Data/Case Study 2004-01

Groundwater Conditions of the Principal Aquifers of Lee, Whiteside, Bureau, and Henry Counties, Illinois

by
Stephen L. Burch
Groundwater Section

Illinois State Water Survey
A Division of the Illinois Department of Natural Resources

2004

Groundwater Conditions of the Principal Aquifers of Lee, Whiteside, Bureau, and Henry Counties, Illinois

by

Stephen L. Burch

Illinois State Water Survey
Champaign, Illinois

Contents

List of Figures

Page

List of Tables

Groundwater Conditions of the Principal Aquifers of Lee, Whiteside, Bureau, and Henry Counties, Illinois

by Stephen L. Burch

Abstract

A large supply of groundwater occurs in a buried aquifer lying in the bedrock valley of the ancestral Mississippi River. This deposit, known as the Sankoty sand, supplies many irrigation wells and underlies more than 750 square miles (sq mi). A shallower and less extensive aquifer, the Tampico, occurs near the surface and underlies more than 480 sq mi. This study defines the regional groundwater flow patterns for these two aquifers in northwestern Illinois and reports the results of measuring groundwater levels in observation wells.

The Tampico aquifer is separated from the underlying Sankoty aquifer by an intervening layer of clay or clays. Groundwater within the upper unit exists under unconfined conditions (that is, at atmospheric pressure). The saturated sands comprising the Tampico aquifer are typically 30 to 40 feet thick and are tapped by shallow wells or sandpoints.

The Sankoty sand is 100 to 150 feet thick and is commonly used in irrigation wells in Illinois. Groundwater within this unit is pressurized and occurs under confined conditions. The pressure head in the aquifer declines from an elevation of about 670 feet near the town of Ohio to less than 570 feet near Albany along the Mississippi River. A steeper gradient occurs as groundwater flows toward a second outlet near Hennepin. As a result, groundwater elevations decline to levels below 450 feet where the aquifer discharges to the Illinois River.

Pumpage during the summer months, largely from irrigation wells, causes groundwater levels in the Sankoty aquifer to decline 11 to 13 feet. The area of greatest drawdown extends from Tampico to Walnut, Illinois. Groundwater levels in the Tampico aquifer do not decline as much. A decline of 3 to 3.5 feet is common in the aquifer's water table. Irrigation wells annually withdraw an estimated 21,000 acre-feet of groundwater. Although the Sankoty aquifer is favored for irrigation, the actual distribution percentage for each aquifer is unknown.

No significant, regional water-quality problems were detected in samples collected from either aquifer. The groundwater in both aquifers is of a calcium-bicarbonate type. The water is very hard, with an average value of 306 milligrams per liter (mg/L) in the Sankoty aquifer and 329 mg/L in the overlying Tampico aquifer. The quality of samples from the Sankoty aquifer was excellent, although they contained more iron and are more alkaline than samples from the Tampico aquifer. No discernible patterns were observed in the distribution of total dissolved solids (TDS) values for either aquifer. The average TDS value for water samples was 435 mg/L (Tampico aquifer) and 363 mg/L (Sankoty aquifer). Groundwater in the Tampico aquifer was usually of excellent quality, but it sometimes contained nitrates.

Introduction

Since the advent of center-pivot irrigation in the 1970s, groundwater has become increasingly important to rural regions for irrigation. Developers and financial institutions need documentation about where the water-bearing units occur and knowledge about the origin of the groundwater. Only a few groundwater maps exist that describe the resources in Lee, Whiteside, Bureau, and Henry Counties of Illinois. This study was designed to increase the knowledge about groundwater sources in the area.

The drilling and observation-well construction phase of the study began in 1991. Additional drilling was done in 1992 and 1995. This report is based on water-level data collected through 1995 from those wells and additional data on file at the Illinois State Water Survey (ISWS). It presents hydrogeologic information and describes present conditions about the groundwater resources of the region. The focus is on the extensive unconsolidated sand-and-gravel deposits, which, where saturated, are the principal aquifers of the region. The geology and hydrology of the bedrock formations are not covered, as these formations contain limited quantities and are of relatively poor quality.

Purpose and Scope

This study had several purposes.

- To construct a water-level map that illustrates the direction of groundwater movement. Associated with this purpose was the desire to construct a map of annual water-level declines and to document the seasonality of these fluctuations.

- To demonstrate how an ISWS study might be conducted using water-level measurements from observation wells instead of relying on privately owned wells. The expectation was that fewer datapoints, but each of high quality, could provide a cost-effective alternative to the "mass measurement" approach previously used by the ISWS.

- To construct an observation well network that would outlast the duration of the project.

- To show that the groundwater levels are dynamic and constantly changing due to pumpage and climatic variations.

- To identify whether a groundwater divide existed in the region. The occurrence of such a divide was suspected because the surface-water divide between the Illinois and Rock Rivers crosses the trace of the previously mapped buried bedrock valley (Horberg, 1946).

Acknowledgments

The principal sponsor of this report was the Illinois Department of Energy and Natural Resources (Aquifer Assessment Program). Additional support was provided by the Division of Water Resources, which at the time was part of the Illinois Department of Transportation. Today, both of these funding agencies have been combined into the Illinois Department of Natural Resources. Their support was made available to the ISWS through the Grants and Contracts Office at the University of Illinois. The views expressed in this report are those of the author and do not necessarily reflect the views of the sponsors or the ISWS.

Appreciation is extended to Gerard Widolf and Scott Church of Tampico for their assistance in surveying the elevations of the observation wells.

Contractual arrangements for rotary drilling services were made with the Albrecht Drilling Company of Ohio, Illinois. The author is particularly indebted to drillers Jet Hall and Harold Albrecht for their knowledge of local conditions and their commitment to successfully building the observation wells.

Members of Illinois State Geological Survey (ISGS) were on site during the drilling at 22 sites and made geophysical logs (natural gamma). Appreciation is extended to Philip C. Reed and Phillip G. Orozco for running the geophysical logger. Additional ISGS personnel on site were David R. Larson and Robert C. Vaiden. Their help in obtaining samples during the drilling phase and preparing subsequent logs is gratefully acknowledged. The observation wells constructed in 1995 were logged (natural gamma) through the casing by Timothy C. Young, also from the ISGS.

Joseph Karny assisted in the collection of groundwater samples and helped in lowering the pump into the observation wells. Loretta Skowron and Lauren F. Sievers provided chemical analyses of water samples collected at the well sites.

Peer review of this report was provided by Adrian P. Visocky and David R. Larson. Agnes Dillon and Eva Kingston provided editorial review, Linda Hascall provided graphical support, and Patti Hill and Pamela Lovett contributed to the final appearance of this report.

Methodology

Method of Investigation

The ISWS has more than 300,000 water well records on file. This study, begun in April 1991, started with an overview of drillers' logs from parts of Lee, Whiteside, Bureau, and Henry Counties. More than 625 logs were selected for further evaluation. Although the process was subjective, an emphasis was put on selecting records of sites for which holes were drilled deep enough to reach the Sankoty sand. Priority was given to selecting the more descriptive logs, not those, for example, that noted "0-200 feet, Drift." The record of any hole reaching bedrock was likely to be selected, regardless of its descriptive qualities on record.

The next step focused on converting the data contained on the well logs into stratigraphic information. The process involved determining land-surface elevations from 7.5-minute topographic maps (1:24,000 scale) for each well location. The logs were examined carefully for information about where the intervals of sand or clay occurred. The depth to the top and bottom of each of these intervals was subtracted from the land surface elevation and noted on a photocopy of the log. If a water-level depth was indicated on the log, its elevation was determined in a similar manner.

A map scale of 1:100,000 was selected to represent the intervals of sand and clay. Stratigraphic data from approximately one-third of the 625 logs selected for study were marked on a sheet of frosted Mylar that was overlaid on the U.S. Geological Survey (USGS) 1:100,000 base maps (Dixon and Kewanee, Illinois, and Davenport, Iowa). About 200 well logs contained information deemed useful enough to define the elevation of the top of the Sankoty sand. This working map was used to estimate depths of observation wells constructed for this project. About 100 of the 275 logs were used to define the elevation of the top of the clay layer that separated the surficial sand from the Sankoty sand.

The western portion of the area was searched for third order, vertical control benchmarks established by the USGS. Although the published data show that several survey lines were run along rights-of-way, few of the monuments still remain. Many, presumably, have been casualties of drainage-ditch modifications.

With a rudimentary understanding of the regional stratigraphy and knowledge of where the benchmarks were located, a drilling plan was developed. The plan sought to minimize the distances to be traversed while still constructing a loosely triangular-shaped pattern of observation wells.

Previous Reports

Until recently, Foster (1956) provided the only detailed report of the Green River Lowlands. A geologic characterization of northwestern Illinois by Hackett and Bergstrom (1956) also identified the abundant groundwater resources of the region. Another study describing related glacial deposits in the Peoria vicinity (Horberg et al., 1950) erroneously included the Green River Lowlands in a list as being a potential recharge area for Peoria.

Concurrent efforts in the early 1990s by researchers at the ISGS resulted in a report by Larson et al. (1995). That report characterizes the hydrogeologic setting, describes the Quaternary deposits of the region, and names the two principal water-bearing units of glacial age as the Tampico aquifer and the Princeton Bedrock Valley aquifer. The name Tampico, proposed by Larson et al. (1995), is used in this report. The name Sankoty aquifer is used because the stratigraphic name is more appropriate for an aquifer that extends beyond the boundaries of the Princeton Bedrock Valley.

The Pleistocene geology and topography of the area also serve as motivation for interest in studying the area. Principal among these descriptions is the stratigraphic report by Willman and Frye (1970). It shows that the western extent of the Wisconsinan glaciation cuts across the study area and results in a varied terrain.

This study is similar to that of McComas (1969) because it describes stratigraphy, bedrock topography, and hydrogeologic conditions. The area covered by McComas overlaps a portion of the study area in this report. McComas, however, investigated much further to the south in a study that extended from near Princeton south to Morton.

Well-Numbering System

The numbering system used to identify observation wells is based on using a three-letter county abbreviation (BUR for Bureau, HRY for Henry, LEE for Lee, and WTS for Whiteside), the last two digits of the year the well was drilled, and an uppercase letter (e.g., BUR-91A). When several wells were drilled in the same county and year, the names were plotted on a map so that their identifying letters would increase in alphabetical order from left to right and top to bottom. For example, BUR-91A is located in the northwestern corner of Bureau County and was drilled in 1991.

Locations of wells used in this study are based upon what generally became known and referred to as “the system of rectangular surveys.” The rectangular system was initiated in the State of Ohio and was, in its early stages, somewhat experimental. Notable revisions of the rules were made as the surveys progressed westward. The system was based on the principle that land should be divided into townships of 36 square miles (sq mi). Each township was to contain 36 sections, each 1 mile in length and numbered according to figure 1.

The location of a particular site in this report also is based on an identification by tier, range, and section. Each section is subdivided into quarters when possible.

A Lambert Conformal Conic Projection for the State of Illinois was developed with computer systems (DuMontelle et al., 1968). This system of x-y coordinates, commonly referred to as Lamberts, is measured in feet from an origin located in Missouri. The origin is 3,000,000

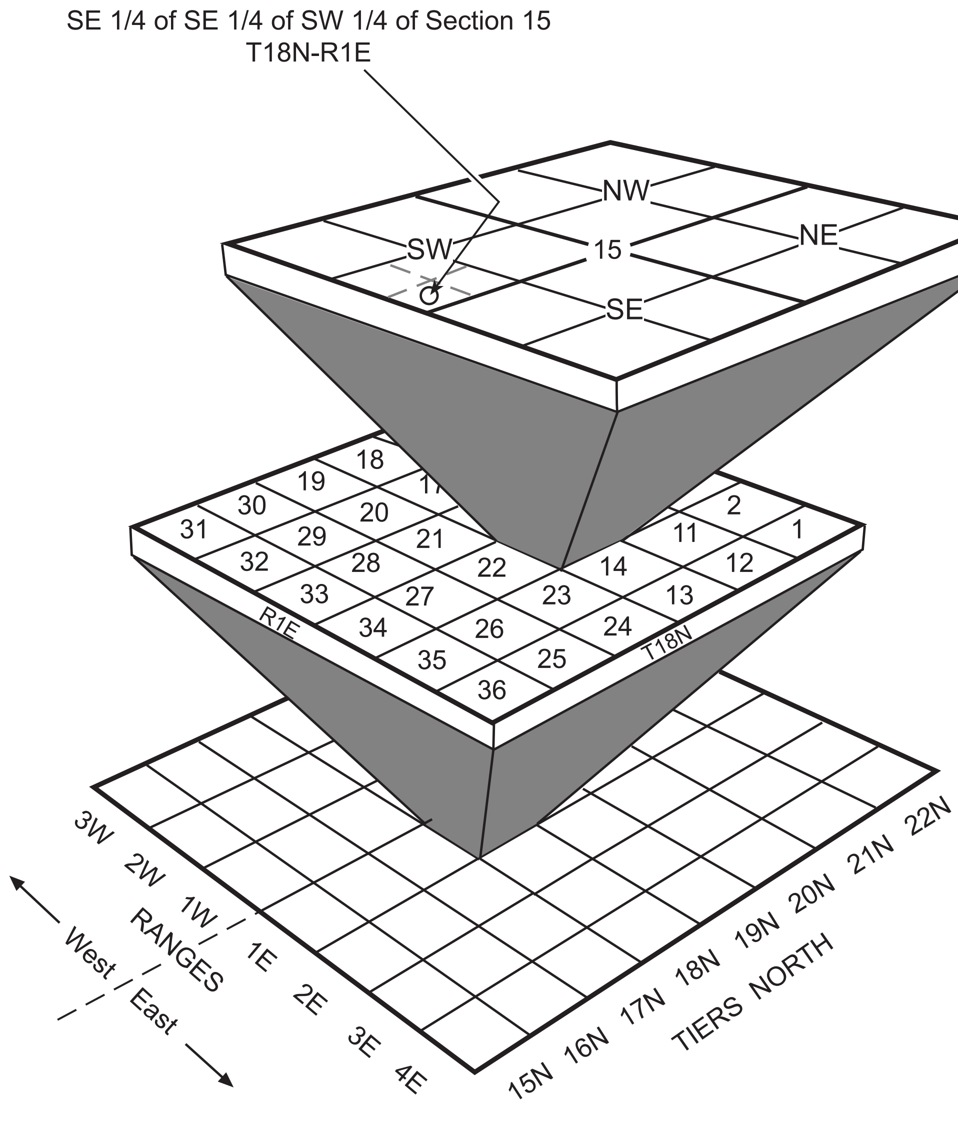


Figure 1. Well location system of tiers, ranges, and sections

feet west of meridian 89° 30' W and coincident with latitude 33° N. Using such coordinates allows a computer system to quickly plot the locations on digital maps that have been developed over the preceding 30 years, or to make new maps.

Geography

Location of Investigation

The study area, in northwestern Illinois, extends across the southern half of Whiteside, southwestern Lee, northwestern Bureau, and northern Henry Counties (figure 2). It lies primarily between parallels 41° 30' and 41° 50' N latitude and meridians 89° 20' and 90° 00' W longitude. The study area was initially sketched on working maps as a rectangular space encompassing townships T17N through T20N and R4E to R9E.

The extent of the study area changed as the data from water well records were examined and approximate boundaries of the sand unit lying in buried valleys became better known. Basically, the area encompasses more than 900 sq mi and extends from Annawan to Erie, to Rock Falls, to Amboy, to Princeton, and back to Annawan. It includes the communities of Walnut, Tampico, Prophetstown, and Ohio. Subsequent extensions of the study area have added the communities of Tiskilwa and Wyanet in Bureau County and Albany in Whiteside County to the study area as shown in figure 3.

Topography

The two most striking topographic features of the study area are the Green River Lowlands and the Bloomington Morainic System. The Green River Lowlands is a topographically low, poorly drained plain with prominent sand ridges and dunes. The term Green River Lowlands is used infrequently today, and can be traced to a work by the ISGS to describe physiographic regions in Illinois (Leighton et al., 1948). Most of the lowland is a modified outwash plain. At the close of the Wisconsin glaciation, the area was a great swamp in which two principal rivers, Rock River and Green River, flowed sluggishly along poorly defined valleys choked with outwash.

The Green River Lowlands is bounded on the south and on the east by the abrupt front of the Bloomington Morainic System. The moraine rises in elevation to more than 900 feet and affords an excellent view of the Green River Lowlands, which lie some 300 feet below. The moraine forms an arcuate pattern as it curves southward and extends beyond the study area as shown on figure 3.

Drainage

Today, the Rock River is the principal stream of the region, with an average flow of 5,299 cubic feet per second (cfs) near Sterling. The maximum streamflow, however, has been observed at 59,700 cfs (Maurer et al., 1993). By contrast, the minimum daily discharge can drop to 450 cfs.

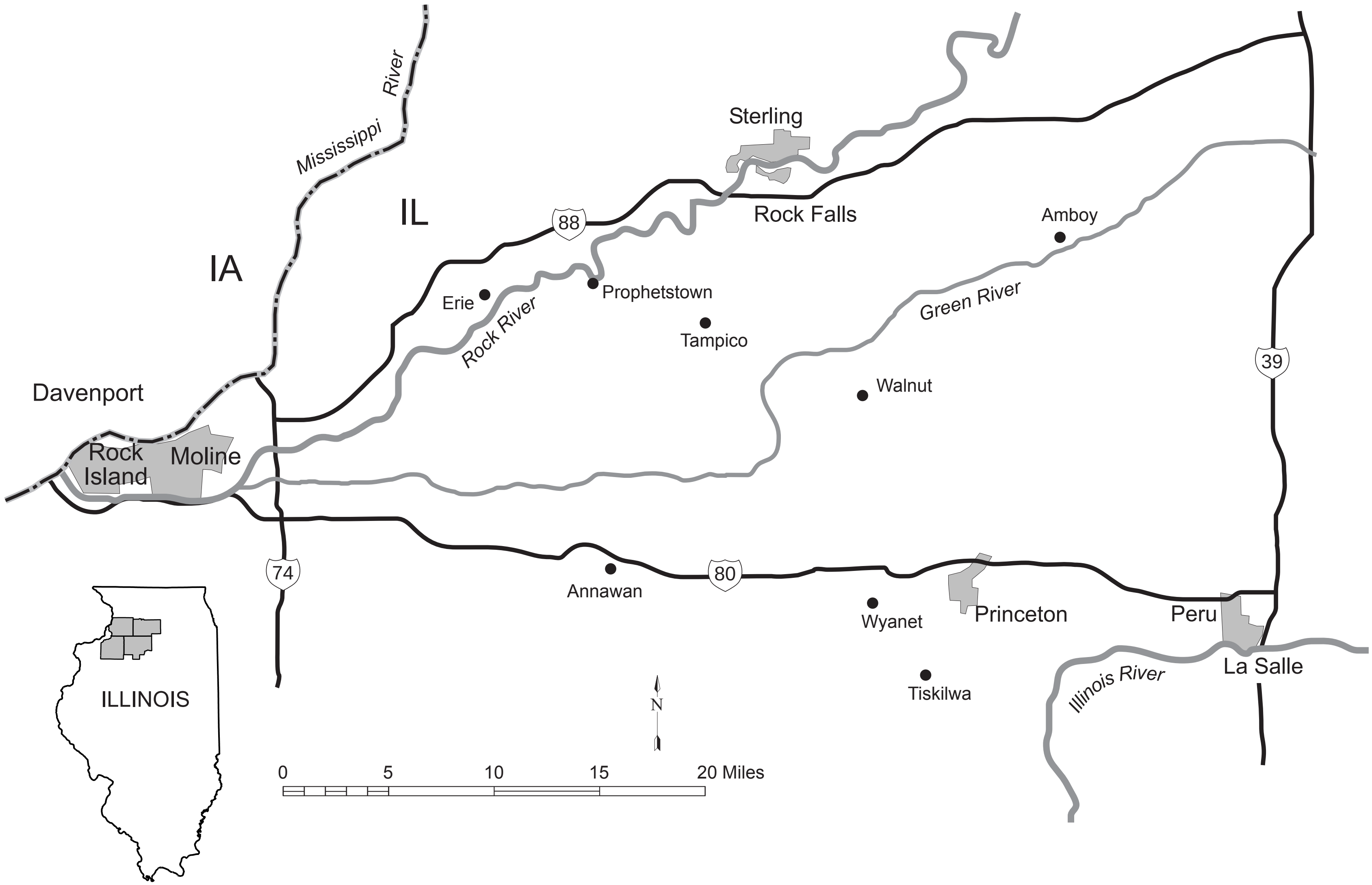


Figure 2. Geographic setting of study area

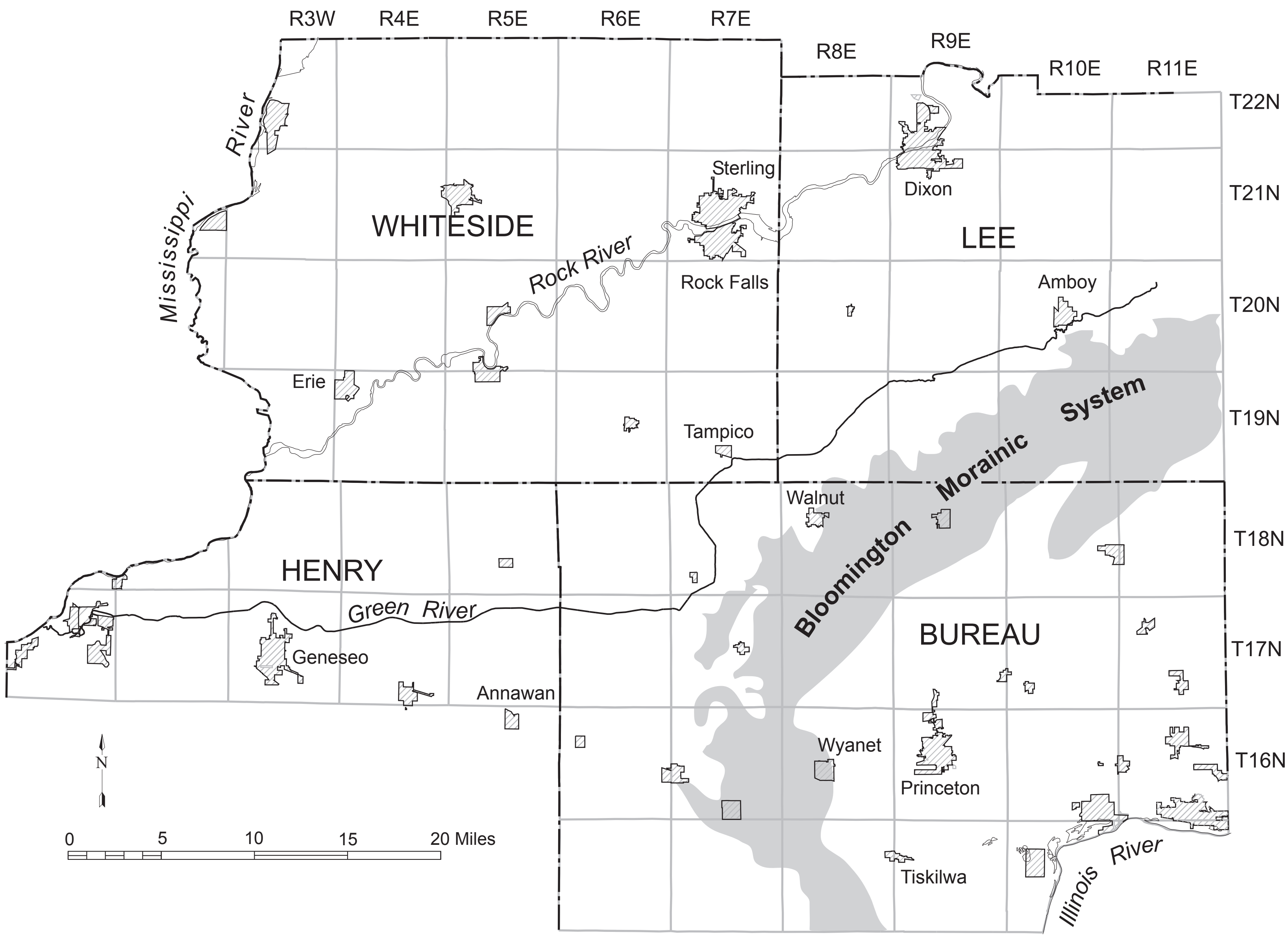


Figure 3. Major physiographic features in study area

The lowland's namesake, the Green River, carries an average discharge of 619 cfs at Geneseo (Maurer et al., 1991). Maximum discharges of 12,100 cfs have been observed following summer thunderstorms, and low flow extremes have dropped to 22 cfs during winter months.

Perhaps the most notable drainageway of the region is the Hennepin Feeder Canal, which bisects the study area and extends 29 miles south from Rock Falls to the main line of the canal near the towns of Mineral and Sheffield (figure 4). The feeder intercepts the main canal at right angles and supplies it with about 100 cfs of Rock River water. The main canal, which is called the Hennepin Canal, connects the Illinois River and the Mississippi River and once was a major transportation link for barge traffic.

Climate

The climate of the region is classified as humid continental (Changnon, 1964). It features warm to hot summers and cool to cold winters. Average annual precipitation in the region ranges from 35 to 36 inches, with about 65 percent of it falling between April 1 and October 1 (Bryan and Wendland, 1993). Precipitation can vary greatly from year to year and from the average monthly rate. Spring and summer thunderstorms are common; typically they occur in the afternoon or evening hours. Approximately 9 inches of the annual precipitation returns to the streams as direct surface runoff (Maurer et al., 1993). Most of the remaining 24 to 25 inches of annual precipitation is lost to evapotranspiration; only a small portion becomes groundwater.

Farnsworth et al. (1982) report that the average annual evaporation, or evaporation from a free water surface (FWS) in the study area, ranges from 39 to 40 inches. They report that many hydrologists consider FWS evaporation to be equivalent to potential evaporation and a good index to potential evapotranspiration (PET), the primary estimate of water demand. Fortunately, much of the water demand is offset by precipitation, especially during the growing season. Nevertheless, PET losses exceed most monthly precipitation maximums (Bowman and Collins, 1987). The resulting deficit during the growing season, coupled with the sandy soils common to the region, often leads to the demand for irrigation water.

A growing season for the region has been defined on the basis of the climate data collected at Moline. The 120-year record shows that the growing season averages 150 days. It extends from about April 25 to September 20 (Bryan and Wendland, 1993). The irrigation season ends sooner than the growing season because the supplemental water for the traditional corn and soybean crops is not needed late in the growing season. An exception is the irrigation season for speciality growers, who may use the entire growing season in an attempt to produce two vegetable crops during one season.

Average monthly amounts of precipitation and temperature have been compiled (table 1). These data, for Walnut during 1961 to 1990, come from the heart of the study area.

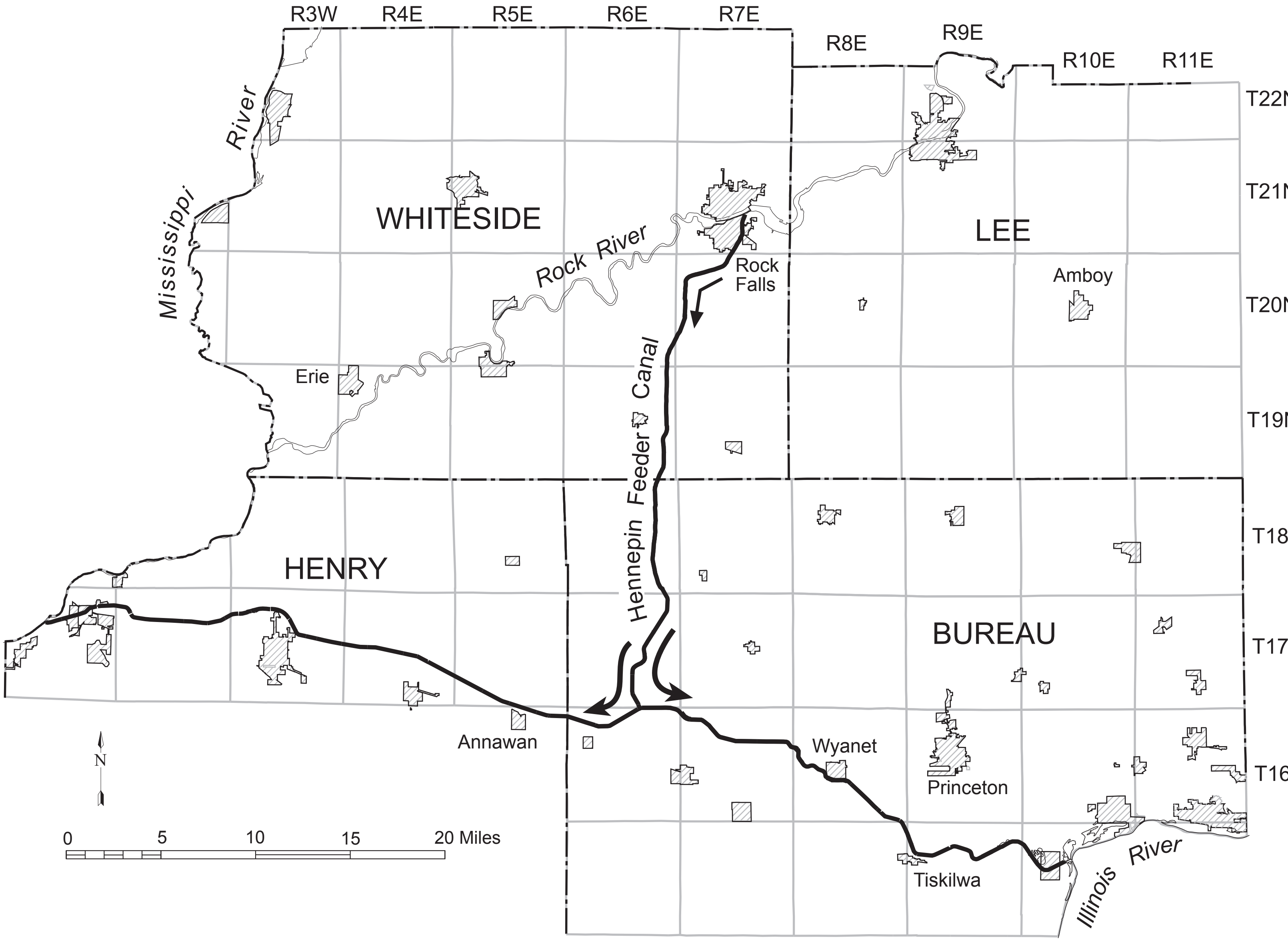


Figure 4. Location of Hennepin Feeder Canal

Table 1. Average Monthly Precipitation and Temperature for Walnut, 1961-1990

Month	*Precipitation (in.)*		*Temperature (°F)*
January	1.26		18.9
February	1.16		23.5
March	2.92		36.4
April	3.97		49.6
May	4.00		60.9
June	4.01		70.5
July	3.86		74.1
August	4.31		71.8
September	3.97		64.3
October	2.68		52.7
November	2.40		38.5
December	2.02		24.6
Total	36.56	Average	48.8

A graph of average monthly precipitation and temperature reveals that both maximums coincide during the region's growing season (see figure 5).

Soils

Soils in the study area vary considerably and have a direct bearing on where irrigation is needed. They occur in an orderly pattern related to geology, landforms, relief, climate, and the natural vegetation of an area. By observing the soil profiles of an area, scientists have recognized that patterns of soil type are principally related to topography. These patterns can be traced because they are repeated from field to field and from farm to farm within a certain geographical area. Soil associations that describe these patterns are named by placing together the names of two or more soil types that occur within the sequence (Oschwald et al., 1965).

Some soils in the Green River Lowlands require frequent moisture replenishment during the growing season. These soils are developed on outwash plains, dunes, and till plains (Chelsea-Sparta-Orio soil association) and can be problematic, particularly during droughts (Soil Conservation Service, 1985). The need for supplemental water coupled with the availability of center-pivot systems and the occurrence of abundant groundwater supplies have encouraged irrigation.

Crops grown in soils that may hold moisture better have less need for irrigation. Poorly drained and nearly level areas may be prone to flooding (Selma-Gifford soil association). However, on the steeper slopes of the Bloomington Morainic System, soils range from well

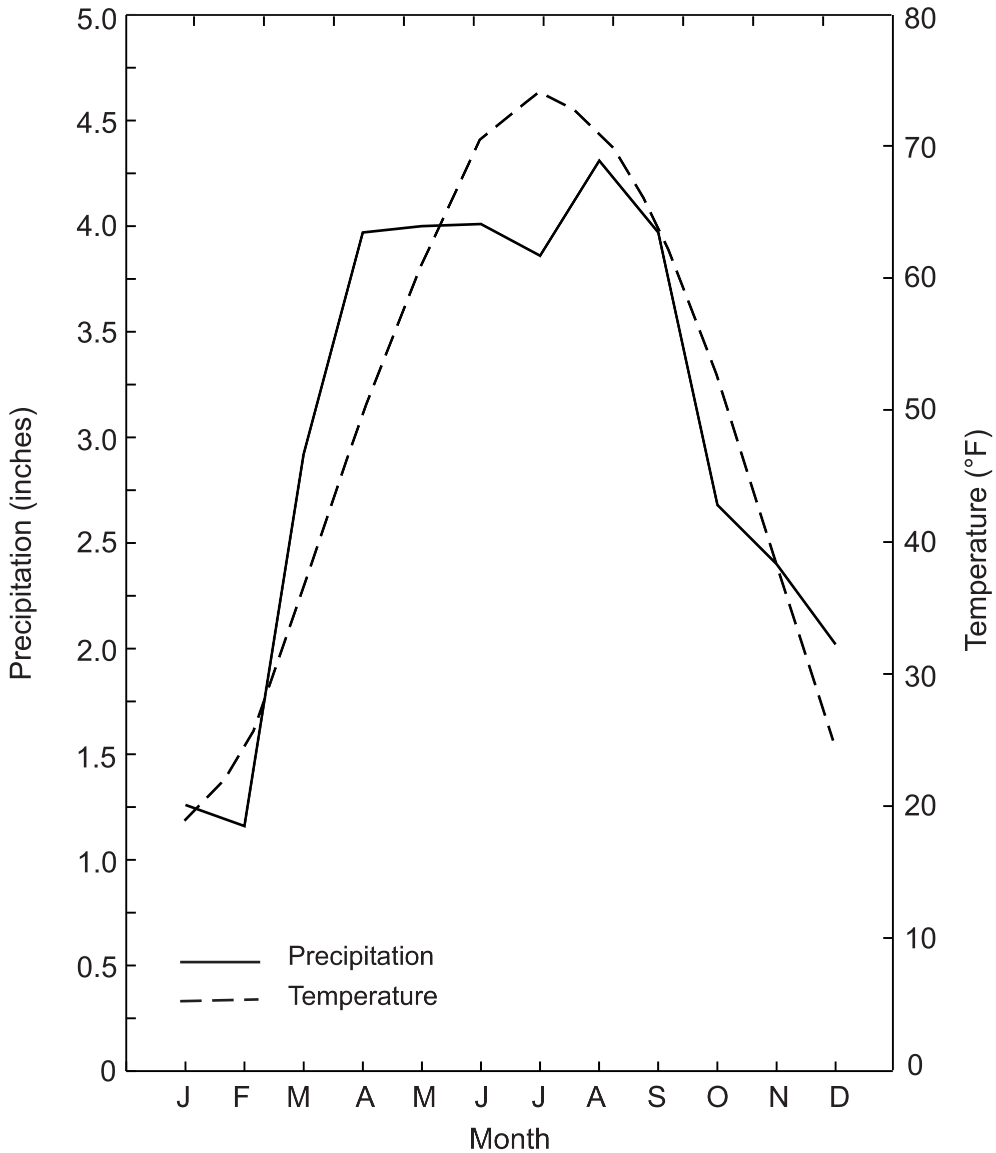


Figure 5. Average monthly precipitation and temperatures for Walnut, 1961-1990

drained to excessively well drained (Parr-Ayr-Chelsea soil association), and they are likely to be irrigated.

Population

According to the township data reported during the 1990 census, about 41,250 people live in the study area, and the rural residents are widely scattered (U.S. Department of Commerce, 1990) . Two population centers, Rock Falls and Princeton, account for 40 percent of the total number of inhabitants. Another 20 percent of the population live in small towns or villages and are served by public water supplies. The remaining people typically have privately owned wells. Census data frequently report only 10 to 20 residents per square mile.

Geological Considerations

Geologists and well drillers studying the subsurface of the upper Midwest frequently think of two types of materials: consolidated and unconsolidated. Consolidated materials are those easily recognizable sedimentary rock types called bedrock. According to geologists, the bedrock of Illinois dates to the Paleozoic Era. These rocks originally were deposited in oceans as unconsolidated sediments. Their once soft clay deposits have hardened and been compacted into shale; the sand grains have been cemented together to form sandstone; and the lime, precipitated in deeper seas, has recrystallized into limestone.

Overlying the bedrock are unconsolidated materials of silt, sand, and clay. These materials were often deposited during the Ice Age, and some may predate the Quaternary Period of the Cenozoic Era. Others postdating the Ice Age are currently being deposited as modern alluvium.

Bedrock Topography

The bedrock was exposed at the Earth's surface for a long time, so long, in fact, that streams and river valleys developed in response to erosion. The most outstanding irregularity on the bedrock surface of the study area is the ancestral valley of the Mississippi River, which does not coincide with the present topography (Horberg et al., 1950). Instead, it represents the course of the river prior to the Ice Age. This bedrock valley extends southeastward from near Albany (Foster, 1956). It crosses through Whiteside County, the northeast corner of Henry County, and Bureau County before turning south near Hennepin. The ancestral Mississippi River cut more than 300 feet deep into the bedrock, and passed beneath the present-day communities of Erie and Princeton. The walls of the valley (Silurian dolomite) are visible today at Fulton and along both the Cordova and Albany Roads in extreme western Whiteside County. The valley of the ancestral Mississippi River joins with another major bedrock valley from the east, the Paw-Paw in central Bureau County, before trending toward Hennepin and the present-day Illinois River valley (figure 6).

The floor of the buried bedrock valley is rounded and typically occurs at an elevation of 350 to 360 feet. Smaller bedrock valleys representing tributary streams also have been identified (figure 7). Key among these, in terms of groundwater, is Elkhorn Creek, which trends north-south and has impacts on public water-supply wells in Sterling and Rock Falls. Other bedrock tributaries near Annawan and Buda, identified by Reinertson (1990), might contain sand deposits that eventually may yield water to wells in those communities.

Glacial Aquifers in Buried Valleys

During the Pleistocene Epoch, large ice sheets covered much of the North American mid-continent. One of the earliest ice sheets overrode the bedrock surface and covered the study area before retreating to Canada. Large volumes of meltwater carried vast amounts of bedrock debris away from the glaciers. The materials carried by the melting ice found their way into the pre-existing bedrock valleys (Horberg et al., 1950).

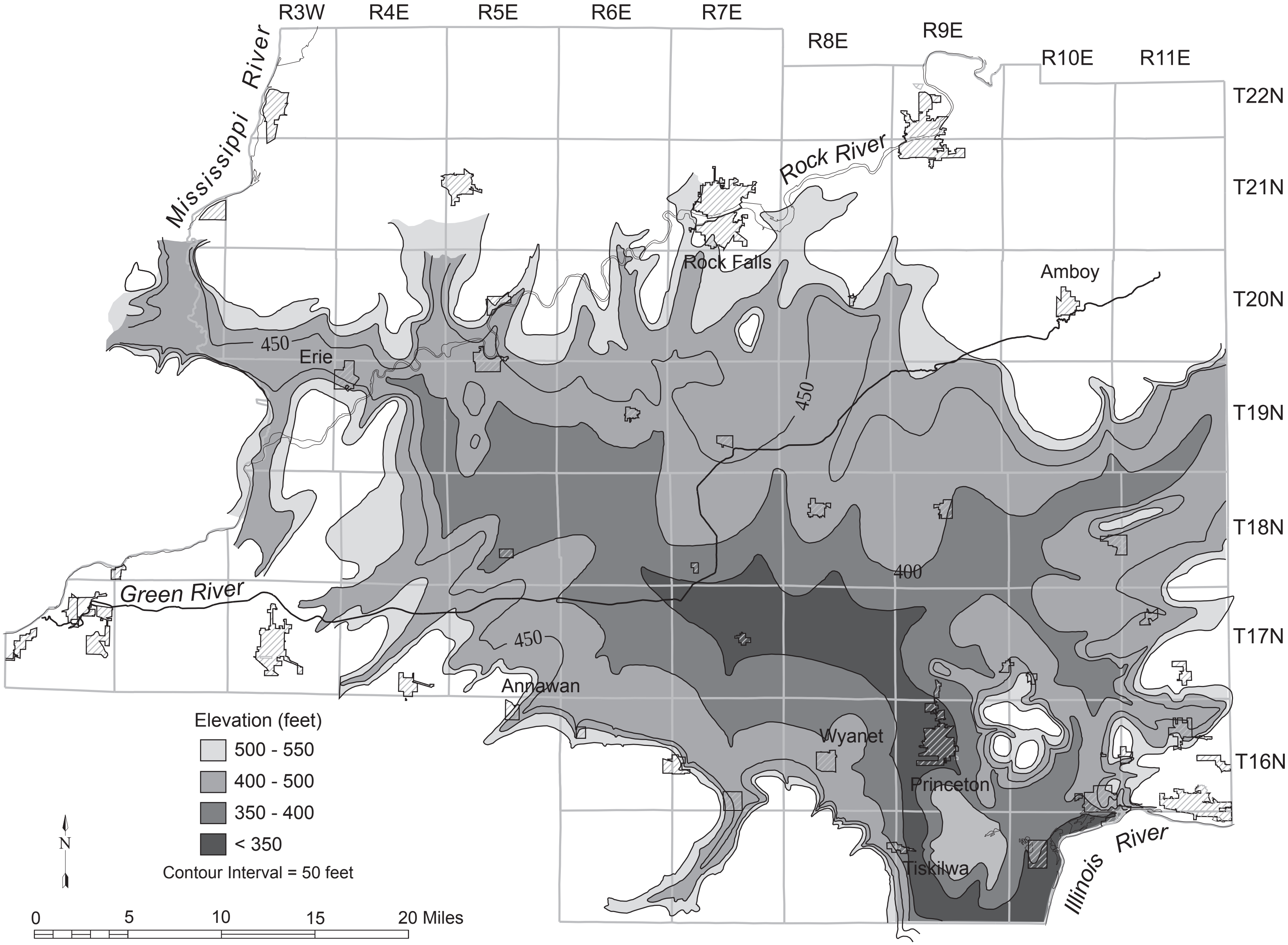


Figure 6. Bedrock topography emphasizing the Princeton Bedrock Valley (after Larson et al., 1995)

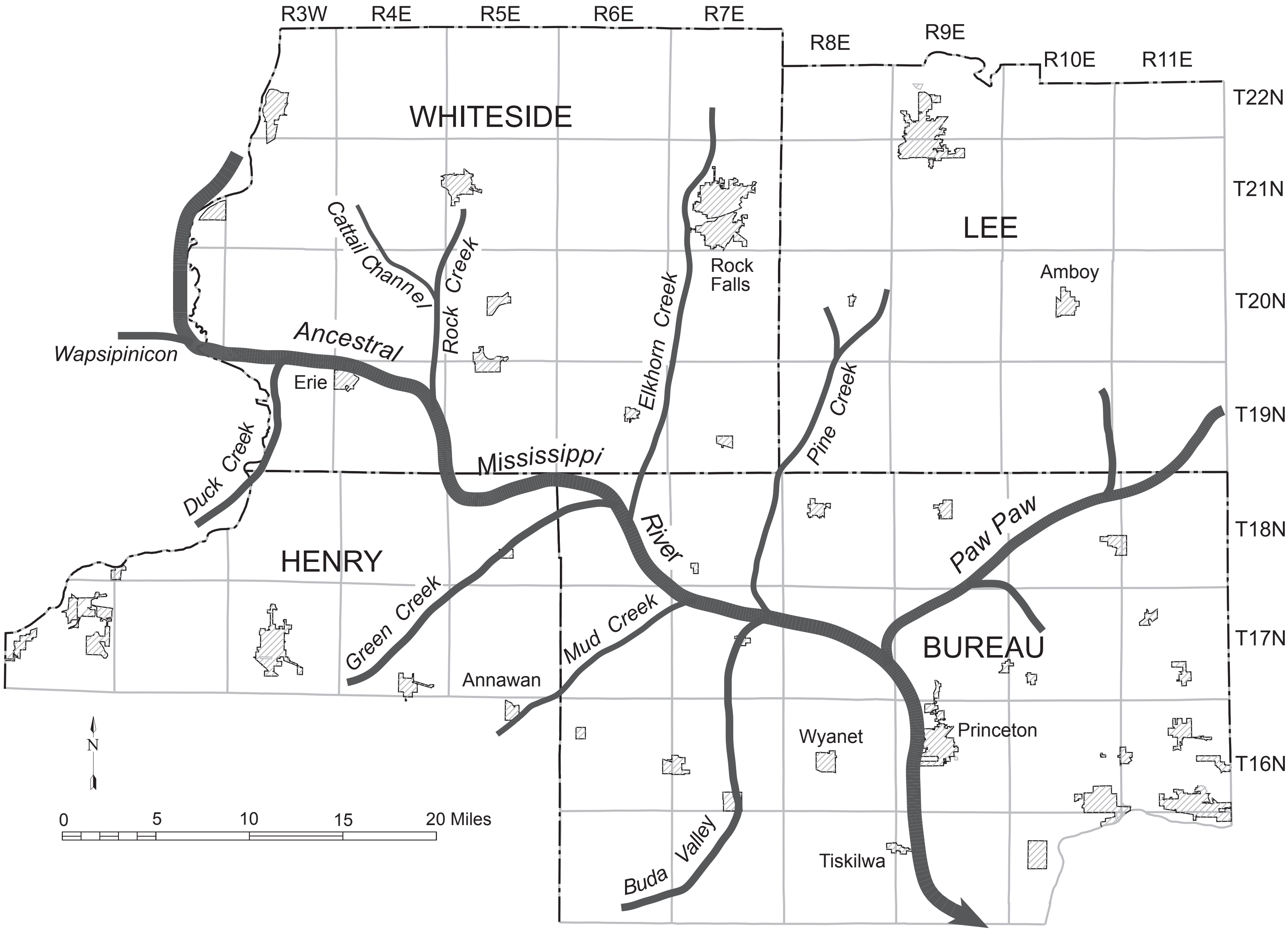


Figure 7. Relationship of tributary streams and resulting bedrock valleys
to ancestral Mississippi River (after Horberg, 1950; Anderson, 1968)

The glaciers retreated to the high latitudes, but evidence of their presence lingers. No longer are deep valleys into the bedrock exposed in northern Illinois. Instead, the valleys are buried or partially filled with glacio-fluvial deposits. Piles of debris were left behind along the edges where the glaciers stood. New river valleys and even drainage systems can be found in the clayey veneer that covers the bedrock. Sometimes the deposits left behind are uniform in character, but they frequently are jumbled as one might expect after an earthmover passes over an area and deposits its scrapings in a heap.

Today when holes are drilled into the ground, the drill cuttings reaching land surface occur in patterns or sequences. Geologists tend to think of equivalency between a vertical sequence at one location and that at another. This demonstration of equivalency leads to stratigraphic correlation. The most common means of correlation is based on lithology, although there are other methods of correlating units. For those working with groundwater, it is more common to think in terms of hydrostratigraphic units with loose references to lithologic or time-stratigraphic nomenclature. The process of correlating geologic units has led to an entire subdiscipline, stratigraphy.

A simple, preliminary, conceptual model was hypothesized as a result of a prior study (Burch et al., 1987). This model was based largely on the assumption that two aquifers, separated by a clay layer, occur in southeastern Whiteside County. This model was supported subsequently by a review of the water well logs on file at the ISWS and, although generally correct, proved simplistic as the investigation was broadened to the entire study area. Figure 8 is a cross section of geologic materials typically encountered in the study area.

The lowermost unconsolidated deposit is comprised principally of a fine-to-medium grained sand, the Sankoty, known to Quaternary stratigraphers as the Banner Formation. It is usually saturated and forms the most extensive aquifer in the area and one of the largest aquifers in the state. Outside of the study region, the Sankoty sand has been described as far south as Mason City. It is named after the water-well field on the northeast side of Peoria, where it was first described by Horberg (1946). Horberg et al. (1950) thought the sand was continuous along the bedrock valley of the ancestral Mississippi River drainage system and may have extended into Wisconsin and Minnesota.

The Sankoty sand is distinctive and readily recognizable in sample cuttings by its uniform quartz grains. Perhaps 25 percent of these grains are pink, apparently from inclusions of hematite (Horberg et al., 1950). The thickness of the Sankoty sand varies from less than 50 feet along the margins of the buried bedrock valley to more than 150 feet near the center of the ancestral Mississippi River Valley. Usually the entire thickness of the sand is saturated, so the average thickness of the aquifer is about 100 feet; but irregularities on the bedrock surface result in thin spots or places where the sand is absent, even though they are located within the margins of the buried bedrock valley.

The elevation on top of the Sankoty sand declines slightly as it progresses southeastward from Rock Falls. Elevations in the northern areas are typically about 540 feet, but they decrease to about 530 feet near Princeton. Knowing this tendency, plus the land surface elevation at a

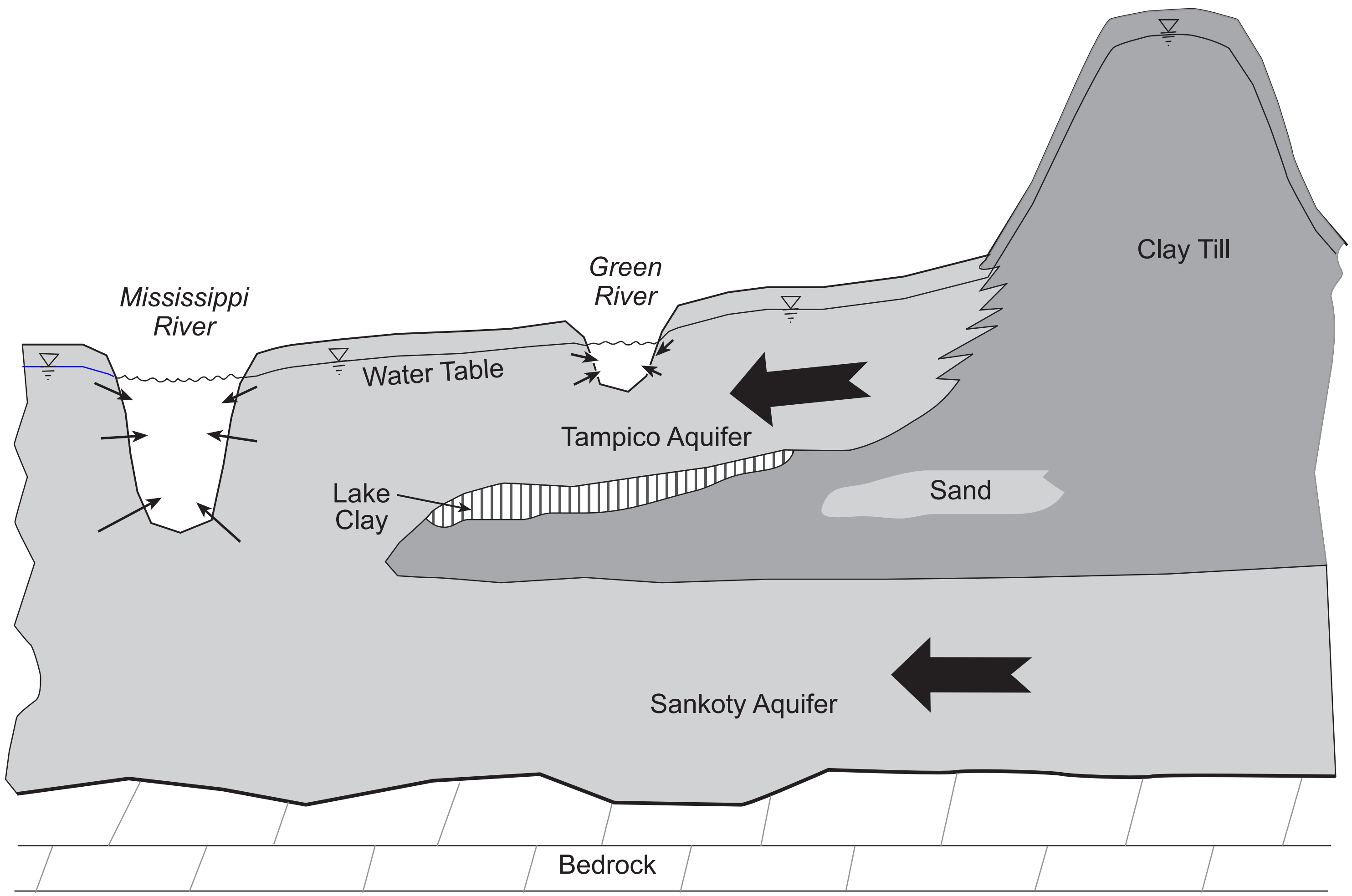


Figure 8. Stratigraphic relationship of major aquifers in study area

prospective drill site, enables the depth to the aquifer to be predicted. Figure 9 illustrates the approximate depth to the top of the Sankoty sand, based on such a subtraction. Obviously, the depth is greatest where the Bloomington Morainic System occurs.

Grain size analyses by McComas (1969) determined that the median grain size of the Sankoty sand in the upper part of the formation was about 0.35 millimeters (mm). The grain size increases with depth, according to McComas (1969) and local drillers. A median grain size of 1.25 mm was observed in 22 samples from lower in the Sankoty sand (McComas, 1969). An even coarser basal unit occurs at the bottom of the Sankoty sand and includes pea-size gravel (McComas, 1969).

The primary source of the Sankoty sand probably is the St. Peter Sandstone. Based on a comparison of McComas' data (1969) and the sieve data provided to the ISWS for 12 holes into the St. Peter Sandstone at a quarry (Kinn-Little Mine) near Oregon, the two deposits are the same. Figure 10 shows the grain-size data for the St. Peter Sandstone. Apparently, the sandstone was eroded from a large area south of the Sandwich fault and deposited in the nearby bedrock valley of the ancestral Mississippi River. The area where the St. Peter Sandstone is completely missing (see figure 11) covers about 450 sq mi. Erosion has thinned another 150 sq mi beyond this area.

The missing area has been shown for decades (Willman et al., 1975; Visocky et al., 1985; Burch, 1991) on geological maps depicting the areal extent of the St. Peter Sandstone. Because this area is topographically higher than the Princeton Bedrock Valley, it easily could have been the source of the uniform quartz grains that characterize the Sankoty sand. Quite likely this erosion and subsequent redeposition took place prior to the Quaternary and under streamflow conditions more uniform than those expected in glacial times. Additional support is garnered from the observation that no glacial tills have been reported underlying the Sankoty sand in the study area.

Overlying the Sankoty sand in most of the study area is a clay layer that increases in thickness from west to east. The clay, which is commonly referred to as the middle clay, is actually a sequence of materials that impede the flow of groundwater. Larson et al. (1995) grouped these materials together and simply referred to this unit as the Green River Lowland confining unit; stratigraphers would likely refer to this interval as the Glasford Formation and possibly formations of the Wedron Group.

The clay interval can be multilayered. In some areas the clay interval consists of a lake (lacustrine) clay under a glacial till and above the Sankoty sand. The area of this occurrence is limited and was observed in drill cuttings and on geophysical logs from test holes in northeastern Henry County and extreme northwestern Bureau County. Lake clay is believed to have been deposited behind a temporary dam on the ancestral Mississippi River and, obviously, prior to deposition of the Glasford till in Henry County (Anderson, 1968). Lake clay disappears in south-eastern Whiteside County (T19N-R7E), leaving only the glacial till to confine the Sankoty sand.

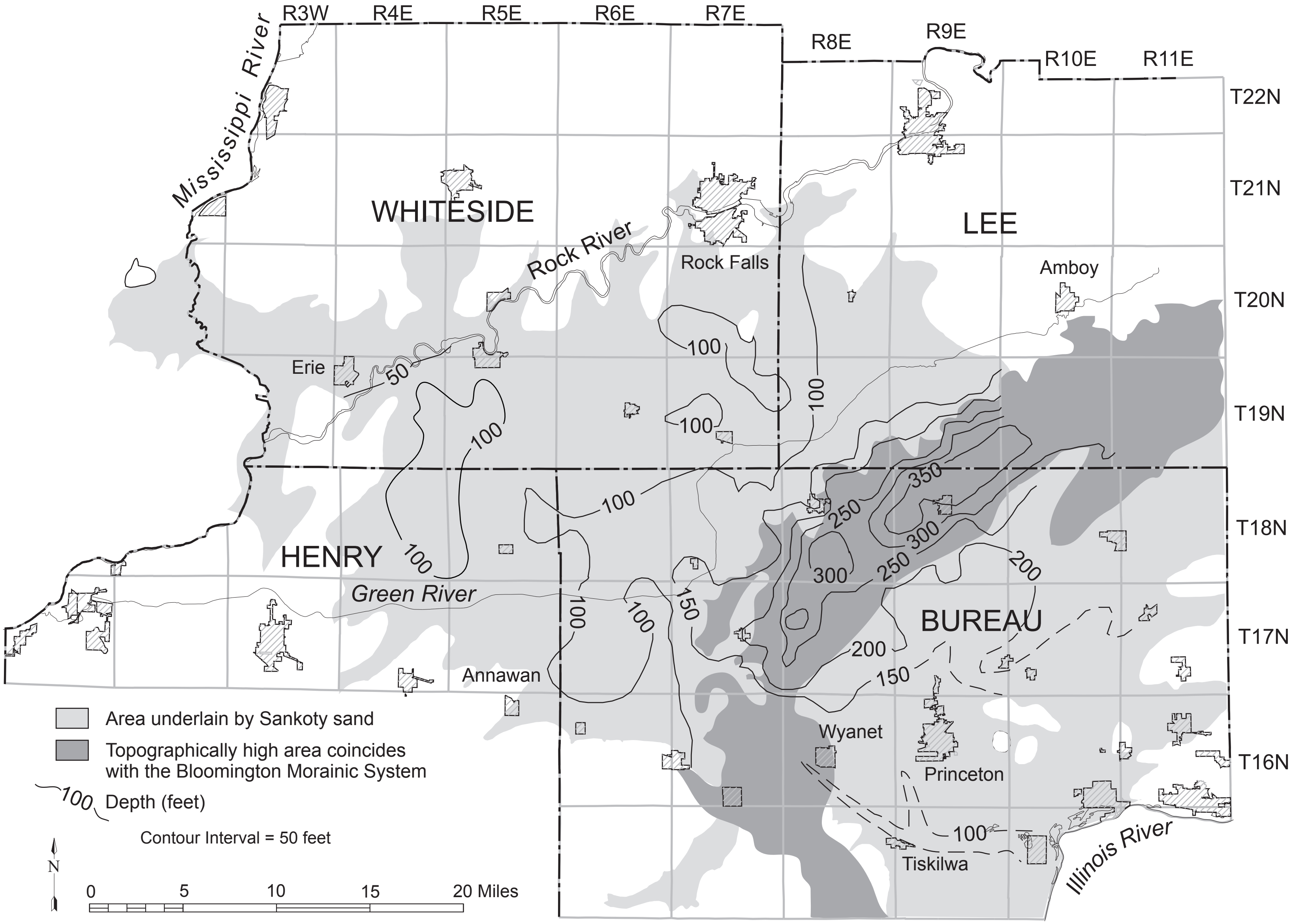
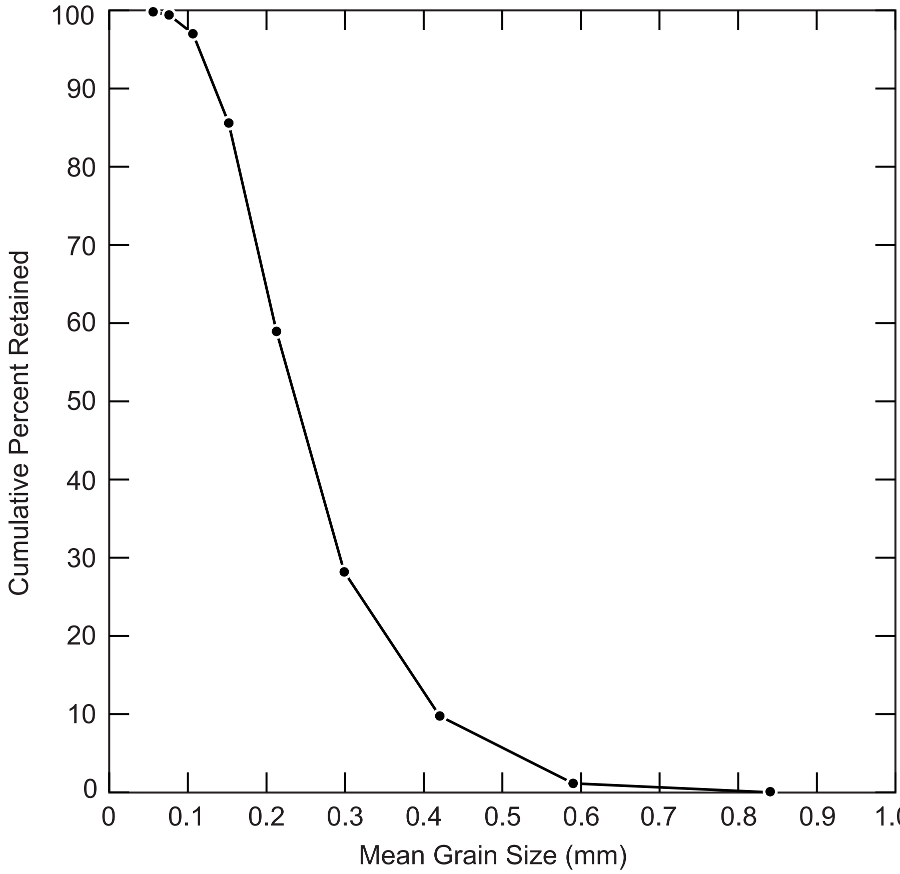


Figure 9. Approximate depth (in feet) to the Sankoty sand



Size (mm)	*Cumulative Percent*
0.841	0.05
0.589	1.45
0.419	10.05
0.297	28.45
0.211	59.15
0.150	85.75
0.104	97.15
0.074	99.55
0.053	99.95

Note: Sieve data information based on samples collected from 12 test holes into the St. Peter sandstone near Oregon, Illinois (Kinn-Little Mine). Amounts were normalized because oversized and excessively fine samples were excluded. Data courtesy of Unimin Corporation (Mark Kerasotes, February 2, 1996).

Figure 10. Grain size distribution for St. Peter sandstone from a nearby quarry

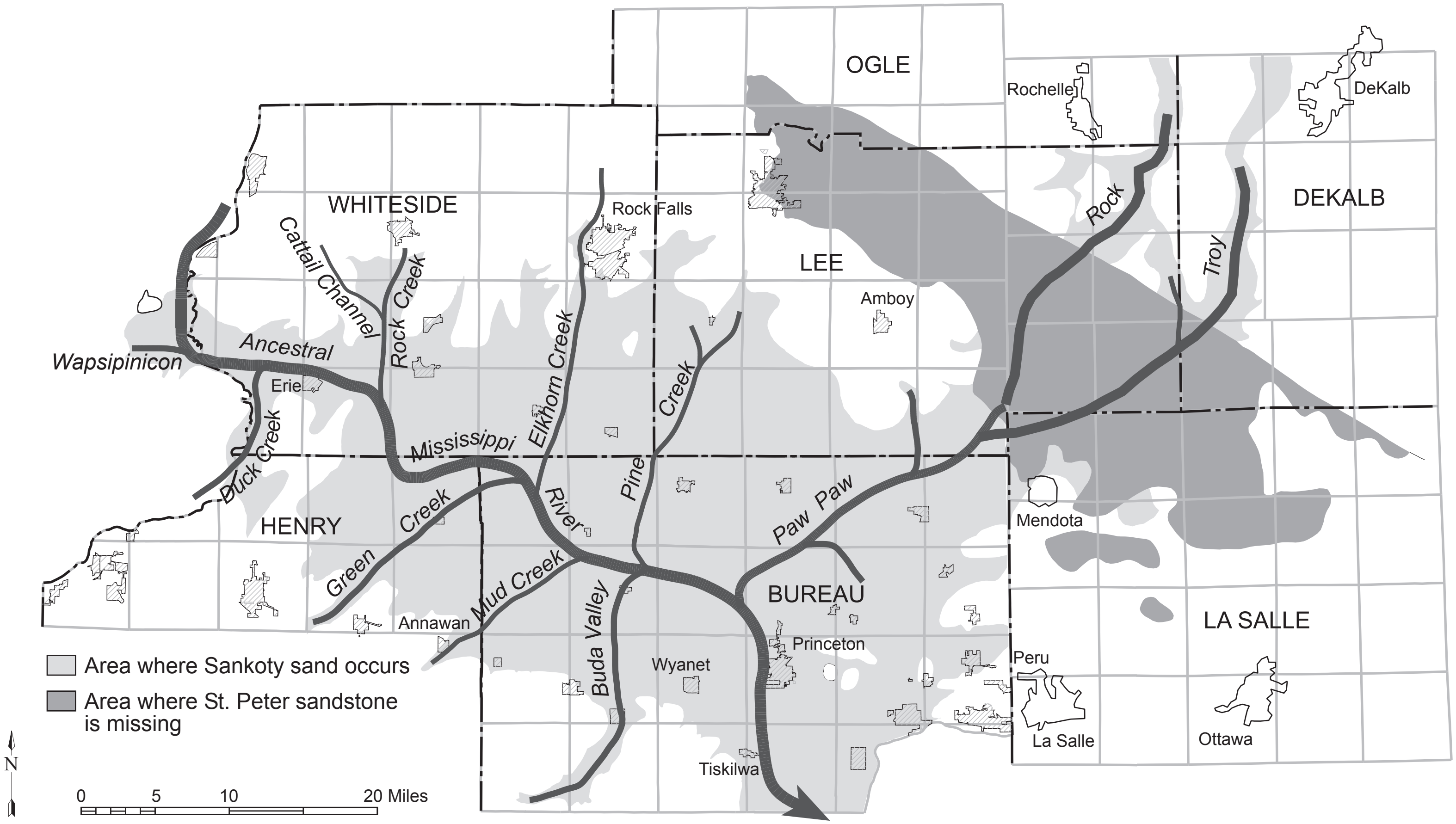


Figure 11. Area where St. Peter sandstone is missing (after Visocky et al., 1985)

Another anomaly occurs within the middle clay unit. Progressing eastward from the boundary of Lee and Whiteside Counties, a third sand unit begins to appear within the middle clay. A study of natural gamma logs reveals that this interval occurs consistently at an elevation of about 580 feet. It thickens to such an extent that, along the northeastern and eastern borders of the study area, water levels can be measured in three distinct sand aquifers. Perhaps the most obvious example of this sand unit occurs in the two townships south and southeast of Rock Falls (T20N, R7-8E) where an additional sand body and clay layer have been observed within the middle clay. A simple cross section (figure 12) between observation wells LEE-92A and WTS-91I illustrates this point. Logs from private irrigation wells along the length of the cross section confirm three sand layers extend east to observation well LEE-92C. No name has yet been proposed for this aquifer. Figure 12 also suggests a fourth sand layer occurs between observation wells LEE-92A and LEE-92C.

A final observation should be made about the middle clay. This interval thins in Whiteside County approaching the Rock River. It was identified on well logs from the areas near Rock Falls (T20N-R7E and T21N-R7E) as being only 5 to 10 feet thick. Near Erie, it thins completely. Where it does so, the sands above and below the middle clay coalesce.

The sand-and-gravel deposit above the middle clay is known as the Henry Formation (Willman and Frye, 1970; Lineback, 1979). It is the widespread sand deposit that occurs at the land surface throughout much of the study area according to Lineback (1979), and is outlined in figure 13. Often 30 to 40 feet of its 50-foot thickness is saturated. The Henry Formation occurs over most of the area in Whiteside County south of the Rock River, southeastern Lee County, northwestern Bureau County, and northern Henry County. The sand is draped up onto and pinches out against the Bloomington Morainic System in Lee and Bureau Counties. Where it is saturated with groundwater, the deposit is used as an aquifer. Larson et al. (1995) proposed naming the aquifer after the town of Tampico. Dunes of Parkland sand, a wind-blown deposit, dot the surface of the Henry Formation and may be part of the aquifer (if saturated).

The glacial deposits of the Bloomington Morainic System are Wisconsinan in age and belong to the Wedron Group. The Wedron Group is extremely variable in thickness and, within the study area, is limited to parts of Lee and Bureau Counties (Willman and Frye, 1970). Two till formations within the Wedron Group, the Tiskilwa and the Malden, are important to the groundwater regime because of their low hydraulic conductivity. The Wedron Group may be as much as 200 to 250 feet thick in the moraine and is typically 100 feet thick (Willman and Frye, 1970). Consequently, the Wedron Group and the underlying Glasford tills act together as an effective confining bed to the Sankoty aquifer in much of Lee and Bureau Counties.

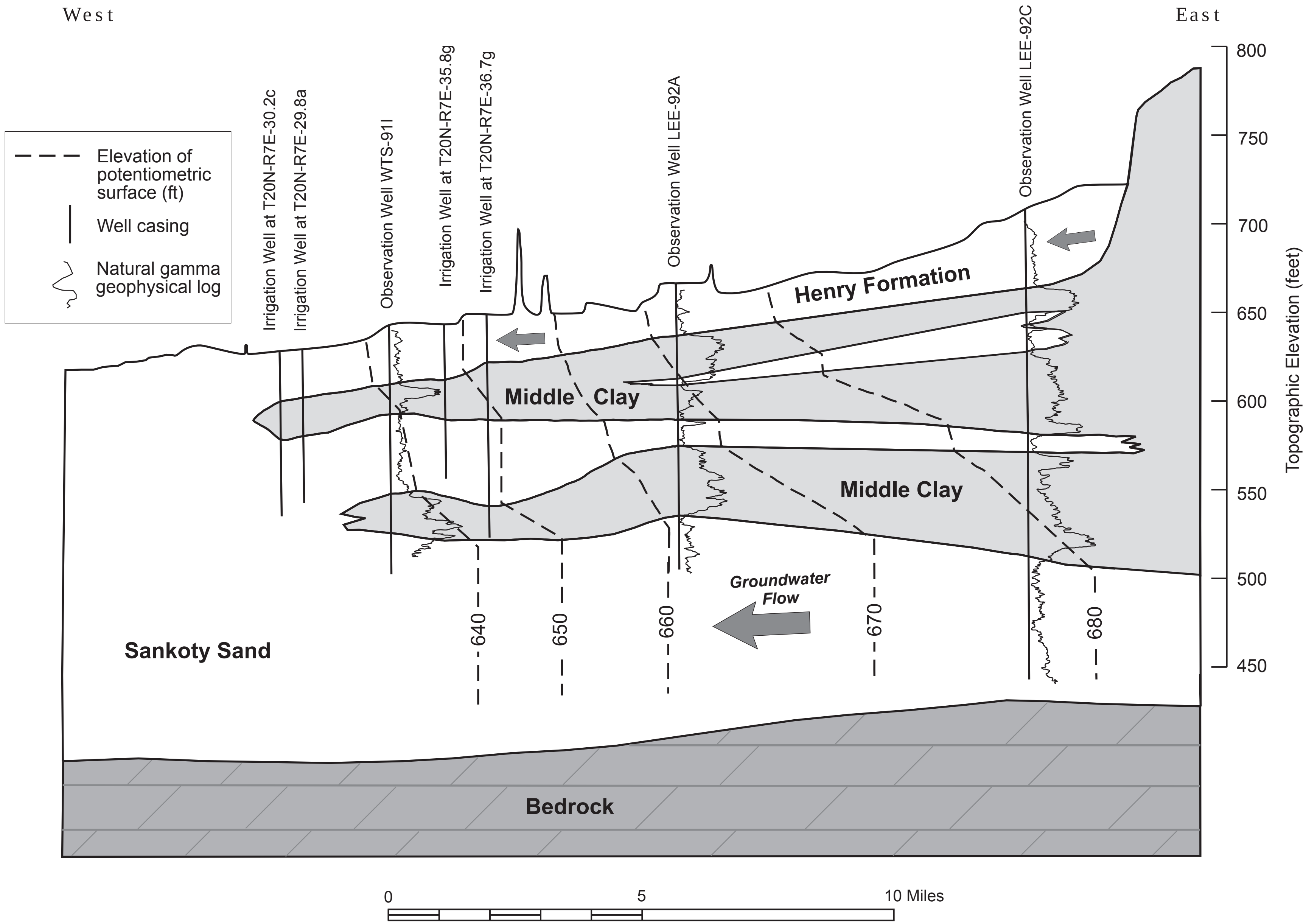


Figure 12. A west-to-east cross section trending between observation wells WTS-91I and LEE-92A (T20N, R7-8E)

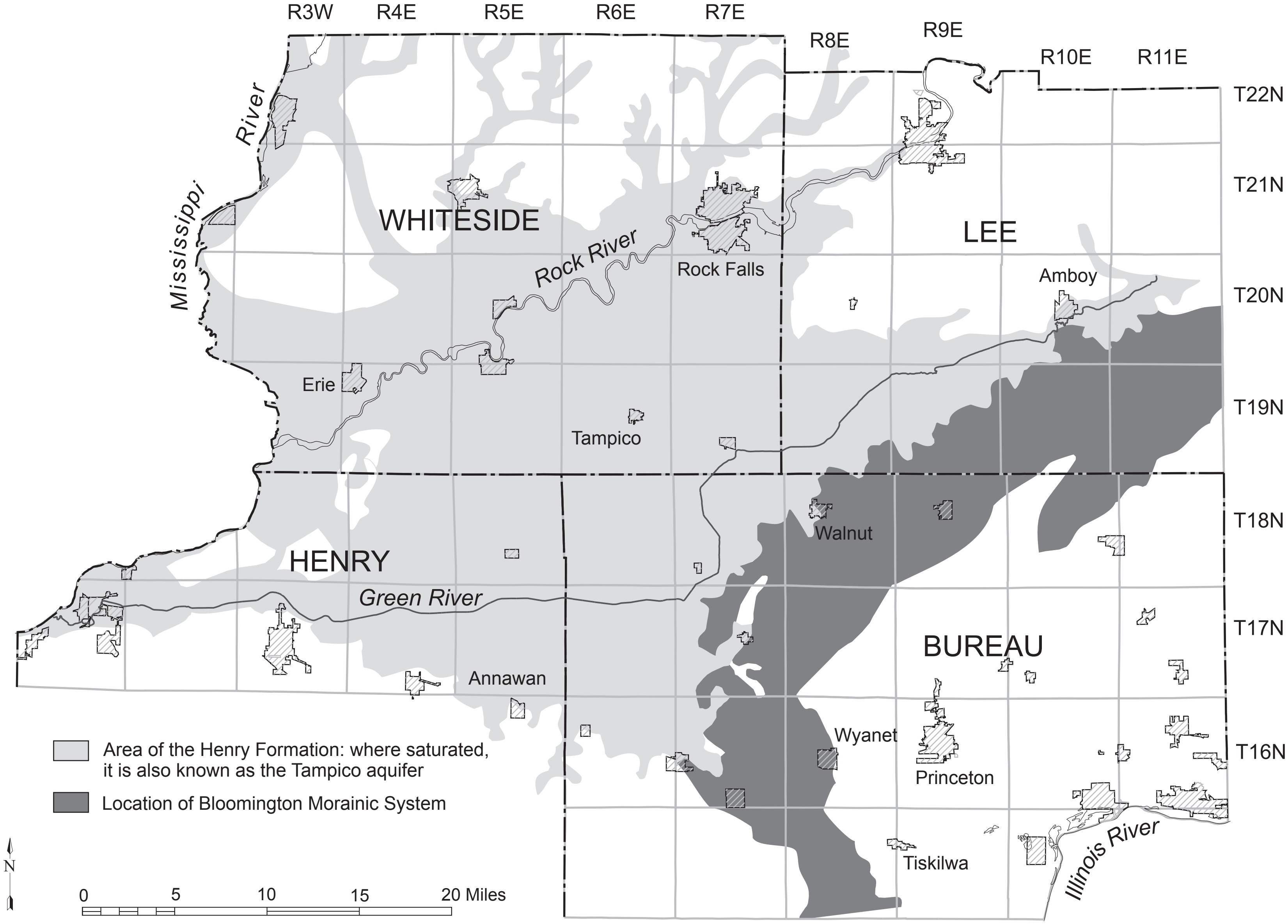


Figure 13. Distribution of Henry Formation

Groundwater

An aquifer is a geologic unit that contains and transmits groundwater to wells and springs in quantities sufficient to warrant economic development. Both yield and quality considerations are important in determining what might be construed as an aquifer. For example, a geologic deposit that is a fine source of water for a rural household may be inadequate for a community or industrial user.

Aquifer names are derived from the following sources: lithologic terms (sand-and-gravel aquifer), rock-stratigraphic terms (Ironton-Galesville aquifer), or geographic features (High Plains aquifer for the saturated parts of the Ogallala Formation). Geographic names are the basis for aquifer names under certain conditions: no rock-stratigraphic names are available, no single rock-stratigraphic name or combination (or lithologic name) is appropriate, or the use of a previously named aquifer in small-area studies is not appropriate (Hansen, 1991). Geographic names are appropriate for aquifers of subregional extent when the location of the aquifer might provide more meaningful information than its physical characteristics.

The groundwater within some of these aquifers is derived from precipitation that infiltrates the land surface and percolates downward. On its way through the unsaturated zone, much of the infiltration is returned to the surface by natural processes: evaporation and vegetative transpiration. Below a certain depth, however, all the pores between the grains of earth are filled. The level defined by this saturated condition is called the water table. In most cases, its configuration is similar to the land's topography. Usually the water table occurs just a few feet below land surface throughout most of Illinois. When the water table intercepts depressions in the land, it occurs as surface water in ponds and lakes.

Observation wells were built for this study to document groundwater conditions and the responsiveness of the principal aquifers in the study area. These wells act as windows into the subterranean world of groundwater.

Test Drilling and Observation Well Construction

Drill Site Selection

The construction of observation wells involves determining what to drill for, where to drill, and executing the logistics needed for such an activity. The selection of potential sites began with an office study of logs of private wells on file at the ISWS in an effort to sketch the approximate boundaries of the aquifer. Examination of these logs provided a stratigraphic sense of the area and estimates of depths to the top and bottom of confining bed(s) at various locations.

A reconnaissance mission to the field area in the spring of 1991 allowed the author to become familiar with ground conditions and gain insights about the availability of benchmarks. Basically, the process involved driving township roadways. Some potential drill sites were immediately obvious: wide, flat places in the right-of-way at which a drill rig could set up without interference from overhead power lines or underground utilities (typically telephone cables and natural gas pipelines).

Complementary sites subsequently were selected so the well locations would be about 4 or 5 miles apart and, when taken together, would form triangular patterns. The selection process sought to take advantage of any benchmark locations and/or favorable drill sites. The process also considered the possibility that a groundwater divide might exist in the region within the Sankoty aquifer, to coincide with the location of the Bloomington Morainic System, and to result in groundwater flowing away from the divide. Therefore, the observation-well pattern was constructed in a manner that would result in the wells being oriented perpendicular to the presumed direction of groundwater flow.

A return visit to the field area provided "ground-truth" information on the less obvious sites. Some of the complementary sites had to be moved a mile or more to avoid steep, narrow ditches that were inaccessible to a drill rig, or that were in some way not favorable. Some landowners were consulted about their feelings regarding drilling in the road ditches; others were not. In the end, 27 sites were selected for drilling. Figure 14 is a location map of the observation wells; detailed location information is listed in appendices A and B.

Drilling

Holes were drilled with the contractor's rotary rig over a period of two weeks in 1991, two weeks in 1992, and one week in 1995. In all cases, the contractor used 5- to 6-inch tri-cone bits to reach the desired depth (or until bedrock was encountered). Drilling holes with a rotary rig requires water, perhaps 1,500 gallons per hole. The water used in drilling operations for this study was obtained from public water supplies close to the drill site. Favorite sources were the community supplies at either Walnut or Tampico. Different types of drilling additives were mixed with the water obtained from public water supplies to make the drilling fluid (mud). The favored choice in 1991 was polymer, although Revert® (Johnson Division, St. Paul, Minnesota) was used in two wells and bentonite was used in two others. During the 1992 and 1995 phases of the study, the driller preferred bentonite for making mud.

Several shallow boreholes were drilled in September 1991 using the ISWS hollow-stem auger rig. Unlike the rotary drill used by the contractor, this machine does not circulate any drilling fluid. It simply screws flights of auger into the ground, which pushes cuttings up to the surface. This method of drilling is more suited to shallow investigations and could not be used for drilling at the depths required in this study.

The drilling phase revealed that stratigraphic variations increased in the eastern part of the study area (Lee County). Nevertheless, the Sankoty aquifer was consistently found below an elevation of 540 feet. Preliminary inspection of drill cuttings indicated that a consistency in mineralogical composition may exist in the aquifer. A more detailed petrographic study of the sand would be interesting and perhaps useful, but it was beyond the scope of this investigation.

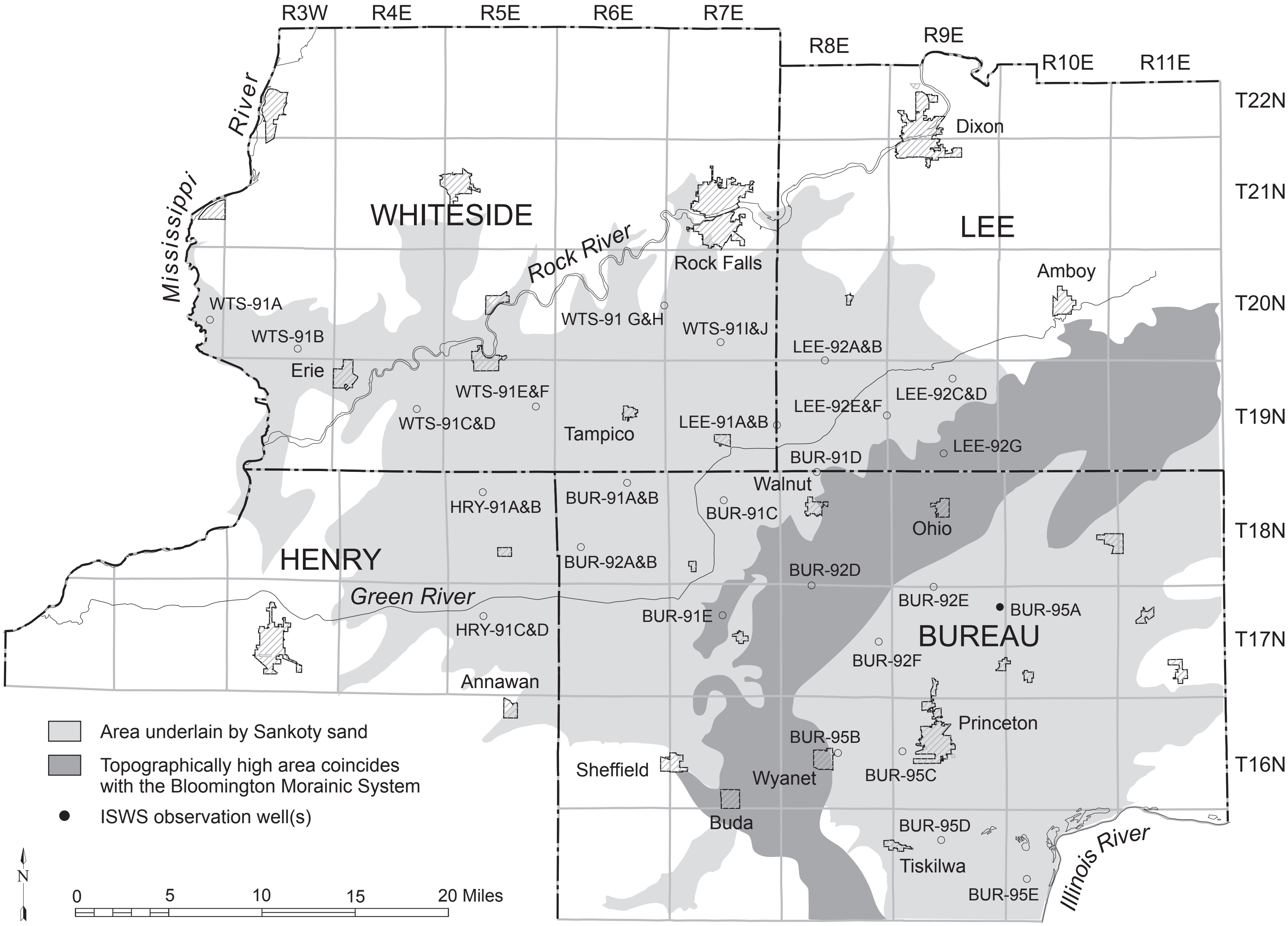


Figure 14. Locations of observation wells

Geophysical Logging

The ISGS ran natural gamma logs at all of the rotary drill sites. These geophysical logs are diagrams showing the relative emission of gamma rays versus depth below land surface. Changes in strata are commonly associated with differences in radiation. Clay and shale usually contain more radioactive elements than limestone, sandstone, or sand. The gamma log, therefore, is a vertical representation of what a Geiger counter might sense if it were lowered down the hole. When paired with the driller's log, the gamma log was extremely effective in documenting the stratigraphic relationships between aquifers and less permeable layers.

Observation Well Construction

Observation wells were constructed at each of the 27 sites primarily to monitor water levels. The wells were constructed of 2-inch diameter, flush-jointed polyvinyl chloride (PVC) casing and a 5-foot length of PVC well screen. The well screen was usually placed at the bottom of the casing, unless stratigraphic conditions dictated placement elsewhere. Each well was capped on the bottom and protected at the land surface with a lockable steel cover. The annulus was filled with gravel (⅜ inch) from the Walnut gravel pit. Layers of bentonite chips were strategically interspersed in the annulus to inhibit groundwater movement up or down the gravel pack. The annulus was sealed with bentonite near land surface.

Generally, the wells reaching the confined portions of the Sankoty aquifer were finished about 20 feet into the aquifer. Two wells often were “nested” at a site (figure 15). That is, one well was drilled deep enough to reach into the Sankoty aquifer. A second hole was drilled into the overlying Tampico aquifer, and a shallow well also was constructed at the site. Depths ranged from 85 to 359 feet for the Sankoty aquifer wells. Many of the shallow observation wells were constructed in September 1991 with the ISWS hollow-stem auger rig, typically to a depth of about 20 feet. Their purpose was to monitor water-table fluctuations in the surficial sand-and-gravel aquifer.

The observation wells were developed within a few days or weeks after being constructed. This was done to remove drilling fluid from the wells and ensure a good hydraulic connection between the well and the aquifer by removing fine-grained sediments from the aquifer immediately adjacent to the well screen. Most of the wells were developed using compressed air, but a few of the shallow observation wells finished in the Tampico aquifer were developed with a suction pump. In the compressed air technique, rising bubbles from compressed air released near the bottom of the well evacuated the water standing in the well. The evacuated water, which was “pumped” to land surface, was replaced by groundwater entering through the well screen. The development process usually was continued for about 30 minutes, or until the discharged water turned clear.

Water-Level Measurements

Depths to water were periodically measured in the wells during the course of this investigation. More than 1,800 measurements of depth to water in the observation wells were

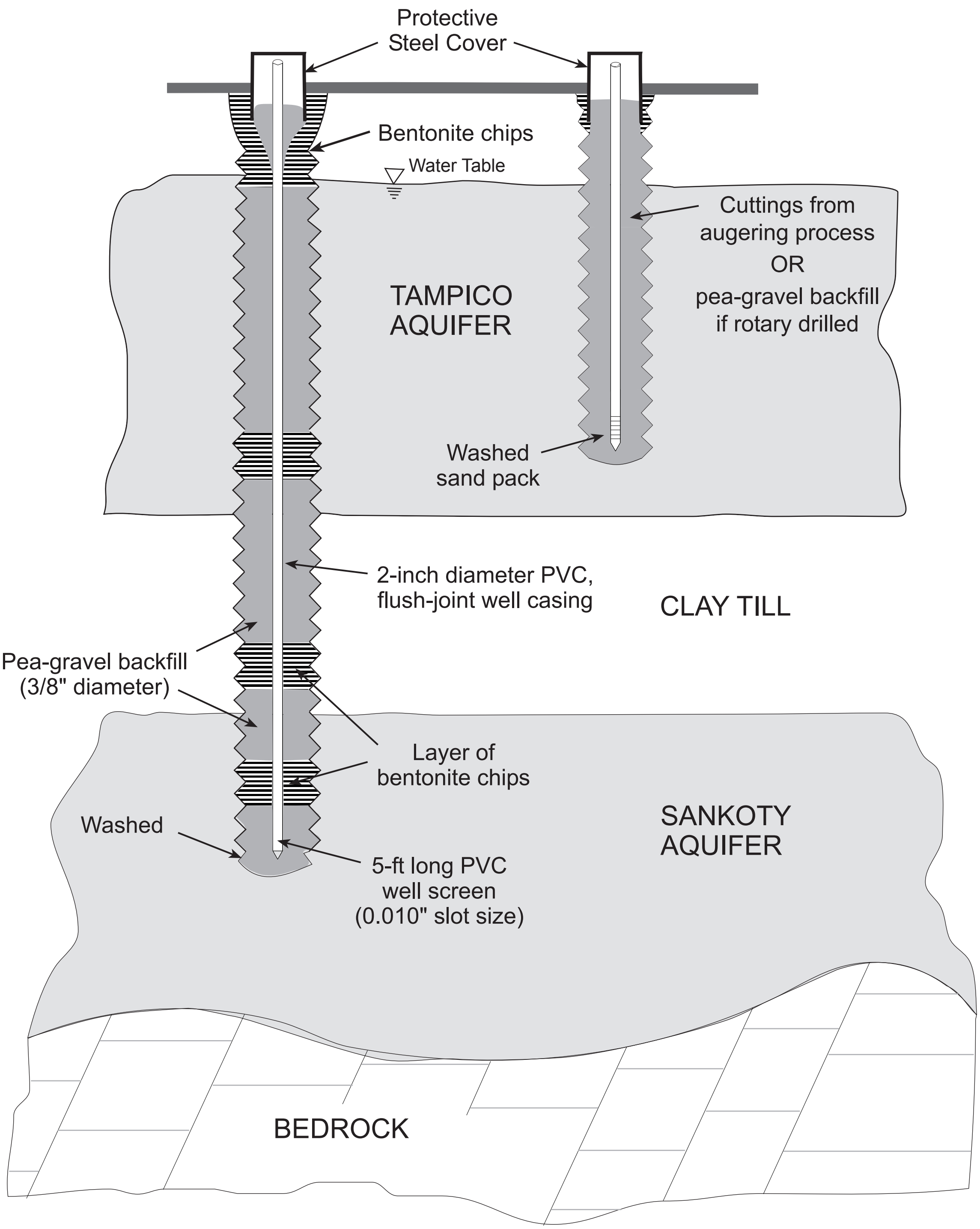


Figure 15. Cross section of typical observation well construction
and example of "nesting" wells at one site

made over a four-year period (1991-1995). The method used for these measurements consisted of fiberglass or steel tape with a weight at one end. The weight was dropped into the well. When the sound of the weight splashing on the water surface was heard, the depth from the top of the well casing was noted. Testing in the laboratory revealed that a person skilled in this inexpensive method will be accurate to within 0.02 foot.

The frequency of measurements changed in accordance with irrigation demand. During the summer, the measurements were made on a biweekly basis. By September, when irrigation demand lessened, the frequency was decreased to once every three or four weeks. The number of readings decreased to once every six to eight weeks during the winter months. The frequency of observations increased in the spring to catch what is traditionally the highest water level. Therefore, 12 to 14 measurements were made for each well per year.

Surveying

Casing-top elevations are critical to any investigation of groundwater flow direction. Water flows down gradient, whether it is groundwater or surface water. Elevations of each casing top were determined for wells drilled in 1991 and 1992. The elevation, relative to the National Geodetic Vertical Datum (NGVD), was determined to an accuracy of 0.01 foot, although measurement error refutes that degree of accuracy. The practical display of water-level maps does not require such precision. Measurements were carried from benchmarks of known elevation: commonly from USGS (third-order vertical control) or U.S. Coast and Geodetic Survey (now known as the National Geodetic Survey) benchmarks. Other benchmarks, established by county and/or state highway departments, also were used. About three weeks were spent surveying after the wells were drilled. Additional elevations were determined for irrigation wells previously monitored by Bowman and Kimpel (1991). Other elevations on selected bridges over the Green River and the Hennepin Feeder Canal were measured to monitor possible interactions between surface water and groundwater.

By using a “leap-frogging” technique and two pickup trucks, the three-person survey team used an automatic level and two surveying rods to traverse about 1 mile every hour. During this procedure, the “instrument person” rode on the tailgate between setups. Drivers alternated positioning themselves 300 to 500 feet ahead of the surveying instrument. Some of the traverses were closed onto benchmarks other than where the line began; other traverses were left open. As an example of accuracy, on two particularly long traverses in Lee County, the team covered more than 11 miles and closed to within 0.5 foot each time. Lee County traverses were more difficult than those in Whiteside County because fewer benchmarks exist in Lee County.

Water-Level Fluctuations in Observation Wells

In the study area, a sand-and-gravel deposit typically occurs near land surface. This unit, referred to as the Tampico aquifer, occurs under water-table conditions because it is unconfined. That is, the groundwater within it is at atmospheric pressure. Beyond the extent of the Tampico aquifer, the water table occurs in fine-grained deposits (clay) not conducive to groundwater flow. Because these deposits do not readily transmit water, they are not considered to be an aquifer, even though a similar water-table elevation can be determined within them.

Another regionally important aquifer, the Sankoty, occurs in the subsurface. It is separated from the Tampico aquifer by a predominantly clay layer of low hydraulic conductivity (permeability). Groundwater within the Sankoty aquifer occurs at a pressure greater than atmospheric pressure. Consequently, groundwater in wells rises to levels above the top of the aquifer. The water within this lower aquifer is said to occur under confined conditions, in contrast to that within the overlying water-table aquifer. Confined groundwater also is called artesian water because it occurs under pressure. The word artesian stems from the Province of Artois in France, where many wells were under enough pressure to cause water flow to the surface. Today, the term artesian has become synonymous with confined conditions (Davis and DeWeist, 1966).

The confining layer that separates the two principal aquifers in the region also demarcates two hydraulic regimes, each with its own properties. The most notable property concerns the storage coefficient. The storage coefficient for the Sankoty aquifer is perhaps three orders of magnitude smaller than that for the overlying Tampico aquifer. The result is that changes in pumpage within the Sankoty aquifer cause exaggerated responses in the water. Consistent with confined aquifer behavior, there may be steeper hydraulic gradients in the Sankoty aquifer, deeper water-level declines in response to pumpage, and quicker recoveries than occur in the Tampico aquifer.

Groundwater-level measurements were made in each of the two principal aquifers, data were grouped by well and sorted by date, and hydrographs were prepared. The hydrographs are simply graphical representations of water levels measured with respect to time. More than 1,800 measurements of all the ISWS observation wells in the study area were made between mid-1991 and the end of 1995. Figure 16 shows hydrographs for two wells in one nest near the Hannaman Elevator along the Lee-Whiteside boundary (T19N-R8E-Sec. 19). A cursory examination of groundwater-level fluctuations reveals the seasonal nature of these changes. When the hydrographs are subdivided into two groups, one for each aquifer, they are even more informative. A discussion for each aquifer follows.

The Tampico Aquifer

Water levels of the Tampico aquifer respond more to seasonal changes in recharge than to changes in irrigation. This is because, in large part, irrigation wells pump from the Sankoty aquifer rather than from the shallower Tampico aquifer. The water table is fairly stable during the year. Its maximum stage occurs in the spring and seems to coincide with flooding of the Rock River. The lowest groundwater elevations occur in the fall and are typically 2 to 4 feet below peak elevations earlier in the year.

The date of minimum groundwater level of the Tampico aquifer occurred later than it did for the Sankoty aquifer in three of the five years studied. Recognition of this difference also

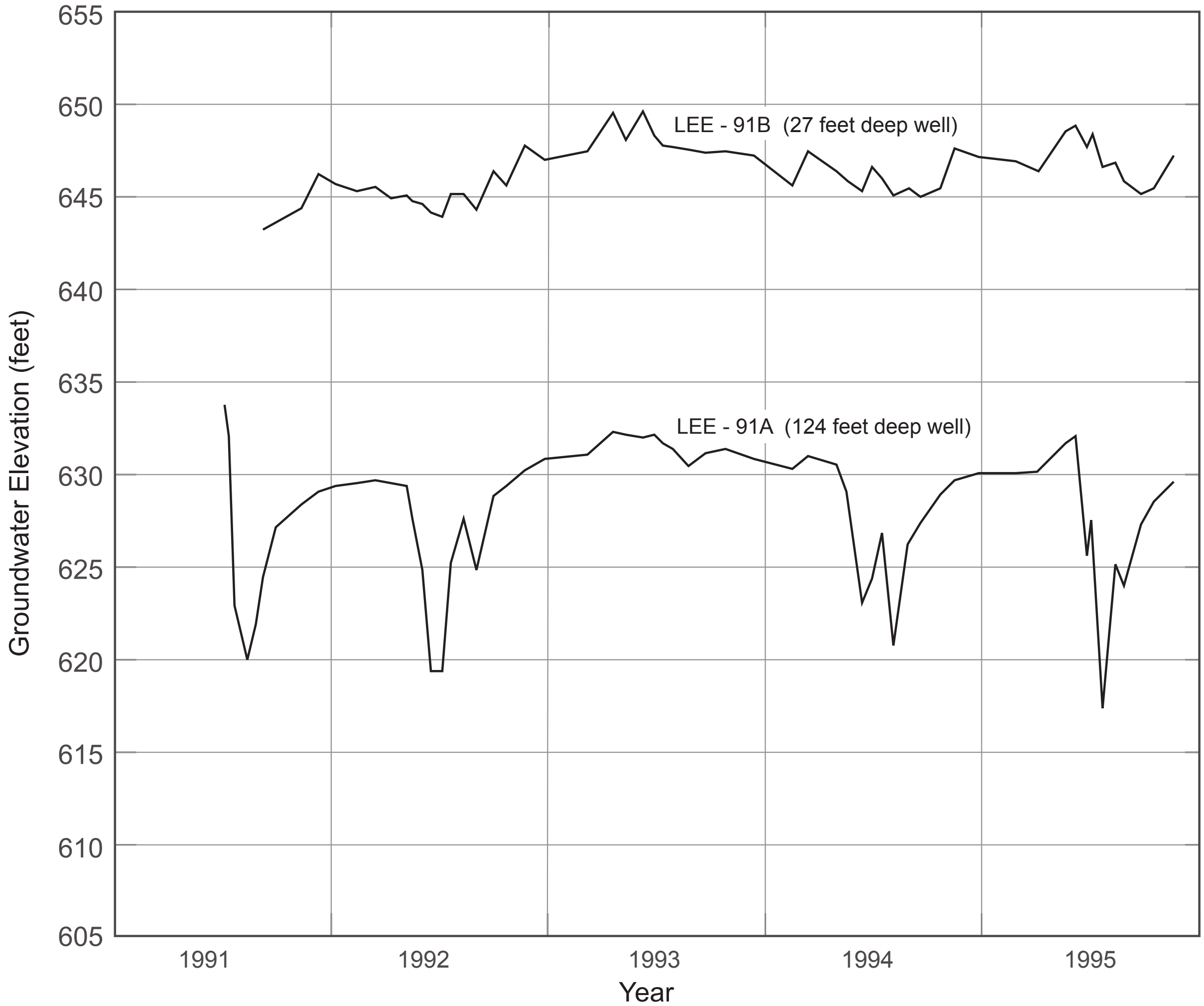


Figure 16. Water-level data from two observations wells
at same nest along the Lee-Whiteside boundary

illustrates that the two aquifers are separate entities. The dates of the minimum groundwater level occurrence for the Tampico and Sankoty aquifers are presented in table 2.

A map for the 1995 season was made and checked for patterns of water-table decline of the Tampico aquifer (figure 17). It reveals that the water table declined from a little more than 4.5 feet north of Walnut to about 2.5 feet on the west end of the aquifer (near Hooppole and Erie).

During particularly wet seasons, the groundwater level of the Tampico aquifer is at or very near the land surface. Ditches, canals, and creeks in the Green River Lowlands often carry away some of the excess groundwater. When the growing season begins, the plants help to lower the water table by tapping the groundwater reservoir with their root systems.

The records in table 3 show, for example, that some groundwater levels rose following the 2.47-inch precipitation event at Walnut during July 4-6, 1995, and others continued downward. Such localized precipitation events can cause localized changes in the elevation of the water table.

Table 2. Dates of Minimum Water Levels, Tampico and Sankoty Aquifers

	Date of typical minimum level (month/day)				
Aquifer name	*1991*	*1992*	*1993*	*1994*	*1995*
Tampico	10/2	7/7	12/15	10/24	9/26
Sankoty	7/24	7/7	12/15	8/5	7/25

Table 3. Effects of July 4, 1995, Thunderstorm near Walnut on Water-Table Elevations (ft)

Observation well	*June 27, 1995*	*July 6, 1995*	*Change*
BUR-91B	629.43	630.18	+0.75
BUR-92B	618.80	619.10	+0.30
HRY-91B	604.37	606.19	+1.82
LEE-91B	647.69	648.39	+0.70
LEE-92B	672.03	672.14	+0.11
LEE-92F	675.22	675.20	-0.02
WTS-91J	641.99	641.65	-0.11
WTS-91H	631.69	631.50	-0.19
WTS-91F	610.46	610.75	-0.29
LEE-92D	698.33	697.87	-0.46

Note: Observation wells HRY-91D, WTS-91A, WTS-91B, and WTS-91D were not measured on July 6, 1995. Consequently, no calculation was possible for them.

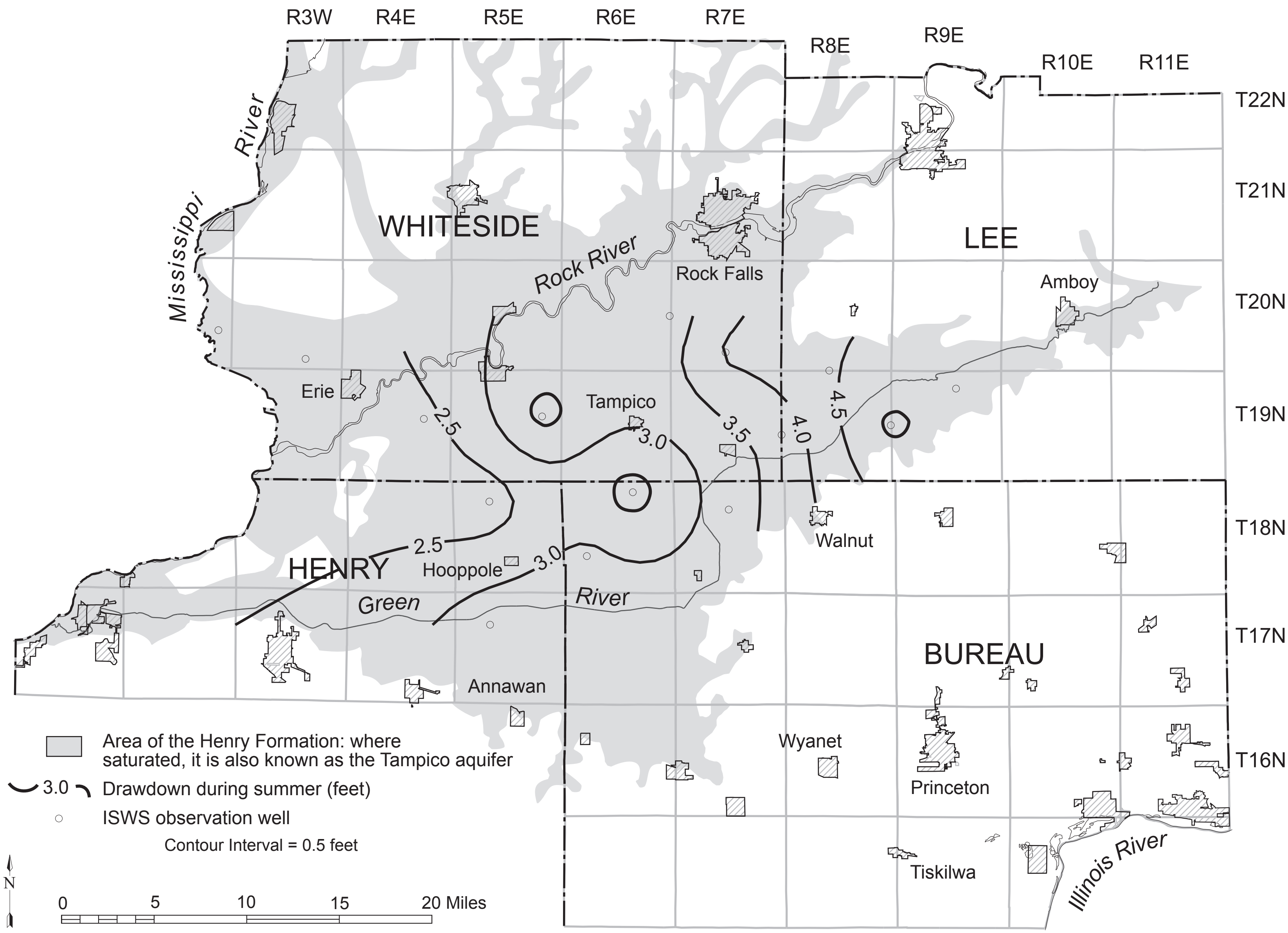


Figure 17. Contour map of water-table drawdown for Tampico aquifer during 1995

The Sankoty Aquifer

Groundwater levels of the Sankoty aquifer rise and fall throughout the year, and even during the course of a day. The changes are caused mostly by pumpage demands, but they are influenced to a lesser extent by changes in barometric pressure and by changes in river stage at outfall locations. The ratio of change in groundwater level in a well to a change in barometric pressure is known as barometric efficiency. Because confined aquifers such as the Sankoty are sensitive to barometric changes, it is important to account for this effect before using drawdown data to calculate hydraulic properties (Walton, 1962). Consequently, a six-week long barometric efficiency test was conducted (observation well BUR-91D) near Walnut. It resulted in a surprisingly low 21 percent correspondence between groundwater level and barometric pressure changes. Stated in another way, it can be expected that a 1.4-inch change in barometric pressure (measured in inches of mercury) will result in a 4-inch change in the groundwater level. When compared to regional changes in groundwater levels caused by pumpage, the changes caused by barometric efficiency are negligible, except during site-specific, controlled aquifer tests.

Artesian pressure within the Sankoty aquifer causes water levels in wells to rise above the top of the aquifer. The distance the levels rise above the top of the aquifer and its interface with the overlying confining layer is a measure of hydrostatic pressure, also known as artesian head. Each pound of pressure per square inch corresponds to about 2.3 feet of head. In the eastern part of the study area, the Sankoty aquifer has more than 120 feet of artesian head. Consequently, groundwater levels can decline considerably without reaching the top of the aquifer. This realization is important to resource managers and has led regulators in western states (such as South Dakota) to adopt a policy of not protecting artesian head because it is regarded as an "artificial" means of conveyance and amounts to only a small amount of water in storage. However, when all of the artesian head is removed, regulators are more cautious about proceeding further with groundwater developments because groundwater-level declines have far more impact on the amount of water in storage.

Most of the changes observed in groundwater levels of the Sankoty aquifer were caused by irrigation demand. The greatest declines were observed in the Tampico-to-Walnut portion of the study area, where drawdowns may be as much as 11 to 13 feet (figure 18). The area of greatest drawdown extends over several townships. The duration of the irrigation season is about 150 days each year. A scatter diagram of all Sankoty groundwater levels observed in well BUR-91D between 1991 and 1995, and calculated as number of days since the beginning of the respective year, is shown in figure 19. This diagram suggests that the maximum drawdown occurs in the summer, on or about July 25 each year. The data also show that the aquifer's rate of response was slightly asymmetric, with levels dropping more sharply than they recovered. This is probably due to a few irrigation systems used for double-cropping vegetables.

Based on figure 19, the irrigation season in the study area typically extends from about May 1 to October 1. The beginning of the season may be delayed, as it was in 1995, if May is wet. Eventually the pumps start and signal the beginning of the irrigation season. Until that time, the groundwater levels rise slightly, as was noticed in 1993, the year of the Great Flood. This

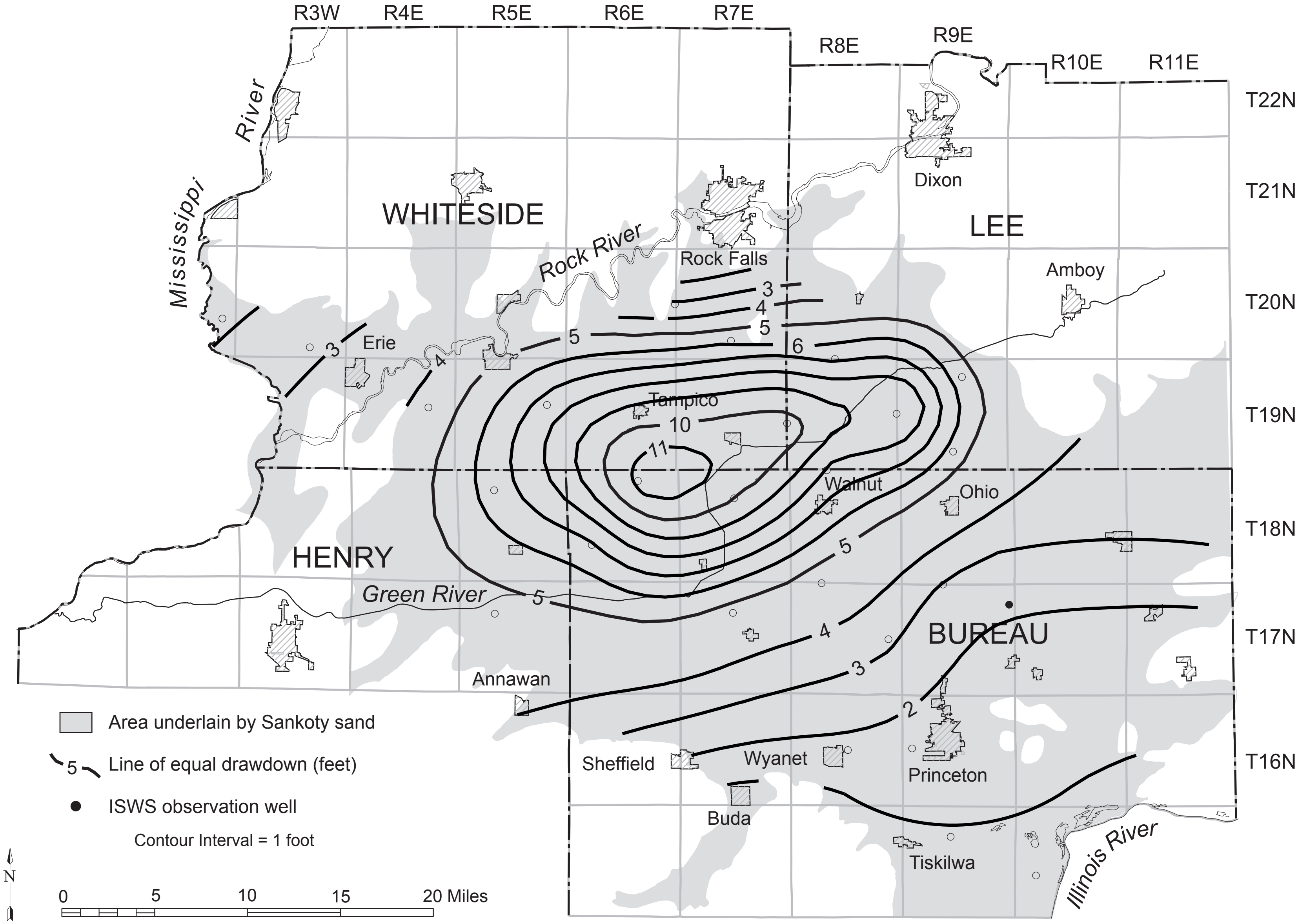


Figure 18. Contour map of drawdown for the Sankoty aquifer during 1995

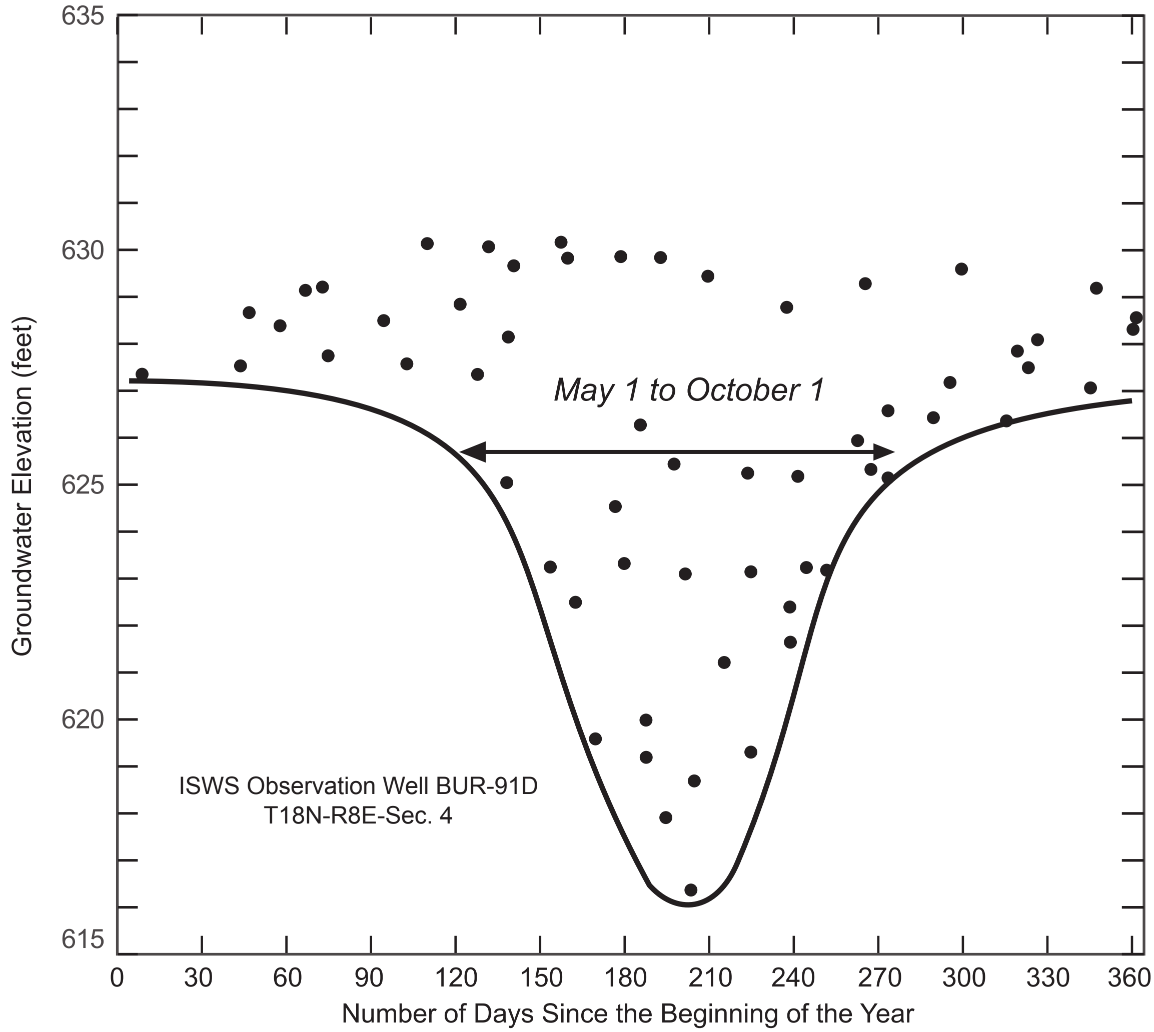


Figure 19. Scatter diagram of 1991-1995 water levels in Sankoty aquifer
and estimate of occurrence of irrigation season

observation leads one to surmise that the truly steady-state levels are slightly higher than any of those observed during this study.

Groundwater levels in central Bureau County are more stable than those in the Green River Lowlands. The stability is due to the lack of irrigation in the area and is indirectly attributed to the heavier soils of the area. Changes in groundwater level observed near Kasbeer (observation well BUR-92E) seem related to changes in stage of the Illinois River at Hennepin. When the river stage is high, the hydrostatic pressure sufficiently blocks the groundwater discharge to the river. When the river stage falls to normal or below normal, groundwater discharge to the Illinois River increases.

A similar situation occurs near Erie; groundwater levels of the Sankoty aquifer are controlled predominantly by fluctuations in the Rock and Mississippi Rivers. The responses are much more subdued than those in central Bureau County because the aquifer near Erie is under water-table conditions rather than confined conditions. When the rivers are in flood stage, groundwater levels rise above their normal highs in observation wells WTS-91A and WTS-91B.

Potentiometric Maps

The Tampico Aquifer

The potentiometric surface of the Tampico aquifer slopes westward (figure 20). Water levels decrease from more than 690 feet in elevation near Amboy to about 540 feet near the Mississippi River. Smaller flow regimes, caused by interaction with surface water, occur within the Tampico aquifer; the most significant of these probably is the Rock River. The Green River also interacts with the aquifer and drains groundwater. Observations made in T20N-R9E-Sec. 36 (Marion Township in Lee County) suggest that the river's influence extends beyond the streambank by as much as one-half mile.

The horizontal hydraulic gradient within the Tampico aquifer is about 5 feet per mile, which is consistent with that of water-table aquifers. The gradient is steepest in Lee County, where it slopes westward at 6.5 feet per mile. It then flattens slightly in Whiteside County, to about 3 feet per mile between observation wells LEE-91B and WTS-91F (Prophetstown Township). The gradient flattens even more beyond Prophetstown, where the Tampico and Sankoty aquifers merge. West of Erie, for example, the hydraulic gradient slopes toward the Mississippi River at only 0.8 foot per mile.

The Sankoty Aquifer

Groundwater levels of the Sankoty aquifer decrease by more than 100 feet in elevation across the study area. The predominant slope, under nonirrigation conditions, is westward (figure 21). The gradient flattens from about 10 feet per mile in southwest Lee County to about 3 feet per mile in Whiteside County. A broad, flat area in the potentiometric surface west of Walnut probably reflects the widening and thickening of the aquifer in that area.

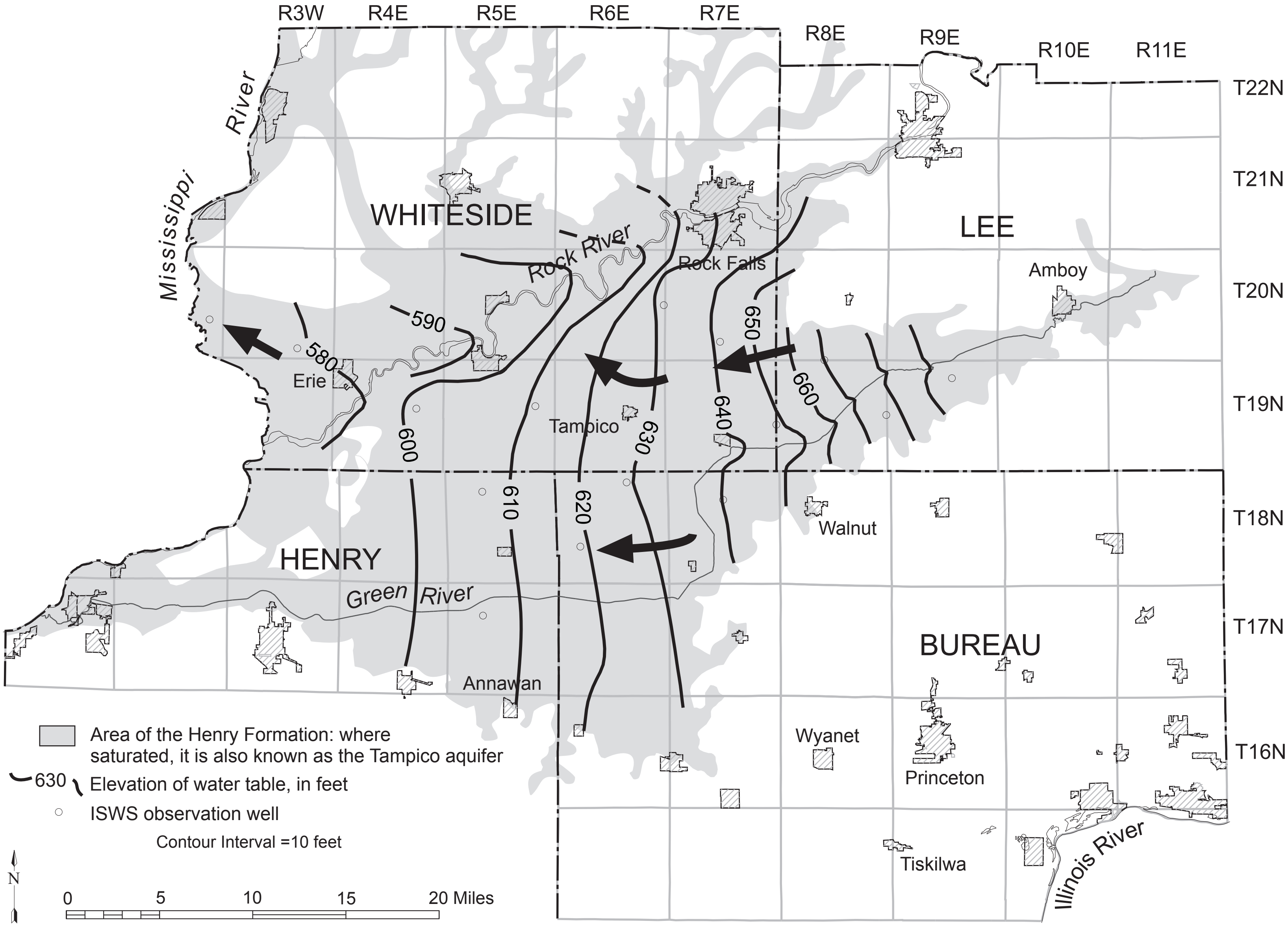


Figure 20. Potentiometric surface of Tampico aquifer in 1995 and predominant flow directions

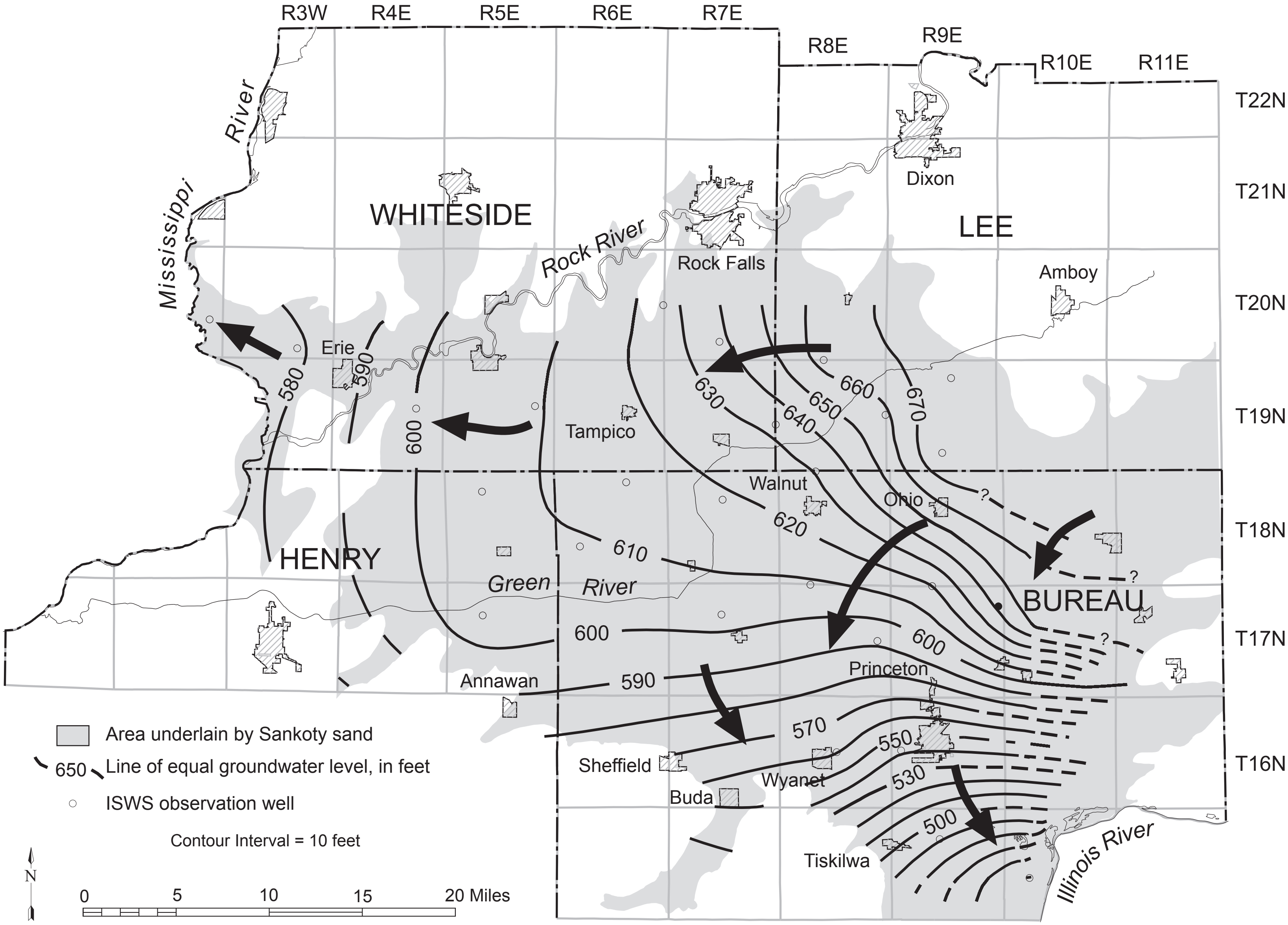


Figure 21. Potentiometric surface of Sankoty aquifer in 1995 and predominant flow directions

A groundwater divide coincides with the location of the Bloomington Morainic System (figure 3). The moraine extends from near the community of Ohio to a point near Manlius, then turns south. Groundwater on one side of the divide flows south and southeast; on the other side of the divide, groundwater flows primarily southwest until near Tampico, where it slowly arcs west and northwest toward Erie.

Under natural conditions, groundwater in the Sankoty aquifer discharges primarily to the Mississippi and Illinois Rivers. Smaller amounts of groundwater are lost to the Rock and Green Rivers, as well as to evapotranspiration in the Green River Lowlands, where the aquifer is unconfined. An initial steady-state condition existed between inflow and outflow prior to settlement of the region, but it probably has not existed since the late 1800s. Today, groundwater levels reflect the new balance between groundwater inflow (recharge) and the combined effects of pumpage, drainage, and discharge. Consequently, a map of today's groundwater levels (figure 21) is probably lower than the elevations of levels that existed 100 years ago.

Head Difference between Aquifers

Because the Tampico and Sankoty aquifers are separated by relatively impermeable glacial till, differences between these two aquifers can be observed in water levels. This difference, when divided by the thickness of the clay layer that separates the aquifers, yields a parameter called the vertical hydraulic gradient.

The observed water-level (head) differences for wells constructed at the same location range from -0.9 foot to almost 21 feet. The thickness of the middle clay, which separates the two aquifers, varies from 16 to 142 feet. Groundwater levels observed on March 9, 1993, at sites with nested observation wells, were used to calculate vertical gradients. Figure 22 shows the distribution of these gradients. The values ranged from near zero to about 0.6. The areas of greatest vertical gradient nearly coincide with the maximum drawdowns, presumably indicating a winter season is an insufficient recovery time. Therefore, the vertical gradient can be expected to be less than 0.6 during predevelopment of the Sankoty aquifer.

The vertical gradient between the two aquifers changes during the year. The downward gradient to the Sankoty aquifer usually increases during the summer because groundwater levels decrease in response to pumpage. Consequently, figure 22 is based on observations made on March 9, 1993, when conditions were nearly stable.

Although downward gradients are more common in Illinois, this is not always the case. For example, at one site in Henry County (T17N-R5E-Sec. 8) the gradient is upward from the Sankoty aquifer. The upward gradient between observation wells HRY-91C and HRY-91D was 0.04 on March 9, 1993. A temporary reversal in gradient direction occurs at the site during the irrigation season when enough hydraulic pressure is removed from the Sankoty aquifer by pumpage to permit the downward migration of groundwater from the Tampico aquifer. Otherwise, the normal gradient is upward to the overlying Tampico aquifer.

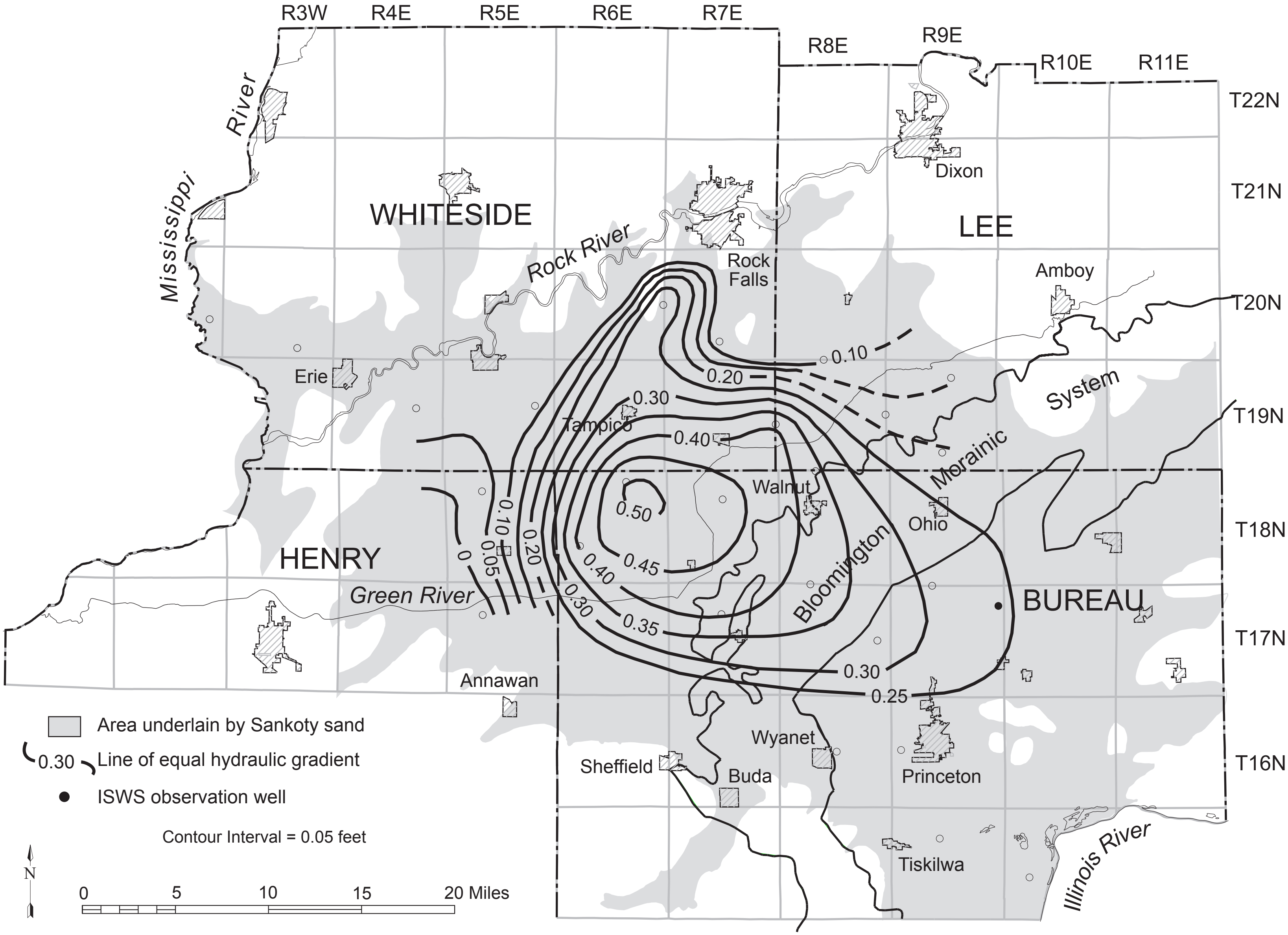


Figure 22. Contour map of vertical hydraulic gradient between Tampico and Sankoty aquifers (based on March 1993 observations)

The reason for the upward gradient direction at observation well HRY-91C probably is linked to the boundary condition created along the western edge of the Sankoty aquifer by the Pennsylvanian age bedrock. These shales bound the aquifer and inhibit westward flow.

Hydraulic Properties of Aquifers

The quantity of water moving laterally through an aquifer under natural conditions and the responsiveness of water levels to pumpage depend largely on factors termed aquifer hydraulic properties. The principal aquifer hydraulic properties are transmissivity and storage coefficient. Transmissivity is the measure of an aquifer's ability to transmit water horizontally. It is defined as the rate of flow, in gallons per day, through a vertical strip of aquifer 1 foot wide and under a hydraulic gradient of 1 foot per foot. Transmissivity is the product of an aquifer's thickness and hydraulic conductivity (permeability). Hydraulic conductivity is also a rate of flow in gallons per day, but only through a cross-sectional area of 1 square foot of the aquifer (unlike transmissivity) under a hydraulic gradient of 1 foot per foot.

The storage coefficient represents the aquifer's ability to release or take in water. The change in volume of water released or stored per unit surface area of aquifer due to a unit change in water level generally is expressed as a decimal fraction. A change in storage can be attributed to expansion of the water and compression of the aquifer material. Under artesian conditions, such as those seen in the Sankoty aquifer, typical values range from 10^{-5} to 10^{-3} (Ferris et al., 1962). The storage coefficient for water-table conditions is called the specific yield. Values for specific yield observed in water-table aquifers, such as the Tampico, range from 0.05 to 0.3 (Ferris et al., 1962).

Controlled aquifer tests are necessary to accurately determine specific aquifer hydraulic properties. During such a test, pumpage is held at a constant rate and water levels are continually measured in the pumped well and in nearby observation wells. These data are analyzed using plots of time versus drawdown and/or distance versus drawdown. Critical to an analysis are details describing drawdown at a known distance from the pumped well (in feet), well discharge (in gallons per minute), and time since pumping began (in minutes). Aquifer tests usually last 24 or more hours. Few aquifer tests are performed, however, and most records are limited to short well-production tests. From a scientific point of view, it is regrettable that the test duration is minimized if a well yields desirable quantities of water because longer-term data would be useful for calculating hydraulic conductivity and storage coefficient.

In many instances, the hydraulic properties of an aquifer must be estimated based on the pumping rate and drawdown observed within the pumping well. The ratio of these two values yields a parameter expressed in gallons per minute per foot (gpm/ft) called specific capacity. High specific capacities generally indicate high transmissivity, and low specific capacities generally indicate low transmissivity (Walton, 1962). The specific capacity of a well cannot be an exact measure of aquifer properties because often it is affected by partial penetration, well loss, and hydrogeologic boundaries. Still, it is a useful tool for comparing imperfect tests.

Groundwater scientists have another method of obtaining estimates of hydraulic conductivity. Although not as accurate as aquifer tests, slug tests can provide useful estimates of hydraulic conductivity. Technological advancements in the 1980s made it possible to test a highly permeable sand deposit using pressure transducers and digital data loggers. The time available for monitoring a slug test may last only a few seconds; consequently, water-level sampling intervals must be kept to fractions of a second.

Tampico Aquifer Hydraulic Properties

A 36-hour pump test at Sterling in 1962 used Northern Illinois Water Corporation's Well No. 6, which is located at T21N-R7E-Sec. 19, in the bedrock valley of Elkhorn Creek. Data from the 860 gallons per minute (gpm) test were used to calculate a transmissivity of 185,200 gallons per day per foot (gpd/ft) in a sand described as "fine to coarse" that occurs with gravel and boulders. A value of 3,860 gallons per day per square foot (gpd/ft^2) was calculated for hydraulic conductivity at this location. The stratigraphic data associated with Well No. 6 indicate that the aquifer lies above elevations normally associated with the top of the Sankoty aquifer, that is, greater than 540 feet. The data also suggest that both Well No. 6 and its nearby companion (No. 7) should have hydraulic connection with the Rock River, about ¾ mile to the south.

At another pump test site, the hydraulic conductivity of the Tampico aquifer was estimated at 985 gpd/ft^2 with transmissivity equal to about 67,000 gpd/ft. The test, run in 1957 on a well owned by the C.O. Larsen Company and located in T20N-R7E-Sec. 2, lasted only four hours. The well was test pumped at 960 gpm with a specific capacity of 60 gpm/ft. Although no effect of the nearby Rock River was noted during the test, because of the well's location on the southeast side of Rock Falls, it is assumed that induced recharge from the river would have taken place if the test had been of longer duration.

Rock Falls City Well No. 3, located in T21N-R7E-Sec. 33, was pumped at 1,250 gpm for 20 hours during 1961. This 70-foot deep well also taps the Tampico aquifer. Hydraulic conductivity calculated was about 1,360 gpd/ft^2, and specific capacity was 83 gpm/ft. Estimated transmissivity was 83,000 gpd/ft.

An irrigation well located in T19N-R4E-Sec. 28 was pumped at 700 gpm for 4.7 hours in 1963. This 63-foot deep well used the Tampico aquifer. Hydraulic conductivity calculated was about 1,330 gpm/ft^2, and specific capacity was 55.2 gpm/ft. Estimated transmissivity was 73,000 gpd/ft. Depth to water in the well, owned by Darwin Knudtson, was 8 feet in 1963. This observation is of interest because the depth to water in the 1990s was nearly the same as it was then.

Other random, but poorly substantiated, data on file at the ISWS suggest even lower values of hydraulic conductivity for the Tampico aquifer. These include estimates of 310, 466, and 176 gpd/ft^2 for Albany Well No. 1, Erie Well No. 2, and Erie Well No. TH53, respectively.

Sankoty Aquifer Hydraulic Properties

Files at the ISWS were reviewed for production tests in the study area. No controlled aquifer tests of the Sankoty aquifer were found, although some data exist. Perhaps the best estimate comes from a three-hour 1980 test of Princeton's Well No. 6, located in T16N-R9E-Sec. 16. Estimated transmissivity was 310,600 gpd/ft, and a value of 2,400 gpd/ft^2 was calculated for hydraulic conductivity. This test, which was conducted at a discharge rate of 1,200 gpm, caused the aquifer to convert from a confined to unconfined condition at the pumped well, thereby complicating analysis of aquifer properties. The well's specific capacity calculated was approximately 45 gpm/ft.

Other estimates of hydraulic properties in the Sankoty aquifer are difficult to obtain. Perhaps the next most useful test was the 10½-hour pump test conducted at Prophetstown on City Well No. 4, located in T19N-R5E-Sec. 5, on September 16, 1977. Records on file at the ISWS indicate that the well was pumped at 1,064 gpm for eight hours. About 12 feet of drawdown was observed inside the 16-inch casing, and the specific capacity calculated was nearly 89 gpm/ft.

A pump test at Tampico in 1964 on Well No. 1, located in T19N-R6E-Sec. 14, also yielded some sketchy information about the Sankoty aquifer. The 8-inch diameter well was pumped at about 200 gpm, and 10 feet of drawdown was observed within the well casing. The resulting specific capacity, 20 gpm/ft, probably reflects more about the well's construction than about the transmissivity of the Sankoty aquifer. Today the well is kept in a standby mode, and the community relies on its shallower well finished in the overlying Tampico aquifer.

Slug Test Data from Observation Wells

Kelly (1991) developed a system specifically for investigating highly permeable aquifers. He called it McDAS, which stands for Microcomputer-based Data Acquisition System. The system consists of two pressure transducers, a data logger, an air compressor, and a slug-test manifold. One transducer is submerged in the well so it can measure the recovery of ground-water levels. The slug test is conducted by pressurizing the air in the well casing so the water level is temporarily depressed by several feet. Then the pressure is suddenly released, and McDAS records the speed of the water level's recovery. Twenty observation wells were pressurized, and their responses were monitored. Data were examined and considered for suitability for analysis using the method described by Bouwer (1989).

Most data collected during the slug tests of the Sankoty aquifer were too difficult to analyze using simple analytical techniques. Oscillations in the responses indicated several possible interpretations. Some data sets exhibited the underdamped responses described by Van Der Camp (1976), and one displayed a classic overdamped response. Only one observation well in the Sankoty aquifer, WTS-91G, exhibited a normal response, and hydraulic conductivity was estimated to be 575 gpd/ft^2 at that site.

Analyses of slug test data collected from observation wells in the Tampico aquifer had similar, poor results. Typical values for hydraulic conductivity ranged from 120 to 800 gpd/ft^2 for the 11 observation wells tested. These values are considered to be conservatively low, and a value of 1,000 gpd/ft^2 (approximately 5×10^{-2} centimeters per second or cm/s) would be a reasonable starting estimate of hydraulic conductivity for the Tampico aquifer.

Transmissivity Maps

Transmissivity is a measure of an aquifer's ability to transmit water horizontally. It is defined as a rate of flow and is the product of an aquifer's thickness and hydraulic conductivity. Because both variables are known only at specific locations, estimates based on partial information and assumptions of homogeneity frequently are made. If it is assumed that the hydraulic conductivity of the Sankoty aquifer is 1,500 gpd/ft^2 and that the thickness can be estimated by subtracting the bedrock elevations from 540 feet (the assumed top of the aquifer), a transmissivity map can be produced.

An illustration of what the Sankoty aquifer's transmissivity distribution map might look like is presented in figure 23. It is loosely contoured on a 50,000 gpd/ft interval to reflect the uncertainty inherent in estimating aquifer thickness. Obviously, if the hydraulic conductivity is greater or smaller than the assumed value, the estimated transmissivities would need to be adjusted accordingly. The map is, nonetheless, useful for interpreting potentiometric surface maps for the Sankoty aquifer.

The transmissivity of the Tampico aquifer is estimated to be 30,000 to 40,000 gpd/ft. This estimate is based on two assumptions: that the aquifer is 30 to 40 feet thick and that the hydraulic conductivity is (as previously mentioned) perhaps 1,000 gpd/ft^2. Larson et al. (1995) speculated that transmissivity in the Tampico aquifer might range from 5,000 to 150,000 gpd/ft. Probably the most important conclusion to make is that the transmissivity of the Tampico aquifer is less than that of the Sankoty aquifer.

Pumpage in the Region

Two things happen when a pump withdraws water from a well: the water level inside the well declines, and a pressure gradient outside the well is formed. The sudden decrease in pressure within the well casing induces "new" water from the aquifer to enter the well. A pressure continuum is created beyond the well in all directions as the aquifer attempts to yield the pump's discharge. As a result, the groundwater level, when viewed in cross section as in figure 24, seems to take the shape of a cone. The deepest part of the cone occurs within the well. The area encompassed by the cone is referred to as the "cone of influence" or "cone of depression."

In a typical artesian aquifer, a single irrigation well may influence groundwater levels more than 1,000 feet away. When many wells are concentrated in a region, their individual cones of influence may overlap and form a regional cone of depression that can temporarily spread over several townships. When the pumping stops, groundwater levels recover over the next few weeks and months to their nonpumping levels.

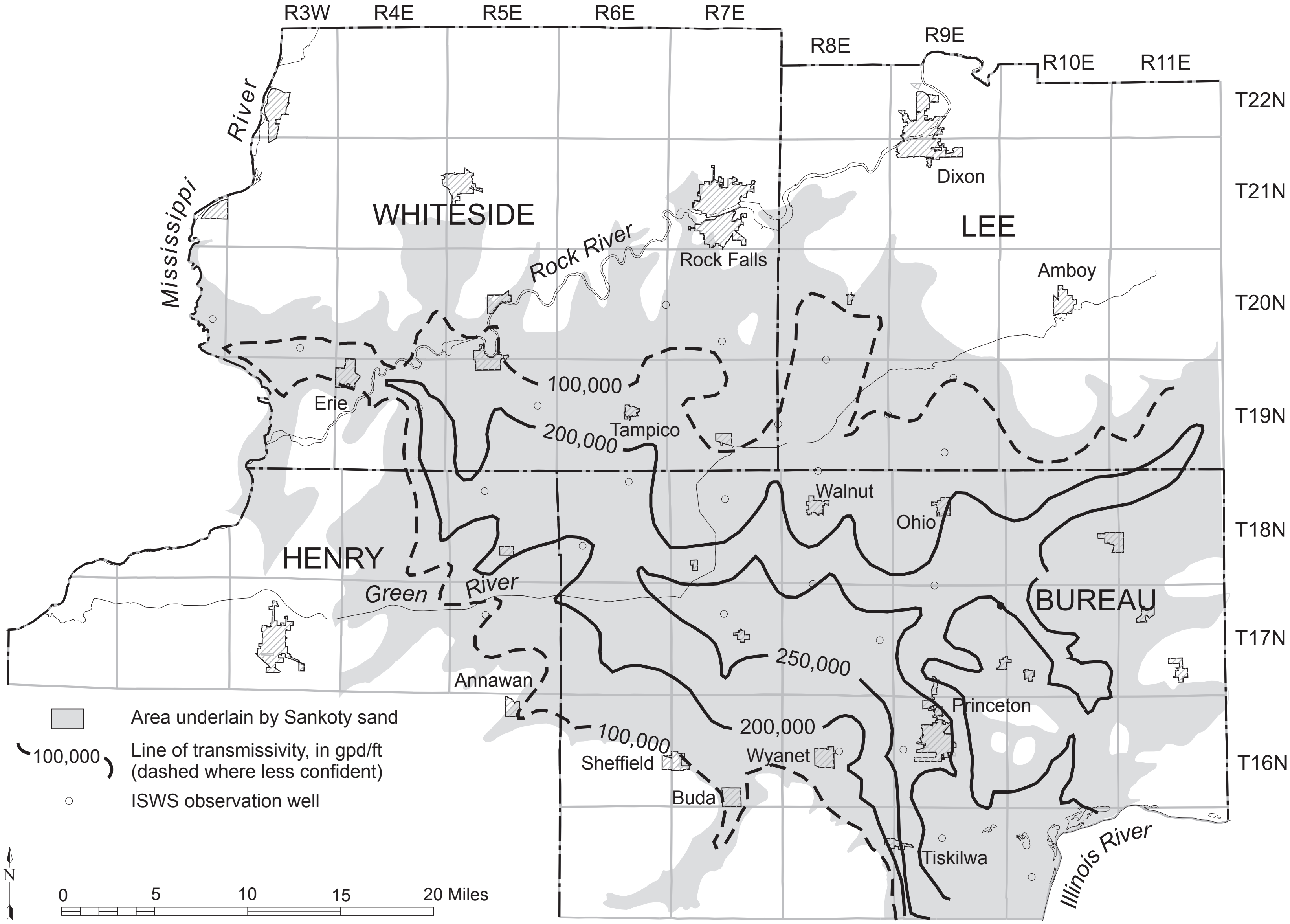


Figure 23. Transmissivity of Sankoty aquifer assuming K = 1,500 gpd/ft^2

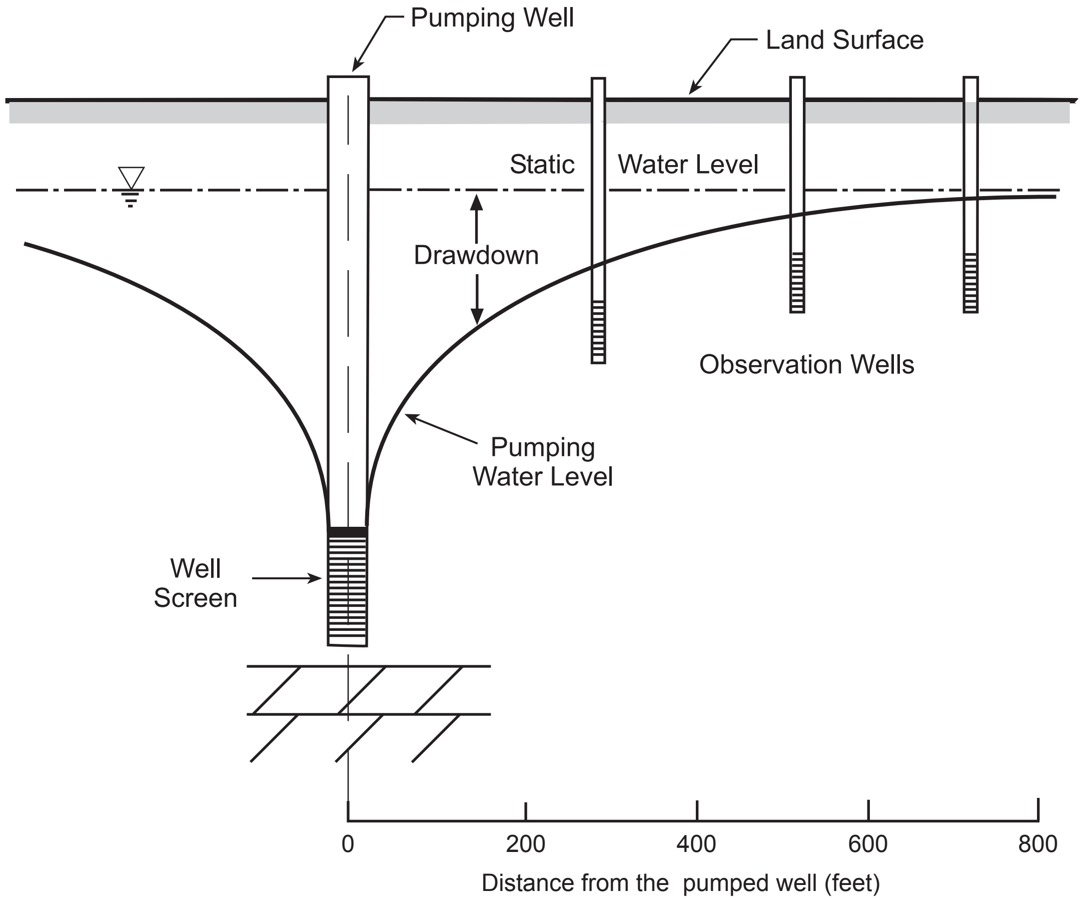


Figure 24. Extension of drawdown beyond a pumping well

Groundwater is a vital resource in the study region. Wells supply most of the water needs of both the urban and rural areas. Public water-supply demands change with the seasons, but the demands are fairly steady and predictable. The ISWS collects annual pumpage data from public water supplies and self-supplied industries. These systems frequently are equipped with usage meters and provide reliable estimates of annual pumpage. If these records are not available, the demand can be predicted based on population figures and per capita usage estimates. Tallies of annual pumpage figures for public water and industrial supplies are commonly expressed in terms of gallons per day.

By contrast, pumpage for irrigation is seasonal and varies considerably from year to year, depending on weather conditions. Data regarding actual irrigation use are sparse, at best. Bowman and Kimpel (1991) studied irrigation demands in the region and found that annual application rates were typically about 7 to 8 inches. Consequently, the most reasonable method of determining irrigation demand depends upon knowing how many acres are irrigated and multiplying it times an application rate. Irrigation demand often is expressed as a volume and in terms of acre-foot (ac-ft), which is a sheet of water 1-foot thick spread over an acre. Each acre-foot is equivalent to about 325,800 gallons of water.

Public Water-Supply Usage

According to figures reported to the ISWS by public water suppliers, daily per capita use varies from about 70 to 95 gallons per person. Table 4 lists the average daily pumpage for each community from 1991 to 1995. The rate is larger for the larger communities, presumably because of commercial and industrial uses. Some municipalities supply users outside the city limits, thereby increasing their apparent per capita use.

Industrial and Commercial Water Usage

Some self-supplied industrial pumpage occurs in the study area, but most of it comes from wells that reach deep into the bedrock aquifers. It is not uncommon for these wells to be 1,500 to 1,600 feet deep and, as such, they have no impact on the Tampico or Sankoty aquifers.

A small amount, perhaps 80,000 gpd, of self-supplied industrial pumpage occurs from the shallow sand-and-gravel aquifer along the Rock River. Most of it is located in Rock Falls, but a smaller amount is withdrawn from the Sankoty aquifer in Prophetstown.

Most commercial and industrial users, however, rely on public water supplies. In 1995, these facilities supplied an average of 996,000 gpd to commercial and industrial users. This amounts to almost 30 percent of the total withdrawals by the public water supplies. Not surprisingly, Princeton and Rock Falls provided the most water to the commercial and industrial users. Those two public water supplies accounted for 818,000 gpd, or 82 percent of that usage category.

Table 4. Average Daily Pumpage Rates from Public Water Supplies (gpd)

Community (Population)	*Location*	*1991*	*1992*	*1993*	*1994*	*1995*
Rock Falls (9,600)	T21N-R7E-Sec. 33	803,871	1,225,960	1,534,247	1,200,748	1,135,890
Princeton (9,200)	T16N-9E-Sec. 16	1,256,956	1,256,956	1,256,956	1,313,700	1,313,700
Prophetstown (1,795)	T19N-5E-Sec. 5	232,348	238,356	222,726	216,526	217,006
Walnut (1,493)	T18N-8E-Sec. 8	213,423	236,997	228,536	191,392	222,864
Erie (1,600)	T19N-4E-Sec. 6	98,904	105,222	105,592	116,954	138,647
Wyanet (1,000)	T16N-8E-Sec. 16	97,473	95,230	101,640	100,822	95,890
Sheffield (1,000)	T16N-7E-Sec. 19	100,101	117,910	116,049	95,805	93,233
Tampico (825)	T19N-6E-Sec. 14	55,525	108,666	80,433	72,225	78,548
Ohio (508)	T18N-9E-Sec. 9	62,613	59,335	59,583	64,960	63,501
Tiskilwa (830)	T15N-9E-Sec. 18	68,336	68,336	66,864	66,864	66,864
Manlius (360)	T17N-7E-Sec. 15	45,814	39,784	38,595	44,786	46,808
Totals (28,211)		3,035,364	3,552,751	3,811,220	3,484,783	3,472,951

Irrigation Water Usage

Large scale irrigation began to flourish in the study region during the mid-1970s with the advent of center-pivot systems. Well records on file indicate that many of these early irrigation wells relied on the shallow water table (Tampico) aquifer. In time, a switch was made to the deeper, more productive Sankoty aquifer. Today the preferred choice, if both are available, is the Sankoty aquifer.

Irrigated agricultural acreage figures are difficult to obtain. The Cooperative Extension Service (J. Morrison, Lee County Extension Advisor, personal communication, January 9, 1992) estimated that some 27,000 acres were under irrigation in 1991 in Lee and Whiteside Counties alone. No estimate was made by the Cooperative Extension Service for Bureau and Henry Counties, although irrigation was practiced there as evidenced by ISWS observation well hydrographs. Since the Cooperative Extension Service survey in 1991, the numbers in Lee and Whiteside Counties have risen steadily and today may exceed 32,000 acres. According to information from the Soil Conservation Service offices in Princeton, another 4,000 acres in northwest Bureau County may be irrigated.

These estimates clearly show that irrigation is the dominant water user in the study area. If we assume 36,000 acres receive 7 inches of irrigation water, the annual total is calculated as 21,000 ac-ft. Recalling that public water supplies pump about 3.5 million gallons per day (mgd), that number can be converted quickly to an annual number of about 3,900 ac-ft. Consequently, irrigation pumpage exceeds public water-supply pumpage by at least five times.

The problem with using acreage figures is that they fail to assign the pumpage to one aquifer. This information is necessary for balancing pumpage with annual recharge to the aquifer. The reliance on counting irrigated acres also can be misleading because it does not distinguish between surface water and groundwater sources. Fortunately, only a few individuals attempt to pump from rivers or ponds.

Importance of Well Spacing

An important difference between irrigation wells and municipal wells is that irrigation wells are not used year round. Most of the year they are dormant. Even when they are in season, their schedules are irregular because irrigation demand depends on the weather. Another difference concerns the magnitude of typical pumping rates. Irrigation pumps may yield 1,000 gpm or more, whereas many of the public water-supply wells pumping from the same aquifer may be intentionally designed to yield only 200 to 400 gpm. Consequently, when compared to public water-supply wells, irrigation wells have a more noticeable drawdown impact on groundwater levels. If the irrigation use was spread over the entire year, their effective pumping rate would be less and the impact on water levels would be less noticeable.

Given certain assumptions, one can estimate the impact of a high-capacity well on groundwater levels in each of the two principal aquifers. A graph of distance from an irrigation well versus estimated drawdown of water levels was constructed to illustrate the calculated impact for each aquifer (figure 25). A well pumping 800 gpm continuously for 80 days was assumed, with transmissivity equal to 75,000 gpd/ft for each aquifer. Consequently, using established equations, the resulting drawdown of water levels of each aquifer can be predicted if appropriate storage coefficient values are chosen. For this hypothetical case, 0.1 was used for the Tampico aquifer, and 3×10^{-4} was selected for the Sankoty aquifer.

A comparison of distance-drawdown graphs illustrates the impact of knowing whether an aquifer is confined or not. The calculations show that, for the assumed conditions, drawdown at a distance of ½-mile would be 8.26 feet for the Sankoty aquifer and 1.41 feet for the Tampico aquifer. In reality the drawdown for the Sankoty aquifer would be smaller than predicted because its transmissivity is more likely to be about 150,000 gpd/ft rather than the 75,000 gpd/ft used in the calculations. Thus, it is more likely that the water-level drawdown would be about 4.6 feet for the Sankoty aquifer, in this pumping scenario.

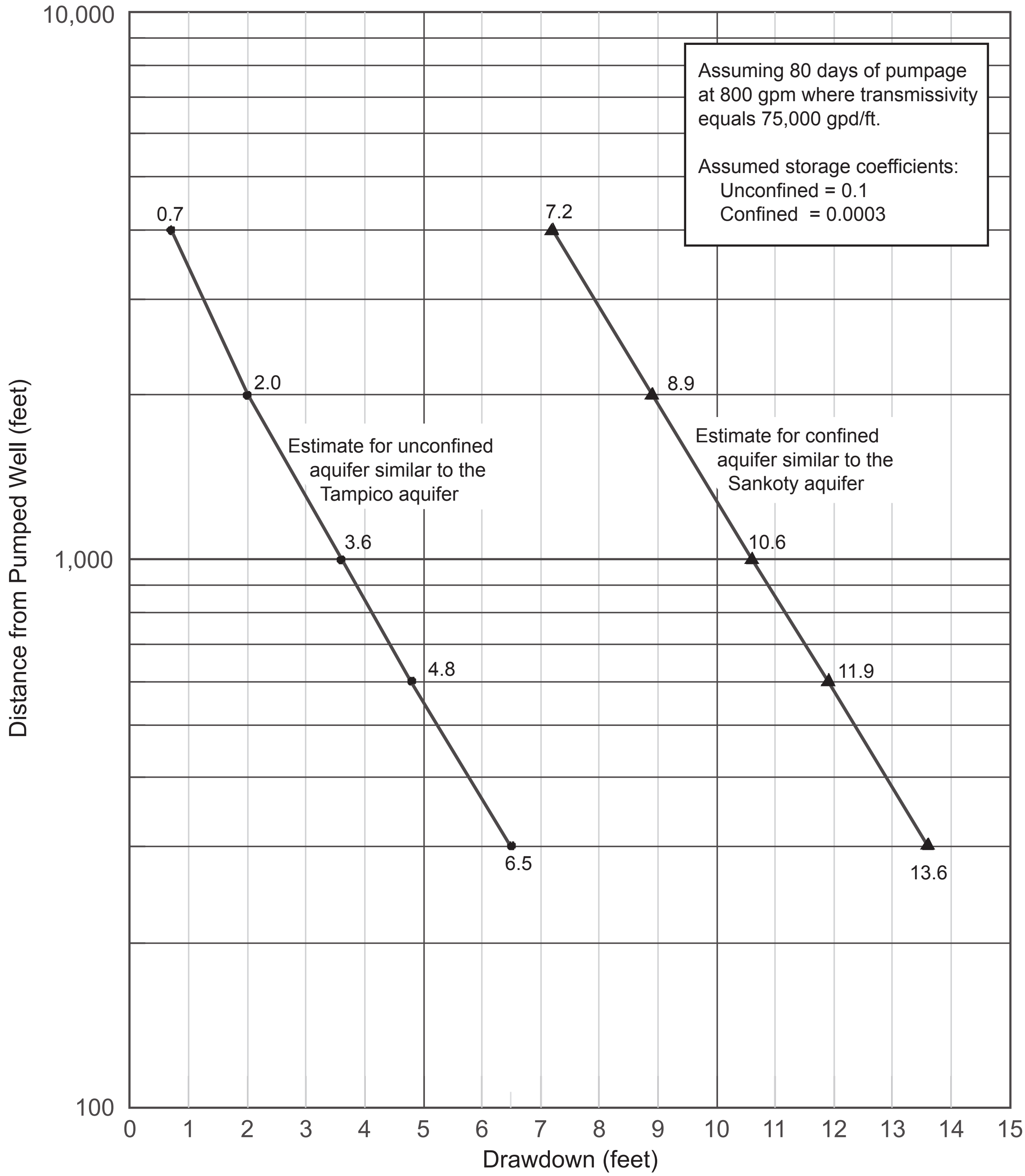


Figure 25. Graphical comparison of distance-drawdown responses for hypothetical confined and unconfined aquifers

These predictions probably are excessive because irrigation wells typically are not operated continuously for 80 days. The more typical pattern is that the pumps switch on for several hours, then remain unused for a few days. The demand for irrigation water is tempered largely by the availability of electric power at reduced rates, which probably is why most irrigators in the study area pump at night.

The important point to conclude from this discussion of distance versus drawdown is that the drawdown caused by one irrigation well is likely to overlap with that from another well. Therefore, irrigators should be conscious of maintaining adequate well spacing while also recognizing that responses differ from aquifer to aquifer. It would be prudent to attempt ½-mile spacings of wells in the Sankoty aquifer, but ¼-mile spacings in the Tampico aquifer would be satisfactory.

Recharge

Groundwater recharge, the most difficult component of the hydrologic budget to quantify, is generally thought of as the small fraction of annual precipitation that infiltrates the land's surface and avoids capture by the roots of plants. The largest proportion of precipitation runs overland to streams or is returned to the atmosphere by evaporation. The amount of infiltration that reaches the zone of saturation and becomes groundwater recharge depends upon several factors. Among these are topography; land use; rainfall intensity, duration, and seasonal distribution; and the occurrence of precipitation as snow (Walton, 1965).

Groundwater recharge is unevenly distributed in time and space; therefore, it is commonly quantified on an annualized basis. Furthermore, it often is thought of as an input to the entire groundwater system. Recharge actually is subdivided on an aquifer-by-aquifer basis because, once in the system, groundwater may flow from one source to another, depending upon hydraulic gradients and permeabilities of the deposits through which recharge occurs. For example, although it is common to think of recharge simply as the movement of groundwater down from the water table, recharge also may occur as upward movement from the bedrock to a glacial aquifer.

Because groundwater recharge is so varied and difficult to quantify, scientists and engineers sometimes attempt to calculate everything else in the water budget, then attribute the remainder to recharge. This strategy has been one method used for the past 40 years and seems appropriate as a rough estimate. The water budget also accounts for groundwater discharge. Most natural discharge, according to Todd (1967), occurs as flow into streams and lakes, direct evaporation to the atmosphere, or plant transpiration. The pumpage of groundwater from wells is regarded as an artificial means of conveyance.

The Tampico aquifer occurs near land surface and is under water-table conditions; consequently, it is quite easily recharged. The Sankoty aquifer, however, is buried beneath a layer of clayey, glacial till that makes recharge more difficult. The Tampico aquifer may overlie the clay layer and act as a source bed of recharge to the Sankoty aquifer. But exceptions occur in the western part of the study area. The roles are reversed in one of these areas, and an upward gradient exists. The middle clay is absent in another area, and the Tampico aquifer easily recharges the Sankoty aquifer.

Recharge to the Tampico Aquifer

The Tampico aquifer lies immediately below the land surface and commonly is covered by permeable soils. Some of the water infiltrating these soils and the unsaturated zone eventually reaches the saturated sand that forms the Tampico aquifer. However, more often than not, the total potential evapotranspiration during the growing season exceeds the precipitation that occurs during those months. Consequently, recharge to the Tampico aquifer is limited to fall and early winter months. The competition between precipitation and potential evaporation, based on data collected at Moline, is shown in figure 26.

An examination of the observation well data from the Tampico aquifer reveals that the water table fluctuates by several feet every year. The records also indicate that the average depth to water below land surface was about 7 feet, although isolated cases exist in which the depth was as little as 0.5 foot and as much as 12 feet. The drawdown map for the Tampico aquifer in 1995 (see figure 17) suggests that the annual water-table decline is about 3 feet.

If it is assumed that the sand in the Tampico aquifer has a porosity of 20 percent and that the 3-foot drawdown is balanced by recharge, perhaps 7 inches of precipitation over the year is needed as recharge (36 inches of decline times 20 percent porosity). Only when one considers that the Tampico aquifer covers more than 480 sq mi, does one begin to realize the enormity of the water budget. Average annual recharge to the Tampico aquifer is about 333,000 gpd/sq mi.

But, as stated previously, most of the recharge is seasonal. Climatic conditions for the region suggest that precipitation available for recharge is limited to just after the growing season. Consequently, the short-term rate of recharge is much higher than the 333,000 gpd/sq mi average. In fact, Visocky and Sievers (1992) observed weekly recharge rates in a similar area of Illinois (Mason County) and measured rates as high as 507,000 gpd/sq mi.

Recharge to the Sankoty Aquifer

Estimating the amount of recharge reaching the Sankoty aquifer is difficult. The rate of recharge to confined aquifers, such as the Sankoty, is dependent upon the vertical hydraulic conductivity (permeability) of the confining bed and the vertical hydraulic gradient through it. Unfortunately, vertical hydraulic conductivity data for unoxidized (gray) glacial till are scarce.

Based on aquifer tests at Champaign, Woodstock, and LaGrange, Walton (1965) calculated vertical hydraulic conductivities (K) of the clay till, which overlies and confines the aquifers at 0.01, 0.012, and 0.008 gpd/ft^2, respectively. These hydraulic conductivity values are higher and would allow more recharge than those used by others. For instance, Hendry (1982) reported values ranging from 5×10^{-7} to 10^{-8} cm/s (0.0002 to 0.01 gpd/ft^2), depending upon the

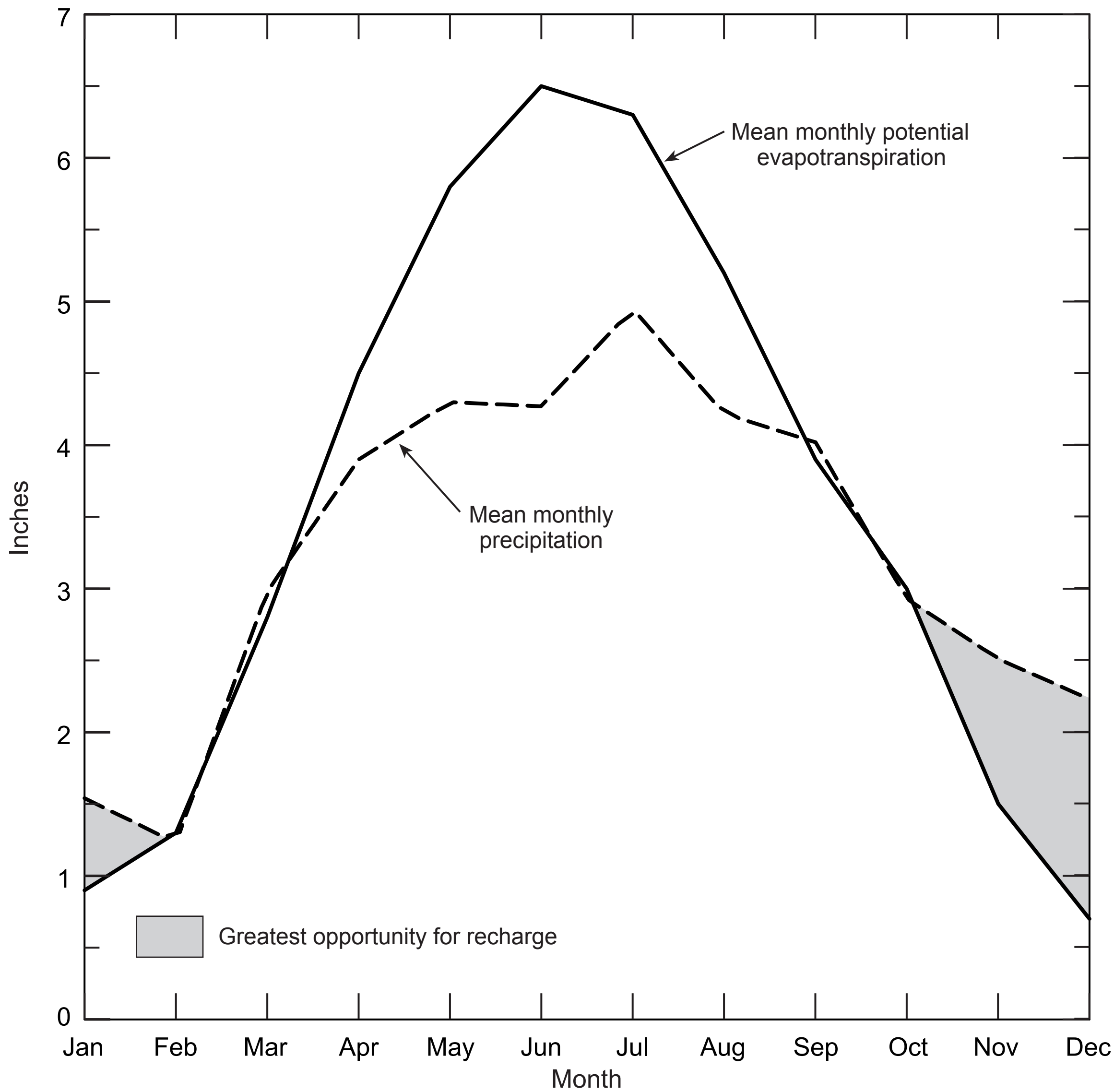


Figure 26. The 30-year mean monthly precipitations and potential evapotranspiration at Moline, 1961 through 1990, illustrates limited oppportunities for recharge to the Tampico aquifer

degree of weathering and fracturing that the till has undergone. Simpkins and Bradbury (1992, p. 291) reported similar values for K and likewise noted the difference between tills that have been weathered brown and the unoxidized (unweathered) gray tills. Simpkins and Bradbury (1992) noted, "In general, hydraulic conductivity decreases with depth .... In general, the contrast in K between the fractured and unfractured zones is consistently one order of magnitude...." Simpkins and Bradbury (1992) then reported K values in the upper portions of till equal to 0.01 gpd/ft^2 (5×10^{-7} cm/s) and decreasing to 0.0006 gpd/ft^2 (3×10^{-8} cm/s) in the lower portions. So Walton's (1965) vertical hydraulic conductivities (referred to as P′ in his table 18) apparently reflect values of the upper portions of till.

The force driving recharge through a confining bed is vertical hydraulic gradient (denoted as "i" in Darcy's Law). Basically, it is the difference in water-level elevations between the source bed and the aquifer in question, divided by the thickness of the intervening confining bed. Walton (1965) recorded data at Champaign, Woodstock, and LaGrange, allowing calculation of the downward vertical hydraulic gradient at those test sites: 0.417, 0.375, and 0.750, respectively.

The contour map of vertical hydraulic gradients in the study area (figure 22) was made using March 1993 water levels. This time was selected because the potentiometric surface of the Sankoty aquifer conditions were reasonably stable. The map illustrates the distribution of values varying from less than 0.1 to 0.5. The location of highest vertical gradients within the Sankoty aquifer coincides with the location of greatest irrigation. The observation well data show that, near Deer Grove and Normandy, the vertical gradient can increase from 0.4 to 0.7 during the summer months. Thus, the usual leakage (recharge) is increased from the surficial sands and gravels of the Tampico aquifer by pumpage of the underlying aquifer.

The question then becomes, how much recharge does the Sankoty aquifer receive in an average year? Walton (1965) reported recharge rates for sand-and-gravel aquifers in Illinois, which also were overlain by thick deposits of glacial till, to range from 115,000 to 279,000 gpd/sq mi. The drilling done for this study encountered similar conditions, commonly 25 feet or more of gray till and sometimes even a tight lake clay limiting leakage to the aquifer. If the confined area of the Sankoty aquifer is assumed to be 750 sq mi, by using Walton's (1965) minimum recharge rate (115,000 gpd/sq mi) as a starting point, it is possible to calculate that a minimum of 86 mgd (96,800 ac-ft per year) of recharge reaches the Sankoty aquifer.

Before accepting Walton's (1965) recharge value, the scale of the water budget for the Sankoty aquifer should be considered. When there is no year-to-year change in groundwater levels, there is no appreciable change in storage. Therefore, it must be concluded that inflow rates to the aquifer approximately equal the outflow rates. This conceptual understanding can be used to advantage in determining vertical recharge to the Sankoty aquifer. Figure 27 provides a useful illustration of the groundwater budget as a series of boxes.

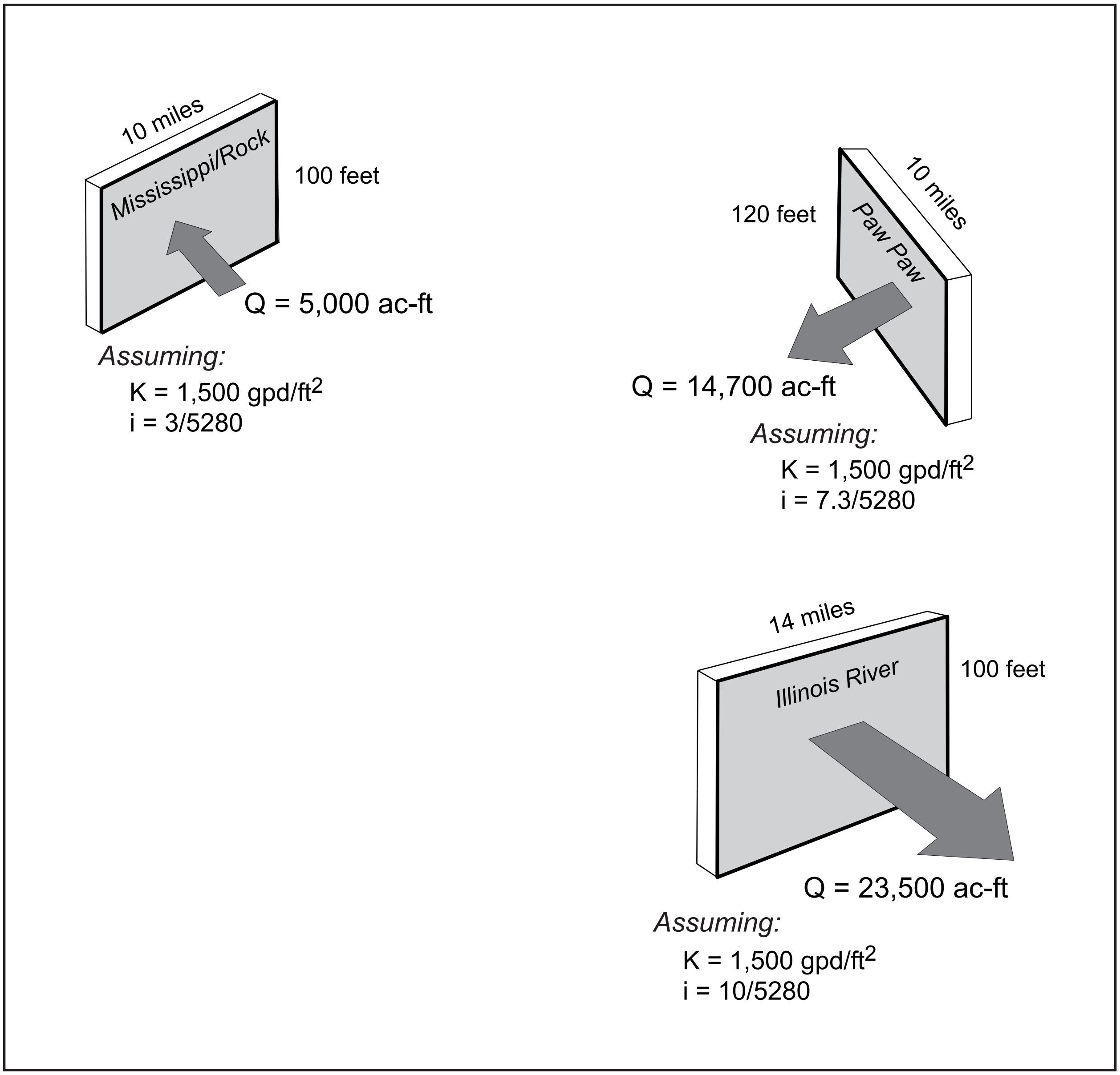


Figure 27. Conceptual diagram of lateral flows into and out of the Sankoty aquifer in Lee, Whiteside, and Bureau counties

Outflows. Two natural outlets from the Sankoty aquifer are known to exist. The largest outlet is to the Illinois River; the second is to the Mississippi/Rock Rivers. Using Darcy's Law, we can calculate the flow out of imaginary rectangles representing the aquifer near these locations. The sum of these outputs (including pumpage), therefore, must equal the sum of vertical recharge and any lateral inflows to the aquifer. In all cases, K of the Sankoty aquifer is assumed equal to K = 1,500 gpd/ft^2, and the possible inaccuracy of that value is recognized.

The first imaginary rectangle depicts outflow to the Illinois River. If drawn at right angles to the prevailing flow direction, the rectangle is 14 miles in length. It is drawn across the buried bedrock valley, from Tiskilwa to Depue; the aquifer here is estimated to average 100 feet in thickness. The hydraulic gradient, calculated from the potentiometric map, is about 10 feet per mile. Under such assumptions, perhaps as much as 21 mgd (23,500 ac-ft per year) discharges from the Sankoty aquifer to the Illinois River near Hennepin.

The second natural outlet occurs near Prophetstown. The Sankoty aquifer interacts with the Rock River and ultimately the Mississippi River. Assuming that the rectangle is 10 miles wide, 100 feet thick, and under the influence of a hydraulic gradient sloping 3 feet per mile, an outflow of about 4.5 mgd (5,000 ac-ft per year) can be calculated.

The final outflow occurs by the pumpage of wells. Groundwater levels of the Sankoty aquifer have been observed to rise and fall by 10 to 12 feet in accordance with the seasonal demands. The irrigation withdrawal (21,000 ac-ft), when projected over an annual basis, amounts to 18.75 mgd from the aquifer. Because it is the second largest outflow from the system, irrigation withdrawal obviously needs to be accounted for in the budget. Pumpage by public water supplies is smaller in size and amounts to about 3.5 mgd (3,900 ac-ft).

The total outflow from the Sankoty aquifer is estimated to be 47.75 mgd (53,400 ac-ft annually). To maintain a mass balance, an equal amount of groundwater must enter the aquifer.

Inflows. The principal inputs to the Sankoty aquifer come from lateral inflow in the Paw Paw Bedrock Valley and recharge as vertical leakage through the overlying confining layer. The lateral inflow is easiest to calculate and is estimated to be 13.1 mgd (14,700 ac-ft annually).

The lateral input estimate is based on an assumption that, if a rectangle is imagined across the Paw Paw Bedrock Valley, it would be 120 feet thick and 10 miles long. If K is 1,500 gpd/ft^2 and the hydraulic gradient is 0.0014 (7.3 feet per mile), perhaps 13.1 mgd (14,700 ac-ft) flow into the Sankoty groundwater system from the east.

To balance the hydrologic budget, the recharge (leakage) would have to be the difference between the total outflow and the lateral inflow, or about 34.65 mgd (17,600 ac-ft annually). For the purpose of comparison with previous studies, this rate can be translated to 46,200 gpd/sq mi, a measure used by Walton (1965). This rate, however, is far more conservative than the 115,000 gpd/sq mi used by Walton (1965) for similar conditions at Champaign.

Table 5. Summary of Sankoty Aquifer Inflows and Outflows

Flow direction	*Daily (million gallons)*	*Annual (ac-ft)*
Outflows		
Illinois River	21	23,500
Mississippi/Rock Rivers	4.5	5,000
Irrigation	18.75	21,000
Public water supplies	3.5	3,900
Total	47.75	53,400
Inflows		
Paw Paw Bedrock Valley	13.1	14,700
Vertical leakage	34.65	38,700
Total	47.75	53,400

Support for using a lower value can be based on the fact that the observation well data suggest that the vertical gradient in the Sankoty aquifer is closer to 0.3 than the 0.42 reported by Walton (1965) for similar conditions for the Mahomet aquifer at Champaign. Such an adjustment to Walton's recharge rate, if used, would lower the rate to 82,800 gpd/sq mi. Even further reductions might be justified based on the work of Hendry (1982) and Simpkins and Bradbury (1992) if a lower value of hydraulic conductivity is used than the one Walton used for the confining bed. One possibility would be to use the smallest value Walton (1965) reported, that is, the 0.008 gpd/ft^2 calculated for the LaGrange test.

If the LaGrange value of K is used for this study, the recharge rate to the Sankoty aquifer may be 67,000 gpd/sq mi. But if applied over the 750-sq-mi extent of the aquifer, even this rate amounts to 50 mgd (56,300 ac-ft per year) and still exceeds what would be required (34.65 mgd) to balance the inflow and outflow estimates.

To balance the inflow and outflow for the Sankoty aquifer, one would have to estimate that 0.97 inch (38,700 ac-ft÷750 sq mi) of recharge reaches the aquifer annually. This estimate is useful because it suggests that the scale of the budget is being approximated. Table 5 summarizes the estimates of flows into and from the Sankoty aquifer as currently understood.

Characterization of Groundwater Quality

Sampling Plan and Procedure

Groundwater samples were collected in an effort to characterize the groundwater quality of the two principal aquifers, the Tampico and the Sankoty. The following means were used in collecting representative groundwater samples for an accurate measure of the hydrochemical parameters of the groundwater in each aquifer. Samples were collected only from the 2-inch diameter observation wells constructed for the study. The sampling process involved purging the PVC well casing of standing water and making field measurements of pH, temperature, and electrical conductivity before collecting the sample. A two-person team visited 20 sites, and samples were collected from 32 observation wells. On arrival at each site, the depth to water was measured using a plopper on the end of either a fiberglass or steel tape, and the water level was recorded to the nearest 0.01 foot.

Many sites have two wells about 10 feet apart: one completed in the Sankoty aquifer and the other completed in the Tampico aquifer. Observation well samples were numbered sequentially, but with the following exceptions: two of the sample numbers refer to sample blanks (No. 8 and No. 23), one (No. 23, also known as KRY-92C) was dosed with a known pesticide concentration, and three duplicates (No. 16, No. 30, and No. 37) were submitted for quality control. The sample from one observation well (BUR-91C, sample No. 34) was excluded from chemical interpretation because the groundwater level in this well was inconsistent with all others and the sample was not likely to be representative of the Sankoty aquifer. Closer scrutiny is necessary to determine if this well is tapping strata other than the Sankoty aquifer. The result was that 31 highly representative samples were collected and used in the final interpretations.

The wells were pumped with a 1.8-inch diameter submersible pump (Grundfos®, Bjerringbro, Denmark) until the temperature and pH stabilized. This process usually involved several minutes, during which time the sample bottles were labeled and cross referenced to an individual log sheet for each site. Additional information also was recorded on the log sheet, such as location (township, range, and section), observation well name, date and time, and any notes describing the visit.

Samples from each observation well were collected in four containers. Two containers, a 500-milliliter (mL) and a 250-mL capacity, were filled with water that had passed through a 0.45-micron filter (either QED or GeoTek brand cellulose nitrate membranes). The filtered samples were collected in two polyethylene bottles because their chemical constituents were determined by different laboratory methods. The sample in one of the bottles was used for the determination of total dissolved solids (TDS), sulfate, nitrate, chloride, and phosphate; the sample in the other bottle was analyzed for metals and was acidified in the field to 0.5 percent nitric acid (HNO_3).

The other two samples were unfiltered and collected in smaller, 60-mL, wide-mouth polyethylene bottles for the purpose of determining alkalinity and ammonia. Attempts were made to be certain the filled bottles contained no air bubbles because the carbon dioxide in the air can alter alkalinity. After many tries, it became apparent that the bottles could not be filled without some air (headspace) remaining. Because alkalinity was not critical to the study, these alkalinity samples were determined to be satisfactory for our characterization. The ammonia sample bottle was preserved with a 0.2 percent sulfuric acid (H_2SO_4) concentration.

Field duplicates (No. 16, No. 30, and No. 37) and blanks (No. 8 and No. 23) also were submitted to the laboratories for quality control. All samples were kept on ice in a cooler during transport. Care was taken to drain meltwater from the cooler and to store the samples in an upright position.

Samples from selected observation wells were collected for pesticide analysis. Fourteen water-table observation wells selected for this rigorous analysis were chosen because they tapped the most susceptible aquifer (the Tampico). These determinations were made for the ISWS by a private laboratory (Daily Analytical Laboratories, Peoria) in accordance with the guidelines of the USEPA (1988).

Laboratory Determinations

The inorganic laboratory determinations were performed at the ISWS facilities in Champaign, which at that time had been certified by the Illinois Environmental Protection Agency (IEPA) and always follows strict quality control and quality assurance procedures. Most determinations were made using an inductively coupled plasma (ICP) argon instrument. Ion chromatographs were made for chloride, nitrate, phosphate, and sulfate.

The analyses (appendix C) are indicative of groundwater quality at or near a particular well at the time of sample collection. Not all sample numbers in appendix C are consecutive because the duplicates and blank samples are not given in this report, but these additional data are on file at the ISWS. The reader can be fairly certain of the validity of the values identified as major constituents in the appendix. A degree of caution should be exercised in interpreting the results for trace constituents. Locations for sample sites are listed in appendices A and B.

Results

Characterizations of water quality are usually expressed in milligrams per liter (mg/L). The following sections of this report describe the major, secondary, and trace constituents found in the groundwater samples collected from ISWS observation wells in the study area.

Major Constituents. The major constituents found in groundwater are calcium, magnesium, sodium, bicarbonate, sulfate, and chloride. Some of these elements are among the most abundant in the earth's crust. The most abundant constituents in seawater are chloride, sodium, sulfate, magnesium, calcium, and bicarbonate. So it is not surprising that “earth products” as dissolved constituents are found in groundwater.

An ionic balance is maintained between positively charged and negatively charged constituents. Positively charged ions are called cations, and negatively charged ions are called anions. Calcium (Ca), magnesium(Mg), and sodium (Na) are the most significant cations in groundwater. Sulfate (SO_4), chloride (Cl), and bicarbonate (HCO_3) are the dominant anions. Together these constituents and all other solid material in solution are called total dissolved solids (TDS). This convenient measure is a frequently used statistic for quickly characterizing groundwater quality.

The groundwater in both aquifers of the Lee-Whiteside-Bureau region is of a calcium-bicarbonate type in which nearly 55 percent of the cations are calcium and 34 percent are magnesium. The water is very hard, and a value was calculated for each sample based on the following formula: total hardness (mg/L as $CaCO_3$) = $(2.497 \times Ca)+(4.116 \times Mg)+(1.142 \times Sr)$.

The average hardness of samples from the Sankoty aquifer is about 306 mg/L; the average value for samples from the Tampico aquifer is slightly higher (329 mg/L). The hardness of the water reflects the geochemical nature of formations with which it has been in contact. In general, hard waters originate in areas with thick topsoil and limestone formations (Sawyer and McCarty, 1967).

Calcium values of 70 to 80 mg/L are typical throughout the study area, although the laboratory determinations ranged from 41 to 121 mg/L. The averages for each aquifer are within the normal range (10 to 100 mg/L) for calcium concentrations in groundwater supplies according to Davis and DeWeist (1966). Calcium values for the Sankoty aquifer averaged 73 mg/L, and ranged from 41 to 100 mg/L. In general, calcium concentrations for the Sankoty aquifer were slightly lower than those for the Tampico aquifer. The most notable feature in the distribution pattern is that calcium values near the Rock River are lower than those obtained from wells located elsewhere. Calcium values from samples collected from the Tampico aquifer averaged 81 mg/L and ranged from 46 to 121 mg/L.

Magnesium values were more constant across the study area than calcium values. They averaged about 30 mg/L in both aquifers. Values for the Sankoty aquifer ranged from 16 to 54 mg/L, and concentrations for the Tampico aquifer ranged from 17 to 47 mg/L. The location of the highest magnesium values coincides with high values for other constituents.

Concentrations of sodium, the third important cation to observe when characterizing groundwater quality, usually are much lower than those for calcium. The difference is so pronounced that it usually is used to differentiate groundwater into either a calcium type or a sodium type. Sodium concentrations in samples collected from the Sankoty aquifer averaged 13 to 14 mg/L. But this statistic is a bit misleading because a few high values biased the average. It probably is more accurate to state that, in the southern part of the study area, the Sankoty aquifer tends to have higher sodium values. These samples included values of 25 and 48 mg/L. One possible explanation for these elevated values is the proximity of the geologic contact with Pennsylvanian age bedrock.

Water samples from the Tampico aquifer also reveal the presence of sodium. Most values are <10 mg/L; 3 to 6 mg/L is near the "norm." Exceptions do occur. The highest value (86.7 mg/L) observed in either aquifer came from a 35-foot deep well (WTS-91J) in the Tampico aquifer. This well and the other wells in the Tampico aquifer with high sodium values are adjacent to intersections of major roads or are near deep ditches, which can accumulate snowmelt. Presumably road salt is the culprit because high chloride values coincide with the observations of high sodium levels.

Nitrate (as NO_3) occurred randomly within the study area. It is not a widespread constituent, but it can be found occasionally. Low levels of nitrate occur, not surprisingly, in the surficial Tampico aquifer. The Sankoty aquifer generally yielded <0.1 mg/L of nitrate to observation-well samples. Higher values of nitrate were more frequently observed in the Tampico aquifer, but only 2 of the 12 observation wells yielded samples that exceeded the drinking water standard (45 mg/L) for nitrate. One of those two wells is adjacent to a pasture in which cattle have grazed for many years. Nitrate in that sample, No. 2, was equal to 61 mg/L. The other Tampico aquifer site is not surrounded by any residential properties or pastures, and there may have been impacts from agricultural fertilizer. Nitrate in this sample, No. 25, had a concentration of 69 mg/L (as NO_3).

A nitrate value (79 mg/L) exceeding the drinking water standard was observed in a 305-foot deep observation well in the Sankoty aquifer. This sample, No. 29, is believed to be unrepresentative and the result of surface runoff rapidly ponding at the site and overtopping the well casing. Seventeen of the 19 Sankoty aquifer samples resulted in nitrate determinations of <0.1 mg/L. Clearly, nitrates are not a problem in the Sankoty aquifer.

Sulfate (SO_4) is also common in groundwater because most sulfate compounds are readily soluble in water. Davis and DeWeist (1966) note that sulfate in groundwater is generally <100 mg/L. In determinations of samples collected in the study region, the sulfate value seemed to be dependent on which aquifer was sampled. Values for samples from the Tampico aquifer were fairly consistent and averaged 63 mg/L. Observed samples from the Sankoty aquifer frequently contained <0.9 mg/L, with randomly located exceptions ranging up to 89 mg/L.

Alkalinity (as $CaCO_3$) is one of the most common attributes of groundwater. It is produced almost exclusively by bicarbonate and carbonate ions that result from chemical reactions involving the carbonate system. Groundwater commonly contains between 50 and 400 mg/L of bicarbonate (Davis and DeWeist, 1966). The laboratory determinations for samples from the Lee-Whiteside-Bureau region ranged from 111 to 580 mg/L. The samples from the Sankoty aquifer were generally more alkaline than those from the Tampico aquifer. Averages were 363 mg/L for the Sankoty aquifer and 246 mg/L for the Tampico aquifer.

The best overall descriptive, water-quality statistic may be TDS, a measure of how mineralized the groundwater has become, or the amount of residue that remains when a water sample evaporates. Natural waters range from <10 mg/L for TDS in rain and snow to >300,000 mg/L for some brines. Water for most domestic and industrial uses should be <1,000 mg/L (Davis and DeWeist, 1966). No discernible patterns were observed in the distribution of TDS values for either aquifer. The average TDS value for water samples from the Tampico aquifer was 435 mg/L; that for the Sankoty aquifer was 363 mg/L. Both averages are within acceptable limits and slightly below the statewide median value (Broten and Johnson, 1985). Based on the data collected, the groundwater from the Tampico aquifer is a bit more mineralized than that from the Sankoty aquifer, but it is less alkaline.

Secondary Constituents. Groundwater also contains elements that occur in concentrations much smaller than those of the major constituents. These secondary constituents normally are found in concentrations <10 mg/L. In this study, iron, manganese, potassium, fluoride, ammonia, and boron were defined as secondary. Iron and manganese are perhaps the best known, not because they represent a health hazard, but because they represent a nuisance to many private-well owners.

Iron is an abundant and widespread constituent of rocks and soil. Concentrations of only a few tenths of a milligram per liter can make water unsuitable for some uses. Although iron is an essential element for both plant and animal metabolism (Hem, 1970), it frequently stains laundry and plumbing fixtures when present in water for domestic use. When exposed to oxygen, iron can cause water to become turbid and unacceptable from an aesthetic viewpoint. Iron also imparts a taste to water (Sawyer and McCarty, 1967).

Groundwater routinely contains more iron than is aesthetically desired by most users. The traditional goal of public water suppliers has been <0.3 mg/L. Unfortunately, iron concentrations in determinations made for samples from the Sankoty aquifer confirm that the average is higher than what is desirable. In samples collected, the average iron value was 2.51 mg/L, with a range from near zero (<0.06 mg/L) to 5.26 mg/L.

By contrast, the Tampico aquifer, which occurs under water-table conditions, lacks high iron concentrations. Almost half of the samples from the Tampico aquifer contained low amounts of iron (<0.06 mg/L), presumably because dissolved oxygen is likely to impede the solubility of iron. However, 4 of the 12 samples contained iron in concentrations of 1.5 to almost 3.5 mg/L, which exceeds the favorable limit of 0.3 mg/L of iron.

Manganese is a close companion of iron; usually where one element exists, so too does the other. Groundwater samples commonly exceed the secondary standard for manganese, which is lower than that for iron. The traditional recommended limit for manganese is 0.05 mg/L, but the Illinois Maximum Contaminant Level (no federal level exists) is 0.15 mg/L. The average value of all samples collected for this study was 0.2 mg/L, although sample determinations ranged from <0.003 to 0.52 mg/L.

Potassium, another secondary constituent in groundwater, is a weathering product of certain clay minerals. All natural waters contain measurable amounts of potassium, and most groundwater supplies contain from 1.0 to 5.0 mg/L (Davis and DeWeist, 1966). In the Lee-Whiteside-Bureau area, values ranged from <0.3 mg/L to 5.43 mg/L, with an average of 1.59 mg/L for the Sankoty aquifer. No average was determined for the Tampico aquifer because 2 of its 12 samples had values less than the detection limit (0.3 mg/L). Based on these data, water in the Tampico aquifer tends to have slightly lower potassium concentrations than those in the Sankoty aquifer.

Fluoride is a secondary constituent sometimes found in groundwater. Most people are aware that fluoridation of public water supplies has become a firmly established public health measure. The drinking water standard for fluoride is 4.0 mg/L, but the USEPA recommends a secondary standard of 2.0 mg/L to public water systems. Samples from the Lee-Whiteside-Bureau region averaged 0.2 mg/L of fluoride for both aquifers, so the natural concentration of fluoride in the study area is below drinking water standards. Davis and DeWeist (1966) noted that waters high in calcium, such as those commonly found in the Sankoty and Tampico aquifers, seldom contain more than 1 mg/L of fluoride.

Ammonia, a chemically reduced form of nitrogen, often is a product of microbial decomposition in which little oxygen is present. The process of ammonification is part of the nitrogen cycle. The cyclic transformation of nitrogen compounds begins with the decay of plant tissue buried within the aquifer and isolated from the atmosphere. The highest values were observed in the southeastern quarter of the study area where the Sankoty aquifer is buried beneath a thick blanket of clayey deposits. The highest observed value was 6.40 mg/L, and 9 of the other 18 values exceeded 1 mg/L. Because the Tampico aquifer is not buried, most samples from it were determined to have less ammonia than, or very near, the detection limit (0.02 mg/L) of the analytical equipment. Average values were not reported because of the bias caused by not including analyses that were below the detection limit.

Trace Constituents. Hem (1970) notes that there is no precise definition of the term "trace" with reference to constituents in natural water. This category is difficult to establish because all elements are soluble in water, at least to a small degree, and those concentrations may be difficult to measure. A working definition for this category might be all those substances that typically occur in concentrations <0.1 mg/L.

Drinking water standards exist for about half of these trace elements. These standards are frequently below the detection limit of the ISWS laboratory equipment, even though the laboratory had been certified by the IEPA. The results from all samples were negative in terms of other trace metals, such as aluminum, beryllium, chromium, cadmium, copper, lead, mercury, molybdenum, nickel, silver, thallium, vanadium, and zinc. Trace elements are not a widespread problem, nor are they common in water samples from either the Tampico or Sankoty aquifers.

The results for two trace constituents, barium and strontium, merit mention. The greatest concentration of barium came from a Sankoty aquifer observation well (BUR-92A). It contained 0.89 mg/L of barium, which is below the 1.0 mg/L drinking water standard. Most samples contained far less barium, but it was clear that groundwater samples from the deeper Sankoty aquifer were more likely to contain higher values than samples from wells into the surficial sand. Average barium values were 0.21 mg/L (Sankoty aquifer) and 0.08 mg/L (Tampico aquifer).

Strontium, for which there is no drinking water standard, was detected in all samples from the region. Concentrations ranged from 0.05 to 2.47 mg/L; they averaged 0.52 mg/L for the Sankoty aquifer and 0.10 mg/L for the Tampico aquifer. Strontium is chemically similar to calcium, contributes to hardness, and occurs in most groundwater samples in concentrations <1 mg/L (Davis and DeWeist, 1966).

Pesticides. Samples were collected from 13 observation wells finished in the Tampico aquifer. This aquifer was selected because it occurs under water-table conditions and was assumed to be the most susceptible to pesticide contamination. The observation wells ranged in depth from 20 to 30 feet below land surface. Ten of the analyses were free of pesticides.

Atrazine was detected in samples from three wells. The highest concentration was only 0.16 micrograms per liter or µg/L (observation well LEE-92F). The two other samples contained atrazine concentrations near the detection limit (0.10 µg/L). The laboratory, of course, detected the field spike (used for quality control), which was dosed with 2.5 μg/L dieldrin, 0.5 μg/L chlordane, and 5 μg/L alachlor. The values reported by the laboratory, 1.2 μg/L dieldrin and 5.1 μg/L alachlor, were considered acceptable. The laboratory's failure to report chlordane was probably because the spike was at the detection limit.

Table 6 lists the pesticide compounds for which tests were made. Only two other observation wells revealed hints of atrazine: observation well BUR-92B contained 0.11 μg/L of atrazine, and observation well WID-V contained 0.13 μg/L of atrazine. These positive responses to the pesticide determinations are close enough to the detection limit of the test equipment to be inconclusive. Further testing would be required to confirm whether a problem exists.

Table 6. Pesticides Checked for and Detection Limits of Test Equipment

Compound	*Detection limit (μg/L)*
Acifluorfen	<5.0
Chlordane-alpha	<0.05
Chlordane-gamma	<0.05
Chlordane	<0.50
Chlorpyrifos	<0.10
Dieldrin	<0.01
Propachlor	<0.50
Trifluralin	<0.05
Alachlor	<0.25
Atrazine	<0.10
Butylate	<0.50
Carboxin	<2.0
Cyanazine	<0.10
Diazinon	<0.25
Dinoseb	<5.0
Ethalfluralin	<0.50
Ethaprop	<0.50
Fonofos	<0.10
Linuron	<0.50
Metolachlor	<0.50
Metribuzin	<0.10
Simazine	<0.05
Terbufos	<0.50

Conclusions

Two aquifers in northwestern Illinois contain abundant supplies of excellent quality groundwater. The lower of these two aquifers, the Sankoty, lies in a buried bedrock valley formed by the ancestral Mississippi River. The aquifer varies in thickness from 0 to 180 feet and extends beneath 750 sq mi of Lee, Whiteside, Bureau, and Henry Counties. The Sankoty aquifer is composed of Sankoty sand, which is distinctive and readily recognizable in sample cuttings by its uniform quartz grains. A comparison of grain-size data and sieve data available to the author leads one to conclude that the primary source of the Sankoty sand probably is the St. Peter Sandstone.

Since the mid-1970s, the Sankoty aquifer has been developed as a source of irrigation water. Wells into the aquifer yield a calcium-bicarbonate type of water to provide irrigation for perhaps 32,000 acres. The water is of excellent quality, although hard. Water-level measurements made by the ISWS between 1991 and 1995 indicate that the groundwater levels rise and fall on an annual cycle, but by each spring they return to the levels of the previous year.

The upper aquifer, named after the town of Tampico (Larson et al., 1995), extends over more than 480 sq mi. It occurs near land surface and is draped onto the Bloomington Morainic System. The Tampico aquifer commonly is 35 feet thick and is recharged by precipitation that occurs during the fall and early winter months. Although not as extensively developed by high-capacity users as the Sankoty aquifer, the Tampico aquifer is important to rural homeowners. It usually supplies excellent quality water and is often preferred because it contains less iron and is less alkaline than the Sankoty aquifer. Because the Tampico aquifer is close to the land surface, it is susceptible to contamination.

A clay layer separates the aquifers in the area south of the Rock River and north of the Bloomington Morainic System. The clay layer ranges in thickness from 0 to 40 feet over much of Whiteside County and effectively isolates the two aquifers. Consequently, water-level measurements made in observation wells completed in either aquifer at the same location are different. In most cases the observation well in the Sankoty aquifer has a lower water level, indicating a potential for downward movement of water from the Tampico aquifer. Perhaps 7 inches of the annual precipitation recharges the Tampico aquifer; but only about 1 inch of leakage reaches the confined Sankoty aquifer each year.

Groundwater pumpage for irrigation far exceeds pumpage for municipal and/or industrial uses. Perhaps 45 mgd of groundwater is withdrawn during a typical 150-day irrigation season by irrigation wells (21,000 ac-ft per year). The maximum impact on the Sankoty aquifer occurs by late July. An examination of the groundwater levels suggests, however, that the irrigation season often lasts less than 150 days. The irrigation demand causes a flattening of the Sankoty aquifer's potentiometric surface, which normally slopes westward. When the irrigation pumps are switched off, groundwater levels quickly recover. Observation well data suggest that 75 percent of the recovery is complete by late November of each year. The recovery of groundwater levels is somewhat slower for the two northernmost Sankoty observation wells: WTS-91G and WTS-91I.

Groundwater supplies more than 45,000 people in the study area with about 3.5 mgd of water (3,900 ac-ft per year). The water utilities in the largest communities, Princeton and Rock Falls, each pump more than a million gallons daily. Most communities record this sort of information and respond to annual ISWS questionnaires; consequently, this information is considered more accurate than that kept for irrigation pumpage.

There are several key points to conclude from this study:

- The two distinct aquifers in the area are hydraulically independent. The lower one, the Sankoty aquifer, is used more frequently by irrigation wells.

- The regional direction of groundwater flow in both aquifers is away from Lee County. In the Tampico aquifer the movement is westward with gradients decreasing from 6.5 to 3 feet per mile. There are two outlets from the Sankoty aquifer, so the directions of flow are toward the Mississippi River and southeast to the Illinois River.

- Observation wells were constructed at 27 sites. At many of these locations, two holes were drilled. One well was constructed about 20 feet deep and finished in the shallower Tampico aquifer, and a second observation well was constructed deeper and into the Sankoty aquifer.

- Groundwater levels for the Sankoty aquifer decline each summer and recover during the winter months to a level near that observed in the preceding year. Drawdown can be as much at 13 feet over several square miles. The greatest drawdown often occurs south of Tampico and reaches its maximum in late July.

- Artesian pressure within the Sankoty aquifer causes water levels in wells to rise above the top of the aquifer. The distance the levels rise above the top of the aquifer, and its interface with the overlying confining layer is a measure of hydrostatic pressure, also known as artesian head. In the eastern part of the study area more than 120 feet of artesian head exists. In the prime areas of irrigation, it is common for 70 to 80 feet of artesian head to exist. Consequently, groundwater levels can decline quite a distance without reaching the top of the aquifer.

- Irrigation use exceeds public water-supply use by a factor of 5.

- The natural discharge to the rivers of the area exceeds irrigation pumpage.

- Because potential evapotranspiration exceeds precipitation during most months, recharge to the water table is limited to October, November, December, and January.

- Groundwater in the Sankoty aquifer tends to be more alkaline and higher in iron concentrations than that from the Tampico aquifer.

- No discernible patterns were observed in the distribution of TDS values for either aquifer. The average TDS value for water samples from the Tampico aquifer was 435 mg/L; that for the Sankoty aquifer was 363 mg/L. Both averages are within acceptable limits and slightly below the statewide median value (Broten and Johnson, 1985).

- Widespread contamination of groundwater was not observed. The most likely contaminant found was nitrate, and its occurrence was limited to the Tampico aquifer.

- The top of the Sankoty aquifer occurs at an elevation of 530-540 feet above the NGVD, with a slight slope from Rock Falls to Hennepin. Because the elevation is consistent, it is possible to predict the aquifer's depth below land surface.

References

Anderson, R.C. 1968. *Drainage Evolution in the Rock Island Area, Western Illinois, and Eastern Iowa*. R.E. Bergstrom, Editor. The Quaternary of Illinois—A Symposium in Observance of the Centennial of the University of Illinois, February 12-13, 1968: University of Illinois College of Agriculture Special Publication 14, University of Illinois, Illinois State Geological Survey, and the Illinois State Natural History Survey. Urbana, IL.

Bouwer, H. 1989. The Bouwer and Rice Slug Test—An Update. *Ground Water* **27**(3):304-309.

Bowman, J.A., and M.C. Collins. 1987. *Impacts of Irrigation and Drought on Illinois Ground-Water Resources*. Illinois State Water Survey Report of Investigation 109.

Bowman, J.A., and B.C. Kimpel. 1991. *Irrigation Practices in Illinois*. Illinois State Water Survey Research Report 118.

Broten, M.D., and A.M. Johnson. 1985. Illinois Regional Ground-Water Quality Assessment. In J.M. Shafer (ed.), *An Assessment of Ground-Water Quality and Hazardous Substance Activities in Illinois with Recommendations for a Statewide Monitoring Strategy (PA 83-1268)*. Illinois State Water Survey Contract Report 367, pp. 45-78.

Bryan, A.A., and W. Wendland. 1993. *Local Climatological Data Summary: Moline, Illinois, 1872-1992*. Illinois State Water Survey Miscellaneous Publication 98-13.

Burch, S.L. 1991. *The New Chicago Model: A Reassessment of the Impacts of Lake Michigan Allocations on the Cambrian-Ordovician Aquifer System in Northeastern Illinois*. Illinois State Water Survey Research Report 119.

Burch, S.L., B.R. Hensel, J.S. Nealon, and E.C. Smith. 1987. *An Assessment of Class V Underground Injection in Illinois*. Illinois State Water Survey Contract Report 425.

Changnon, S.A. 1964. *Local Climatologic Data, 1901-1962, Ottawa*. Illinois State Water Survey Miscellaneous Publication 23.

Davis, S.N., and R.J.M. DeWeist. 1966. *Hydrogeology*. John Wiley & Sons, Inc., New York, NY.

DuMontelle, P.B., P.C. Heigold, M. Heidari, and D.H. Swann. 1968. *Computer-Calculated Lambert Conformal Conic Projection Tables for Illinois*. Illinois State Geological Survey Industrial Minerals Notes 35, Champaign, IL.

Farnsworth, R.K., E.S. Thompson, and E.L. Peck. 1982. *Evaporation Atlas for the Contiguous 48 United States*. National Oceanic and Atmospheric Administration Technical Report NWS 33. U.S. Department of Commerce, Washington, DC.

Ferris, J.G., D.B. Knowles, R.H. Brown, and R.W. Stallman. 1962. Theory of Aquifer Tests. U.S. Geological Survey Water-Supply Paper 1536-E, USGS, Washington, DC.

Foster, J.W. 1956. *Groundwater Geology of Lee and Whiteside Counties, Illinois*. Illinois State Geological Survey Report of Investigations 194, Champaign, IL.

Hackett, J.E., and R.E. Bergstrom. 1956. *Groundwater in Northwestern Illinois*. Illinois State Geological Survey Circular 207, Champaign, IL.

Hansen, W.R. 1991. *Suggestions to Authors of the Reports of the United States Geological Survey,* Seventh Edition. USGS , Washington, DC.

Hem, J.D. 1970. *Study and Interpretation of the Chemical Characteristics of Natural Water*, Second Edition. U.S. Geological Survey Water Supply Paper 1473, USGS, Washington, DC.

Hendry, M.J. 1982. Hydraulic Conductivity of a Glacial Till in Alberta. *Ground Water* **20**:162-169.

Horberg, C.L. 1946. Pleistocene Deposits below the Wisconsin Drift in Illinois. Abstract in *Geological Society of America Bulletin* **57**:1204.

Horberg, C.L. 1950. *Bedrock Topography of Illinois*. Illinois State Geological Survey Bulletin 73, Urbana, IL.

Horberg, C.L., M. Suter, and T.E. Larson. 1950. *Groundwater in the Peoria Region*. Illinois State Water Survey Bulletin 39 and as Illinois State Geological Survey Bulletin 75, Urbana, IL.

Kelly, D.J. 1991. *Collection and Interpretation of Pneumatic Slug Test Data in a Highly Permeable Aquifer*. Unpublished M.Sc. thesis. Geology Department, University of Illinois, Urbana.

Larson, D.R., B.L. Herzog, R.C. Vaiden, C.A. Chenoweth, Y. Xu, and R.C. Anderson. 1995. *Hydrogeology of the Green River Lowland and Associated Bedrock Valleys of Northwestern Illinois*. Illinois State Geological Survey Environmental Geology 149, Champaign, IL.

Leighton, M.M., G.E. Ekblaw, and L. Horberg, 1948. Physiographic Divisions of Illinois. *Journal of Geology* **56**(1):16-33 and reprinted as Illinois State Geological Survey Report of Investigations No. 129, Champaign, IL.

Lineback, J.A. 1979. *Quaternary Deposits of Illinois*. Illinois State Geological Survey, Champaign, IL.

Maurer, J.C., J.M. Sterling, T.E. Richards, and P.D. Hayes. 1991. *Water Resources Data, Illinois Water Year 1990*. U.S. Geological Survey Water-Data Report IL-90-1, Vol. 1, USGS, Urbana, IL.

Maurer, J.C., T.E. Richards, J.K. LaTour, and R.H. Coupe. 1993. *Water Resources Data, Illinois Water Year 1992*. U.S. Geological Survey Water-Data Report IL-92-1, Vol. 1, USGS, Urbana, IL.

McComas, M.R. 1969. *Pleistocene Geology and Hydrogeology of the Middle Illinois Valley*. Ph.D. thesis, Department of Geology, University of Illinois, Urbana, IL.

Oschwald, W.R., F.F. Riecken, R.I. Diderisksen, W.H. Scholtes, and F.W. Schaller. 1965. *Principal Soils of Iowa*. Iowa State University, Cooperative Extension Service Special Report No. 42, Ames, IA.

Reinertson, D.L. 1990. *Guide to the Geology of the Oregon Area, Ogle County*. Geological Science Field Trip Guidebook 1990-C, Illinois State Geological Survey, Champaign, IL.

Sawyer, C.N., and P.L. McCarty. 1967. *Chemistry for Sanitary Engineers,* Second Edition. McGraw-Hill Book Company, New York, NY.

Simpkins, W.W., and K.R. Bradbury. 1992. Groundwater Flow, Velocity, and Age in a Thick, Fine-grained Till Unit in Southeastern Wisconsin. *Journal of Hydrology* **132**:283-319.

Soil Conservation Service. 1985. *Soil Survey of Lee County, Illinois*. Illinois Agricultural Experiment Station Soil Report No. 118, University of Illinois Cooperative Extension Service, Urbana, IL.

Todd, D.K. 1967. *Ground Water Hydrology*. John Wiley & Sons, Inc., New York, NY.

U.S. Department of Commerce. 1990. *1990 Census of Population and Housing*, 1990 Summary Tape File 1 (STF 1), Detailed Table P001 (Persons) for Illinois, County Subdivisions, <http://factfinder.census.gov> (November 29, 2001).

U.S. Environmental Protection Agency. 1988. *Methods for Determination of Organic Compounds in Drinking Water*. EPA 600/4-88-039, Environmental Monitoring Systems Laboratory, Cincinnati, OH, pp. 31-62.

Van Der Camp, G. 1976. Determining Aquifer Transmissivity by Means of Well Response Tests: The Underdamped Case. *Water Resources Research* **12**(1):71-77.

Visocky, A.P., M.G. Sherrill, and K. Cartwright. 1985. *Geology, Hydrology, and Water Quality of the Cambrian and Ordovician Systems in Northern Illinois*. Illinois State Water Survey and Illinois State Geological Survey Cooperative Report 10.

Visocky, A.P., and M.E. Sievers. 1992. *Ground-Water Investigation at Jake Wolf Fish Hatchery, Mason County, Illinois*. Illinois State Water Survey Research Report 120.

Walton, W.C. 1962. *Selected Analytical Methods for Well and Aquifer Evaluation*. Illinois State Water Survey Bulletin 49.

Walton, W.C. 1965. *Ground-Water Recharge and Runoff in Illinois*. Illinois State Water Survey Report of Investigation 48.

Willman, H.B., and J.C. Frye. 1970. *Pleistocene Stratigraphy of Illinois.* Illinois State Geological Survey Bulletin 94, Champaign, IL.

Willman, H.B., E. Atherton, T.C. Buschback, C. Collinson, J.C. Frye, M.E. Hopkins, J.A. Lineback, and J.A. Simon. 1975. *Handbook of Illinois Stratigraphy*. Illinois State Geological Survey Bulletin 95, Champaign, IL.

Appendix A. Sankoty Aquifer Observation Well Locations and Map Coordinates

Well name	*Location (section, township-range)*	*Lambert coordinates (ft)*	*Latitude and longitude*
BUR-91A	SE¼, SW¼, SE¼, NE¼ of Sec. 03, T18N-R6E	2921730, 3109970	N41° 34' 35" W89° 47' 13"
BUR-91C	SE¼, SE¼, SE¼, NE¼ of Sec. 09, T18N-R7E	2949100, 3105040	N41° 33' 45" W89° 41' 12"
BUR-91D	NE¼, NE¼, NE¼, NE¼ of Sec. 05, T18N-R8E	2975490, 3113040	N41° 35' 05" W89° 35' 24"
BUR-91E	NW¼, NW¼, NE¼, SE¼ of Sec. 09, T17N-R7E	2948770, 3072440	N41° 28' 19" W89° 41' 13"
BUR-92A	NE¼, NE¼, NW¼, NW¼ of Sec. 29, T18N-R6E	2908620, 3091770	N41° 31' 31" W89° 50' 06"
BUR-92C	SW¼, SE¼, SE¼, SW¼ of Sec. 13, T18N-R8E	2993650, 3096300	N41° 31' 18" W89° 31' 23"
BUR-92D	NW¼, NE¼, NW¼, NE¼ of Sec. 05, T17N-R8E	2973990, 3080910	N41° 29' 46" W89° 35' 48"
BUR-92E	SW¼, SE¼, SW¼, SW¼ of Sec. 33, T18N-R9E	3008560, 3080510	N41° 29' 42" W89° 28' 07"
BUR-92F	SW¼, SW¼, SE¼, SW¼ of Sec. 13, T17N-R8E	2993020, 3064950	N41° 27' 08" W89° 31' 33"
BUR-95A	SW¼, SE¼, SE¼, SW¼ of Sec. 08, T17N-R10E	3036770, 3070170	N41° 28' 00" W89° 22' 03"
BUR-95B	SW¼, SW¼, SW¼, SW¼ of Sec. 15, T16N-R8E	2981470, 3033420	N41° 21' 56" W89° 34' 06"
BUR-95C	SE¼, NE¼, SE¼, SW¼ of Sec. 18, T16N-R9E	2999740, 3033880	N41° 22' 00" W89° 30' 05"
BUR-95D	NE¼, SE¼, NE¼, SW¼ of Sec. 09, T15N, R9E	3010710, 3008750	N41° 17' 49" W89° 27' 39"
BUR-95E	SW¼, SW¼, NW¼, SW¼ of Sec. 20, T15N, R10E	3034990, 2997730	N41° 16' 01" W89° 22' 24"

Appendix A. (concluded)

Well name	*Location (section, township-range)*	*Lambert coordinates (ft)*	*Latitude and longitude*
HRY-91A	NW¼, NW¼, NW¼, NW¼ of Sec. 09, T18N-R5E	2880740, 3107320	N41° 34' 05" W89° 56' 16"
HRY-91C	SW¼, SE¼, NE¼, SE¼ of Sec. 08, T17N-R5E	2881020, 3072170	N41° 28' 16" W89° 56' 17"
LEE-91A	SW¼, SW¼, SW¼, NW¼ of Sec. 19, T19N-R8E	2964170, 3126330	N41° 37' 15" W89° 37' 53"
LEE-92A	SW¼, SW¼, SW¼, SE¼ of Sec. 33, T20N-R8E	2977770, 3144650	N41° 40' 18" W89° 34' 47"
LEE-92C	SW¼, SW¼, SW¼, SE¼ of Sec. 03, T19N-R9E	3013930, 3139520	N41° 39' 27" W89° 26' 55"
LEE-92E	SE¼, SE¼, SE¼, SE¼ of Sec. 13, T19N-R8E	2995330, 3129070	N41° 37' 43" W89° 31' 01"
LEE-92G	NW¼, NW¼, NW¼, NW¼ of Sec. 34, T19N-R9E	3011410, 3118310	N41° 35' 57" W89° 27' 29"
WTS-91A	SE¼, SE¼, SW¼, SW¼ of Sec. 24, T20N-R2E	2803520, 3156170	N41° 42' 05" W89° 13' 22"
WTS-91B	SW¼, SW¼, SW¼, NW¼ of Sec. 35, T20N-R3E	2828390, 3147980	N41° 40' 46" W89° 07' 52"
WTS-91C	SW¼, NW¼, NW¼, SE¼ of Sec. 14, T19N-R4E	2862130, 3130880	N41° 37' 58" W90° 00' 25"
WTS-91E	SE¼, SE¼, SE¼, NE¼ of Sec. 14, T19N-R5E	2895860, 3131420	N41° 38' 06" W89° 53' 00"
WTS-91G	SW¼, SE¼, SE¼, SE¼ of Sec. 13, T20N-R6E	2932420, 3160220	N41° 42' 52" W89° 45' 00"
WTS-91I	SE¼, SE¼, SE¼, SE¼ of Sec. 28, T20N-R7E	2948190, 3149820	N41° 41' 11" W89° 41' 31"

Appendix B. Tampico Aquifer Observation Well Locations and Map Coordinates

Well name	*Location (section, township-range)*	*Lambert coordinates (ft)*	*Latitude and longitude*
BUR-91B	SE¼, SW¼, SE¼, NE¼ of Sec. 03, T18N-R6E	2921730, 3109970	N41° 34' 35" W89° 47' 13"
BUR-92B	NE¼, NE¼, NW¼, NW¼ of Sec. 29, T18N-R6E	2908620, 3091770	N41° 31' 31" W89° 50' 06"
HRY-91B	NW¼, NW¼, NW¼, NW¼ of Sec. 09, T18N-R5E	2880740, 3107320	N41° 34' 05" W89° 56' 16"
HRY-91D	SW¼, SE¼, NE¼, SE¼ of Sec. 08, T17N-R5E	2881020, 3072170	N41° 28' 16" W89° 56' 17"
LEE-91B	SW¼, SW¼, SW¼, NW¼ of Sec. 19, T19N-R8E	2964170, 3126330	N41° 37' 15" W89° 37' 53"
LEE-92B	SW¼, SW¼, SW¼, SE¼ of Sec. 33, T20N-R8E	2977770, 3144650	N41° 40' 18" W89° 34' 47"
LEE-92D	SW¼, SW¼, SW¼, SE¼ of Sec. 03, T19N-R9E	3013930, 3139520	N41° 39' 27" W89° 26' 55"
LEE-92F	SE¼, SE¼, SE¼, SE¼ of Sec. 13, T19N-R8E	2995330, 3129070	N41° 37' 43" W89° 31' 01"
WTS-91A	SE¼, SE¼, SW¼, SW¼ of Sec. 24, T20N-R2E	2803520, 3156170	N41° 42' 05" W89° 13' 22"
WTS-91B	SW¼, SW¼, SW¼, NW¼ of Sec. 35, T20N-R3E	2828390, 3147980	N41° 40' 46" W89° 07' 52"
WTS-91D	SW¼, NW¼, NW¼, SE¼ of Sec. 14, T19N-R4E	2862130, 3130880	N41° 37' 58" W90° 00' 25"
WTS-91F	SE¼, SE¼, SE¼, NE¼ of Sec. 14, T19N-R5E	2895860, 3131420	N41° 38' 06" W89° 53' 00"
WTS-91H	SW¼, SE¼, SE¼, SE¼ of Sec. 13, T20N-R6E	2932420, 3160220	N41° 42' 52" W89° 45' 00"
WTS-91J	SE¼, SE¼, SE¼, SE¼ of Sec. 28, T20N-R7E	2948190, 3149820	N41° 41' 11" W89° 41' 31"

Appendix C. Results of Sampling Illinois State Water Survey Observation Wells

Parameter (mg/L)	*Observation well name/sample number*				
	HRY-91C	*HRY-91D*	*HRY-91A*	*HRY-91B*	*WTS-91C*
	01	*02*	*03*	*04*	*05*
Major constituents					
Calcium	71.6	68.3	69.8	121	67.4
Magnesium	35.4	33.5	31.1	47.0	22.1
Sodium	25.4	3.3	15.0	18.6	5.5
Nitrate (as NO_3)	<0.1	61	<0.1	<0.1	<0.1
Sulfate	<0.9	36.2	<0.9	107	76.4
Chloride	1.0	15.4	0.7	95	20.5
Alkalinity	403	228	360	333	197
TDS @ 180°C	391	357	348	693	342
Secondary constituents					
Iron	0.54	0.02	1.09	2.98	0.12
Manganese	0.519	0.032	0.480	0.400	0.339
Potassium	2.64	0.55	1.97	2.28	5.43
Fluoride	0.3	0.2	0.2	0.3	0.1
Ammonium	0.98	<0.02	1.4	0.05	<0.02
Boron	0.11	<0.06	0.07	<0.06	<0.06
Trace constituents					
Aluminum	0.011	0.008	<0.006	0.006	0.012
Antimony	<0.08	<0.08	<0.08	<0.08	<0.08
Arsenic	<0.03	<0.03	0.05	<0.03	<0.03
Barium	0.526	0.026	0.586	0.078	0.071
Beryllium	<0.001	<0.001	<0.001	<0.001	<0.001
Cadmium	<0.004	<0.004	<0.004	<0.004	<0.004
Chromium	<0.004	0.00525	<0.004	0.00415	0.00412
Cobalt	<0.003	<0.003	<0.003	<0.003	<0.003
Copper	<0.002	<0.002	<0.002	<0.002	<0.002
Lead	<0.014	<0.014	<0.014	<0.014	<0.014
Lithium	0.00322	<0.003	<0.003	0.00331	0.00602
Mercury	<0.008	<0.008	<0.008	<0.008	<0.008
Molybdenum	0.00761	<0.007	<0.007	<0.007	<0.007
Nickel	<0.010	<0.010	<0.010	<0.010	<0.010
Orthophosphate	<0.5	<0.5	<0.5	<0.5	<0.5
Phosphorus	0.13	<0.07	0.19	<0.07	<0.07
Selenium	<0.06	<0.06	<0.06	<0.06	<0.06
Silicon	9.59	8.10	9.19	5.76	6.42
Silver	<0.003	<0.003	<0.003	<0.003	<0.003
Strontium	0.482	0.070	0.595	0.150	0.101
Sulfur	0.08	11.7	<0.08	35.7	24.5
Thallium	<0.12	<0.12	<0.12	<0.12	<0.12
Tin	<0.02	<0.02	<0.02	<0.02	<0.02
Titanium	<0.002	<0.002	<0.002	<0.002	<0.002
Vanadium	<0.003	<0.003	<0.003	<0.003	<0.003
Zinc	0.011	0.071	0.049	0.019	0.044
Field pH	7.71	7.46	7.68	7.11	7.64
Lab pH	8.0	8.0	8.0	7.6	7.9
Field temperature (°C)	12.4	–	12	12.2	12.9
Conductivity	1032	916	838	1401	802

Appendix C. (continued)

Parameter (mg/L)	*Observation well name/sample number*				
	WTS-91D	*BUR-91C*	*WTS-91G*	*WTS-91H*	*WTS-91E*
	06	07	09	10	11
Major constituents					
Calcium	49.7	83.9	70.7	92.8	80.6
Magnesium	17.3	37.2	23.8	35.0	31.1
Sodium	3.97	23.0	4.52	11.8	8.31
Nitrate (as NO_3)	2.9	<0.1	<0.1	<0.1	<0.1
Sulfate	66.2	<0.9	74.5	83.9	<0.9
Chloride	13.3	0.8	19.3	45.0	0.7
Alkalinity	137	447	202	282	378
TDS @ 180°C	280	436	372	527	352
Secondary constituents					
Iron	0.00487	5.18	2.33	3.32	4.88
Manganese	0.263	0.122	0.126	0.148	0.051
Potassium	0.70	2.40	0.81	2.14	1.11
Fluoride	0.1	0.4	0.2	0.2	0.2
Ammonium	<0.02	6.4	0.10	0.18	1.0
Boron	<0.06	0.39	<0.06	<0.06	<0.06
Trace constituents					
Aluminum	<0.006	0.007	0.010	0.007	<0.006
Antimony	<0.08	<0.08	<0.08	<0.08	<0.08
Arsenic	<0.03	<0.03	<0.03	<0.03	0.06
Barium	0.057	0.166	0.043	0.047	0.333
Beryllium	<0.001	<0.001	<0.001	<0.001	<0.001
Cadmium	<0.004	<0.004	<0.004	<0.004	<0.004
Chromium	<0.004	<0.004	0.00467	0.00427	<0.004
Cobalt	<0.003	<0.003	<0.003	<0.003	<0.003
Copper	<0.002	<0.002	<0.002	<0.002	<0.002
Lead	<0.014	<0.014	<0.014	<0.014	<0.014
Lithium	<0.003	<0.003	<0.003	<0.003	<0.003
Mercury	<0.008	<0.008	<0.008	<0.008	<0.008
Molybdenum	<0.007	<0.007	<0.007	<0.007	<0.007
Nickel	<0.010	0.01654	<0.010	<0.010	<0.010
Orthophosphate	<0.5	<0.5	<0.5	<0.5	<0.5
Phosphorus	0.12	0.16	0.11	0.47	<0.07
Selenium	<0.06	<0.06	<0.06	<0.06	<0.06
Silicon	11.9	11.7	7.36	7.04	10.8
Silver	<0.003	<0.003	<0.003	<0.003	<0.003
Strontium	0.064	1.025	0.081	0.088	0.441
Sulfur	21.4	0.18	24.5	27.2	<0.08
Thallium	<0.12	<0.12	<0.12	<0.12	<0.12
Tin	<0.02	<0.02	<0.02	<0.02	<0.02
Titanium	<0.002	<0.002	<0.002	<0.002	<0.002
Vanadium	<0.003	<0.003	<0.003	<0.003	<0.003
Zinc	0.006	0.070	0.049	0.023	0.018
Field pH	7.92	7.28	7.3	7.18	7.41
Lab pH	7.9	7.8	7.9	7.7	8.1
Field temperature (°C)	11.7	12.9	–	–	12.2
Conductivity	597	1076	778	1096	909

Appendix C. (continued)

Parameter (mg/L)	*Observation well name/sample number*				
	WTS-91F	*BUR-91A*	*BUR-91B*	*BUR-92A*	*BUR-92B*
	12	*13*	*14*	*15*	*17*
Major constituents					
Calcium	115	73.0	82.8	80.1	63.7
Magnesium	32.5	27.7	35.0	30.3	24.8
Sodium	5.92	7.50	6.95	11.1	2.51
Nitrate (as NO_3)	<0.1	<0.1	9.5	<0.1	23.4
Sulfate	73.0	<0.9	41.7	<0.9	17.3
Chloride	32.6	0.7	7.1	0.7	2.8
Alkalinity	346	333	320	372	243
TDS @ 180°C	544	331	396	373	288
Secondary constituents					
Iron	3.46	4.95	0.06	4.90	0.04
Manganese	0.300	0.149	0.015	0.383	0.095
Potassium	1.86	1.18	<0.30	1.39	0.34
Fluoride	0.3	0.2	0.2	0.3	0.2
Ammonium	0.28	1.6	<0.02	1.8	0.05
Boron	0.08	<0.06	<0.06	<0.06	<0.06
Trace constituents					
Aluminum	<0.006	0.009	0.007	0.006	<0.006
Antimony	<0.08	<0.08	<0.08	<0.08	<0.08
Arsenic	<0.03	<0.03	<0.03	0.05	<0.03
Barium	0.160	0.188	0.049	0.894	0.063
Beryllium	<0.001	<0.001	<0.001	<0.001	<0.001
Cadmium	<0.004	<0.004	<0.004	<0.004	<0.004
Chromium	0.0042	<0.004	0.00452	0.0043	<0.004
Cobalt	<0.003	<0.003	<0.003	<0.003	<0.003
Copper	<0.002	<0.002	<0.002	<0.002	<0.002
Lead	<0.014	0.022	<0.014	<0.014	<0.014
Lithium	<0.003	<0.003	<0.003	<0.003	<0.003
Mercury	<0.008	<0.008	<0.008	<0.008	<0.008
Molybdenum	<0.007	<0.007	<0.007	<0.007	<0.007
Nickel	<0.010	<0.010	<0.010	<0.010	<0.010
Orthophosphate	<0.5	<0.5	<0.5	<0.5	<0.5
Phosphorus	<0.07	0.18	0.08	0.20	<0.07
Selenium	<0.06	<0.06	<0.06	<0.06	<0.06
Silicon	7.37	12.0	10.1	10.8	9.19
Silver	<0.003	<0.003	<0.003	<0.003	<0.003
Strontium	0.103	0.580	0.073	0.747	0.110
Sulfur	22.4	<0.08	13.3	<0.08	5.86
Thallium	<0.12	<0.12	<0.12	<0.12	<0.12
Tin	<0.02	<0.02	<0.02	<0.02	<0.02
Titanium	<0.002	<0.002	<0.002	<0.002	<0.002
Vanadium	<0.003	<0.003	<0.003	<0.003	<0.003
Zinc	0.025	0.023	0.020	0.013	0.007
Field pH	7.18	7.27	7.34	7.42	7.37
Lab pH	7.7	7.9	7.9	8.0	7.7
Field temperature (°C)	13.2	13.1	–	–	13.9
Conductivity	1150	874	952	916	747

Appendix C. (continued)

Parameter (mg/L)	Observation well name/sample number				
	WTS-91I	*WTS-91J*	*LEE-92A*	*LEE-92B*	*LEE-92C*
	18	*19*	*24*	*25*	*26*
Major constituents					
Calcium	44.3	87.1	84.8	45.7	60.5
Magnesium	16.1	35.5	31.9	18.0	24.5
Sodium	4.76	86.7	10.4	3.11	6.39
Nitrate (as NO_3)	<0.1	<0.1	<0.1	69.0	<0.1
Sulfate	<0.9	84.3	<0.9	19.1	7.0
Chloride	1.0	200	0.6	10.8	0.8
Alkalinity	204	231	363	111	274
TDS @ 180°C	206	683	354	247	271
Secondary constituents					
Iron	1.25	1.65	5.26	0.01	0.55
Manganese	0.295	0.337	0.348	0.005	0.213
Potassium	0.61	2.98	0.98	<0.30	1.07
Fluoride	0.2	0.4	0.3	<0.1	0.2
Ammonium	0.23	<0.02	0.33	<0.02	0.12
Boron	<0.06	<0.06	<0.06	<0.06	<0.06
Trace constituents					
Aluminum	0.00873	<0.006	0.011	0.019	0.008
Antimony	<0.08	<0.08	<0.08	<0.08	<0.08
Arsenic	<0.03	<0.03	<0.03	<0.03	<0.03
Barium	0.035	0.082	0.135	0.029	0.057
Beryllium	<0.001	<0.001	<0.001	<0.001	<0.001
Cadmium	<0.004	<0.004	<0.004	<0.004	<0.004
Chromium	0.0069	<0.004	<0.004	0.00638	0.00461
Cobalt	<0.003	<0.003	<0.003	<0.003	<0.003
Copper	<0.002	<0.002	<0.002	<0.002	<0.002
Lead	<0.014	<0.014	<0.014	<0.014	<0.014
Lithium	<0.003	<0.003	<0.003	<0.003	<0.003
Mercury	<0.008	<0.008	<0.008	<0.008	<0.008
Molybdenum	<0.007	<0.007	<0.007	<0.007	<0.007
Nickel	<0.010	<0.010	<0.010	<0.010	<0.010
Orthophosphate	<0.5	<0.5	<0.5	<0.5	<0.5
Phosphorus	0.23	<0.07	0.08	0.08	0.08
Selenium	<0.06	<0.06	<0.06	<0.06	<0.06
Silicon	9.28	4.20	10.3	8.01	7.84
Silver	<0.003	<0.003	<0.003	<0.003	<0.003
Strontium	0.072	0.138	0.189	0.055	0.135
Sulfur	<0.08	27.2	<0.08	6.84	2.63
Thallium	<0.12	<0.12	<0.12	<0.12	<0.12
Tin	<0.02	<0.02	<0.02	<0.02	<0.02
Titanium	<0.002	<0.002	<0.002	<0.002	<0.002
Vanadium	<0.003	<0.003	<0.003	<0.003	<0.003
Zinc	0.048	0.020	0.064	0.230	0.031
Field pH	7.53	7.32	7.36	7.98	7.52
Lab pH	7.9	7.9	7.8	7.9	8.0
Field temperature (°C)	12.9	–	13.2	13.1	–
Conductivity	494	1630	829	514	674

Appendix C. (continued)

Parameter (mg/L)	*Observation well name/sample number*				
	LEE-92D	*BUR-91D*	*LEE-92G*	WID-V	LEE-92E
	27	*28*	*29*	31	32
Major constituents					
Calcium	77.0	67.9	70.3	66.2	81.1
Magnesium	32.0	25.2	29.2	28.2	36.1
Sodium	3.83	7.94	6.46	17.7	4.78
Nitrate (as NO_3)	8.7	<0.1	79.0	112	<0.1
Sulfate	92.0	<0.9	37.8	28.6	89.5
Chloride	20.0	0.6	35.0	26.0	16.1
Alkalinity	231	305	174	179	259
TDS @ 180°C	413	297	364	391	397
Secondary constituents					
Iron	0.05	4.91	0.04	0.03	1.02
Manganese	0.254	0.196	0.003	<0.003	0.092
Potassium	1.81	0.84	1.07	1.57	0.85
Fluoride	0.1	0.2	0.1	0.1	0.2
Ammonium	0.08	2.2	<0.02	<0.02	<0.02
Boron	<0.06	<0.06	<0.06	<0.06	<0.06
Trace constituents					
Aluminum	0.007	0.008	0.010	0.013	0.010
Antimony	<0.08	<0.08	<0.08	<0.08	<0.08
Arsenic	<0.03	<0.03	<0.03	<0.03	<0.03
Barium	0.094	0.084	0.046	0.024	0.041
Beryllium	<0.001	<0.001	<0.001	<0.001	<0.001
Cadmium	<0.004	<0.004	<0.004	<0.004	<0.004
Chromium	<0.004	<0.004	0.005	0.005	<0.004
Cobalt	<0.003	<0.003	<0.003	<0.003	<0.003
Copper	<0.002	<0.002	<0.002	<0.002	<0.002
Lead	<0.014	<0.014	<0.014	<0.014	<0.014
Lithium	<0.003	<0.003	<0.003	<0.003	<0.003
Mercury	<0.008	<0.008	<0.008	<0.008	<0.008
Molybdenum	<0.007	<0.007	<0.007	<0.007	<0.007
Nickel	<0.010	<0.010	<0.010	<0.010	<0.010
Orthophosphate	<0.5	<0.5	<0.5	<0.5	<0.5
Phosphorus	<0.07	0.20	<0.07	<0.07	<0.07
Selenium	<0.06	<0.06	<0.06	<0.06	0.07
Silicon	4.14	10.9	6.59	7.46	6.68
Silver	<0.003	<0.003	<0.003	<0.003	<0.003
Strontium	0.098	0.220	0.204	0.156	0.094
Sulfur	30.0	<0.08	12.2	9.61	30.3
Thallium	<0.12	<0.12	<0.12	<0.12	<0.12
Tin	<0.02	<0.02	<0.02	<0.02	<0.02
Titanium	<0.002	<0.002	<0.002	<0.002	<0.002
Vanadium	<0.003	<0.003	0.005	0.005	<0.003
Zinc	0.039	0.039	0.009	0.067	0.024
Field pH	7.49	7.38	7.41	7.5	7.57
Lab pH	8.0	7.8	8.0	7.9	8.0
Field temperature (°C)	–	–	14.1	–	–
Conductivity	887	730	881	870	821

Appendix C. (concluded)

Parameter (mg/L)	*Observation well name/sample number*			
	LEE-92F	*BUR-92C*	*BUR-92E*	*BUR-92F*
	33	*34*	35	36
Major constituents				
Calcium	86.3	59.2	96.9	40.7
Magnesium	34.5	37.8	53.6	20.6
Sodium	6.31	34.8	32.8	48.2
Nitrate (as NO_3)	29.0	<0.1	10.9	<0.1
Sulfate	66.5	<0.9	50.8	<0.9
Chloride	21.0	0.9	59.0	1.2
Alkalinity	255	471	403	308
TDS @ 180°C	411	381	580	302
Secondary constituents				
Iron	0.05	0.06	0.06	0.12
Manganese	0.157	0.235	0.079	0.120
Potassium	0.94	2.12	0.56	2.11
Fluoride	0.2	0.5	0.3	0.6
Ammonium	<0.02	2.9	0.07	2.2
Boron	<0.06	0.30	<0.06	0.27
Trace constituents				
Aluminum	0.009	0.017	0.007	0.011
Antimony	<0.08	<0.08	<0.08	<0.08
Arsenic	<0.03	<0.03	<0.03	<0.03
Barium	0.070	0.168	0.100	0.108
Beryllium	<0.001	<0.001	<0.001	<0.001
Cadmium	<0.004	<0.004	<0.004	<0.004
Chromium	0.005	<0.004	<0.004	<0.004
Cobalt	<0.003	<0.003	<0.003	<0.003
Copper	<0.002	<0.002	<0.002	<0.002
Lead	<0.014	<0.014	<0.014	<0.014
Lithium	<0.003	<0.003	0.00539	<0.003
Mercury	<0.008	<0.008	<0.008	<0.008
Molybdenum	<0.007	<0.007	<0.007	0.026
Nickel	<0.010	<0.010	0.01019	<0.010
Orthophosphate	<0.5	<0.5	<0.5	<0.5
Phosphorus	<0.07	<0.07	<0.07	0.16
Selenium	<0.06	<0.06	<0.06	<0.06
Silicon	4.37	9.52	9.08	4.30
Silver	<0.003	<0.003	<0.003	<0.003
Strontium	0.112	2.48	0.362	0.332
Sulfur	22.0	0.20	16.6	0.14
Thallium	<0.12	<0.12	<0.12	<0.12
Tin	<0.02	<0.02	<0.02	<0.02
Titanium	<0.002	<0.002	<0.002	<0.002
Vanadium	<0.003	<0.003	<0.003	<0.003
Zinc	0.018	0.009	0.010	0.007
Field pH	7.36	7.63	7.16	7.71
Lab pH	7.7	8.1	7.8	8.2
Field temperature (°C)	–	–	13.3	–
Conductivity	937	894	1327	714

Notes: TDS = total dissolved solids and – = missing value