock-stratigraphic name.

c) If the middle rock-stratigraphic unit is the primary aquifer, that name may be used, provided that the overlying and underlying stratigraphic units are clearly identified. For example, the Edwards aquifer in Texas is in the Georgetown Limestone (youngest), Edwards Limestone, and Comanche Peak Limestone.

d) An aquifer that includes many rock-stratigraphic units that are water-bearing and hydraulically connected vertically and laterally should have a name that is not based on any of the individual rock-stratigraphic names. A geographic name would be appropriate. For example, the Floridan aquifer system includes the Tampa Limestone, Suwanee Limestone, Ocala Limestone, Avon Park Formation, Oldsmar Formation, and part of the Cedar Keys Formation.

(5) An abandoned rock-stratigraphic name should not be used for an aquifer name; the newly assigned stratigraphic name should be used instead. However, if the usage of the abandoned name is entrenched in the area or is a legal term in State regulations, the author may use the term but should describe the stratigraphic change in the introduction of the report and show the correlation in a chart so that the reader is aware of the new terminology.

Geographic Names

Geographic names could be the basis for aquifer names where no rock-stratigraphic names are available, no single rock-stratigraphic name or combination of rock-stratigraphic names (or lithologic names) would be appropriate, or the use of previously named aquifers in small-area studies would not be appropriate or correct. Geographic names also include names of physiographic regions or subregions. In addition to geographic names, a regional aquifer name could be derived from a geologic structural feature (a basin, for example) that has relevance in the area underlain by the aquifer. Physiographic names should be from a well-known source, such as, N. M. Fenneman's map (1946), "Physical Divisions of the United States." The "High Plains aquifer" and the "Floridan aquifer system" are two examples of regional aquifer names that are derived from geographic names. Geographic names could be used for aquifers of subregional extent where the location of the aquifer might provide more meaningful information than its physical characteristics, and/or no rock-stratigraphic name is available for derivation of the aquifer name.

Non-Recommended Sources for Aquifer Names

Time-Stratigraphic Names

Time-stratigraphic boundaries do not necessarily coincide with rock-stratigraphic boundaries or other physical changes in the hydrologic characteristics of rocks and, as a result, should not be used as a basis for aquifer boundaries or naming individual aquifers. Aquifers have been named after time-stratigraphic terms; later studies and more detailed mapping have shown that some parts of the aquifer are older or younger than that of the time-stratigraphic unit in the aquifer name. For example, several years after the aquifer was originally named, the Tertiary limestone aquifer in the southeastern United States was found to contain Upper Cretaceous rocks. Another possible complication is that long-standing time-stratigraphic boundaries have been changed in this country to agree with boundaries developed under international geologic agreements (e.g., the change in the Miocene-Pliocene boundary from 10 to 5 million years). Also, terms such as "Cretaceous aquifers", are not strictly correct. The aquifer is not of Cretaceous age, but consists of rocks of Cretaceous age whose hydrologic properties are not now the same as when the rocks were first formed. "Aquifers in rocks of Cretaceous age" is correct and should be used instead.

Aquifer names based on time-stratigraphic names currently are in the literature and are commonly used--the Cambrian-Ordovician aquifer of the north-central United States, for example. Other aquifers in the country have similar time-stratigraphic names that are entrenched in local usage. The use of these names should be phased out in WRD reports where possible. Time-stratigraphic nomenclature should not be used for newly named aquifers, and existing time-stratigraphically based aquifer names should not be extended from local use to aquifers of regional scale.

Relative Position

If a layer of saturated permeable rock overlies another layer of saturated permeable rock--regardless of differences in lithology--they form one aquifer and should not be designated "upper and lower" aquifers. If they are separated at most locations by mappable distinctly less permeable material (confining units) they are two separate aquifers.

The terms "upper", "lower", and so forth may be used where parts of the aquifer are separated by confining units and the full extent of the aquifer or aquifer system is reasonably well known. For example, the Floridan aquifer system was described as the "Upper Floridan aquifer" and "Lower Floridan aquifer" in the part of the area where the two units are separated by a regional confining unit. In other parts of the area where the confining unit is not present, the term "Floridan aquifer system" is used. In reality, considering the definition of "aquifer system," it is also the "Floridan aquifer system" throughout the extent of the area, including places where the two parts are separated by the confining unit. When referring to parts of the same aquifer that have some distinctive difference use of the term "zone" is preferred. For example,

Use upper zone of the Chicot aquifer--not upper Chicot aquifer.

Use lower zone of the Chicot aquifer--not lower Chicot aquifer.

Alphanumeric Designations

Alphanumeric designations, such as, A1 aquifer layer, C1 confining layer, and so forth are useful in discussing layers of a numerical ground-water flow model; they should not, however, be used as aquifer names. A clear distinction must always be made in a report between the the real flow system and the simulated flow system. Illustrations such as figures 1 help differentiate these distinctions and relation.

Depositional Environment

Names based on depositional environment can be misleading and should not be used for aquifer names. For example, "shallow marine aquifer" may be totally unclear as to what it includes and means. Even if it is described as consisting of "sand deposited in a shallow sea", problems and additional confusion may arise if the rocks of the aquifer grade into hydrologically continuous deposits from a different depositional environment or into different rocks in a similar depositional environment. Likewise the term "glacial aquifer" may contain or be hydrologically continuous with other deposits or rocks that are not of glacial origin. Lithologic terms or geographic locations would be more appropriate.

Depth of Occurrence

Aquifers should not be named after depth of occurrence. The aquifer named after the "2,000-foot" sand may well be present at a depth of about 2,000 feet at a given location where it was named in a local study. On a regional scale, however, the sand may be present elsewhere at a greater or lesser depth and have no relationship to the name derived from the local study. Established local usage may require the continued use of these names at the local level, but the name should not be extended to studies of larger areas.

Acronyms

Aquifers or aquifer systems should not have acronyms for names, such as, an aquifer name derived from the first letter of each rock-stratigraphic unit that makes up the aquifer. In this situation, if many rock-stratigraphic units make up the aquifer, a geographic name unrelated to any of the rock-stratigraphic names should be used.

Hydrologic Condition

Terms such as water-table aquifer and artesian aquifer are not recommended because they are names that are based on hydrologic conditions that can change as outside stresses change (pumping, climatic change). Hydrologic conditions also can vary from place to place in the aquifer's area of occurrence. For example, an artesian aquifer can be dewatered by pumping, and an aquifer that is considered to be under artesian conditions within the study area may be under water-table conditions in a recharge area inside or outside the study area.

RECOMMENDATIONS FOR NAMING CONFINING UNITS

Confining units should not be named unless a clear-cut need exists for understanding a complex aquifer system. In studies where several aquifers and confining units are discussed, the confining units could be given individual names, but, a heirarchy of terms for confining units comparable to aquifer system, aquifer, and zone is not necessary. If names are applied to confining units they should be derived in a similar manner as aquifer names, that is, after lithologic terms, rock-stratigraphic names, or geographic names. If the confining unit consists of one rock-stratigraphic unit, the confining unit may be named after the rock-stratigraphic unit. If the confining unit consists of several rock-stratigraphic units, it could be given a hyphenated name of the youngest and oldest unit, or, probably more preferable, or geographic name.

A confining unit could be named after the aquifer it confines, but two potential situations may cause confusion if confining units are named in this manner. In the first situation, what name should be given to a confining unit that separates two aquifers? It confines both. A logical order of naming confining units should be followed. For example, confining units could be named after the aquifers they overlie. In areas where crystalline basement rocks or other rocks having low hydraulic conductivity form the lowest confining unit a name unrelated to an aquifer name should be chosen.

The term "basal confining unit" could be used for the lower-most confining unit of the known flow system.

In the second situation, if an aquifer is named after a rock-stratigraphic unit that forms all or a major part of an aquifer, this name should not be used to name the confining unit that overlies or underlies the aquifer. In other words, the confining unit should not be named after a rock-stratigraphic unit that is not part of the confining unit. For example, in western South Dakota, the upper part of the Minnelusa Formation is an aquifer named the Minnesula aquifer. This aquifer is overlain by a confining unit that consists of six formal rock-stratigraphic units. The confining unit should not be called the "Minnelusa confining unit" because the Minnelusa Formation is not a part of the confining unit. The options are not to name the confining unit, name it after an appropriate combination of rock-stratigraphic units that are in the confining unit, or name the confining unit after a geographic feature. The lower part of the Minnelusa Formation is a confining unit and could be named the "Minnelusa confining unit."

In summary, it is recommended that confining units not be named unless a serious potential exists for confusing such units in the text. If the confining units are named they could be named after the rock-stratigraphic unit or units that compose them, after the aquifers they confine, (unless the aquifers are named after rock-stratigraphic units), or after a geographic feature.

GENERAL PROCEDURES, STYLE, AND EXPRESSION

Cautions in using rock-stratigraphic names for aquifer names

The use of rock-stratigraphic names for aquifer names is simple in concept, but has some risk for confusion if not done carefully. When using a rock-stratigraphic name for an aquifer name, the author must make the distinction throughout the text and illustrations of the report between the rock-stratigraphic unit and the aquifer. In writing reports authors have a tendency (not necessarily incorrect) to shorten the name of both rock-stratigraphic and aquifer names after they have been described by their full name a few times. For example, if the Baker aquifer makes up a large part, but not all, of the Baker Formation, confusion may be caused by using the expression "The Baker is 450 feet thick south of the Possum River." Is this the Baker Formation or the Baker aquifer? If situations such as this arise, the term "aquifer" should always be included when discussing the aquifer.

Lithologic modifiers in rock-stratigraphic names should not be used in aquifer names. Not only will this avoid unnecessarily long names, it also will help keep clear the distinction between the aquifer and rock-stratigraphic unit. If an aquifer is made up largely of the Jacob Sand Member of the Blackjack Formation, the aquifer should be called the Jacob aquifer, not the Jacob Sand Member aquifer. Lithologic modifiers are often used in aquifer names because the author believes that the modifiers add additional information to the aquifer name. If the aquifer is clearly defined in the comparison charts there should be no problem in knowing what constitutes the aquifer. A reader who desires information on the characteristics of the water-bearing units in an area will know what makes up the aquifer, regardless of its name, after reading a comparison chart(s) that is clearly constructed. In addition, a single lithologic modifier may be incorrect if more than one rock type makes up the aquifer.

Descriptions of aquifers and rock-stratigraphic units should be clearly separated or distinguished in the text and illustrations. For example,

(1) Hydrologic information on potentiometric surface, storage coefficient, and specific yield, describes the aquifer not the rock-stratigraphic unit.

(2) Geologic information on dip, strike, plunge, and deposition of sediments describes the rock-stratigraphic unit, not the aquifer.

Terms such as porosity and permeability could refer to either the aquifer or the rock-stratigraphic unit.

Redefining and Renaming Previously Named Aquifers

A previously named aquifer can be redefined and renamed, and the approach is the same as naming an aquifer for the first time. All the guidelines that are given in the previous sections apply also to redefining and renaming aquifers. The comparison charts are particularly important in this endeavor, especially the one represented in figure 2 that shows the relation of the renamed aquifer(s) to the previously named aquifer(s). Redefining and renaming an aquifer should not be done casually or done just to change the name. However, no hard, fast rules will be given here as to what constitutes justification for redefining and renaming an aquifer, except that it should be the result of a thorough analysis of the hydrogeology of the area and represent an improvement in the understanding of the hydrology. Technical review should be used to judge the merit of the nomenclature changes. The work of Miller (1986) is an example of a detailed hydrogeological analysis that resulted in redefining and renaming the water-bearing units the Floridan aquifer system. In reality, all aquifer names are informal names (article 26, 1983 North American Stratigraphic Code) that might be changed with additional study. It is more important to represent clearly the hydrology of a particular area than to retain old or introduce new naming conventions.

Format Conventions For Aquifer Names

The following format conventions are recommended for reports of the Water Resources Division that name aquifers or contain discussions of aquifer names:

1) The terms aquifer, aquifer system, zone, and confining unit are not capitalized.
2) Terms such as sand and gravel aquifer, and limestone aquifer, etc., are not capitalized or hyphenated.
3) Adjective modifiers, except parts of formal geographic names, are not capitalized: Mississippi River alluvial aquifer.
4) Relative-position terms--i.e., upper, middle, and lower--are not capitalized. However, the terms may be capitalized if they represent parts of a regional aquifer system that are seperated by a major confining unit. For example, Miller (1986) formally divided the Floridan aquifer system into an Upper Floridan aquifer and a Lower Floridan aquifer in all Florida and parts of adjacent States.
5) Quotation marks are not used for aquifer names unless the term is a misnomer. The "500-foot" sand is in quotes because it is not at 500 feet below land surface everywhere. As mentioned in the section on nonrecommended criteria, depth of occurence should not be used for new aquifer names.

6) Usage of hydrologic and geologic terminology will vary depending on context and structure of the sentence, but certain distinctions between the two should be kept clear:

   a) Water from the Madison aquifer--not Madison water

   b) Wells completed in Madison Limestone (or aquifer)--not Madison wells

EXAMPLES OF DESIGNATING AND NAMING AQUIFERS

Examples of designating and naming aquifers are shown in figure 4. The examples are hypothetical and generalized for convenience, but they illustrate characteristics of hydrologic settings throughout the country. Even though most of the examples use rock-stratigraphic names, it should be remembered that the options for naming aquifers in order of consideration are: (1) do not name the aquifer, (2) use a lithologic name, and (3) use a rock-stratigraphic or geographic name which ever is appropriate.

Example 1--Aquifer and Rock-Stratigraphic Unit Coincide

Example 1 shows an aquifer that coincides with the rock-stratigraphic unit and is confined above and below by much less permeable material. The aquifer probably would be named the Johnsville aquifer even though the full lateral extent of the aquifer may not be known.

Example 2--Aquifer consists of one rock-stratigraphic unit and part of an adjacent rock-stratigraphic unit

The aquifer shown in example 2 is made up of the lower two-thirds of Whiskey Creek Formation (sandy silt and clayey sand) and the moderately cemented Devils Lake Sandstone. Hydrologically, the two units are continuous

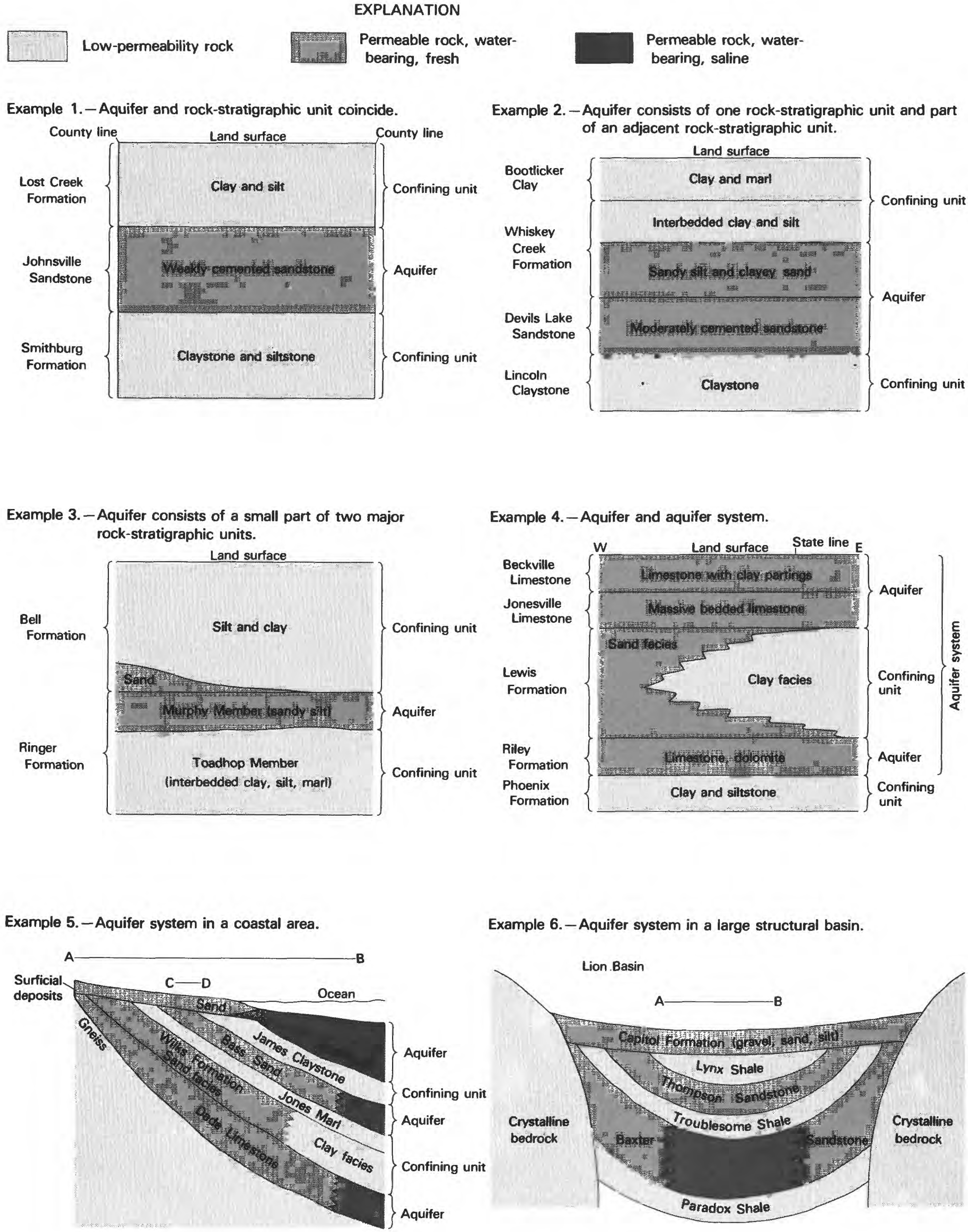
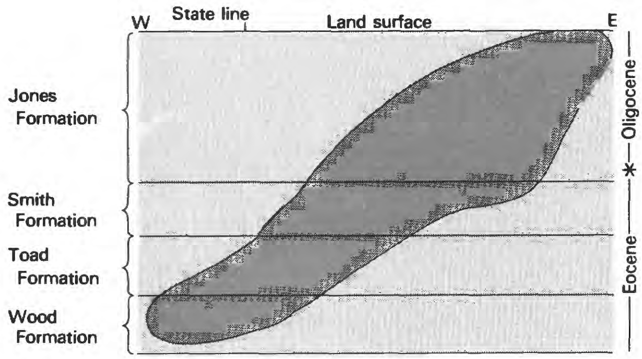
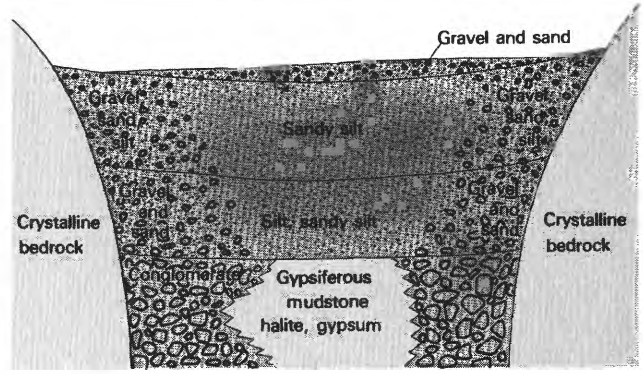


Figure 4.--Examples of Designating and Naming Aquifers.

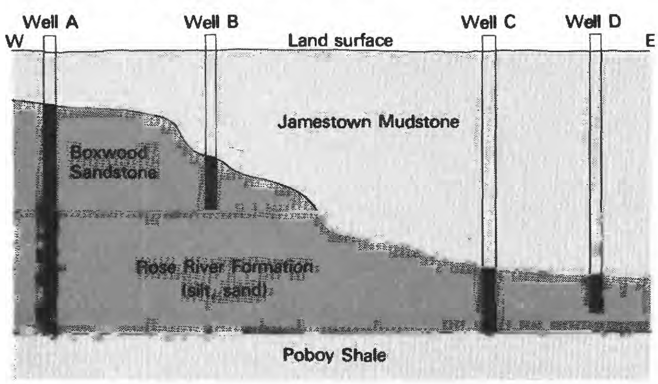
Example 7.—Aquifer crosses boundaries of rock-stratigraphic units and time-stratigraphic units.



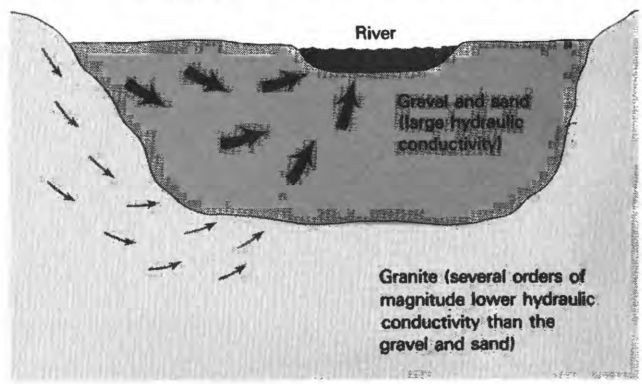
Example 8.—Aquifers in an alluvial basin in the West or Southwest.



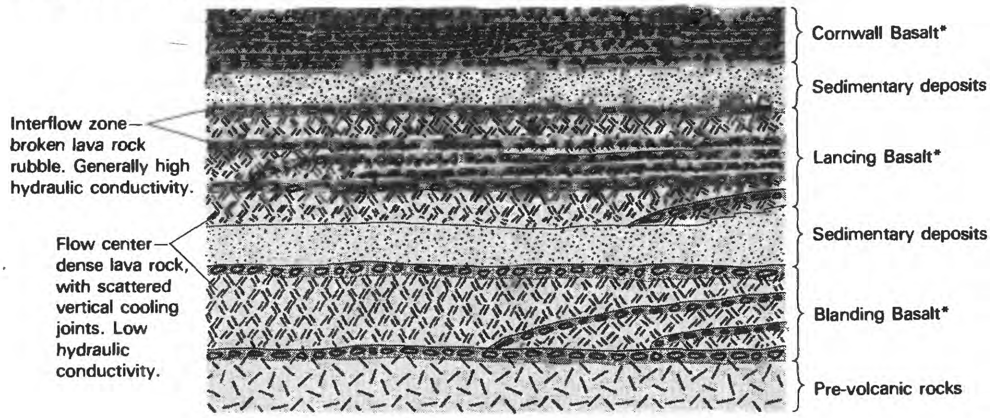
Example 9.—Use of aquifer terminology where rock-stratigraphic units are discontinuous.



Example 10.—Designation of aquifers and confining units for different purposes and scales of investigations.



Example 11.—Designation of aquifers in thick lava-flow sequences.



*Represents only a few of the flows in each basalt unit.

Figure 4.--Continued

and form a single aquifer. The aquifer is confined above and below. The name of the aquifer could be taken from the rock-stratigraphic name--Whiskey Creek-Devils Lake aquifer. Likewise if a prominent geographic feature were near where the aquifer was described (by wells or outcrops), it could be the basis of the aquifer name. The description of the aquifer in the text, comparison chart, and illustrations should carefully describe the reasoning for the selection of the upper and lower boundaries of the aquifer. In addition, it should be made clear that the upper formation and aquifer are not totally coincident.

Example 3--Aquifer consists of a small part of two major rock-stratigraphic units

The aquifer in example 3 this example consists mostly of the Murphy Member of the Ringer Formation, and probably would be called the Murphy aquifer. If the Murphy Member had not been named, the aquifer might be called the Bell-Ringer aquifer. However, the aquifer makes up only a small part of each formation, especially the Bell Formation. In this case, a local geographic name might be more appropriate.

Example 4--Aquifer and aquifer system

The cross section in example 4 represents an aquifer system consisting of three permeable carbonate formations and the sand facies of a clastic formation. The clay facies forms a confining unit over part of the area. If the study had included only the area east of the Stateline, two separate aquifers could have been defined--the Beckville-Jonesville aquifer and the Riley aquifer (or two aquifers named for geographic locations). If the study included only the area west of the Stateline the following options could be considered for naming the aquifer: (1) The aquifer might be called the Lewis aquifer if the sand was significantly more permeable than the limestone units; or (2) If the permeability of the four units was not greatly different the aquifer might be called the Beckville-Riley aquifer, or could be named after an appropriate geographic feature. If the study area included all the units shown on the cross section, no individual rock-stratigraphic unit would be representative everywhere and a geographic name should be used to name the aquifer system. If the sketch represented the full extent of the aquifer, and the aquifer was given a name, say the Williamsburg aquifer, the parts above and below the confining unit could be named the Upper Williamsburg aquifer and the Lower Williamsburg aquifer in a manner similar to the Floridan aquifer system of Miller (1986). For local studies on either side of the Stateline, the local aquifer name could still be used if the names were entrenched in usage, but the authors of local reports should clearly show and explain the broader relationships, if known.

Example 5--Aquifer systems in a coastal area

In hydrologic studies of coastal areas shown in example 5, the tendency has been to give hydrologically contiguous rock-stratigraphic units separate aquifer names. For example, in a study area represented by section A-B, the aquifers from youngest to oldest are: surficial aquifer (the sand unit), Ford aquifer, Bass aquifer, Wilks aquifer, and Dade aquifer. In reality, all these units form a single aquifer system that should be named after a physiographic or geographic feature. In a local-scale study represented by section C-D, the surficial deposits and the Bass Sand form one aquifer that should have a single name. It could be called the Bass aquifer as long as it was explained clearly that this name also included the surficial deposits. The second aquifer under C-D would be the Wilks-Dade aquifer.

It should be noted that the aquifer materials that contain saline water are part of the same aquifer that contains fresh water. Interfaces between saltwater and freshwater are subject to movement depending on the hydrologic conditions of the area and should not be used as aquifer boundaries. However, the boundary between the saltwater and freshwater and its apparent stability (or instability) should be defined as clearly as possible in the report.

Example 6--Aquifer system in a large structural basin

The sketch for example 6 represents an aquifer system in a large structural basin. The aquifer system should be named after a physiographic, geographic, or in this case perhaps, a geologic structural name after the basin--the Lion aquifer system. If the tops and bottoms of the Capitol Formation, Thompson Sandstone, and Baxter Sandstone are all well defined, and if it is known that the boundaries of these units largely correspond to the boundaries of the aquifers of the system, then the rock-stratigraphic names could be used for individual aquifer names in the Lion aquifer system. If the subsurface extent and boundaries of the rock-stratigraphic units are not well known, however, and (or) if the individual aquifers consist of several rock-stratigraphic units, names unrelated to rock-stratigraphic terms should be assigned to the individual aquifers. If considerable uncertainty exists in defining the boundaries of the aquifers, this should be indicated in the comparison charts and text. If the aquifer is well defined, it could be subdivided into the Upper Lion aquifer, Middle Lion aquifer, and Lower Lion aquifer in a manner similar to that done for the Floridan aquifer system. In local studies preceeding the regional evaluation, such as in the area represented by the section A-B, individual aquifers might have been designated--the Capitol aquifer, the Thompson aquifer, and the Baxter aquifer.

In local studies subsequent to the regional study, the Lion aquifer system names could be used for individual aquifers unless the rock-stratigraphic names were entrenched or otherwise advantageous. If the rock-stratigraphic names are used as the basis for aquifer names, their corresponding equivalents in the regional aquifer system should be discussed and shown in the comparison table of the report.

Example 7--Aquifer crosses boundaries of rock-stratigraphic units and time-stratigraphic units

The example 7 sketch shows an aquifer that crosses the boundaries of and comprises parts of four rock-stratigraphic units. East of the Stateline the aquifer could be named the Jones-Smith aquifer and west of the Stateline it could be called Toad-Wood aquifer. The boundaries of the aquifer bear no relation to the time-stratigraphic boundaries. In studies involving the entire aquifer, a single rock-stratigraphic name is not appropriate; a geographic name should be used for the basis of the aquifer name. Ofcourse, a geographic name rather than a rock-stratigraphic name could be selected for the aquifer name at the local scale.

Example 8--Aquifers in an alluvial basin of the West and Southwest

In example 8, the sedimentary units shown in the sketch are representative of closed-basin deposits. Generally in such a setting, the grain size decreases basinward from the source areas, and the amount of cementation increases downward in the deposits. Hydraulic conductivity likewise decreases in the same directions. Even though the hydraulic conductivity generally is lower in the deeper units, a large part of the deposits in the upper part of the basin are hydraulically connected and consist of one aquifer. Most of the deposits do not have formal rock-stratigraphic names, but may have informal names, such as, basin fill, valley fill, cemented gravel, playa deposits, lake deposits, etc. Other rock units such as volcanic flows may be interbedded with the basin deposits, complicating the picture. Well-defined confining clay units may be present in some basins, making it convenient to subdivide the materials into two or more aquifers. In other basins, however, well-defined clay layers are absent, or clay deposits form "plugs" at depth in the centers of the basins. The diagonally lined area of the sketch could be considered one aquifer unless well-log data or hydraulic-head data indicate a significant discontinuity with depth. The first option to consider is to not name an aquifer, but describe the water-bearing characteristics of the informally named deposits. Informal rock names could be retained for the aquifer name (e.g., valley-fill aquifer), or, if necessary, the aquifer could be named for a geographic feature, such as the name of the basin or valley. Zones could be designated for hydraulic features that require emphasis or separation.

Example 9--Use of aquifer terminology where rock-stratigraphic units are discontinuous

In example 9, the aquifer in the study area represented by the sketch could be called the Boxwood-Rose River aquifer. The upper boundary of the aquifer coincides with an erosional discontinuity, and the Boxwood Sandstone is not present in the eastern part of the area. However, within the study area the aquifer name (Boxwood-Rose River aquifer) would be used in the report even though the Boxwood Sandstone is not present throughout. Use of the aquifer name is illustrated by the wells in the sketch: well A completely penetrates the Boxwood-Rose River aquifer; well B partially penetrates the Boxwood-Rose River aquifer; well C completely penetrates the Boxwood-Rose River aquifer; and well D partially penetrates the Boxwood-Rose River aquifer.

If a study were done in an area represented by C-D on the sketch, the aquifer could be called the Rose River aquifer in the report because the Boxwood Sandstone is not present in that study area. However, if the study area represented by the entire sketch were completed and the Boxwood-Rose River aquifer already named, the later report must contain statements in the text and show on the comparison charts that the Rose River aquifer thickens west of the study area to include the overlying Boxwood Sandstone and forms the Boxwood-Rose River aquifer.

Example 10--Designation of aquifers and confining units for different purposes and scales of investigations

The sketch in example 10 represents a highly permeable deposit of gravel and sand in a valley occupied by a major perennial stream. The bedrock is granite that is several orders of magnitude less permeable than the gravel and sand.

Based on the large contrast in permeability, the gravel and sand is the aquifer and the granite is the confining unit. In an investigation to evaluate the potential for developing ground-water supplies from the gravel and sand, and(or) to evaluate interaction between ground-water and surface-water, the granite might be considered effectively "impermeable" and the flow in the granite ignored. In an evaluation of the potential for establishing a respository for high-level radioactive wastes in the granite, the designations of the aquifer and confining unit would not necessarily change, but the flow system through both units would have to be considered. The rate of flow through the granite into the gravel and sand would be slow, but could not be ignored in evaluating minimum travel times of radionuclides that the ground water might transport through the granite. This situation is similar to an aquifer overlain by a confining unit (e.g., clay over sand) that contributes water to the aquifer by leakage. A small to large part of the water withdrawn from the aquifer could come from the confining unit, but the designations of the aquifer and confining unit would not change. Therefore, the purpose of an investigation in a given area should not affect the designations of aquifers and confining units.

Aquifers and confining units may be designated differently in two or more investigations because of differences in scale and/or areal extent of the study areas. If a water-resources investigation were undertaken of just the granitic terrain in the sketch (e.g., an evaluation of ground-water availability for domestic use) the granite would be the aquifer because it is the only water-bearing unit in the study area. If the report were completed and published, on the larger area that included the gravel it would provide information to the reader to mention the other report and show the relation between the two studies and how the hydrogeologic units were selected. A similar situation could arise where a unit of low hydraulic conductivity is utilized for domestic water supplies and locally is considered an aquifer, and an evaluation from a regional perspective shows that the same unit is a regional confining unit. Again, it is the responsibility of the author to discuss these relationships in the comparison charts and text so that this apparent anomaly is explained.

Example 11--Designation of aquifers and confining units in thick lava-flow sequences.

Thick lava-flow sequences, such as in the Columbia Lava Plateau (Heath, 1984), require special consideration in the designation of aquifers and confining units. These sequences are as much as several hundred to a few thousand feet thick and consist of individual flows that range from a few feet to a few hundred feet in thickness. The most permeable parts of the sequence are the interflow zones that consist of a few feet of broken lava-rock rubble that formed at the top of a flow during deposition and a thinner rubbly zone at the base of the overlying flow (see sketch for example 11). The interflow zones are interrupted laterally or terminate; therefore, continuous aquifers are identifiable for only a few miles (Newcomb, 1969). The part of the flow between interflow zones--the flow center--cooled more slowly and consists of dense vertically jointed lava rock. The interflow zones may account for 1 to 30 percent of the volume of the rock, but the lateral hydraulic conductivity of the interflow zones may be several orders of magnitude greater than the vertical hydraulic conductivity of the dense zone unless the top of the flow has been subjected to a long period of subaerial weathering. If the top of a flow was extensively weathered before being covered by another lava flow, the minerals in the lava rock may be altered to clay minerals that reduce the permeability of the interflow zone. The flows may contain discontinuous deposits of fine-grained sediments in the interflow zones that have little affect on the hydrologic properties of the flow sequence or may grade into and (or) be divided by widespread sedimentary deposits. The hydraulic conductivity of the widespread sedimentary deposits is variable but, usually is much less than that of a rubbly interflow zone.

Designation of aquifers may be governed by the scale of the study and the thickness of the individual lava flows. For example, where individual flows are several hundred feet thick (the middle and lower part of the sketch) the interflow zones are easily recognized as individual aquifers and the dense rock between interflow zones are confining units. The part of the flow sequence consisting of several permeable interflow zones separated by dense, much thicker lava would be an aquifer system. At the other extreme, a sequence of flows where the individual flows are only a few feet thick (the upper part of the sketch) the designation of aquifer versus aquifer system may not be as clear cut. At some point the ratio of interflow zone to dense zone may become large enough that the multiple thin-flow sequence could be considered a single aquifer. A comparison can be made to that of sandstone interbedded with shale, which taken as a whole, might behave hydrologically as a single aquifer and not an aquifer system, even though thin continuous "confining units" are part of the aquifer. Other information, such as head measurements versus depth in areas where the aquifer is under stress, might be used to determine whether the sequence under study behaves as a single aquifer or as several aquifers separated by confining units.

Assuming that the thin-bedded flows in the upper part of the sketch behave as a single aquifer, the hypothetical lava-flow sequence consists of an aquifer and two aquifer systems all of which constitute an even larger aquifer system. It might appear that a larger category than aquifer system is needed in the hierarchy of nomenclature to classify the water-bearing rocks in this example. However, the term "aquifer system" is adequate to encompass the example shown here (see definition, p. 6). An appropriate geographic name should be used for the entire hydrologic system represented by the sketch, such as, the Rome River aquifer system after a major river in the area. The individual parts of the system could be called the upper, middle, and lower Rome River aquifer in a similar manner as was done for the Floridan aquifer system. An alternate method of naming consists of giving the upper, middle, and lower parts individual names based on the rock-stratigraphic units (or appropriate geographic names) that make up the aquifers as follows:

	Cornwall aquifer (after Cornwall Basalt)
Rome River aquifer system ---	Lancing aquifer (after Lancing Basalt)
	Blanding aquifer (after Blanding Basalt)

As in any other aquifer description, the characteristics of the dense, less permeable parts of the aquifer versus the very permeable interflow zones must be carefully described in the comparison tables and text.

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Expert Report on the Interstate Nature of the Memphis/Sparta Sand Aquifer

Volume 1 of 2: Report Text

Submitted on behalf of the City of Memphis, Tennessee, and Memphis Light, Gas & Water Division

in the matter of

State of Mississippi
v.
State of Tennessee, City of Memphis, Tennessee, and Memphis Light, Gas & Water Division

Supreme Court of the United States of America, No. 143 Orig.

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June 27, 2017

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- **Hydrostratigraphic Unit:** "A formation, part of a formation, or a group of formations in which there are similar hydrologic characteristics that allow for a grouping into aquifers and associated confining layers" (Domenico and Schwarz, 1998, p. 16).
- **Memphis/Sparta Sand Aquifer (MSSA):** The aquifers of the Middle Claiborne, Lower Claiborne, and Upper Wilcox units, represented by layers 5-10 in the US Geological Survey (USGS) Mississippi Embayment Regional Aquifer Study (MERAS) model (see below). The MSSA consists predominantly of the aquifer known as the Sparta Sand Aquifer in Mississippi, southern Arkansas, and Louisiana and the Memphis Sand Aquifer in Tennessee, northern Mississippi, and northeastern Arkansas.
- **Mississippi Embayment:** The northern portion of the Gulf Coast regional syncline (trough) in the Paleozoic rocks that has filled with sediments during subsequent geologic periods, with alternating periods of terrestrial and inundated environments (Hosman and Weiss, 1991, pp. B3-B4; Hosman, 1996, pp. G1, G4). The north-south axis of the Mississippi Embayment is generally coincident with the Mississippi River, the northern extent of the Mississippi Embayment is approximately where the Ohio River joins the Mississippi River, and the southern extent is in southern Mississippi and central Louisiana.
- **Mississippi Embayment Aquifer System:** The regionally extensive and vertically interconnected group of aquifers and confining units present in the Mississippi Embayment (Hart *et al*., 2008, pp. 3, 5).
- **Mississippi Embayment Regional Aquifer Study (MERAS) Model:** A numerical simulation model developed by the USGS for the aquifers in the Mississippi Embayment Aquifer System (Clark and Hart, 2009).
- **Outcrop:** The area where a geologic formation is exposed at or very near the ground surface (Stokes and Varnes, 1955, p. 101).
- **Particle Tracking:** A method of visualizing the pathway traveled by groundwater using discrete, imaginary particles. The particles are initially placed at selected locations in the model and are then repeatedly moved to new locations after a given amount of time, based on the water flow direction and velocity. In this manner the particles move in the same direction and with the same velocity as the water moves. The "track" of the particle then shows the pathway traveled by that parcel of water and, as a result, provides information about the flowpath of the groundwater. Both defining the flow direction/rate and performing the particle tracking itself are most commonly done using electronic computers, due to the computational intensity of these evaluations (Pollock, 2012).
- **Potentiometric Head:** Potentiometric head is the sum of pressure and elevation at a given location in the aquifer and is commonly measured as the height to which water rises in a standpipe open to the aquifer. Equivalent terms include "piezometric head," "hydraulic head," "total head," or "head" (Heath, 1983, p. 10). Potentiometric head is the driving force for groundwater flow, with groundwater flowing from locations of higher head to locations of lower head.
- **Potentiometric Surface:** A representation of the potentiometric head of an aquifer over a region (USGS, 2017a). The surface is often represented in terms of lines of equal potentiometric head, commonly called contour lines.

Prepared in cooperation with the Tennessee Valley Authority

Evaluation of Effects of Groundwater Withdrawals at the Proposed Allen Combined-Cycle Combustion Turbine Plant, Shelby County, Tennessee

Scientific Investigations Report 2016–5072

U.S. Department of the Interior
U.S. Geological Survey

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By Connor J. Haugh

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U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Contents

Figures

Table

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Evaluation of Effects of Groundwater Withdrawals at the Proposed Allen Combined-Cycle Combustion Turbine Plant, Shelby County, Tennessee

By Connor J. Haugh

Abstract

The Mississippi Embayment Regional Aquifer Study groundwater-flow model was used to simulate the potential effects of future groundwater withdrawals at the proposed Allen combined-cycle combustion turbine plant in Shelby County, Tennessee. The scenario used in the simulation consisted of a 30-year average withdrawal period followed by a 30-day maximum withdrawal period. Effects of withdrawals at the Allen plant site on the Mississippi embayment aquifer system were evaluated by comparing the difference in simulated water levels in the aquifers at the end of the 30-year average withdrawal period and at the end of the scenario to a base case without the Allen combined-cycle combustion turbine plant withdrawals. Simulated potentiometric surface declines in the Memphis aquifer at the Allen plant site were about 7 feet at the end of the 30-year average withdrawal period and 11 feet at the end of the scenario. The affected area of the Memphis aquifer at the Allen plant site as delineated by the 4-foot potentiometric surface-decline contour was 2,590 acres at the end of the 30-year average withdrawal period and 11,380 acres at the end of the scenario. Simulated declines in the underlying Fort Pillow aquifer and overlying shallow aquifer were both less than 1 foot at the end of the 30-year average withdrawal period and the end of the scenario.

Introduction

The Tennessee Valley Authority (TVA) proposes to reduce sulfur dioxide emissions at its Allen Fossil Plant (ALF) in Shelby County, Tennessee, by retiring the coal units and constructing a natural gas power plant. The existing coal-fired units at the ALF provide real and reactive power for the Memphis, Tennessee, area. To continue to reliably serve the area, generation resources must be located at or near the ALF. The proposed plant will be a two-on-one natural gas plant that can run in either simple- or combined-cycle mode. The simple-cycle mode uses very little water, whereas the combined-cycle mode is projected to use an annual average of 2,500 gallons per minute (gal/min) and a maximum of 5,000 gal/min from wells screened in the Memphis aquifer (table 1).

In 2016, the U.S. Geological Survey (USGS), in cooperation with the TVA, conducted an investigation to define the potential effects of groundwater withdrawals associated with the proposed Allen combined-cycle combustion turbine plant (hereafter referred to as the Allen plant site) on water levels in the Mississippi embayment aquifer system. Groundwater from the Memphis and Fort Pillow aquifers, which are in the Mississippi embayment aquifer system, is used to supply municipal and industrial water needs in West Tennessee (Parks and Carmichael, 1989, 1990). Self-supplied domestic groundwater withdrawals are usually from shallower zones including the alluvium or the fluvial deposits, which constitute the shallow aquifer at many locations.

The Mississippi Embayment Regional Aquifer Study (MERAS) was completed as part of the USGS Groundwater Resources Program to assess groundwater availability within the Mississippi embayment. The primary tool used in the assessment of groundwater availability is the MERAS groundwater-flow model (Clark and Hart, 2009). In the study described in this report, the effects of groundwater withdrawals associated with operation of the proposed Allen plant site were estimated by using the MERAS groundwater-flow model.

Purpose and Scope

This report presents an analysis of the potential effects of groundwater withdrawals associated with operation of the proposed Allen combined-cycle combustion turbine plant in Shelby County, Tennessee (fig. 1). The effects of groundwater withdrawals at the Allen plant site, in conjunction with existing withdrawals, were analyzed using the MERAS groundwater-flow model (Clark and Hart, 2009). This analysis will help further the understanding and evaluation of the effects of increased water use on an important multistate aquifer. This report does not address the potential effects of water leakage from the shallow aquifer on groundwater quality in the Memphis aquifer.

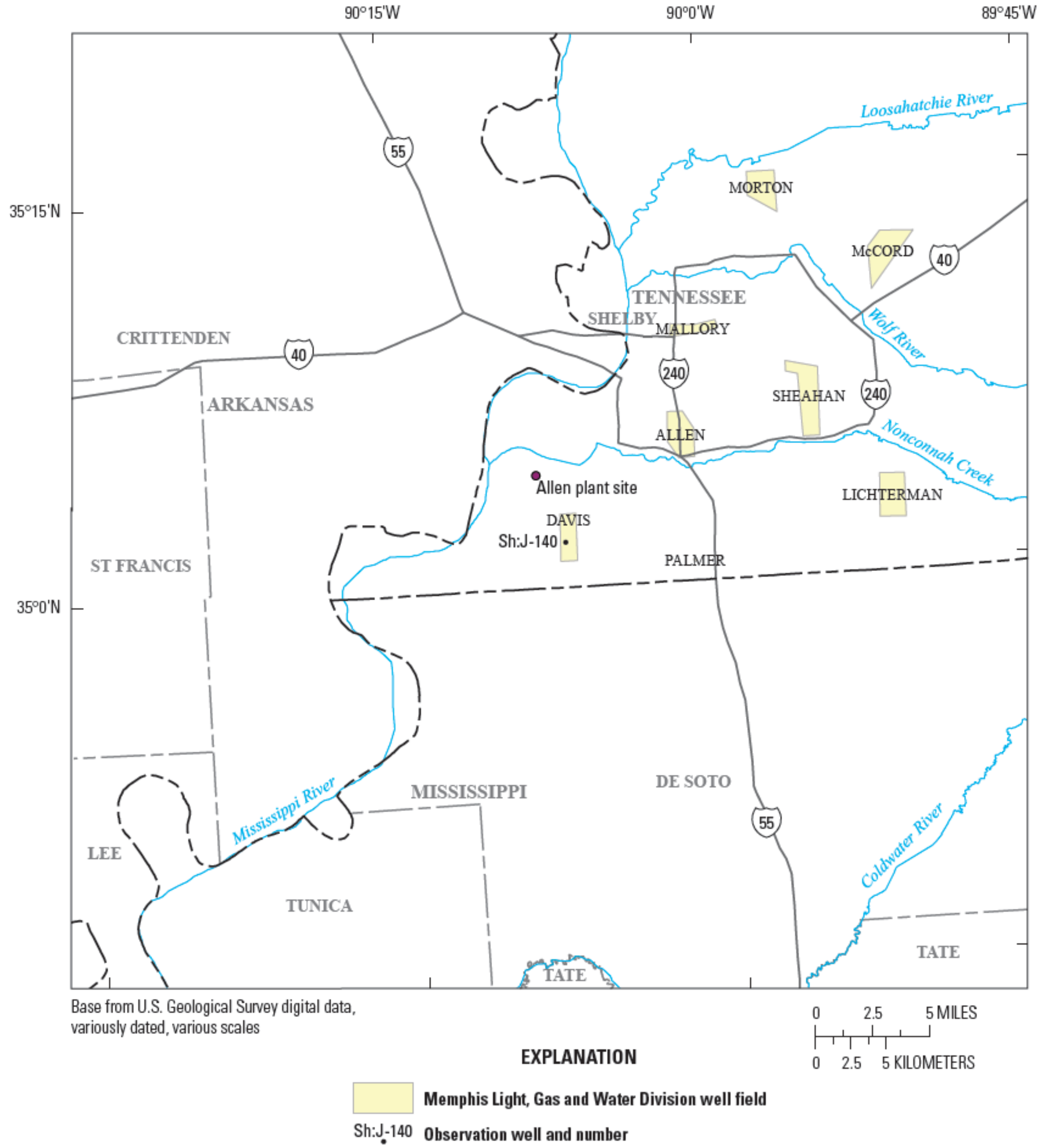

Figure 1. Location of the proposed Allen combined-cycle combustion turbine plant, Shelby County, Tennessee.

Approach

The effects on water levels in the aquifer system from the Allen plant site withdrawals were evaluated by comparing the difference in simulated water levels in the aquifers at the end of the 30-year average withdrawal period and at the end of the scenario (30-year average plus 30-day maximum withdrawal, hereafter referred to as the TVA withdrawal scenario) to a base case with no withdrawals at the Allen plant site. The differences in water levels between the simulations with and without the Allen plant withdrawals were contoured to provide an overall measure of withdrawal effects. The areas encompassed by the –4-ft potentiometric surface change contour were used to compare the affected areas (Haugh, 2012).

The Allen plant site (fig. 1) is simulated to have an annual average groundwater withdrawal of 2,500 gal/min and a 30-day maximum groundwater withdrawal of 5,000 gal/min. The wells at the proposed site would pump water from the Memphis aquifer (table 1). The rate of groundwater withdrawal by the proposed Allen combined-cycle combustion plant was assumed to be constant at the annual average rate over the 30-year period. This same approach was used during an investigation by the USGS, in cooperation with the TVA, conducted during 2008–2009 to define the potential effects of

Table 1. Generalized correlation chart of units of Tertiary age of the Claiborne and Wilcox Groups in West Tennessee and northern Mississippi.

[Fm, formation]

System	Series	Group	West Tennessee	Northern Mississippi	Regional hydrogeologic unit
Quaternary	Holocene and Pleistocene		Alluvium	Alluvium	Shallow aquifer
Quaternary	Pleistocene		Fluvial Deposits (terrace deposits)	Fluvial Deposits (terrace deposits)	
Tertiary	Eocene	Claiborne	Cockfield Fm	Cockfield Fm	Upper Claiborne aquifer
			Cook Mountain Fm	Cook Mountain Fm	Middle Claiborne confining unit
			Memphis Sand (Memphis aquifer)	Sparta Sand (Sparta aquifer)	Middle Claiborne aquifer
				Zilpha Clay	Lower Claiborne confining unit
				Lower sands in the Claiborne Group	Lower Claiborne-Upper Wilcox aquifer
		Wilcox	Flour Island Fm	Upper sands in the Wilcox Group	
	Paleocene		Fort Pillow Sand (Fort Pillow aquifer)		Middle Wilcox aquifer
				Lower sands in the Wilcox Group	
			Old Breastworks Fm		Lower Wilcox aquifer
		Midway	Porters Creek Clay	Porters Creek Clay	Midway confining unit
			Clayton Fm	Clayton Fm	

Modified from Hosman and Weiss, 1991.

groundwater withdrawals associated with the operation of five proposed combined-cycle combustion turbine plants on the Mississippi embayment aquifer system in West Tennessee and northern Mississippi (Haugh, 2012).

unit is thin, sandy, or absent. The MERAS model simulations spanned more than 130 years from 1870 to 2007 and incorporated the most current water withdrawal data available (Clark and Hart, 2009).

Regional Model

The MERAS model covers 97,000 square miles (mi^2) and consists of 13 model layers with grid cells of 1 mi^2 (Clark and Hart, 2009). The modeling code used for the MERAS model is MODFLOW-2005 (Harbaugh, 2005). Model layers correspond to aquifers and confining units from land surface down to the top of the Midway Group (table 1). In Shelby County, these include the following aquifers: the “shallow aquifer” (alluvium and fluvial deposits), the Memphis aquifer, and the Fort Pillow aquifer (table 1). In Shelby County, the Memphis aquifer is confined by the overlying Cook Mountain Formation. Recharge to the Memphis aquifer is primarily from the infiltration of rainfall in the outcrop area (east of Shelby County). The Memphis aquifer also receives some water as vertical leakage from the shallow aquifer where the confining

Effects of Groundwater Withdrawals

The differences in water levels between simulations with and without pumping at the Allen plant site were contoured to provide an overall measure of the effects of pumping at the Allen plant site. At the end of the 30-year average withdrawal period, the simulated potentiometric surface of the Memphis aquifer in the model cell containing the Allen plant site declined by about 7 feet (ft; fig. 2). Simulated declines in the underlying Fort Pillow aquifer and overlying alluvial aquifer did not exceed 1 ft. The area encompassed by the –4-ft potentiometric surface change contour at the end of the 30-year average withdrawal period is 2,590 acres. At the end of the TVA withdrawal scenario (30-year average plus 30-day maximum withdrawal), the simulated potentiometric surfaces of the Memphis aquifer in the model cell containing the Allen plant site declined by 11 ft (fig. 3). Simulated declines in the underlying Fort Pillow aquifer and overlying shallow aquifer did not exceed 1 ft. The area encompassed by the –4-ft potentiometric surface change contour (affected area) at the end of the TVA withdrawal scenario is 11,380 acres.

The simulated potentiometric surface decline of about 7 ft in response to the estimated average groundwater withdrawal at the Allen plant site can be compared to measured water levels from well Sh:J-140 (http://dx.doi.org/10.5066/F7P55KJN, USGS station no. 350124090072200), an observation well completed in the Memphis aquifer and located in the Davis well field (about 3 miles [mi] to the southeast) (fig. 1). The Davis well field began withdrawals in August 1971 with average withdrawals of about 8,300 gal/min from 1972 through 2000 (Parks and others, 1995). In the early 2000s, withdrawals at the Davis well field increased and averaged about 12,900 gal/min from 2006 through 2014. Periodic water-level measurements from well Sh:J-140 show an initial decline during 1971–72 of about 20 ft due to withdrawals at the Davis well field (fig. 4). Annual water-level variations in subsequent years (1973–2015) in well Sh:J-140 average about 10 ft. Seasonal water-level fluctuations in the Memphis aquifer in the Davis well field area are related to variations in withdrawals at the well field or in the Memphis area (Parks and others, 1995). The simulated potentiometric surface declines at the Allen plant site of about 7 ft in response to average withdrawals at the Allen plant site would be less than the typical seasonal variations in water levels observed in observation well Sh:J-140 at the Davis well field.

The simulated potentiometric surface decline of 11 ft at the end of the TVA withdrawal scenario at the Allen plant site is notably less than the simulated declines (20 to 56 ft) in source aquifers from the five sites previously analyzed by Haugh (2012). The affected area at the Allen site (11,380 acres) is near the minimum area from the five sites previously analyzed where affected areas ranged from 11,362 to 535,143 acres (Haugh, 2012). Pumping rates at the Allen site were similar to those at the previously studied sites where four of the five sites had annual average water withdrawals of 2,460 gal/min and 30-day maximum water withdrawals of 3,473 gal/min. The magnitude of change at all the sites and the spatial extent of affected areas varied depending on the transmissivity and storativity of the aquifers, the amount of confinement from above and below, the withdrawal rates, and the effects of nearby boundary conditions (Haugh, 2012). At the Allen plant site, the simulated decline is smaller than the decline at any of the previously studied sites, most likely due to the greater thickness and transmissivity of the Memphis aquifer at the Allen plant site.

The simulations show less than a 1-ft decline in the overlying shallow aquifer; however, the potential effect of the withdrawals on water levels in the shallow aquifer as well as the potential for water-quality changes due to the leakage of water from the shallow aquifer near the Allen plant site cannot be fully evaluated with the available data and the scope of the current investigation. Water-quality changes in the Memphis aquifer due to the leakage of water from the shallow aquifer have been noted in nearby Memphis Light, Gas and Water Division well fields at Davis (about 3 mi to the southeast) (Parks and others, 1995) and at Allen (about 6 mi to the west) (Parks, 1990). The simulated declines in the potentiometric surface of the Memphis aquifer as a result of simulated withdrawals at the Allen plant site were localized and similar in magnitude and extent to declines associated with other users over the simulation period.

Model Limitations

Models are simplifications of natural systems. Factors that affect how well a model represents a given natural system include the model scale, the accuracy and availability of hydraulic property data, the accuracy of withdrawal, water-level, and streamflow data, and appropriately defined boundary conditions. The MERAS model, used for the analysis presented in this report, is consistent with the conceptual model and hydrologic data of the MERAS study area. The MERAS model uses a grid-cell size of 1 mi^2, and a model will not provide accurate prediction on a scale smaller than the grid resolution. The hydraulic-conductivity zones used in the MERAS model represent large-scale variation in hydraulic properties; the actual spatial variations of hydraulic properties of the aquifer system occur on a much smaller scale and are poorly defined. Further discussion of the limitations of the MERAS model are reported by Clark and Hart (2009, p. 56).

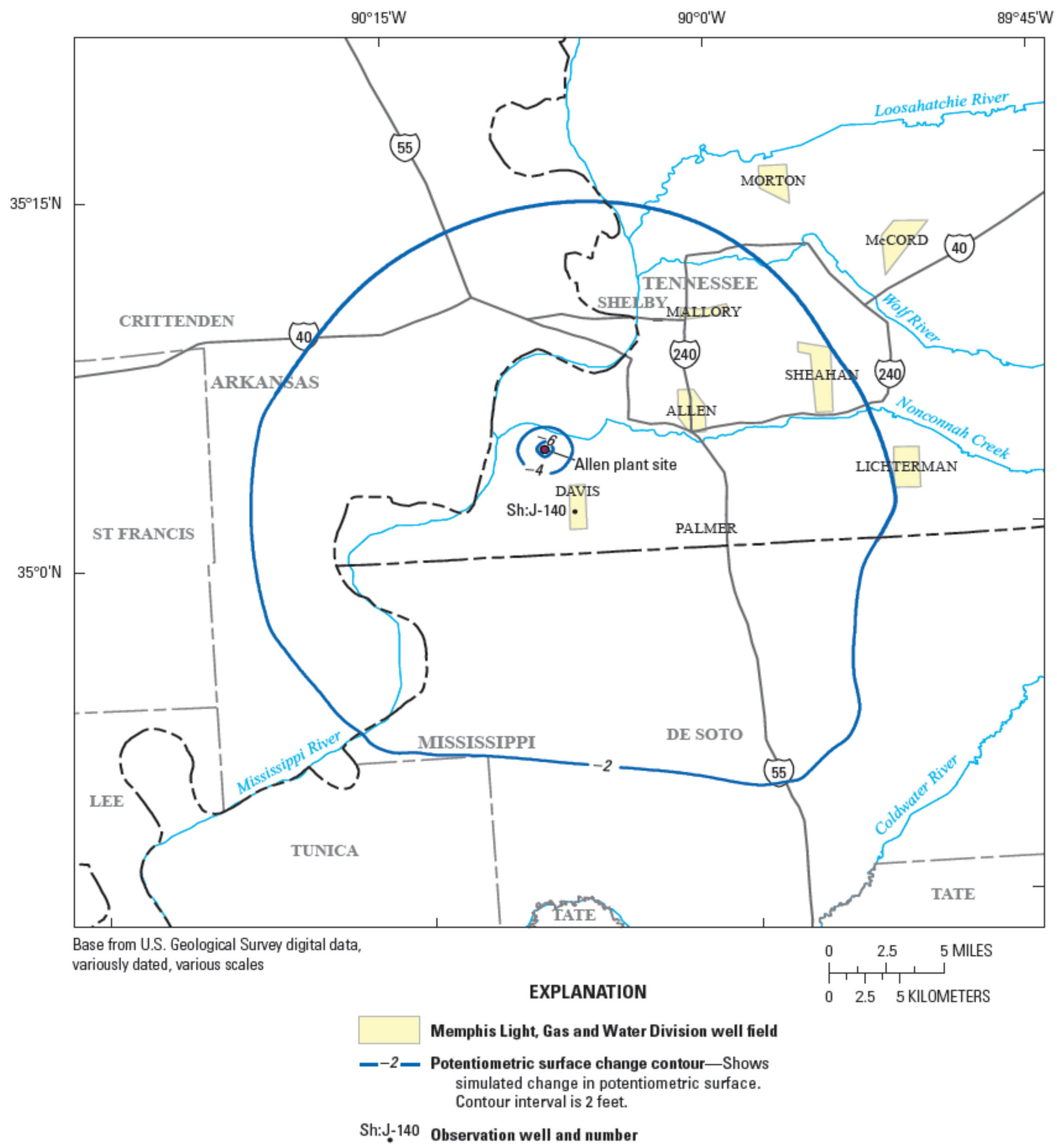

Figure 2. Simulated potentiometric surface change in the Memphis aquifer at the end of the 30-year average withdrawal period at the proposed Allen combined-cycle combustion turbine plant, Shelby County, Tennessee.

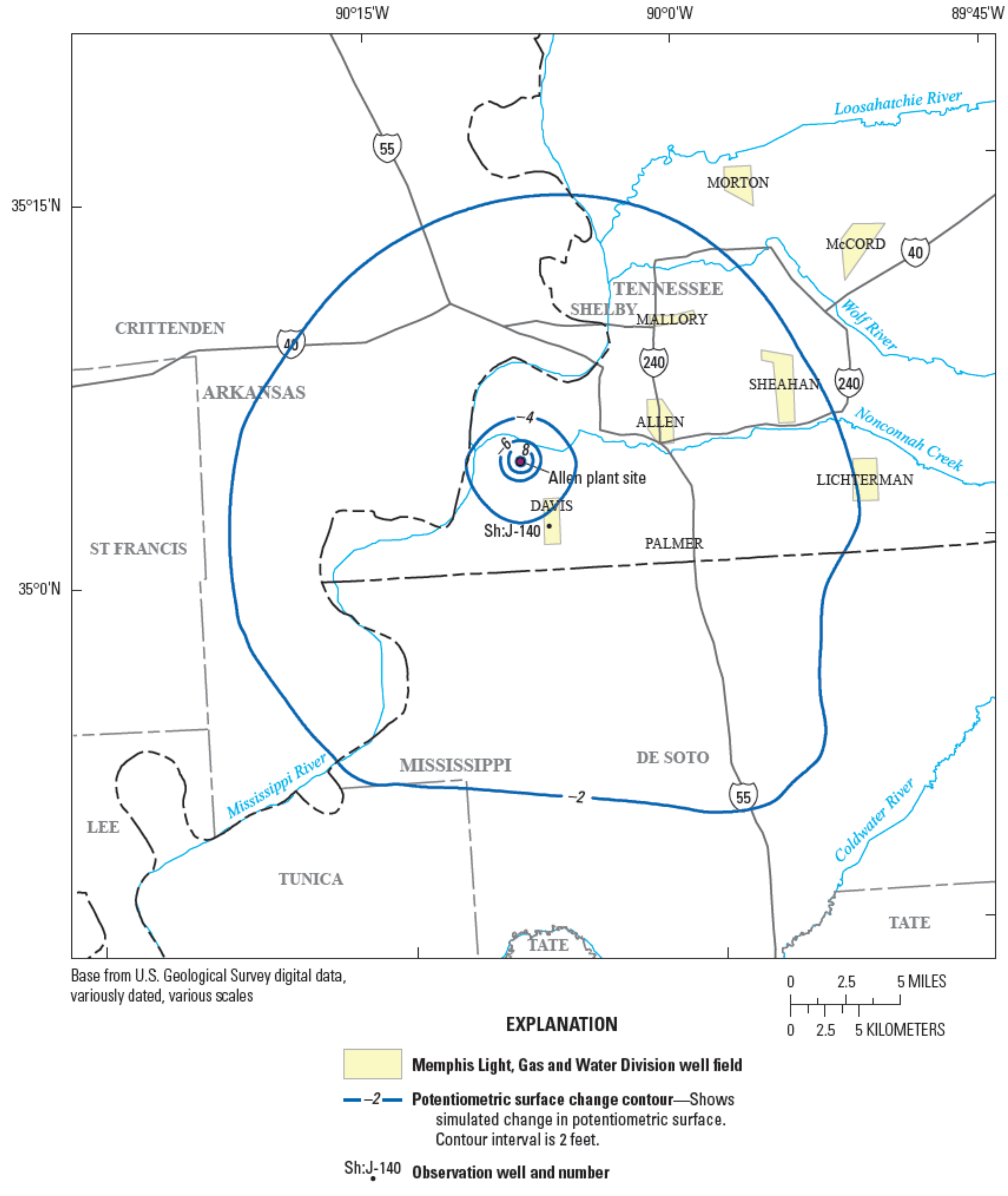

Figure 3. Simulated potentiometric surface change in the Memphis aquifer at the end of the Tennessee Valley Authority withdrawal scenario at the proposed Allen combined-cycle combustion turbine plant, Shelby County, Tennessee.

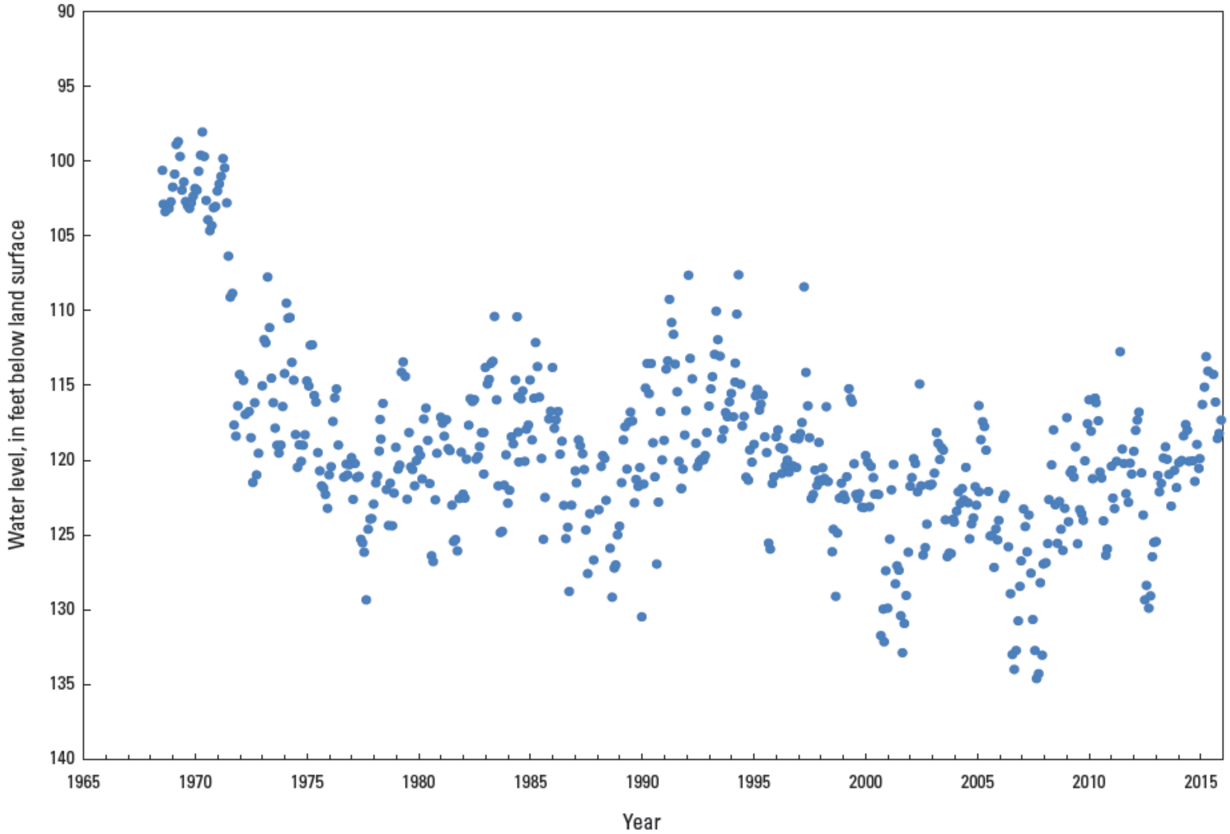

Figure 4. Periodic water levels in well Sh:J-140 from 1968 to 2015, Davis well field, Shelby County, Tennessee.

Summary

The Tennessee Valley Authority (TVA) proposes to reduce sulfur dioxide emissions at its Allen Fossil Plant (ALF) in Shelby County, Tennessee, by retiring the coal units and constructing a natural gas power plant. The proposed plant (the Allen combined-cycle combustion turbine plant, referred to as the Allen plant site) will be a two-on-one natural gas plant that can run in either simple- or combined-cycle mode. The combined-cycle mode is projected to use an annual average of 2,500 gallons per minute (gal/min) and a maximum of 5,000 gal/min. Therefore, the effects of groundwater withdrawal at the proposed Allen plant site on the aquifers and on groundwater levels were evaluated.

Model results indicate potentiometric surface declines at the Allen plant site of about 7 feet (ft) at the end of a 30-year period of average groundwater withdrawal and 11 ft at the end of the TVA withdrawal scenario (30 years average withdrawal plus 30 days maximum withdrawal). The change at the Allen plant site is smaller than the declines at any of the five sites studied during 2008–2009, which ranged from 20 to 56 ft. The simulated decline of 7 ft in response to average groundwater withdrawal is also smaller than seasonal variations of about 10 ft observed in Sh:J-140, an observation well completed in the Memphis aquifer at the Davis well field (about 3 miles to the southeast). Simulated declines in the potentiometric surface of the Memphis aquifer from simulated withdrawals at the Allen plant site were localized and similar in magnitude and extent to declines associated with other users of the Memphis aquifer.

The potential effect of the withdrawals at the Allen plant site on water levels in the shallow aquifer as well as the potential for water-quality changes due to the leakage of water from the shallow aquifer near the Allen plant site cannot be fully evaluated with the available data. Simulated declines in the overlying shallow aquifer at the Allen site were less than 1 ft; however, water-quality changes in the Memphis aquifer due to the leakage of water from the shallow aquifer have been noted in nearby Memphis Light, Gas and Water Division well fields at Davis and Allen.

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Expert Report of Brian Waldron, Ph.D.

Prepared on Behalf of the State of Tennessee

In the Matter of *Mississippi v. Tennessee et al.*, No. 143, Original (U.S.)

June 30, 2017

Signed: B

Brian Waldron, Ph.D.

SECTION 2. Summary of opinions

5. The central question that I have been asked to give my opinion about is whether the groundwater in the Middle Claiborne aquifer is an "interstate resource."

6. The Middle Claiborne aquifer is part of a larger set of aquifers within the regional geologic framework, the Mississippi embayment, which underlies portions of the states of Louisiana, Mississippi, Tennessee, Arkansas, Alabama, Kentucky, Illinois, and Missouri. Naming conventions of the aquifers change as they cross state boundaries and as the formations split, merge, or otherwise change over distance. Waldron et al. (2011) detailed these naming convention changes and correlated geologic formations across state boundaries. In Shelby County, Tennessee, the Middle Claiborne is locally named the Memphis Sand. In DeSoto County, Mississippi, the Middle Claiborne is locally named the Sparta Sand. The Middle Claiborne aquifer will be the geologic name applied in this report to represent the Memphis aquifer and the Sparta aquifer.

7. I understand that Mississippi asserts that a certain portion of the groundwater within the Middle Claiborne aquifer under Mississippi constitutes an "intrastate" resource because it allegedly would remain confined within the state boundaries under natural conditions, because it allegedly crosses into Tennessee only because of pumping, and because it would not otherwise flow across the Mississippi-Tennessee boundary. These assertions are not supported by the scientific consensus about the nature of the aquifer generally or by any valid analysis of groundwater flow in the aquifer.

8. The water in the aquifer is an interstate resource. I base this conclusion on two opinions, as described below.

Opinion 1: The Middle Claiborne aquifer extends continuously underneath Tennessee and Mississippi, and groundwater in the aquifer is not and has never been "confined" to the borders of Mississippi or any other state.

9. There is a scientific consensus that the "Memphis aquifer" and the "Sparta aquifer" are parts of one aquifer, a single hydrological unit referred to as the Middle Claiborne aquifer. The Middle Claiborne aquifer extends, continuously and without meaningful change that would prevent groundwater flow from one part to another, under Mississippi, Tennessee, and Arkansas, as well as other states. There are no physical or hydrological barriers that separate the portions of the aquifer within Mississippi from other parts of the same aquifer at the Tennessee-Mississippi-Arkansas state lines, and groundwater naturally can and does move freely across political boundaries within the aquifer.

10. The term "confined" as used in Mississippi's assertions differs in meaning from the same term used in basic hydrology when characterizing an aquifer as confined or unconfined. A confined aquifer is vertically bounded above and below by a less permeable layer such as clay that pressurizes the groundwater. As a result, when a well is emplaced into a confined aquifer, the static water level in the well rises above the basal elevation of the upper impermeable (or confining) layer. An unconfined aquifer is not under pressure, and the static water level in a well rises to the elevation of the water table.

EXPERT REPORT

Hydrogeologic Evaluation and Opinions for
State of Mississippi versus
State of Tennessee, City of Memphis,
and Memphis Light, Gas & Water Division

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June 30, 2017

Richard K. Spruill, Ph.D., P.G.
Principal Hydrogeologist

I. Introduction

Groundwater Management Associates (GMA) was retained by the firm of Daniel Coker Horton & Bell, P.A. (DCH&B) to provide expert geologic and hydrogeologic consulting regarding the origin and distribution of groundwater, interactions between surface water and groundwater, natural and man-induced migration patterns of groundwater, and specific topics regarding the geology and hydrogeology of predominantly sandy sediments comprising the Eocene-age Middle Claiborne Group that host the Sparta-Memphis Sand aquifer system in northwestern Mississippi and southwestern Tennessee. GMA's services included producing this expert report, which is focused on known or likely impacts on groundwater distribution and migration patterns within the Sparta-Memphis Sand (aka, the Sparta Sand, Memphis Sand, Memphis Aquifer, and other variations) in response to historic and ongoing pumping in Shelby County, Tennessee.

This expert report was produced for DCH&B using information available from publicly-available maps and reports from a variety of sources, including federal agencies such as the United States Geological Survey (USGS). This information was used in combination with the professional training and experience of the report's author, Dr. Richard K. Spruill, to develop opinions about the geologic and hydrogeologic setting of the study area. A partial list of resources and documents that were reviewed or employed to prepare the expert report is provided as Appendix A.

II. Qualifications

Richard K. Spruill, Ph.D, is GMA's Principal Hydrogeologist, president, and co-owner of the firm. Dr. Spruill's professional practice is focused on the hydrogeological exploration, evaluation, development, sustainable management, and protection of groundwater resources. He has been a geologist for over 40 years, and he is licensed in North Carolina as a professional geologist. Since 1979, Dr. Spruill has been a faculty member in the Department of Geological Sciences at East Carolina University (ECU), Greenville, North Carolina. He teaches hydrogeology, mineralogy, petrology, field geology, and physical geology at ECU. Dr. Spruill has provided litigation support and testified previously regarding geology, hydrogeology, water resources, and environmental contamination. His *curriculum vitae* is provided as Appendix B.

I, Dr. Richard K. Spruill, am the author of this expert report. My descriptions, interpretations, conclusions, and professional opinions described within this expert report are subject to revision, expansion, and/or retraction as additional information becomes available.

III Summary of General Opinions

The following is a summary of my opinions provided within this expert report. The opinions itemized below are based on (1) my education, training, experience, (2) detailed study of the geology and hydrogeology of the Mississippi Embayment, (3) evaluation of the specific geological and hydrological characteristics of the pertinent geological formations in north Mississippi and west Tennessee, and, (4) specific resources and materials referred to and identified with this report.

- The Sparta-Memphis Sand, also known as the Middle Claiborne Aquifer or the Memphis Aquifer, is an important source of potable groundwater within northwestern Mississippi and southwestern Tennessee. Most of the Sparta-Memphis Sand is a hydraulically-confined aquifer that consists of geologic deposits that accumulated within the Mississippi Embayment approximately 40 million years ago. The Sparta-Memphis Sand is inclined (dips) toward the west from areas where the unit crop out in both Mississippi and Tennessee. These sandy deposits thicken toward the center of the Embayment, which generally coincides with the present trace of the Mississippi River.
- The Middle Claiborne formation contains several lithologic constituents, including the Sparta Sand, that comprise an aquifer that has accumulated groundwater over many thousands of years. Historically, most of that groundwater originated as surface precipitation that infiltrated the formation where exposed at or near

they are predominantly calcareous sands, chalks, marls, and clay that are grouped together as the McNairy-Nacatoch Formations (Grubb, 1998; Cushing et al., 1964).

Cenozoic Era sediments that overly the McNairy-Nacatoch Formations were deposited in the Tertiary Period between 65 million years ago and approximately 3 million years ago. From oldest to youngest, these deposits are subdivided into the Midway, Wilcox, Claiborne, and the Jackson-Vicksburg groups (Grubb, 1998). Thick sand beds characterize the Wilcox and Claiborne groups (Figure 4), while finer grained deposits of clay and silt dominate the Midway and Jackson-Vicksburg groups. Sediments deposited during the Quaternary Period are less than approximately 3 million years old, and are predominantly sands, silts, and clays deposited by the Mississippi River (Figure 4).

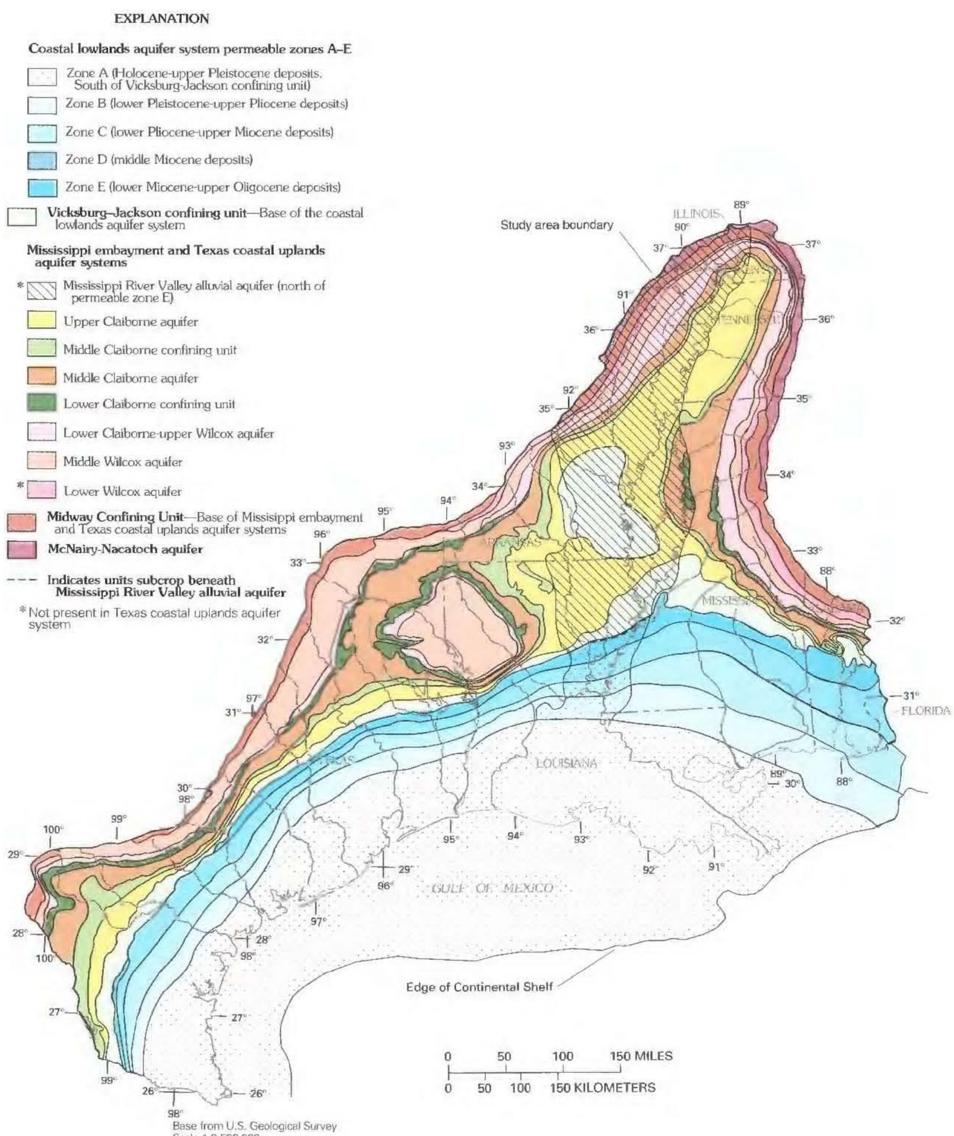
Figure 4: Stratigraphic Correlation of Paleocene and Younger Sedimentary Units and Aquifers in Northern Mississippi and Western Tennessee (Haugh, 2016, Table 1)

<table>
<tr><th>System</th><th>Series</th><th>Group</th><th>West Tennessee</th><th>Northern Mississippi</th><th>Regional hydrogeologic unit</th></tr>
<tr><td>Quaternary</td><td>Holocene and Pleistocene</td><td></td><td>Alluvium</td><td>Alluvium</td><td rowspan="2">Shallow aquifer</td></tr>
<tr><td>Quaternary</td><td>Pleistocene</td><td></td><td>Fluvial Deposits (terrace deposits)</td><td>Fluvial Deposits (terrace deposits)</td></tr>
<tr><td rowspan="11">Tertiary</td><td rowspan="6">Eocene</td><td rowspan="5">Claiborne</td><td>Cockfield Fm</td><td>Cockfield Fm</td><td>Upper Claiborne aquifer</td></tr>
<tr><td>Cook Mountain Fm</td><td>Cook Mountain Fm</td><td>Middle Claiborne confining unit</td></tr>
<tr><td rowspan="3">Memphis Sand (Memphis aquifer)</td><td>Sparta Sand (Sparta aquifer)</td><td>Middle Claiborne aquifer</td></tr>
<tr><td>Zilpha Clay</td><td>Lower Claiborne confining unit</td></tr>
<tr><td>Lower sands in the Claiborne Group</td><td rowspan="2">Lower Claiborne-Upper Wilcox aquifer</td></tr>
<tr><td rowspan="4">Wilcox</td><td>Flour Island Fm</td><td rowspan="2">Upper sands in the Wilcox Group</td></tr>
<tr><td rowspan="5">Paleocene</td><td rowspan="2">Fort Pillow Sand (Fort Pillow aquifer)</td><td rowspan="2">Middle Wilcox aquifer</td></tr>
<tr><td rowspan="2">Lower sands in the Wilcox Group</td></tr>
<tr><td>Old Breastworks Fm</td><td>Lower Wilcox aquifer</td></tr>
<tr><td rowspan="2">Midway</td><td>Porters Creek Clay</td><td>Porters Creek Clay</td><td rowspan="2">Midway confining unit</td></tr>
<tr><td>Clayton Fm</td><td>Clayton Fm</td></tr>
</table>

V.3 General Hydrogeology of the Mississippi Embayment

There are three major aquifer systems in the Mississippi Embayment recognized in the vicinity of southwestern Tennessee and northwestern Mississippi (Figure 4): The Wilcox System (composed of the lower, middle, and upper Wilcox Aquifers), the Claiborne System (composed of the lower, middle, and upper Claiborne Aquifers), and the shallow alluvial aquifer system located within the Mississippi River valley. Figure 5 shows the areal exposures of these aquifers at the land surface.

Figure 5: Surface Distribution of Regional Aquifers and Confining Units in the Mississippi Embayment and Gulf Coastal Plain **(Grubb, 1998, Figure 7)**



In northwestern Mississippi and western Tennessee, most of the Lower Claiborne and Upper Wilcox Aquifers are confined (i.e., are 'artesian' aquifers). The Lower Claiborne Aquifer and the Upper Wilcox Aquifer are often considered to form one aquifer, and they are separated by a confining layer from the overlying Middle Claiborne Aquifer.

The Claiborne Group is a package of sediments deposited in the Mississippi Embayment approximately 40 million years ago during the middle of the Eocene Epoch of the Cenozoic Era. Historically, the Middle Claiborne Aquifer was called the 500 Foot Sand to reflect the typical depth of the sands being targeted for water-supply wells in the Mississippi-Tennessee border area (Criner et al., 1964). In Tennessee, the names Memphis Sand or Memphis Aquifer (Figure 4) are synonymous with the Middle Claiborne Aquifer. In Mississippi, the upper part of the Middle Claiborne Aquifer is called the Sparta Sand (e.g., Clark et al., 2011), which is correlative with the upper part of the Memphis Sand (Figure 4). The Claiborne and Wilcox Aquifer Systems are the major sources of public water supply in the vicinity of the City of Memphis, both north and south of the Mississippi-Tennessee border. Of these, the Middle Claiborne Aquifer is the primary source of water used to supply municipalities and individual home owners, and that aquifer has experienced the most obvious impacts from extensive pumping in Shelby County, Tennessee. The Middle Claiborne Aquifer in western Tennessee and northwestern Mississippi is inclined (dips) generally westward from where the sand deposits crop out to beneath the Mississippi River.

The upper part of the Middle Claiborne Aquifer (i.e., the Sparta Sand) is the primary water-producing zone exploited by municipal well fields (Clark et al., 2011), and the name Sparta-Memphis Sand is employed in this expert report to refer to the Middle Claiborne Aquifer that is being pumped extensively in Shelby County, Tennessee. The terms Middle Claiborne Aquifer or Memphis Aquifer are considered synonymous with the SMS for purposes of this expert report. It is important to recognize that pumping has also impacted the Lower Claiborne-Upper Wilcox Aquifer, and focus on the SMS is <u>not</u> intended to discount pumping impacts on that deeper aquifer system.

In the Matter Of:

STATE OF MISSISSIPPI vs

STATE OF TENNESSEE

OF TENNESSEE,

RICHARD SPRUILL

September 28, 2017

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just ask that you answer whatever question is pending, and then we can take a break. Is that fair?

A. Fair enough.

Q. We're going to talk a lot today about an aquifer that you have called the Sparta Memphis Sand in your reports. Do you recall that?

A. Yes.

Q. Do you agree that the term "Middle Claiborne" -- you understand that if I use that term, that I'm referring to the same aquifer?

A. Yes.

Q. Do you understand the names "Memphis Sand" and "Sparta Sand" as used at various times in this case are both referring to the same aquifer?

A. I think the "Memphis Sand" and "Sparta Sand" are often used interchangeably, but there are regional differences in the two. In terms of what I would call hydrostratographic interpretations, they are more or less equivalent.

Q. When you say "more or less equivalent," just to make sure we're on the same page, you understand that they are part of a single geological formation, correct?

A. They are part of a single geological formation. The Sparta Sand is not the same unit as the Memphis Sand in terms of its thickness and its areal distribution. There are some differences. They are part of the same hydrostratographic unit.

Q. If I talk about the "Middle Claiborne," you'll understand that name is referring to the entire geologic formation that encompasses what you are referring to, both the Sparta Sand and the Memphis Sand, correct?

A. I think it is really important to say which geographic area we're talking about and make that distinction. Generally I would agree with what you said.

Q. Is there a geographic distinction you would need clarification on if I use the term "Middle Claiborne"?

A. If you use the term "Middle Claiborne," my interpretation is that it would involve both the Memphis Sand, the Sparta Sand and various submembers of the Memphis Sand further south, say into Mississippi, where there are local confining layers that may not exist in the Memphis Sand.

Q. When you say the sub -- what was the term you used?

A. Submemembers.

Q. What do you mean by that?

A. My opinion is as you move south from Tennessee into Mississippi, the thick unit that people in Tennessee call the Memphis Sand becomes more complex in its nature, and it has some interlayers that are actually of lower permeability than you might find in the same Middle Claiborne Aquifer system further north.

Q. We will get to more details about that a little bit later. Just to be sure that we're on the same page terminology-wise, when I use the term "Middle Claiborne," I'm referring to the entire formation that includes both the Sparta Sand and Memphis, the sub units you referred to. Do you understand that?

A. I do.

MR. ELLINGBURG: And the entire

Mississippi Embayment?
Q. (BY MR. BRANSON) Dr. Spruill, would that be your understanding?
A. There are lots of different subformations that make up the Middle Claiborne Aquifer in the Mississippi Embayment. It is pretty complex.
Q. The word "Middle Claiborne" today will refer to the entire embayment that you just referred to. Okay?
A. Okay.
Q. If you need clarification on which part or if the distinctions between the different parts of the Middle Claiborne are relevant to your answer, please ask me, and we'll drill down and be more specific. Okay?
A. Okay.
Q. When I refer to "predevelopment" today, will you understand that I'm referring to the time period before 1986?
A. Yes.
Q. You understand that this case concerns in part pumping by Memphis MLG&W, correct?
A. Yes.