Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data

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FOREWORD

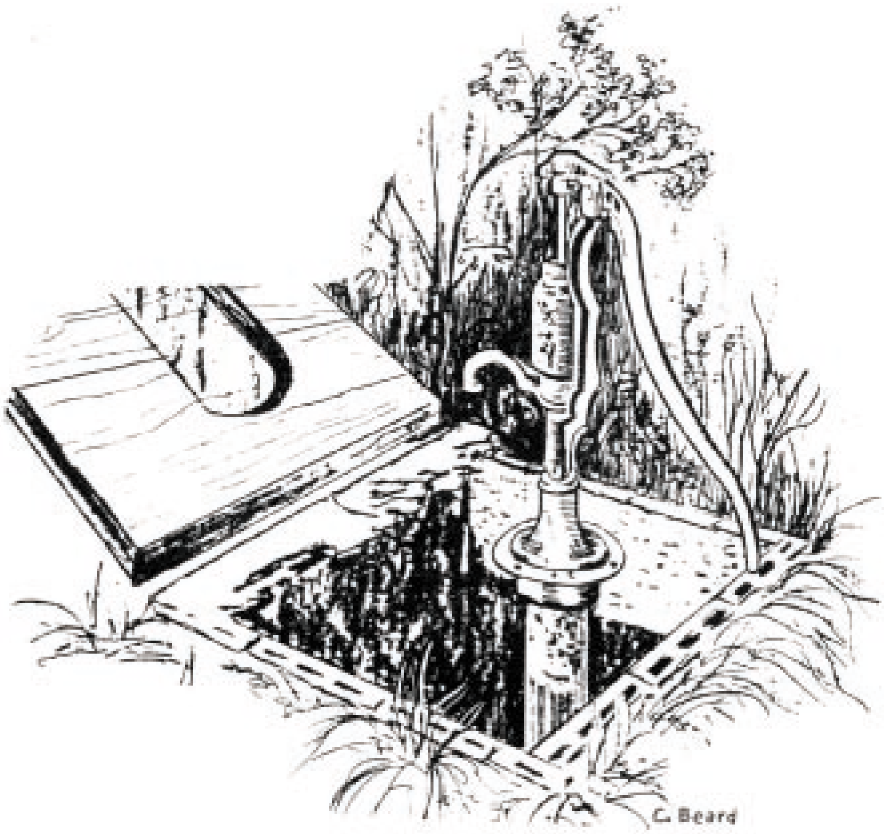
Ground water is among the Nation's most precious natural resources. Measurements of water levels in wells provide the most fundamental indicator of the status of this resource and are critical to meaningful evaluations of the quantity and quality of ground water and its interaction with surface water. Water-level measurements are made by many Federal, State, and local agencies. It is the intent of this report to highlight the importance of measurements of ground-water levels and to foster a more comprehensive and systematic approach to the long-term collection of these essential data. Through such mutual efforts, the Nation will be better positioned in coming decades to make wise use of its extensive ground-water resources.

(Signed)

Robert M. Hirsch
Associate Director for Water

CONTENTS

BOXES


C. Beard

Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data

by Charles J. Taylor
William M. Alley

INTRODUCTION

Ground water is one of the Nation's most important natural resources. It is the principal source of drinking water for about 50 percent of the United States population, providing approximately 96 percent of the water used for rural domestic supplies and 40 percent of the water used for public supplies (Solley and others, 1998). In addition, more than 30 percent of the water used for agricultural purposes is withdrawn from wells. Ground water also is a significant, but often unrecognized, component of the Nation's surface-water resources. Much of the flow in streams and the water in lakes and wetlands is sustained by the discharge of ground water, particularly during periods of dry weather.

Ground-water systems are dynamic and adjust continually to short-term and long-term changes in climate, ground-water withdrawal, and land use (Box A). Water-level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect ground-water recharge, storage, and discharge. Long-term, systematic measurements of water levels provide essential data needed to evaluate changes in the resource over time, to develop ground-water models and forecast trends, and to design, implement, and monitor the effectiveness of ground-water management and protection programs.

"Water-level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect ground-water recharge, storage, and discharge."

The U.S. Geological Survey (USGS) has collected water-level data for more than a hundred years, and many State and other agencies have a long history of water-level monitoring. However, water-level monitoring in the United States is fragmented and largely subject to the vagaries of existing local projects. A stable, base network of water-level monitoring wells exists only in some locations. Moreover, agency planning and coordination vary greatly throughout the United States with regard to construction and operation of water-level observation networks and the sharing of collected data.

For many decades, periodic calls have been made for a nationwide program to obtain more systematic and comprehensive records of water levels in observation wells as a joint effort among USGS and State and local agencies. O.E. Meinzer described the characteristics of such a program over 65 years ago:

> **The program should cover the water-bearing formations in all sections of the country; it should include beds with water-table conditions, deep artesian aquifers, and intermediate sources; moreover, it should include areas of heavy withdrawal by pumping or artesian flow, areas which are not affected by heavy withdrawal but in which the natural conditions of intake and discharge have been affected by deforestation or breaking up of prairie land, and, so far as possible, areas that still have primeval conditions. This nation-wide program should furnish a reliable basis for periodic inventories of the ground-water resources, in order that adequate provision may be made for our future water supplies.**
>
> ***—O.E. Meinzer, 1935, Introduction to "Report of the Committee on Observation Wells, United States Geological Survey" (Leggette and others, 1935)***

More recently, the National Research Council (2000) reiterated, "An unmet need is a national effort to track water levels over time in order to monitor water-level declines."

This report reviews the uses and importance of data from long-term ground-water-level monitoring in the United States. Case studies are presented to highlight the broad applicability of long-term ground-water-level data to water-resource issues commonly faced by hydrologists, engineers, regulators, and resource managers. It is hoped that this report will provide a catalyst toward the establishment of a more rigorous and systematic nationwide approach to ground-water-level monitoring—clearly an elusive goal thus far. The time is right for progress toward this goal. Improved access to water data over the Internet offers the opportunity for significant improvements in the coordination of water-level monitoring and the sharing of information by different agencies, as well as the potential means for evaluation of water-level monitoring networks throughout the United States.

A

Hydraulic Head and Factors Causing Changes in Ground-Water Levels

This section describes some basic ground-water terms and provides a general description of natural and human factors that affect ground-water levels (heads). It is intended as background information for the reader who may have limited knowledge of ground-water hydrology.

Hydraulic head (often simply referred to as "head") is an indicator of the total energy available to move ground water through an aquifer. Hydraulic head is measured by the height to which a column of water will stand above a reference elevation (or "datum"), such as mean sea level. A water-level measurement made under static (nonpumping) conditions is a measurement of the hydraulic head in the aquifer at the depth of the screened or open interval of a well (Figure A–1). Because hydraulic head represents the energy of water, ground water flows from locations of higher hydraulic head to locations of lower hydraulic head. The change in hydraulic head over a specified distance in a given direction is called the "hydraulic gradient."

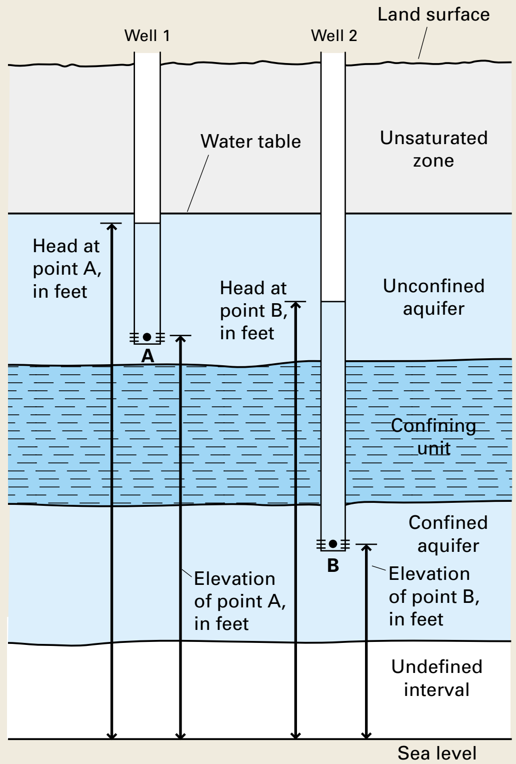


Figure A–1. *Sketch showing the relation between hydraulic heads and water levels in two observation wells—Well 1 screened in an unconfined aquifer and Well 2 screened in a confined aquifer. Hydraulic heads in each of these two aquifers are determined by the elevation of the water level in the well relative to a vertical datum—in this case, sea level.*

Two general types of aquifers—unconfined and confined—are recognized (Figure A–2). In unconfined aquifers, hydraulic heads fluctuate freely in response to changes in recharge and discharge. Water levels measured in wells completed in the upper part of an unconfined aquifer help define the elevation of the water table, which is the top of the saturated zone. In confined aquifers, sometimes known as "artesian" aquifers, water in the aquifer is "confined" under pressure by a geological body that is much less permeable than the aquifer itself. Water levels in tightly cased wells completed in confined aquifers often rise above the elevation of the top of the aquifer (Figure A–2). These water levels define an imaginary surface, referred to as the potentiometric surface, which represents the potential height to which water will rise in wells completed in the confined aquifer. Many aquifers are intermediate between being completely unconfined or confined.

Ground-water levels are controlled by the balance among recharge to, storage in, and discharge from an aquifer. Physical properties such as the porosity, permeability, and thickness of the rocks or sediments that compose the aquifer affect this balance. So, too, do climatic and hydrologic factors, such as the timing and amount of recharge provided by precipitation, discharge from the subsurface to surface-water bodies, and evapotranspiration. When the rate of recharge to an aquifer exceeds the rate of discharge, water levels or hydraulic heads will rise. Conversely, when the rate of ground-water withdrawal or discharge is greater than

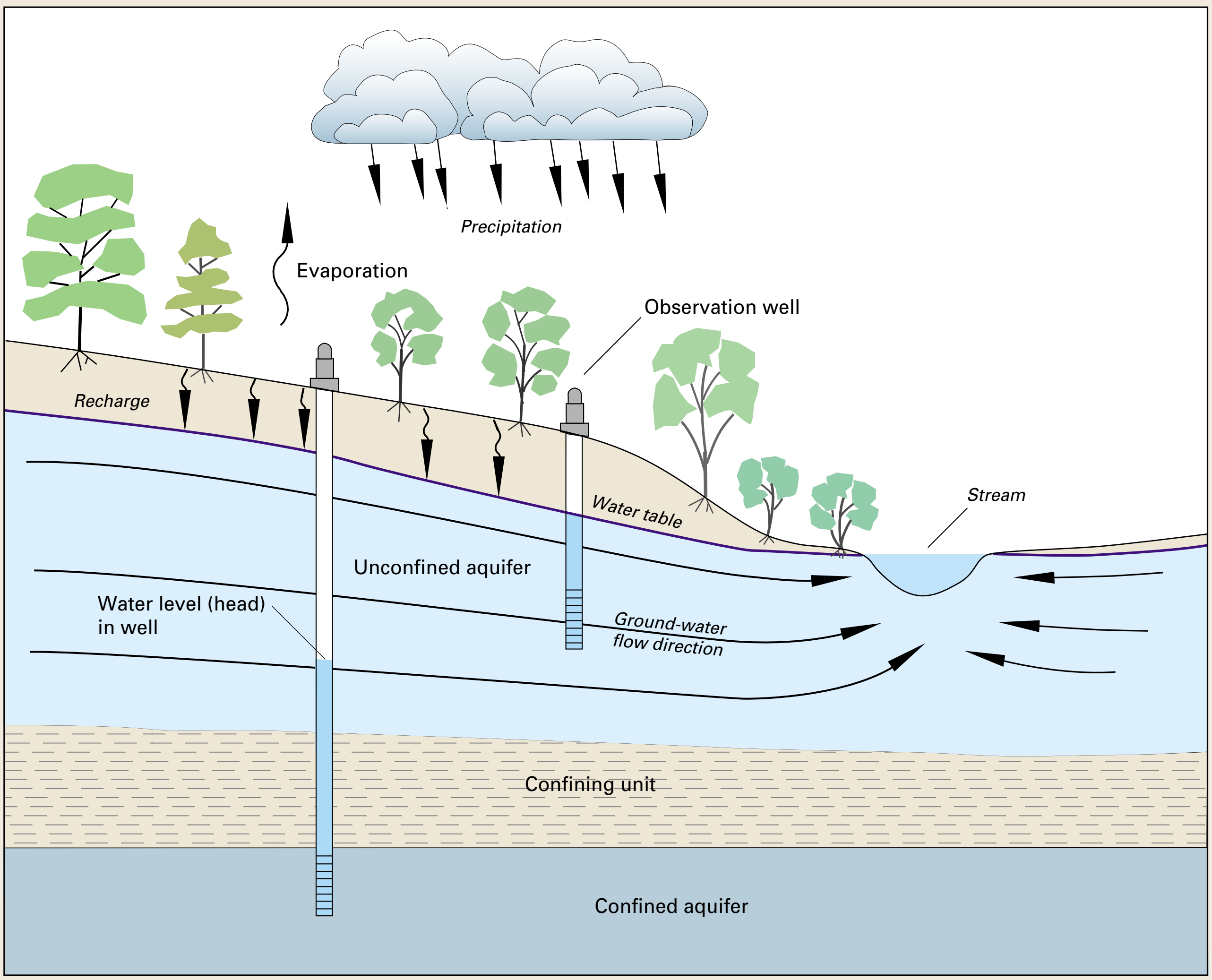


Figure A–2. *Cross-section sketch of a typical ground-water-flow system showing the relation between an unconfined and confined aquifer, a water table, and other hydrologic elements.*

the rate of ground-water recharge, the water stored in the aquifer becomes depleted and water levels or hydraulic heads will decline.

Water levels in many aquifers in the United States follow a natural cyclic pattern of seasonal fluctuation, typically rising during the winter and spring due to greater precipitation and recharge, then declining during the summer and fall owing to less recharge and greater evapotranspiration. The magnitude of fluctuations in water levels can vary greatly from season to season and from year to year in response to varying climatic conditions. Changes in ground-water recharge and storage caused by climatic variability commonly occur over decades, and water levels in aquifers generally have a delayed response to the cumulative effects of drought.

The range and timing of seasonal water-level fluctuations may vary in different aquifers in the same geographic area, depending on the sources of recharge to the aquifers and the physical and hydraulic properties of each. This is illustrated by hydrographs for two wells (GW–11 and MW–1) completed in a layered alluvial aquifer system near the Ohio River in northern Kentucky (Figure A–3). The two wells are approximately 250 feet apart; however, well GW–11 is completed in a shallow aquifer zone consisting of a mixture of silty clay and sand approximately 40 feet thick, while well MW–1 is completed in a deeper aquifer zone consisting of a mixture of sand and gravel approximately 20 feet thick.

Because the silty clay does not easily transmit water, the shallow aquifer zone exhibits a relatively muted response to a seasonal increase in recharge that typically occurs at this

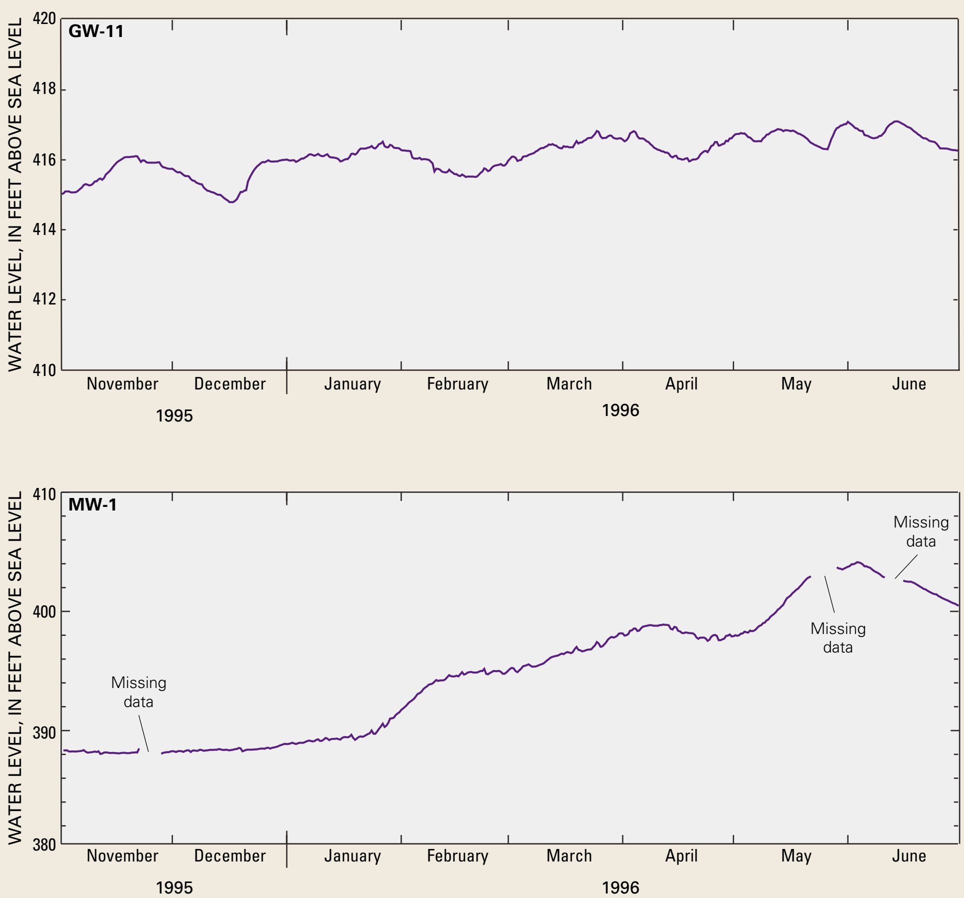


***Figure A–3.** Example hydrographs showing the difference in timing and range of water-level fluctuations in two observation wells (GW–11 and MW–1) in an alluvial aquifer near the Ohio River, northern Kentucky.*

location during the late winter and spring. As seen on the hydrograph, water levels in well GW–11 fluctuate slightly from November to June in response to individual precipitation events, but exhibit an overall seasonal increase of less than 2 feet. In contrast, the more permeable sand and gravel in the deeper aquifer zone transmits water very easily, and the deeper aquifer zone exhibits a much greater response to the seasonal increase in recharge. On the hydrograph for well MW–1, water levels increase gradually at first from November through January, then more sharply from February to June, and exhibit an overall seasonal increase of more than 12 feet.

Superimposed on natural, climate-related fluctuations in ground-water levels are the effects of human activities that alter the natural rates of ground-water recharge or discharge. For example, urban development, deforestation, and draining of wetlands can expedite surface runoff and thus reduce ground-water recharge. Agricultural tillage, the impoundment of streams, and creation of artificial wetlands can increase ground-water recharge. Long-term water-level monitoring during periods of significant land-use change is important to the protection of aquifers. The effects of such human-induced changes on ground-water recharge and storage are often incremental, and the cumulative effects may not become evident for many years.

The withdrawal of ground water by pumping is the most significant human activity that alters the amount of ground water in storage and the rate of discharge from an aquifer. The removal of water stored in geologic materials near the well sets up hydraulic gradients that induce flow from more distant parts of the aquifer. As ground-water storage is depleted within the radius of influence of pumping, water levels in the aquifer decline. The area of water-level decline is called the cone of depression, and its size is controlled by the rate and duration of pumping, the storage characteristics of the aquifer, and the ease with which water is transmitted through the geologic materials to the well. The development of a cone of depression can result in an overall decline in water levels over a large geographic area, change the direction of ground-water flow within an aquifer, reduce the amount of base flow to streams, and capture water from a stream or from adjacent aquifers. Within areas having a high density of pumped wells, multiple cones of depression can develop within an aquifer.

As the reader examines the case studies discussed in this report, it is instructive to identify the natural and human-induced stresses on the aquifers described and the relative and combined effects of each on ground-water levels. This will illustrate the primary point of emphasis—that ground-water-level data must be collected accurately and over periods of sufficient time to enable the proper development, management, and protection of the Nation's ground-water resources.

Measuring water level in dewatering well near Yuma, Arizona. Photograph by Sandra J. Owen-Joyce, U.S. Geological Survey.

ESSENTIAL COMPONENTS OF WATER-LEVEL MONITORING PROGRAMS

Before discussing the uses and importance of long-term water-level data, it is useful to review essential components of a water-level monitoring program. These include: (1) selection of observation wells, (2) determination of the frequency of water-level measurements, (3) implementation of quality assurance, and (4) establishment of effective practices for data reporting.

Selection of Observation Wells

All water-level monitoring programs depend on the operation of a network of observation wells—wells selected expressly for the collection of water-level data in one or more specified aquifers. Decisions made about the number and locations of observation wells are crucial to any water-level data collection program. Ideally, the wells chosen for an observation well network will provide data representative of various topographic, geologic, climatic, and land-use environments. Decisions about the areal distribution and depth of completion of observation wells also should consider the physical boundaries and geologic complexity of aquifers under study. Water-level monitoring programs for complex, multilayer aquifer systems may require measurements in wells completed at multiple depths in different geologic units. Large, regional aquifers that extend beyond State boundaries require a network of observation wells distributed among one or more States. If one of the purposes of a network is to monitor ambient ground-water conditions, or the effects of natural, climatic-induced hydrologic stresses, the observation network will require wells that are unaffected by pumping, irrigation, and land uses that affect ground-water recharge. These and many other technical considerations pertinent to the design of a water-level observation network are discussed in more detail in technical papers by Peters (1972), Winter (1972), and Heath (1976).

Commonly overlooked is the need to collect other types of hydrologic information as part of a water-level monitoring program. Meteorological data, such as precipitation data, aid in the interpretation of water-level changes in observation wells. Where observation wells are located in alluvial aquifers or other aquifers that have a strong hydraulic connection to a stream or lake, hydrologic data, such as stream discharge or stage, are useful in examining the interaction between ground water and surface water. Meteorological and streamflow data commonly are available from other sources; but if not, some monitoring of variables such as streamflow and precipitation may be needed to supplement the water-level data, particularly in remote areas or in small watersheds. In addition, water-use data, such as pumping rates and volumes of pumped water, can greatly enhance the interpretation of trends observed in water levels and explain changes in the storage and availability of ground water that result from water withdrawals over time.

Well with tipping-bucket rain gage mounted on top.

Frequency of Water-Level Measurements

The frequency of water-level measurements is among the most important components of a water-level monitoring program. Although often influenced by economic considerations, the frequency of measurements should be determined to the extent possible with regard to the anticipated variability of water-level fluctuations in the observation wells and the data resolution or amount of detail needed to fully characterize the hydrologic behavior of the aquifer. These aspects are discussed more fully in Box B.

Typically, collection of water-level data over one or more decades is required to compile a hydrologic record that encompasses the potential range of water-level fluctuations in an observation well and to track trends with time. Systematic, long-term collection of water-level data offers the greatest likelihood that water-level fluctuations caused by variations in climatic conditions and water-level trends caused by changes in land-use or water-management practices will be "sampled." The availability of long-term water-level records greatly enhances the ability to forecast future water levels. Therefore, observation wells should be selected with an emphasis on wells for which measurements can be made for an indefinite time.

Typically, collection of water-level data over one or more decades is required to compile a hydrologic record that encompasses the potential range of water-level fluctuations in an observation well and to track trends with time.

Downloading water-level data from an observation well in Oregon instrumented with a downhole transducer/logger. Photograph by David S. Morgan, U.S. Geological Survey.

Quality Assurance

Good quality-assurance practices help to maintain the accuracy and precision of water-level measurements, ensure that observation wells reflect conditions in the aquifer being monitored, and provide data that can be relied upon for many intended uses. Therefore, field and office practices that will provide the needed levels of quality assurance for water-level data should be carefully thought out and consistently employed.

Some important field practices that will ensure the quality of ground-water-level data include the establishment of permanent datums (reference points for water-level measurements) for observation wells, periodic inspection of the well structure, and periodic hydraulic testing of the well to ensure its communication with the aquifer. The locations and the altitudes of all observation wells should be accurately surveyed to establish horizontal and vertical datums for long-term data collection. Inaccurate datums are a major source of error for water-level measurements used as control points for contoured water-level or potentiometric-surface maps and in the calibration and sensitivity analysis of numerical ground-water models. Recent advances in the portability and operation of traditional surveying equipment, and in Global Positioning System (GPS) technology, have simplified the process of obtaining a fast, accurate survey of well location coordinates and datums.

Existing wells selected and used for long-term water-level monitoring should be carefully examined to ensure that no construction defects are present that might affect the accuracy of water-level measurements. This may entail the use of a down-hole video camera to inspect the well screen and casing construction. Over time, silting, corrosion, or bacterial growth may adversely affect the way the well responds to changes in the aquifer. Any well selected for inclusion in an observation network should be hydraulically tested to ensure it is in good communication with the aquifer of interest. Hydraulic tests should be repeated periodically to ensure that hydraulic communication between the well and the aquifer remains optimal and that the hydraulic response of the well reflects water-level (head) fluctuations in the aquifer as accurately as possible.

To help maintain quality assurance, a permanent file that contains a physical description of well construction, location coordinates, the datum used for water-level measurements, and results of hydraulic tests should be established for each observation well. Recent water-level measurements should be compared with previous measurements made under similar hydrologic conditions to identify potential anomalies in water-level fluctuations that may indicate a malfunction of measuring equipment or a defect in observation-well construction.

Hydraulic tests should be repeated periodically to ensure that the hydraulic response of the well reflects water-level (head) fluctuations in the aquifer as accurately as possible.

Data Reporting

Water-level data reporting techniques vary greatly depending on the intended use of the data, but too often water-level measurements are simply tabulated and recorded in a paper file or electronic database. Simple tabulation is useful for the determination of average, maximum, and minimum water levels but does not easily reveal changes or trends caused by seasonal and annual differences in precipitation, water use, or other hydrologic stresses.

Water-level hydrographs—graphical plots showing changes in water levels over time—are a particularly useful form of data reporting. Such hydrographs provide a visual depiction of the range in water-level fluctuations, seasonal water-level variations, and the cumulative effects of short-term and long-term hydrologic stresses. In general, the value and reliability of the information presented by a water-level hydrograph improves with increasing frequency of measurement and period of record. Hydrographs that are constructed from infrequent water-level measurements, or that have significant gaps in time between the measurements, generally are difficult to interpret and may lead to biased or mistaken interpretations about the frequency and magnitude of water-level fluctuations and their causes. Depending on the frequency of water-level measurement and period of hydrologic record, water-level hydrographs can be constructed to illustrate historical water levels, compare recent and historical water-level data, and present descriptive statistics for water-level measurements (Figure 1).

The accessibility of water-level data is greatly enhanced by the use of electronic databases, especially those that incorporate Geographic Information System (GIS) technology to visually depict the locations of observation wells relative to pertinent geographic, geologic, or hydrologic features. The availability of electronic information transfer on the Internet greatly enhances the capability for rapid retrieval and transmittal of water-level data to potential users. Water-level hydrographs, maps of observation-well networks, tabulated water-level measurements, and other pertinent information all can be configured for access on the Internet. A significant advantage of this method of data reporting is the ease and speed with which ground-water-level data can be updated and made available to users.

Measuring well "stickup" to establish water-level measurement datum. Photograph by Heather Handran, U.S. Geological Survey.

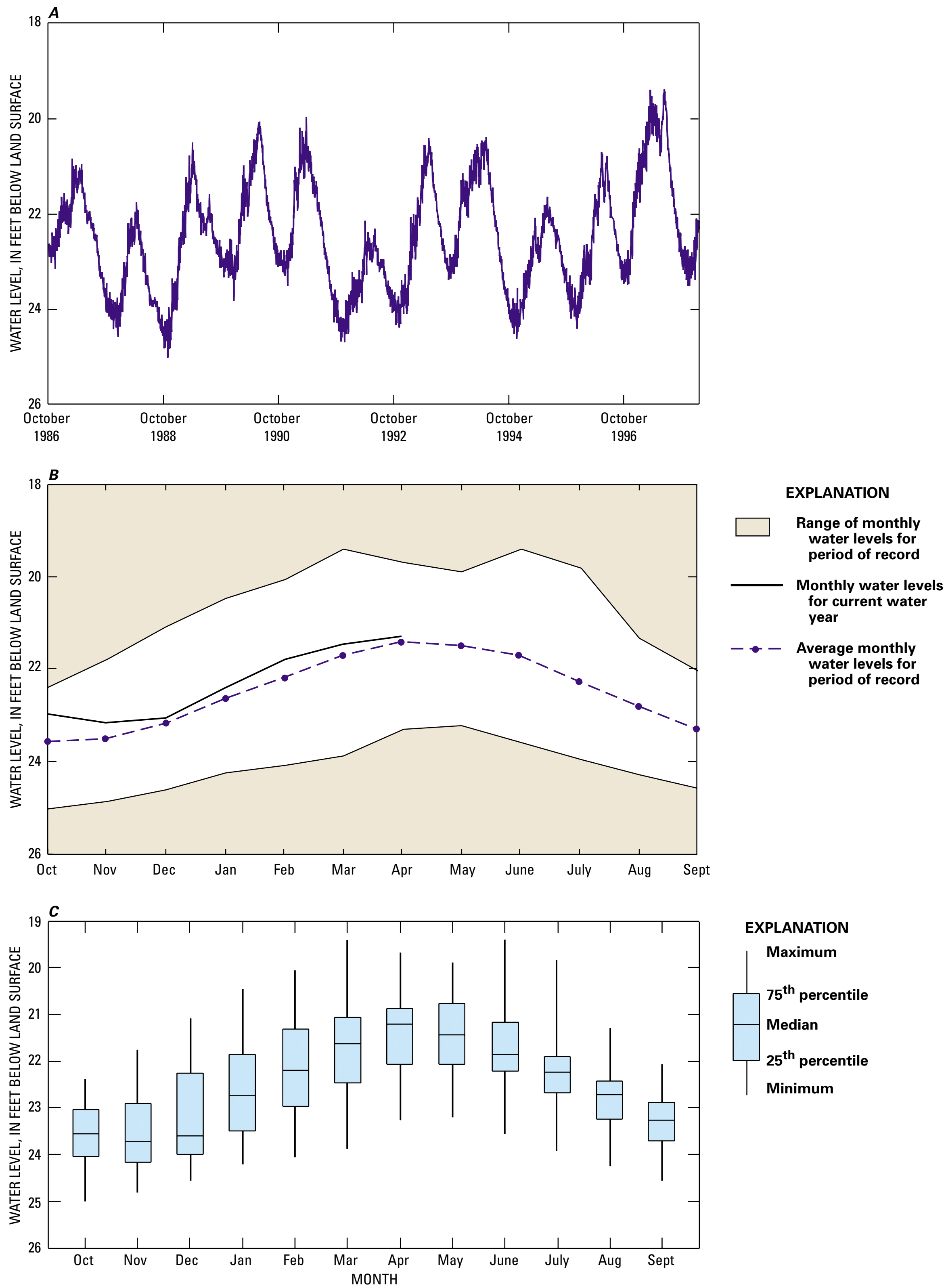


Figure 1. *Hydrographs for a well in Vanderburgh County, Indiana, showing (A) continuous record of daily water-level measurements made over about a decade, (B) comparison between water-level measurements made in a single year to historical high and low water-level measurements, and (C) statistical distribution (boxplots) of water levels for each month.*

B

Ground-Water-Level Measurements: Why the Choice of Frequency Matters

The frequency of measurement is one of the most important considerations in the design of a water-level monitoring program. The development of a plan for water-level monitoring that will be used for each well in the observation network is dependent on the objectives of the program and the intended use and level of analysis required of the data. The frequency of measurement should be adequate to detect short-term and seasonal ground-water-level fluctuations of interest and to discriminate between the effects of short- and long-term hydrologic stresses (Figure B–1).

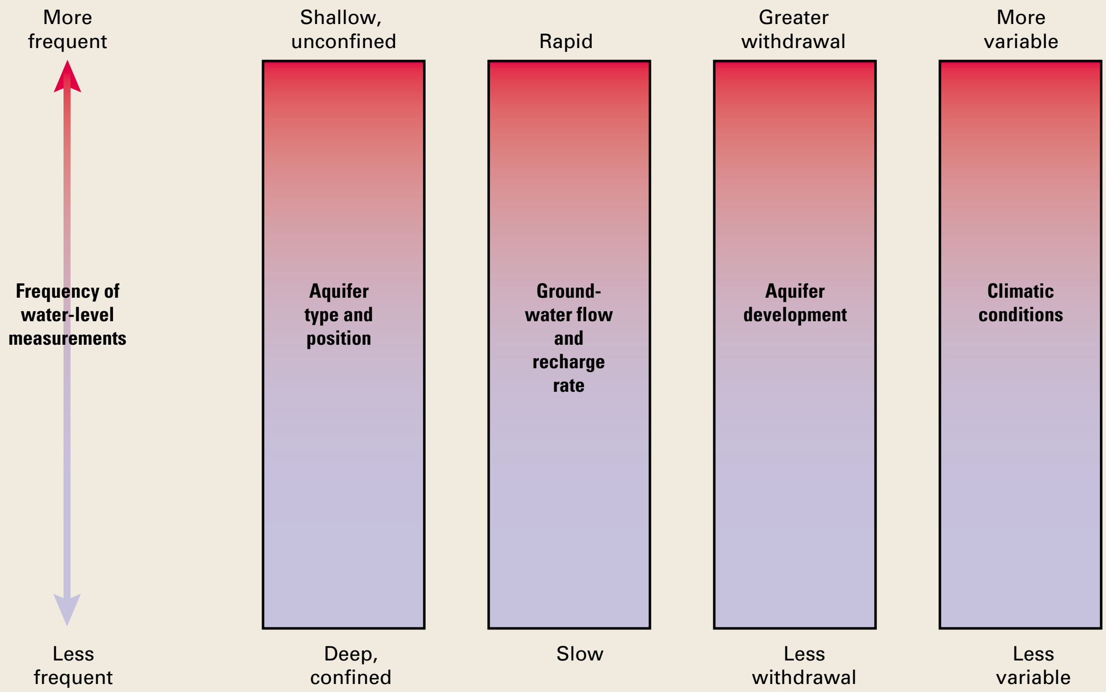


Figure B–1. *Common environmental factors that influence the choice of frequency of water-level measurements in observation wells.*

Water-level monitoring may involve "continuous" or periodic measurements. Continuous monitoring involves the installation of automatic water-level sensing and recording instruments that are programmed to make measurements in observation wells at a specified frequency. Continuous monitoring provides the highest level of resolution of water-level fluctuations. Hydrographs constructed from frequent water-level measurements collected with continuous monitoring equipment can be used to accurately identify the effects of various stresses on the aquifer system and to provide the most accurate estimates of maximum and minimum water-level fluctuations in aquifers. For these reasons, it is often advisable that new observation wells initially be equipped with continuous monitoring equipment to identify stresses on the aquifer and the magnitude and frequency of water-level fluctuations. Continuous monitoring may not be required where the hydraulic response of an aquifer to stresses is slow and the frequency and magnitude of water-level changes in an observation well are not great. However, it is often the best technique to use for monitoring fluctuations in ground-water levels during droughts and other critical periods when hydraulic stresses may change at relatively rapid rates. Near real-time data collection also can be accomplished using a continuous recording device and telecommunication or radio transmitter equipment.

Periodic ground-water-level measurements are those made at scheduled intervals (weeks, months, or years) and are generally used for water-table or potentiometric surface mapping and to reduce the costs of long-term monitoring. Periodic water-level measurements are made by manually using electronic-sensor tapes, chalked metal tapes, or acoustic sounding devices. Potential drawbacks to periodic monitoring are that hydraulic responses to short-term stresses may occur between measurements and may be missed, extreme water-level fluctuations cannot be determined with certainty, and apparent trends in water levels potentially are biased by the choice of measurement frequency.

Synoptic water-level measurements are a special type of periodic measurement in which water levels in wells are measured within a relatively short period and under specific hydrologic conditions. Synoptic water-level measurements provide a "snapshot" of heads in an aquifer. Synoptic measurements commonly are taken when data are needed for mapping the altitude of the water table or potentiometric surface, determining hydraulic gradients, or defining the physical boundaries of an aquifer. Regional synoptic measurements made on an annual or multiyear basis can be used as part of long-term monitoring to complement more frequent measurements made from a smaller number of wells.

An example of the effects of different measurement frequencies is provided by water-level hydrographs for an observation well in Massachusetts. The well is completed in bedrock to a depth of 740 feet, and the characteristics of this well fall in the middle range of the temporal response categories shown in Figure B–1.

A daily water-level hydrograph for the Massachusetts well and hydrographs that would have been obtained for the same well if measurements had been made only monthly or quarterly are shown in Figure B–2. Comparing the effects of different measurement frequencies on the hydrographs illustrates several features. First, monthly water-level measurements for this well generally are adequate to discern overall seasonal patterns in water levels and long-term trends but miss some short-term effects from pumping or recharge. Second, unless quarterly measurements correspond with regular patterns of seasonal variability of water levels, it can be difficult or impossible to discern anything beyond simple long-term water-level trends. Figure B–3, which overlays the daily and quarterly hydrographs from Figure B–2, illustrates how less frequent water-level measurements lead to lower estimates of the range of fluctuations in water levels in an observation well.

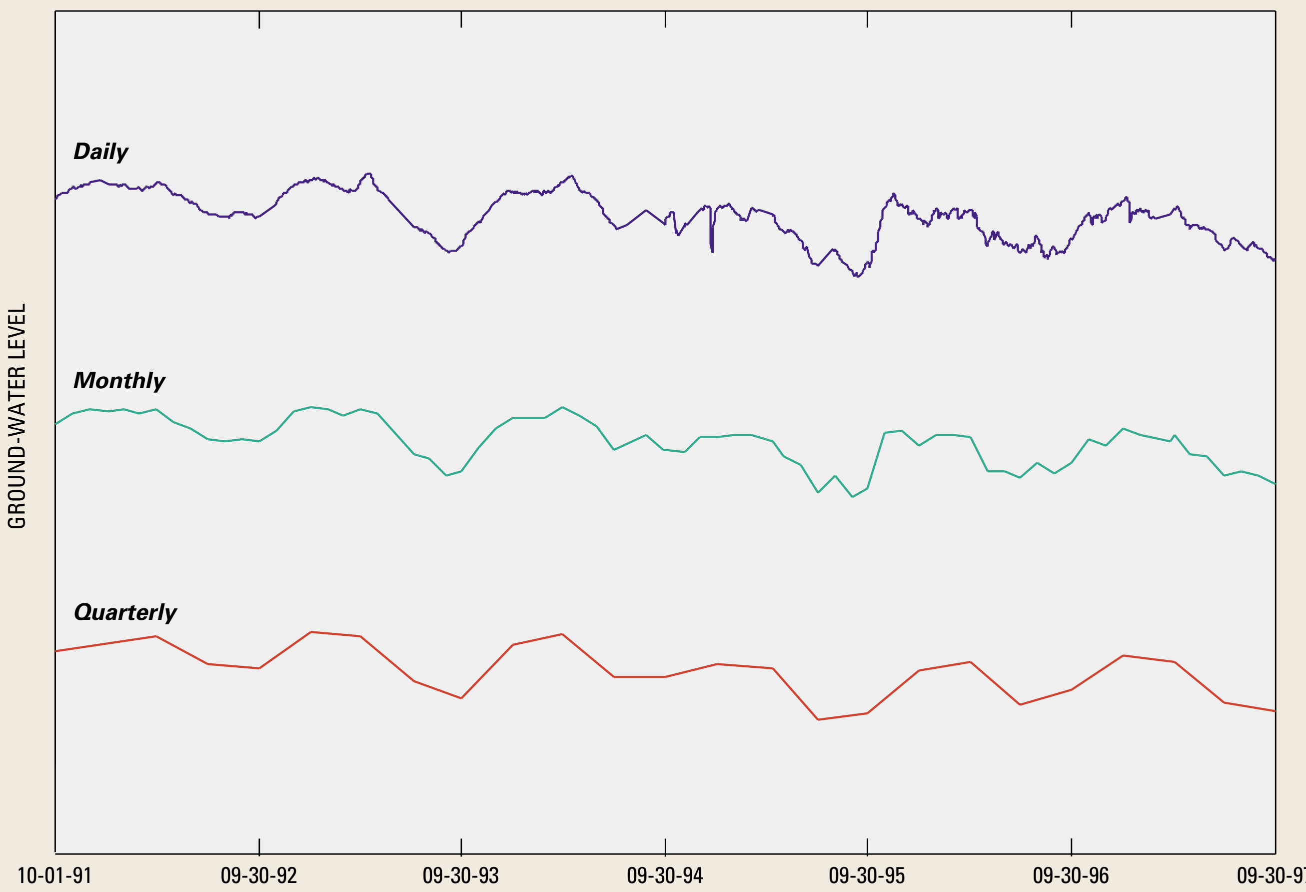


Figure B–2. *Water-level hydrographs for well PDW 23 in western Massachusetts, based on daily, monthly, and quarterly measurements, plotted to same scale but vertically offset.*

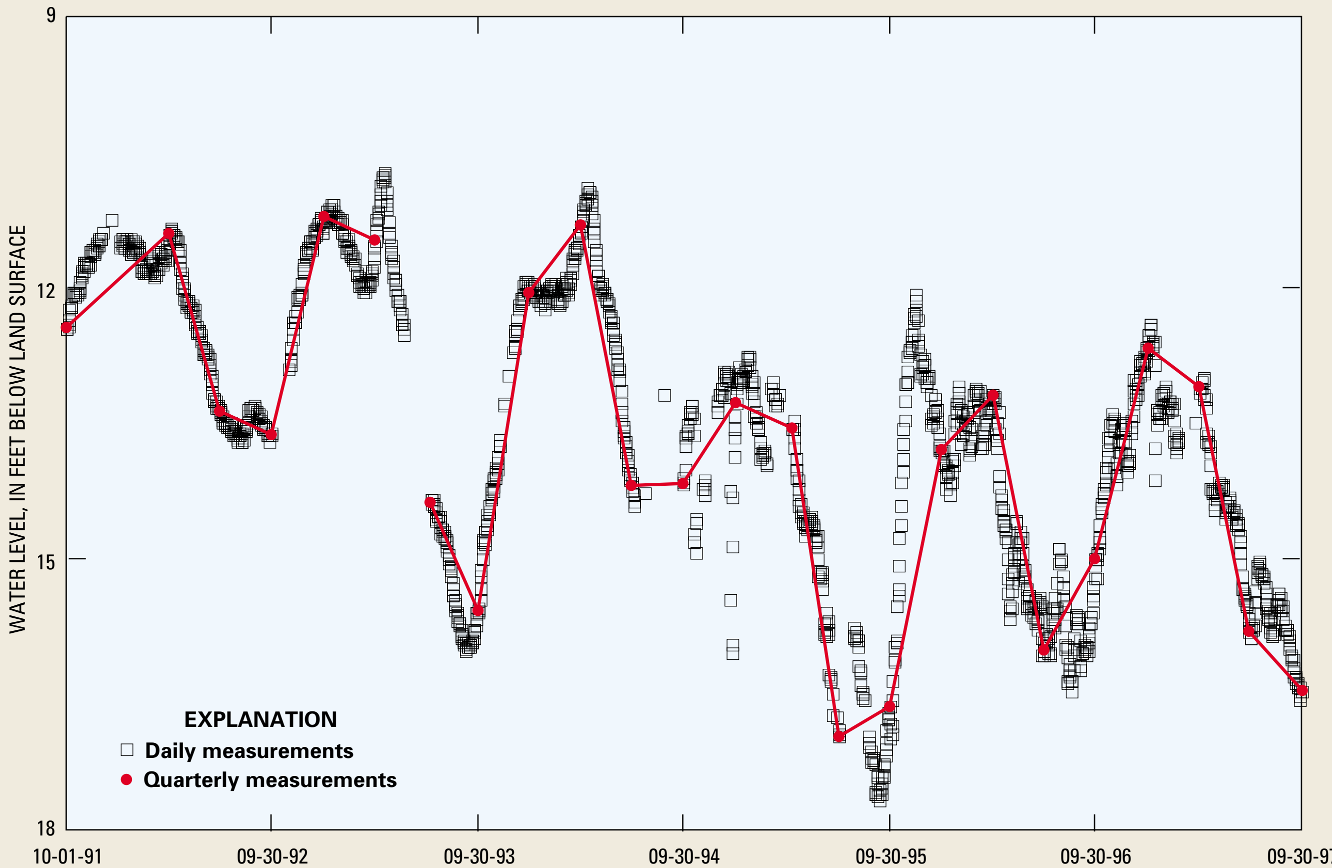


Figure B–3. *Overlaid daily and quarterly hydrographs for well PDW 23 in western Massachusetts.*

USES AND IMPORTANCE OF LONG-TERM WATER-LEVEL DATA

Water-level data are collected over various lengths of time, dependent on their intended use(s). Short-term water-level data are collected over periods of days, weeks, or months during many types of ground-water investigations (Table 1). For example, tests done to determine the hydraulic properties of wells or aquifers typically involve the collection of short-term data. Water-level measurements needed to map the altitude of the water table or potentiometric surface of an aquifer are generally collected within the shortest possible period of time so that hydraulic heads in the aquifer are measured under the same hydrologic conditions. Usually, water-level data intended for this use are collected over a period of days or weeks, depending on the logistics of making measurements at different observation-well locations.

Table 1. *Typical length of water-level-data collection as a function of the intended use of the data*

Intended use of water-level data	Typical length of data-collection effort or hydrologic record required			
	Days/weeks	Months	Years	Decades
To determine the hydraulic properties of aquifers (aquifer tests)	✓	(✓)		
Mapping the altitude of the water table or potentiometric surface	✓	(✓)		
Monitoring short-term changes in ground-water recharge and storage	✓	✓	(✓)	
Monitoring long-term changes in ground-water recharge and storage			✓	✓
Monitoring the effects of climatic variability			✓	✓
Monitoring regional effects of ground-water development			✓	✓
Statistical analysis of water-level trends			✓	✓
Monitoring changes in ground-water flow directions	(✓)	✓	✓	✓
Monitoring ground-water and surface-water interaction	✓	✓	✓	✓
Numerical (computer) modeling of ground-water flow or contaminant transport	(✓)	✓	✓	✓

EXPLANATION

✓ **Most applicable for intended use**

(✓) **Sometimes applicable for intended use**

In this report, the systematic collection of long-term water-level data is emphasized. Long-term data are fundamental to the resolution of many of the most complex problems dealing with ground-water availability and sustainability (Alley and others, 1999). As stated previously, significant periods of time—years to decades—typically are required to collect water-level data needed to assess the effects of climate variability, to monitor the effects of regional aquifer development, or to obtain data sufficient for analysis of water-level trends (Table 1).

Many of the applications of long-term water-level data involve the use of analytical and numerical (computer) ground-water models. Water-level measurements serve as primary data required for calibration and testing of ground-water models, and it is often not until development of these models that the limitations of existing water-level data are fully recognized. Furthermore, enhanced understanding of the ground-water-flow system and data limitations identified by calibrating ground-water models provide insights into the most critical needs for collection of future water-level data. Unfortunately, this second step of using ground-water models to help improve future water-level monitoring is rarely taken.

The uses and importance of long-term water-level data are more fully realized by examining actual case studies. Several are presented here to demonstrate the applicability of water-level data to a wide range of water-resource issues. These include the effects of ground-water withdrawals and other hydrologic stresses on ground-water availability, land subsidence, changes in ground-water quality, and surface-water and ground-water interaction.

Enhanced understanding of the ground-water-flow system and data limitations identified by calibrating ground-water models provide insights into the most critical needs for collection of future water-level data. Unfortunately, this second step of using ground-water models to help improve future water-level monitoring is rarely taken.

Ground-Water Development in the High Plains and Gulf Coastal Plain

In areas where aquifers are undergoing development, a long-term record of water-level measurements may encompass the transitional period between the natural and the developed state of the aquifer. Such records are invaluable in understanding and addressing problems that have developed in response to local and regional patterns of withdrawal, land use, and other human activities. This is demonstrated by the history of ground-water development of the High Plains aquifer and the Gulf Coastal Plain aquifer system (Figure 2).

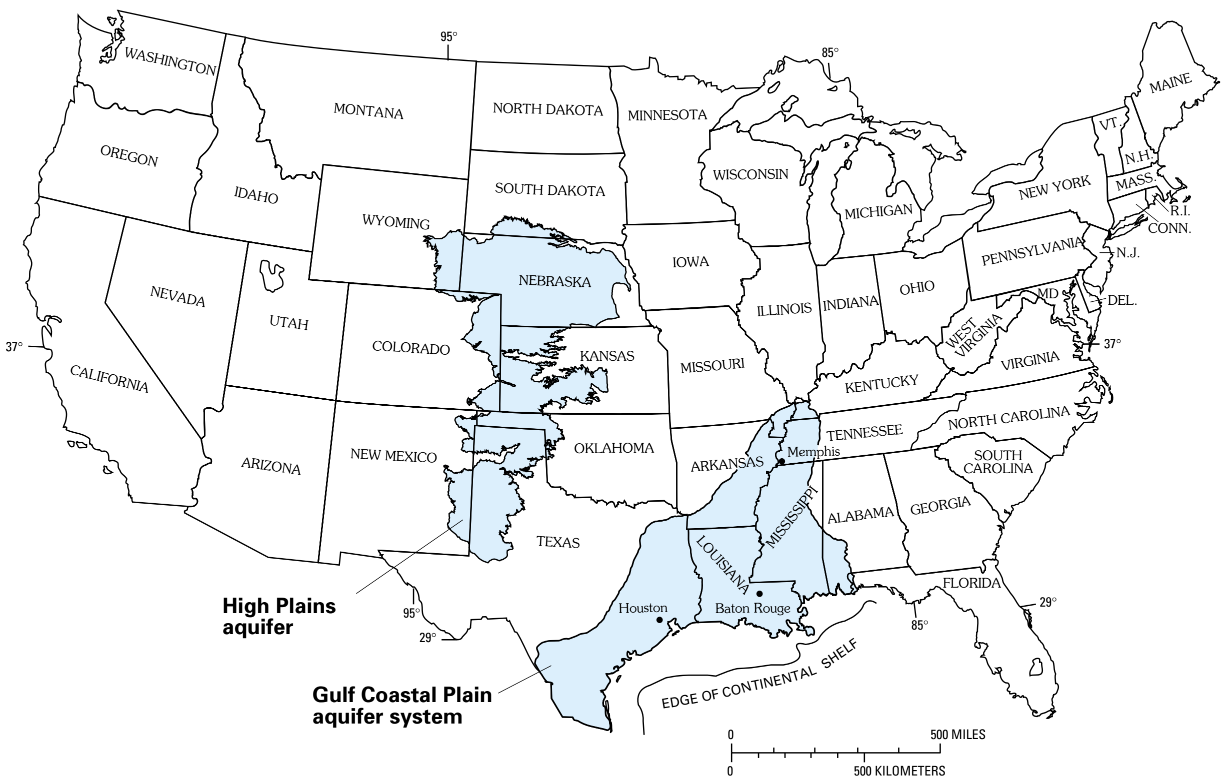


Figure 2. *Location of the High Plains aquifer and the Gulf Coastal Plain aquifer system.*

THE HIGH PLAINS AQUIFER

The High Plains is a 174,000-square-mile area of flat to gently rolling terrain that includes parts of eight States from South Dakota to Texas. The area is characterized by moderate precipitation but in general has a low natural-recharge rate to the ground-water system. Unconsolidated alluvial deposits that form a water-table aquifer called the High Plains aquifer underlie the region. During the late 1800's, settlers and speculators moved to the plains, and farming became the major land-use activity in the area. Since that time, irrigation water pumped from the aquifer has made the High Plains one of the Nation's most important agricultural areas.

Changes in ground-water levels in the High Plains aquifer are tracked annually through the cooperative effort of the USGS and State and local agencies in the High Plains region. Typically, water-level measurements are collected from about 7,000 wells distributed throughout the aquifer. Water-level measurements are made in the spring prior to the start of the irrigation season to provide consistency across the region. Information gathered in this multi-State cooperative effort reveals how changes in water stored in the aquifer vary from place to place depending on soil type, irrigation practices, recharge from precipitation, and the areal extent and magnitude of water withdrawals.

Over the years, the intense use of ground water for irrigation in the High Plains has caused major water-level declines (Figure 3) and decreased the saturated thickness of the aquifer significantly in some areas. For example, in parts of Kansas, New Mexico, Oklahoma, and Texas, ground-water levels have declined more than 100 feet. Decreases in saturated thickness of the aquifer exceeding 50 percent of the predevelopment saturated thickness have occurred in some areas. In other parts of the aquifer, such as along the Platte River in Nebraska, the recharge provided by the infiltration of excess irrigation water has caused ground-water levels to rise. The multi-State ground-water-level monitoring program has allowed all of these changes to be tracked over time for the entire High Plains region and has provided data critical to evaluating different options for ground-water management. This level of coordinated ground-water-level monitoring is unique among major multi-State regional aquifers.

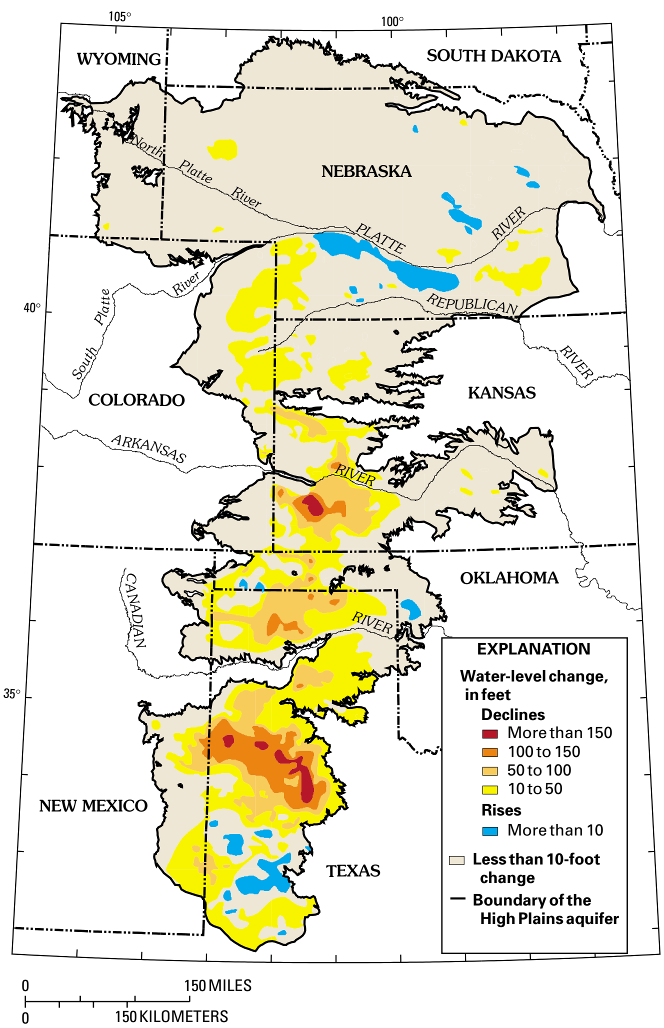


Figure 3. *Changes in ground-water levels in the High Plains aquifer from before ground-water development to 1997. (V.L. McGuire, U.S. Geological Survey, written commun., 1998.)*

THE GULF COASTAL PLAIN AQUIFER SYSTEM

The Gulf Coastal Plain aquifer system consists of a large and complex system of aquifers and confining units that underlie about 290,000 square miles extending from Texas to westernmost Florida, including offshore areas to the edge of the Continental Shelf. The Gulf Coastal Plain aquifer system represents a composite example of many of the issues for which long-term water-level data are collected and used. Water withdrawals from the aquifer system have caused lowering of hydraulic heads at and near pumping centers; reduced discharges to streams, lakes, and wetlands; induced movement of saltwater into parts of aquifers that previously contained freshwater; and caused land subsidence in some areas as a result of the compaction of interbedded clays within aquifers.

The Gulf Coastal Plain aquifer system represents a good example of the need to measure water levels in wells completed at different depths and in the context of a three-dimensional ground-water-flow system. For example, in order to simulate ground-water flow for the entire aquifer system, Williamson and Grubb (in press) subdivided the aquifer system into 17 regional aquifers and confining units, most of which are shown in the vertical section in Figure 4. Even this level of subdivision represents a very coarse subdivision of the aquifer system given its complexity and variability. Numerous more refined subdivisions of parts of the aquifer system for smaller scale studies have been made during the long history of ground-water studies in the region.

The value of long-term water-level data for the Gulf Coastal Plain aquifer system is illustrated by briefly examining the history of ground-water development near three large cities (Memphis, Tennessee; Houston, Texas; and Baton Rouge, Louisiana) and by examining some fundamental changes in the regional ground-water-flow system.

The Gulf Coastal Plain aquifer system represents a good example of the need to measure water levels in wells completed at different depths and in the context of a three-dimensional ground-water-flow system.

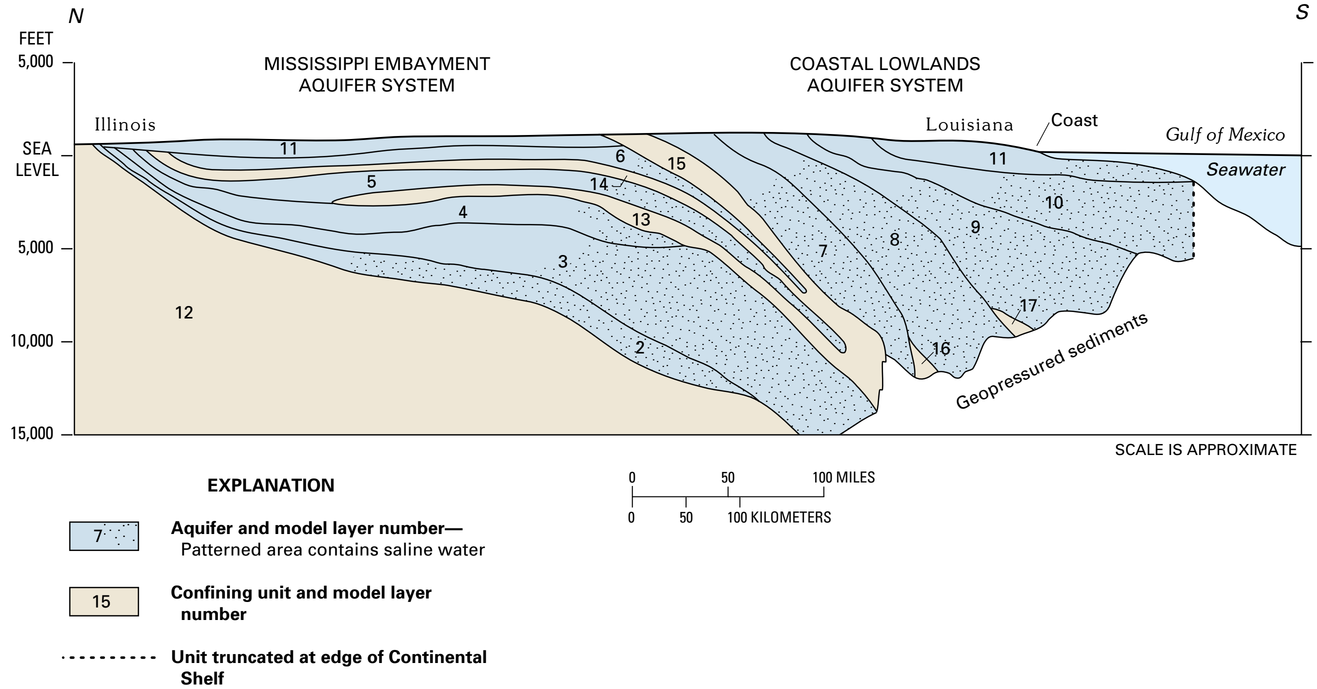


Figure 4. *Aquifers and confining units and designation of layers in a regional model of the Gulf Coastal Plain aquifer system. (Modified from Williamson and Grubb, in press.)*

Memphis, Tennessee

The Memphis aquifer (Memphis Sand) is the principal source of water for municipal, commercial, and industrial uses in the Memphis area of Tennessee. Pumpage increased from completion of the first well in 1886 until about 1974, when rates stabilized. Prior to development, the potentiometric surface of the Memphis aquifer is presumed to have been a smooth surface with a gentle slope to the west-northwest (Figure 5). Water-level data indicate that over the years a regional cone of depression has developed in the potentiometric surface of the aquifer, centered near downtown Memphis (Figure 6). As a result of ground-water withdrawals, the general direction of ground-water flow is toward the center of the regional cone of depression. Smaller cones of depression are superimposed upon this regional cone in areas heavily pumped by municipal and industrial wells.

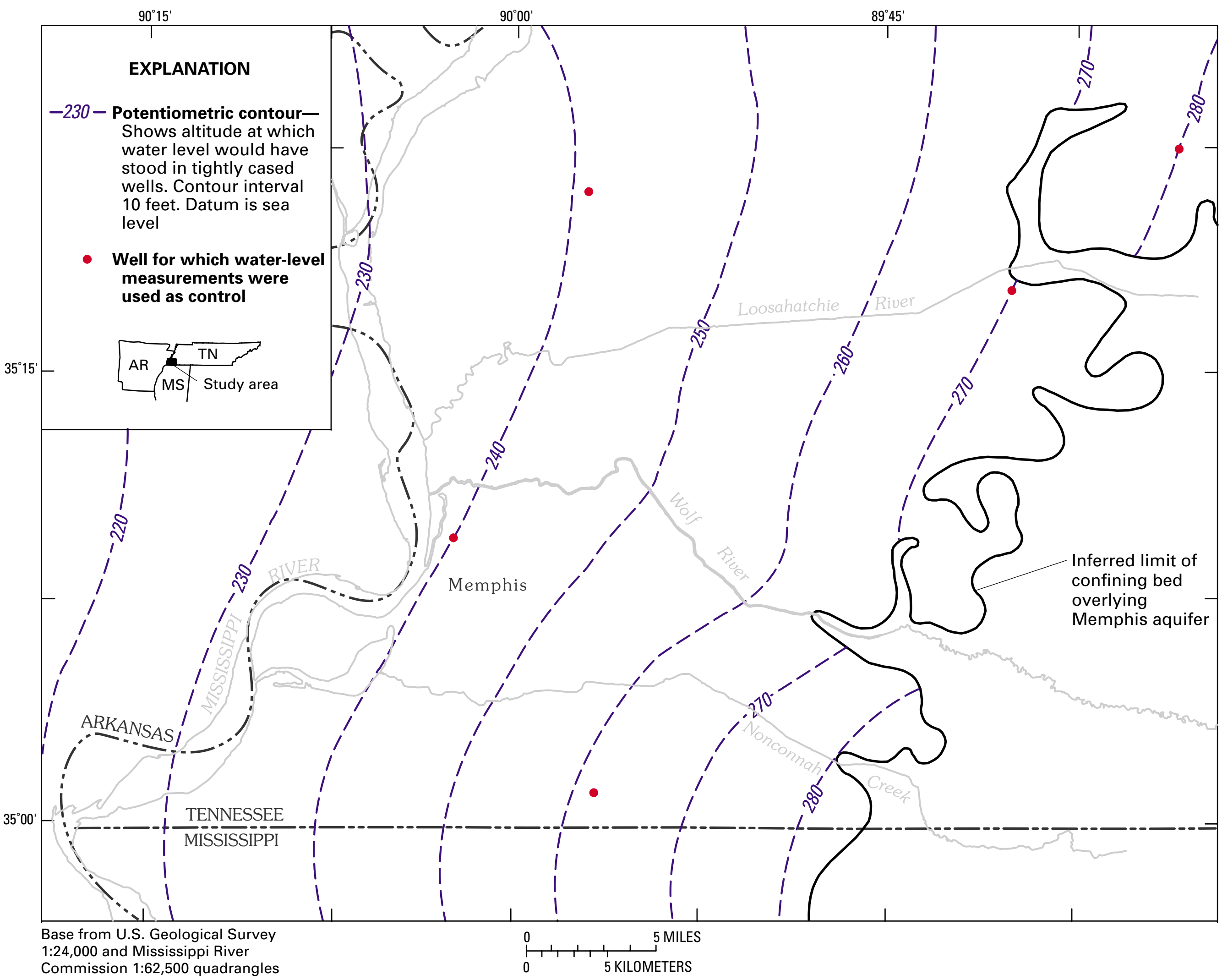


Figure 5. *Inferred potentiometric surface of the Memphis aquifer prior to ground-water development. The observation wells shown were selected for their early records away from initial pumping centers. (Modified from Criner and Parks, 1976.)*

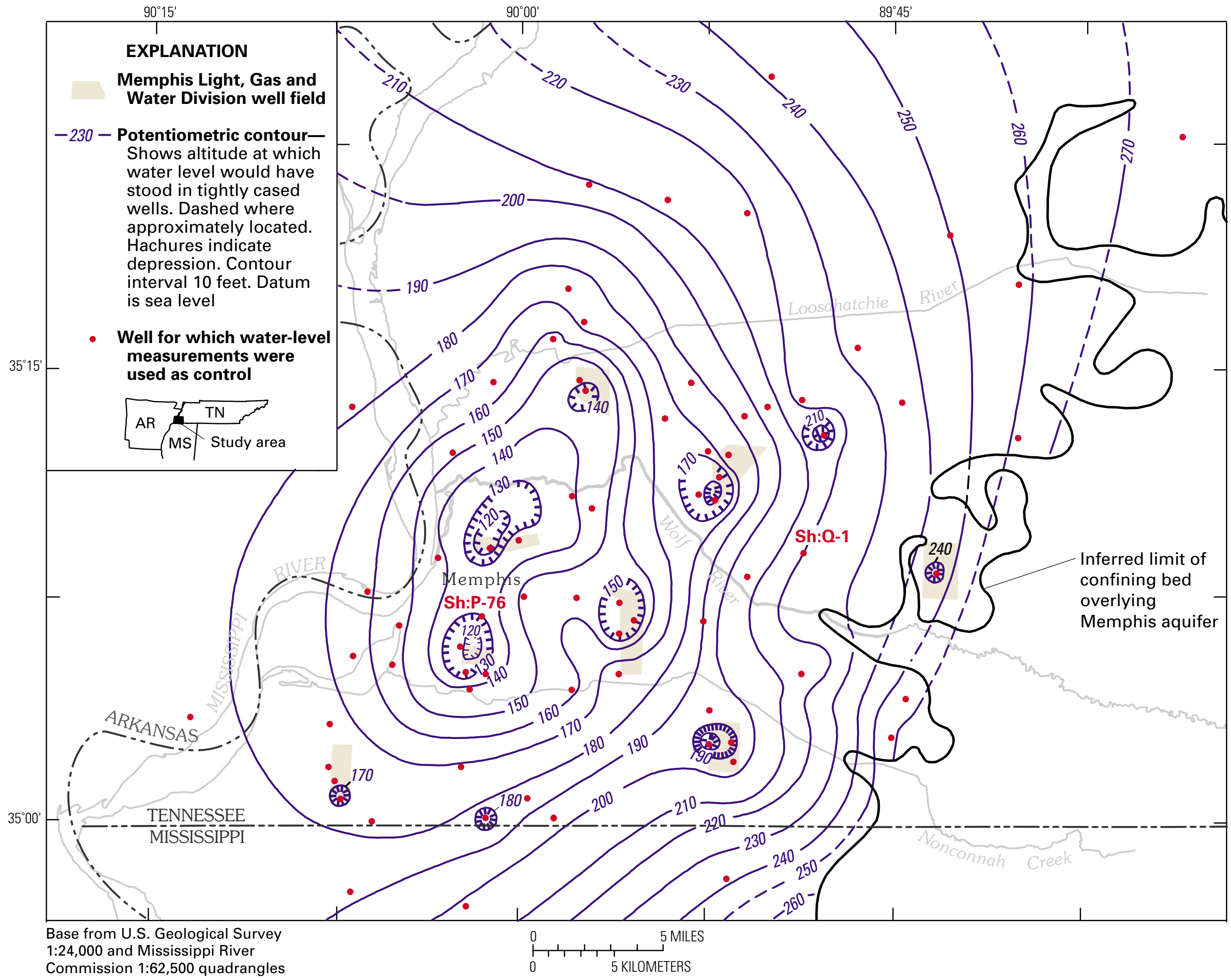


Figure 6. *Potentiometric surface of the Memphis aquifer in 1995 showing cones of depression and location of observation wells Sh:P–76 and Sh:Q–1. (Modified from Kingsbury, 1996.)*

Water-level hydrographs for two selected wells through 1995 show the effects of long-term pumpage (Figure 7). One well (Figure 7*A*) is near the center of the regional cone of depression and has one of the longest nearly continuous records of water-level measurements in the United States. Between 1928 and 1975, the water level in this well declined about 70 feet and then stabilized as the pumping rates stabilized. A second well (Figure 7*B*) is east of the center of the regional cone of depression. Water levels in this well have declined steadily since records began in 1940, suggesting that the cone of depression continued to expand eastward for at least 20 years past the overall stabilization in pumping rates. Note that the seasonal fluctuation in water levels recorded in these observation wells is primarily a result of seasonal differences in water demand and pumping (as opposed to changes in aquifer recharge) and is much greater near the center of the cone of depression (Figure 7*A*) than in outlying areas (Figure 7*B*).

Long-term monitoring of water levels in the Memphis aquifer continues to provide essential information for management of this critical aquifer. As noted, monitoring is important not only near the major pumping centers but also in outlying areas.

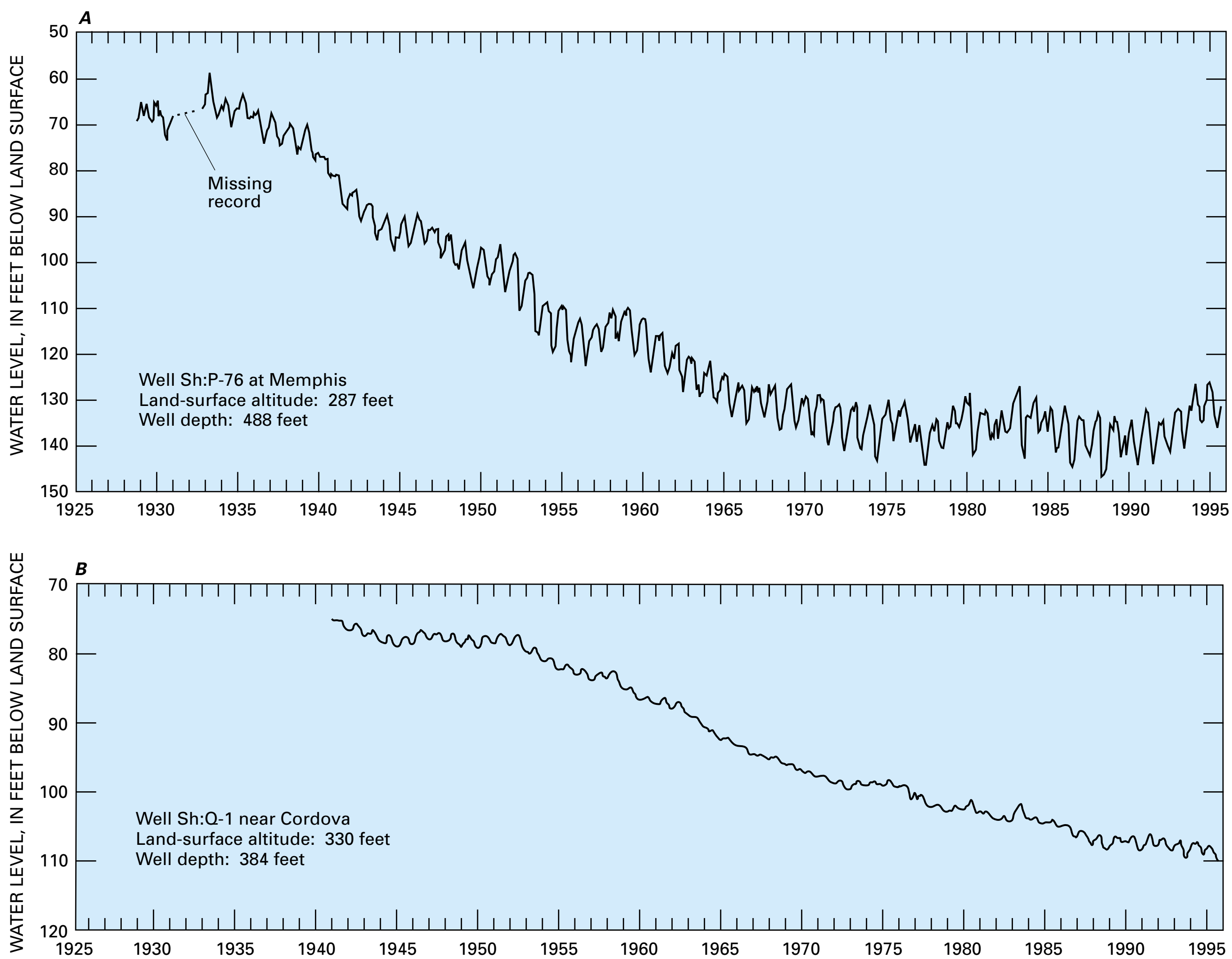


Figure 7. *Declining water-level trends in two long-term observation wells in the Memphis area. Locations of wells are shown in Figure 6.*

Houston, Texas

Trends in ground-water withdrawals in the Houston, Texas, area are related to population and industrial growth, replacement of ground water by surface water as a source of supply in some parts of the area, and a shift from withdrawal for irrigation to public supply as a result of urban expansion. Ground-water withdrawals more than doubled every 20 years in the area during 1900–60 (Wood and Gabrysch, 1965). Ground water was the sole source of public-water supply for Houston until 1954, when surface water was introduced from the San Jacinto River. As a result of the increased use of surface water and reduced ground-water withdrawals, ground-water levels stabilized in the industrial district of Houston in the mid-1970's and began to recover in 1977 (Figure 8*A*). However, ground-water withdrawals continued to increase to the north and west of Houston because of urban development. As a result, water levels in these areas continued to decline (Figure 8*B*).

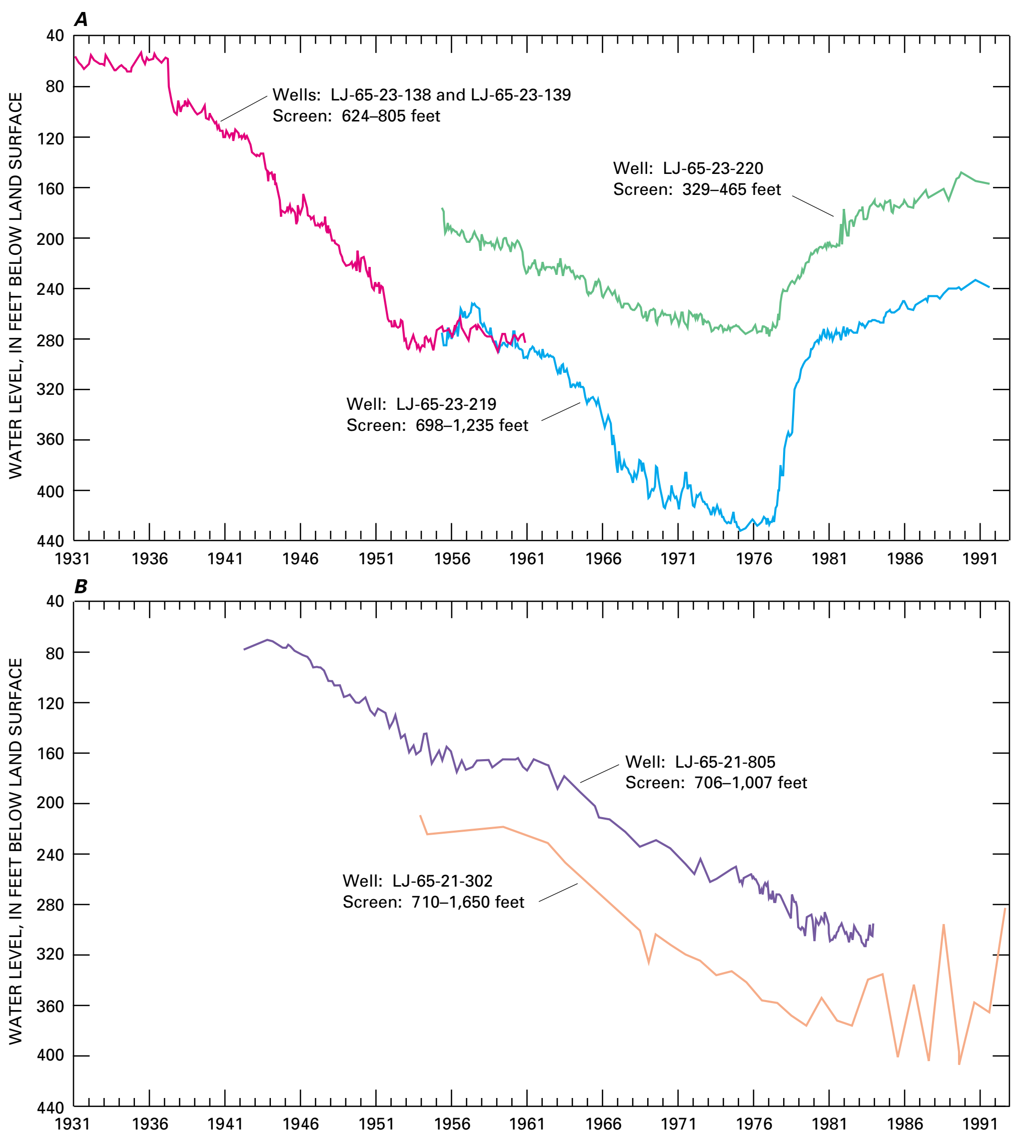


***Figure 8.** Water-level trends in selected wells in the Houston area showing (A) stabilization and recovery of water levels in the industrial district and (B) declining water levels north and west of Houston. (Modified from Grubb, 1998.)*

Extensive land subsidence has occurred in the greater Houston area as a consequence of the decline in ground-water levels. Long-term water-level measurements in the Houston area are invaluable indicators of the potential for subsidence. So long as hydraulic heads (indicated by water-level measurements) remain above previous minimum heads, the deformation of the aquifer is reversible. When hydraulic heads decline below previous lows, the structure of interbedded clay and silt layers may undergo significant rearrangement, resulting in irreversible aquifer-system compaction and land subsidence. In this low-lying coastal environment, as much as 10 feet of subsidence has increased the vulnerability of much of the area to flooding, caused permanent inundation of some areas, and activated faults causing damage to buildings, highways, and other structures. Subsidence to the east of Houston has been arrested as imported surface-water supplies have been substituted for ground-water pumpage, but the fast-growing areas to the north and west, which still depend largely on ground water, are subsiding in response to declining ground-water levels (Figure 9).

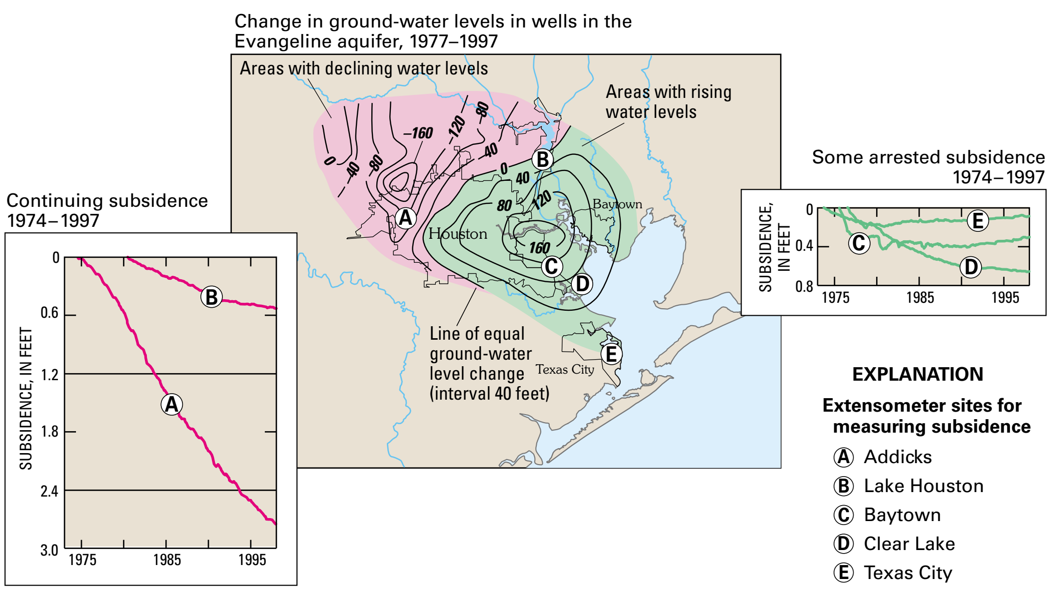


Figure 9. *Relation between water-level trends and land subsidence in the Houston area. (Modified from Kasmarek and others, 1997; Coplin and Galloway, 1999.)*

Baton Rouge, Louisiana

Trends in ground-water levels in the Baton Rouge area reflect growth in population and industry. Withdrawals increased more than tenfold from the 1930's to 1970 and have since leveled off to some extent. In 1995, about 140 million gallons per day (Mgal/d) of ground water were pumped in the Baton Rouge area.

Sand layers at depths between about 400 and 2,800 feet are major aquifers in the Baton Rouge area. Locally, the aquifers are referred to by the general depth of the top of the aquifer in the area, for example, the "2,000-foot" sand. The effects of overall increases of withdrawals on ground-water levels, as well as of a shift in pumpage from shallower to deeper sands, are shown for wells in the industrial area of Baton Rouge in Figure 10.

The hydrograph in Figure 10 for the shallower ground water is a composite of water levels in three wells monitored over the years in the "400-foot" and "600-foot" sands. During the early 1940's to mid-1950's, the "400-foot" and "600-foot" sands were the most heavily pumped aquifers in the Baton Rouge area, and pumpage reached a peak of 35 Mgal/d about 1942 (Kuniansky, 1989). The hydrograph indicates that, after reaching record water-level lows in the mid-1950's, water levels (heads) in these aquifers rose steadily from the late 1950's to 1990. During that period, deeper aquifers were developed, pumpage from the "400–600 foot" sands declined (to about 12 Mgal/d in 1990), and pumping centers became distributed over wide areas. Water levels again declined in the 1990's as withdrawals from the

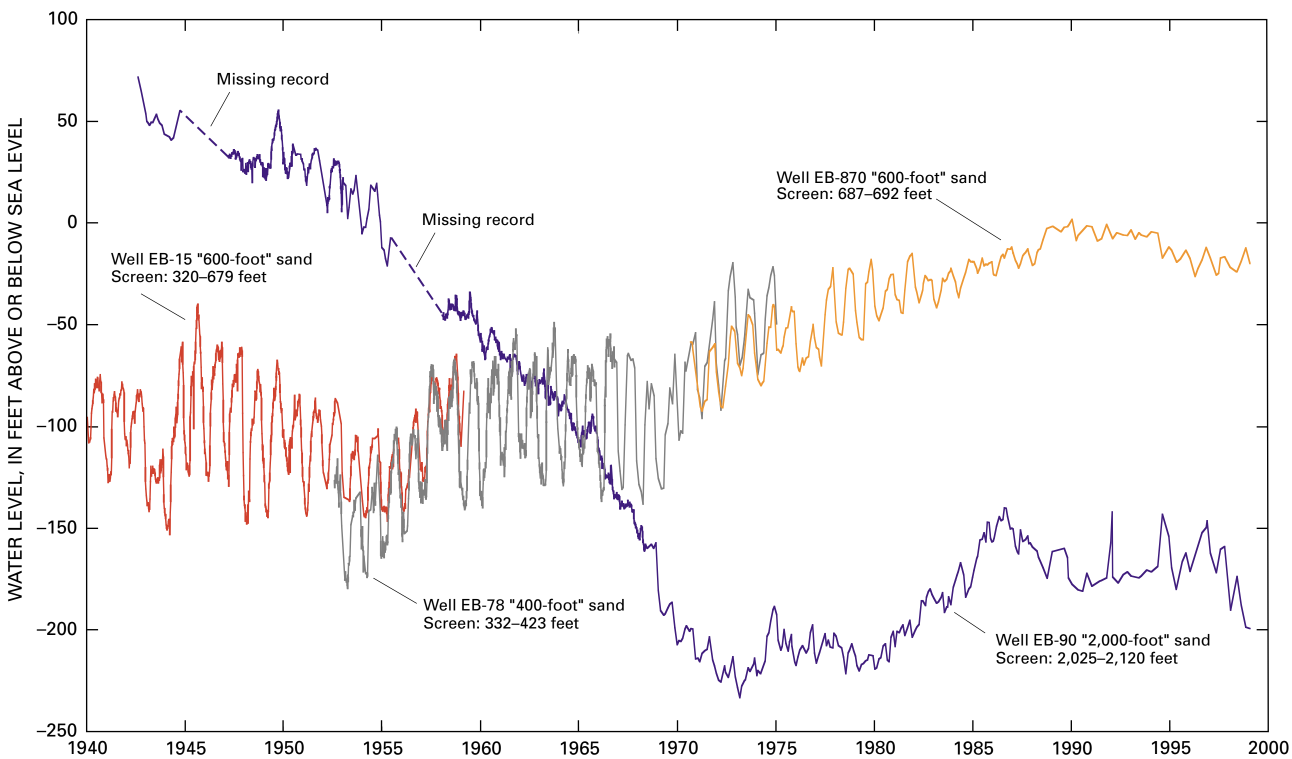


Figure 10. *Water-level trends in the Baton Rouge area, Louisiana, 1940–99. (Modified from Grubb, 1998.)*

shallow aquifers increased (pumpage was about 20 Mgal/d in 1995). Water-level declines in the well shown (well EB–870) were limited, however, because the pumping was less concentrated near that well location.

Prior to about 1920, pumpage from the “2,000-foot” sand was small (less than 0.5 Mgal/d) and had little effect on heads in the aquifer (Torak and Whiteman, 1982). Pumping increased sharply to more than 10 Mgal/d after 1940 and has become redistributed in the Baton Rouge area as the locations of the major pumping centers have changed. A long-term hydrograph for well EB–90 (Figure 10) completed in the “2,000-foot” sand shows that, as water use from this deeper aquifer increased, heads in the aquifer continued to decline from 1940 to the 1970’s. After reaching a maximum rate of 44 Mgal/d in 1976, pumpage from the “2,000-foot” sand began to decline to about 32 Mgal/d by 1985, resulting in a slight recovery in heads. From 1985 to 1995, pumpage increased, and water levels in well EB–90 declined again in the 1990’s, albeit at a slower rate than before.

The large water-level (head) declines in the Baton Rouge area caused saltwater encroachment from the south in several of the sand aquifers (Figure 11). Long-term water-level monitoring is essential to continued understanding and forecasting movement of saltwater in the Baton Rouge area (as well as in other areas of the country, as discussed in later examples).

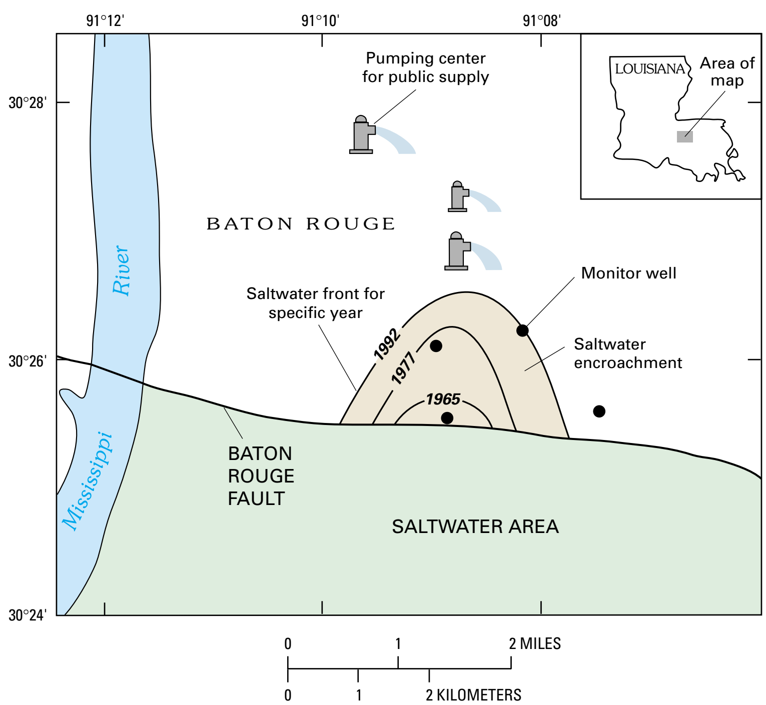


Figure 11. *Saltwater encroachment in the “1,500-foot” sand aquifer moving toward pumping centers in the Baton Rouge area, Louisiana. A low-hydraulic-conductivity fault zone retards saltwater movement in the area. Nevertheless, saltwater has leaked through the fault zone in some areas in response to pumping. (Modified from Tomaszewski, 1996.)*

The preceding examples for Memphis, Houston, and Baton Rouge illustrate how the history of ground-water development is reflected in long-term water-level records and how these records are essential to monitoring the effects of development and providing data needed for quantitative assessments of future management and development options. For all three metropolitan areas, individual long-term monitoring wells have provided valuable information about water-level trends at specific locations, but multiple wells are needed to track conditions in different aquifers and changes in cones of depression as pumping centers evolve. Furthermore, the examples show how information about ground-water withdrawals can be critical to the interpretation of water-level data.

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Changes in Regional Ground-Water Flow

As illustrated in the previous examples, more than 100 years of ground-water withdrawals have greatly altered ground-water conditions in the Gulf Coastal Plain aquifer system. As a result, there have been large-scale, regional changes in directions of horizontal flow, changes in vertical direction of flow between aquifers, increases in regional recharge to aquifers, and decreases in regional discharge from aquifers.

Ground-water withdrawals from deeper aquifers in the Gulf Coastal Plain aquifer system have caused a reversal of vertical-flow directions from upward to downward throughout thousands of square miles. This was evident locally for the Baton Rouge area by the crossing of the water-level hydrographs in Figure 10. That is, heads in the upper sands were lower than heads in the underlying "2,000-foot" sand prior to the early 1960's, resulting in upward flow. As withdrawals shifted to the deeper aquifers, heads in the "2,000-foot" sand declined below those in the shallower sands, reversing the vertical direction of flow from upward to downward.

The relative changes in heads with depth and the magnitude and direction of vertical flow between aquifers are significant factors affecting future pumping lifts, base flow to streams, saltwater intrusion, and land subsidence. Such changes in an aquifer system typically are evaluated using computer model simulations. For example, the simulated widespread reversal of vertical-flow directions from predevelopment to 1987 for the upper part of the Gulf Coastal Plain aquifer system is shown in Figure 12. Model calibration and estimation of model accuracy required water levels measured at different depths before and after development and relied heavily on a compilation of water-level data collected by many prior studies throughout the region (Williamson and Grubb, in press).

Measuring water level in observation well in Colorado. Photograph by Heather S. Eppler, U.S. Geological Survey.

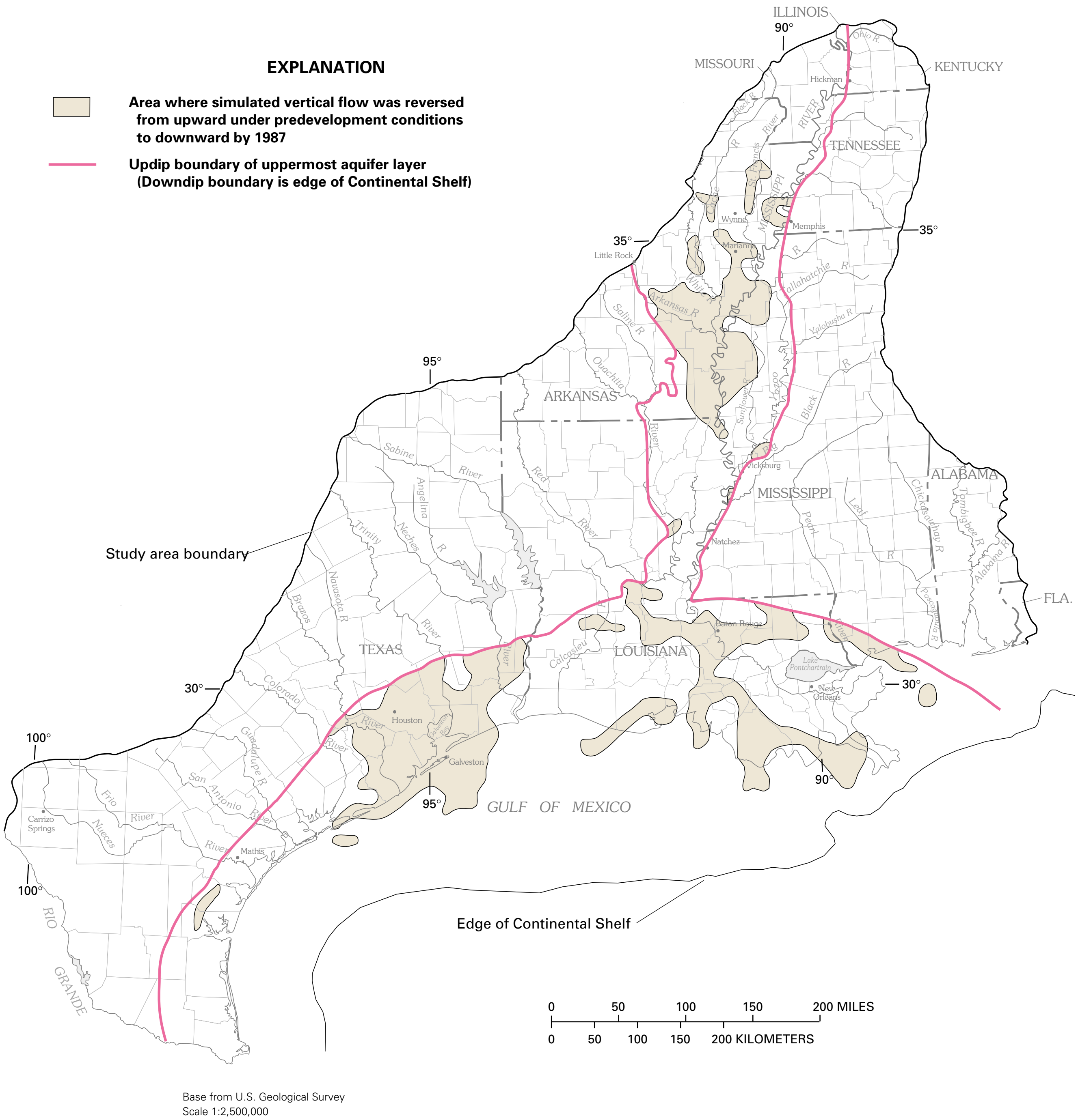

Figure 12. *Areas where vertical flow between uppermost aquifer layers reversed from upward under predevelopment conditions to downward by 1987, as simulated in regional model of Gulf Coastal Plain aquifer system. (Modified from Grubb, 1998.)*

Drought Monitoring in Pennsylvania

More than 40 million people in the United States supply their own drinking water from domestic wells. Many of these wells are shallow and vulnerable to extended droughts. Yet, relatively few observation wells are measured regularly to provide an indication of the response of ground water to climatic conditions. Wells for such purposes are needed in relatively undeveloped recharge areas where water-level fluctuations primarily reflect climatic variation rather than ground-water withdrawals or human-induced recharge. The timeliness of water-level data also is a critical factor. Most wells are measured monthly or less frequently. Even if wells are equipped with a digital water-level recorder, the data must be retrieved and processed before they are available. As a result, available water-level data commonly lag behind current conditions from one to several months.

Continuous collection, processing, and transmittal of water-level data by satellite and other telecommunication methods are increasingly being used to display real-time ground-water conditions on the Internet. The need for this type of information became evident during the summer of 1999, when drought in the Eastern United States resulted in drought declarations or water restrictions in 15 States. Following a relatively dry spring and summer, rainfall from several large storms, including Tropical Storm Dennis and Hurricane Floyd, occurred in many of these States during the months of August and September 1999. After each storm, questions arose about whether water restrictions should be lifted. Each time, information on ground-water conditions was sought to help provide a complete picture of the drought conditions. The information typically was limited and not current. The State of Pennsylvania was an exception.

Continuous collection, processing, and transmittal of water-level data by satellite and other telecommunication methods are increasingly being used to display real-time ground-water conditions on the Internet.

In 1931, in response to concerns about ground-water-level declines caused by the drought of 1930, a statewide well network was established in Pennsylvania to monitor water-level fluctuations. Today, this network consists of about 50 wells (Figure 13) operated by the USGS in cooperation with the Pennsylvania Department of Environmental Protection. The primary purpose of the observation-well network is to monitor ground-water conditions for indications of drought. The Pennsylvania Emergency Management Council uses data from the wells when categorizing counties for a drought declaration. Currently (2001), water levels for about 80 percent of the network wells are transmitted by satellite telemetry and displayed on the USGS Web pages for Pennsylvania.

An observation-well network of 23 wells established in 1973 provides additional spatial resolution for ground-water conditions in Chester County, Pennsylvania (Schreffler, 1997). The Chester County network was established through a cooperative agreement between the Chester County

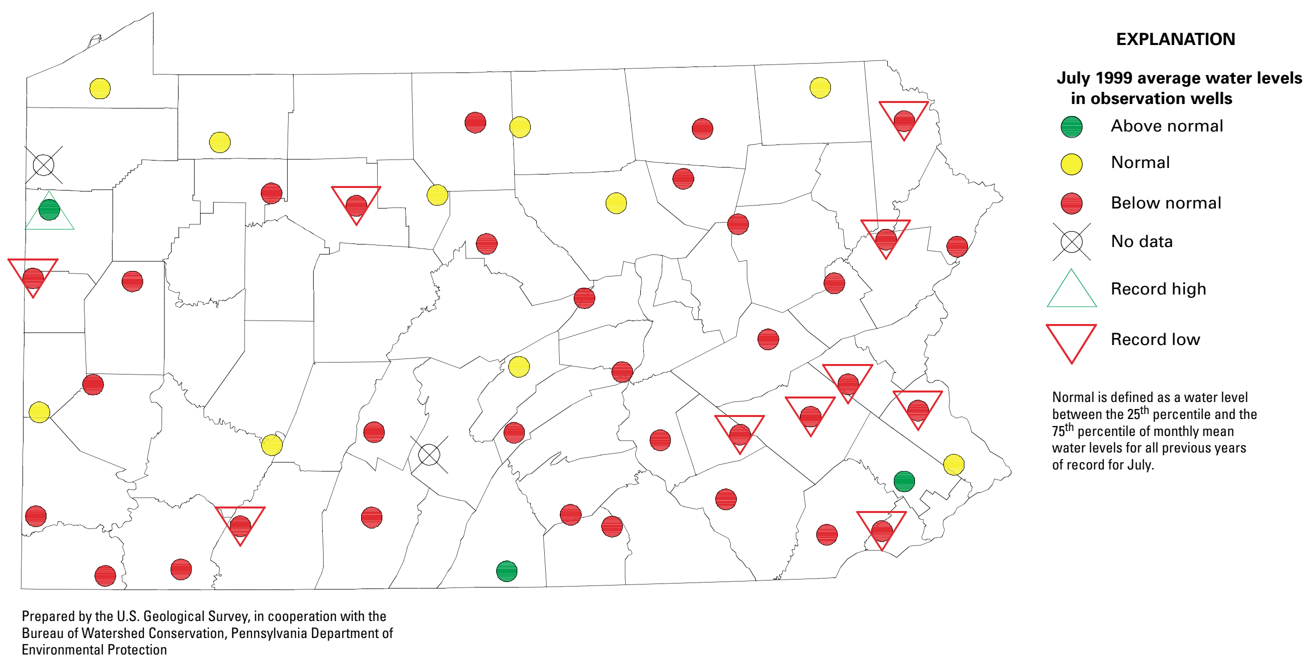

Figure 13. *Location of drought-index wells and ground-water-level conditions in Pennsylvania in July 1999.*

Water Resources Authority and the USGS. The wells are distributed throughout the county in different geographic and geologic settings. A water-level hydrograph for a well that is in both the state-wide network and the Chester County network is shown in Figure 14 for water years 1998 and 1999.

Data from the Pennsylvania network were used by the State to help respond to the 1999 drought. When drought emergency was declared in 55 Pennsylvania Counties in July 1999, one-third of the State's network wells had record-low seasonal levels. The Governor was able to note that "(ground-) water levels we're seeing today—in the middle of summer—are on par with levels we would see in September or October…Groundwater levels typically won't begin to recharge until the leaves are off the trees and we get sustained rains in the fall" (Pennsylvania Department of Environmental Protection, news release, July 20, 1999).

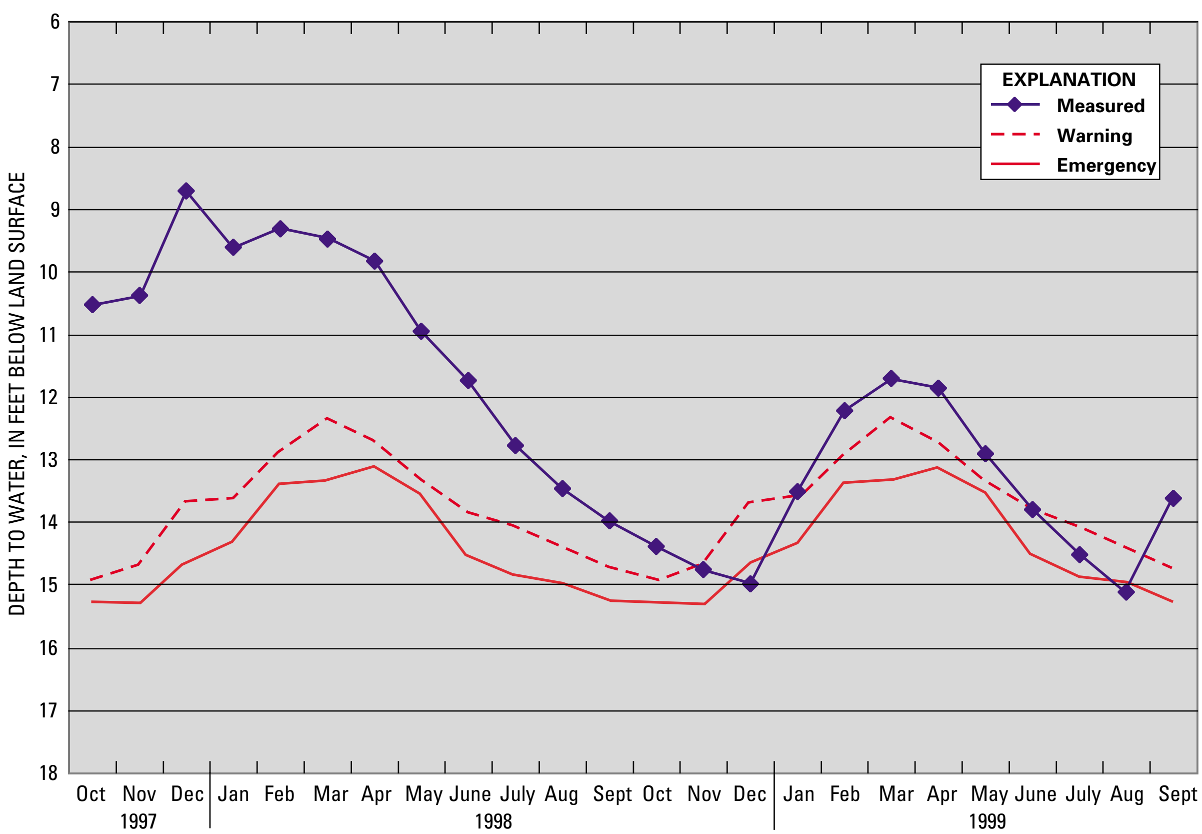

Figure 14. *Hydrograph for drought-index well in Chester County, Pennsylvania, showing water levels from October 1997 to September 1999, compared to established monthly drought-warning and drought-emergency water levels. (D.W. Risser, U.S. Geological Survey, written commun., 2000.)*

Estimation of High Ground-Water Levels in Massachusetts and Rhode Island

Statistical evaluations of water-level data collected for one or more decades can be used to estimate future high, low, and medium or "normal" water levels. The accuracy of these water-level estimates improves as the length of record increases.

In populous areas of coastal Massachusetts and Rhode Island, water levels normally change by several feet annually but can change by as much as 20–30 feet (Socolow and others, 1994). This potentially wide range of ground-water fluctuation can result in adverse effects to home and building construction. Estimates of the maximum (highest) probable ground-water levels are needed to assess the likely chances for basement flooding, damage to building foundations due to increased hydrostatic pressure, and the potential failure of septic tanks and leach fields in unsewered areas (Figure 15).

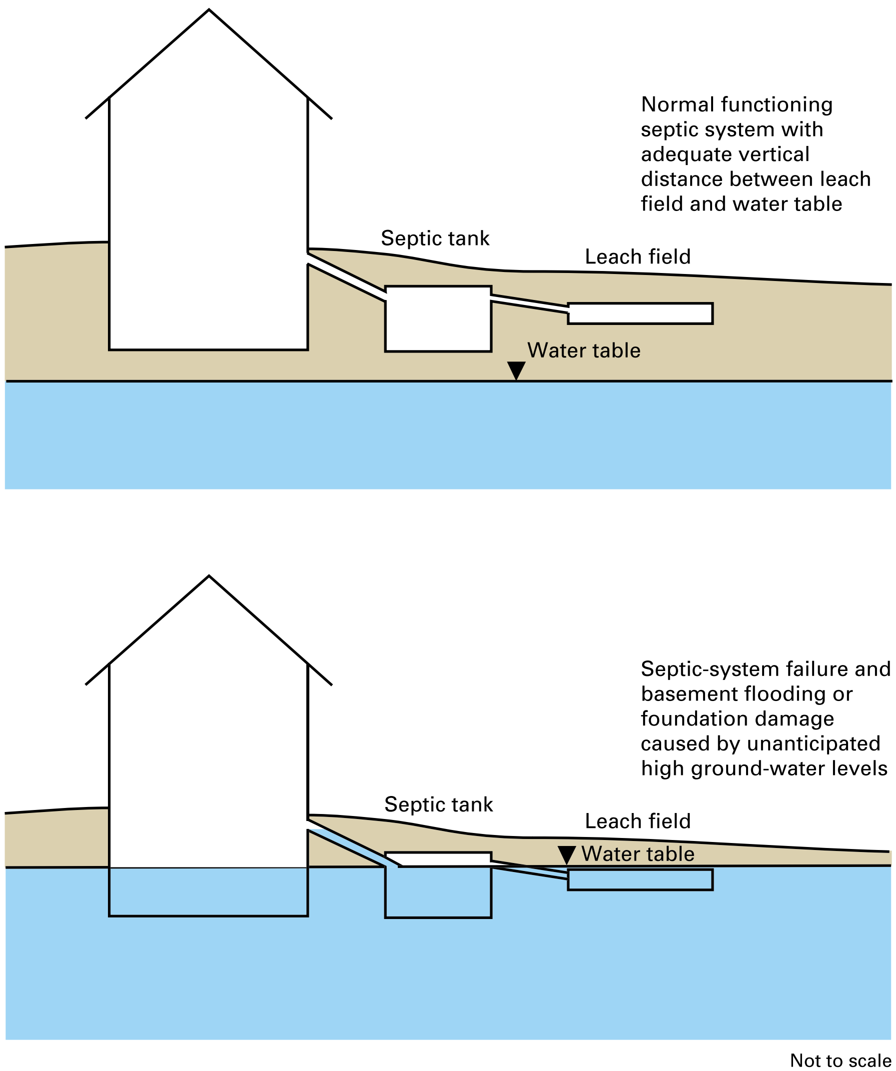

Figure 15. *Sketch showing effects of unanticipated high ground-water-level fluctuations on housing structures. (Modified from Socolow and others, 1994.)*

To address this problem, USGS hydrologists in Massachusetts developed a technique to estimate the potential maximum ground-water level at a site where only a single measurement of water level may be available (Frimpter, 1980; Frimpter and Fisher, 1983). The technique uses a water-level measurement taken at the site of interest in combination with information on the concurrent water level and statistical distribution of water levels in a long-term observation well chosen as an "index" well and information on the range of water-level fluctuations at observation wells in similar geologic and hydrologic settings. The index well should be unaffected by pumping and other human-induced hydraulic stresses, completed in the same geologic material as that underlying the site of interest, and located in a similar topographic setting. Moreover, the index well must have a hydrologic record sufficiently long to provide for a statistically based determination of the range in water-level fluctuations.

In Massachusetts, water-level measurements from nine index wells having 16–28 years of hydrologic record and about 160 wells having shorter periods of record were used to map five zones of different ranges in annual water-level fluctuations in glacial sand, gravel, and till deposits that underlie Cape Cod (Frimpter and Fisher, 1983). Subsequent application of the technique in Rhode Island was limited by the distribution of suitable index wells (Socolow and others, 1994). Approximately 15 wells completed in glacial sand and gravel deposits and having hydrologic records that span the period between 1946 and 1989 were determined to be of suitable length for use as index wells. Because of relatively short (generally less than 5 years) or discontinuous hydrologic records, however, no suitable index wells were identified among the observation wells available in the till deposits of Rhode Island.

Water well instrumented for satellite transmission and real-time reporting on the Internet. Photograph by William L. Cunningham, U.S. Geological Survey.

Ground-Water and Surface-Water Interaction in Oregon

The effect of ground-water development on surface-water resources is increasingly a focus of ground-water studies (Winter and others, 1998). Yet, stream-gaging and water-level monitoring networks are rarely jointly designed with this use of data in mind. The upper Deschutes Basin, an area of rapid population growth in central Oregon, provides an example of the importance of combined ground-water and surface-water data.

Quantitative assessments of the ground-water system and its interaction with surface-water resources of the upper Deschutes Basin have been crucial in supporting resource-management decisions in the basin. Surface-water resources in the area have been closed by the State to additional appropriation for many years. Thus, virtually all new development in the basin must rely on ground water as a source of water supply.

Locations of long-term observation wells and field-located wells for measurements during a recent multiyear study of the basin (Caldwell and Truini, 1997; Gannett and others, 2001) are shown in Figure 16. The temporal distribution of water-level measurements from these wells during and prior to the study is shown as a three-dimensional plot in Figure 17 for the period 1977–98. The sporadic nature of the available water-level data is evident from Figure 17 and, as in many areas, complicates analysis of the data. Only a few wells—primarily those measured as part of a statewide network by the Oregon Department of Water Resources—have periods of record of 10 or more years.

Recharge resulting from leakage from streams and irrigation canals and from on-farm irrigation losses greatly exceeds recharge from precipitation in the dry plains of the eastern and central part of the basin. Examples of combined use of water-level and stream-gaging data to provide information on the streams and canals as a source of recharge to the basin are shown in Figures 18 and 19. Understanding these relations is critical to quantitative modeling of the basin hydrologic system.

Figure 18 shows hydrographs of the stage of the Deschutes River at Benham Falls and water levels in wells 500 and 5,000 feet from the river. This is a reach in which the river loses

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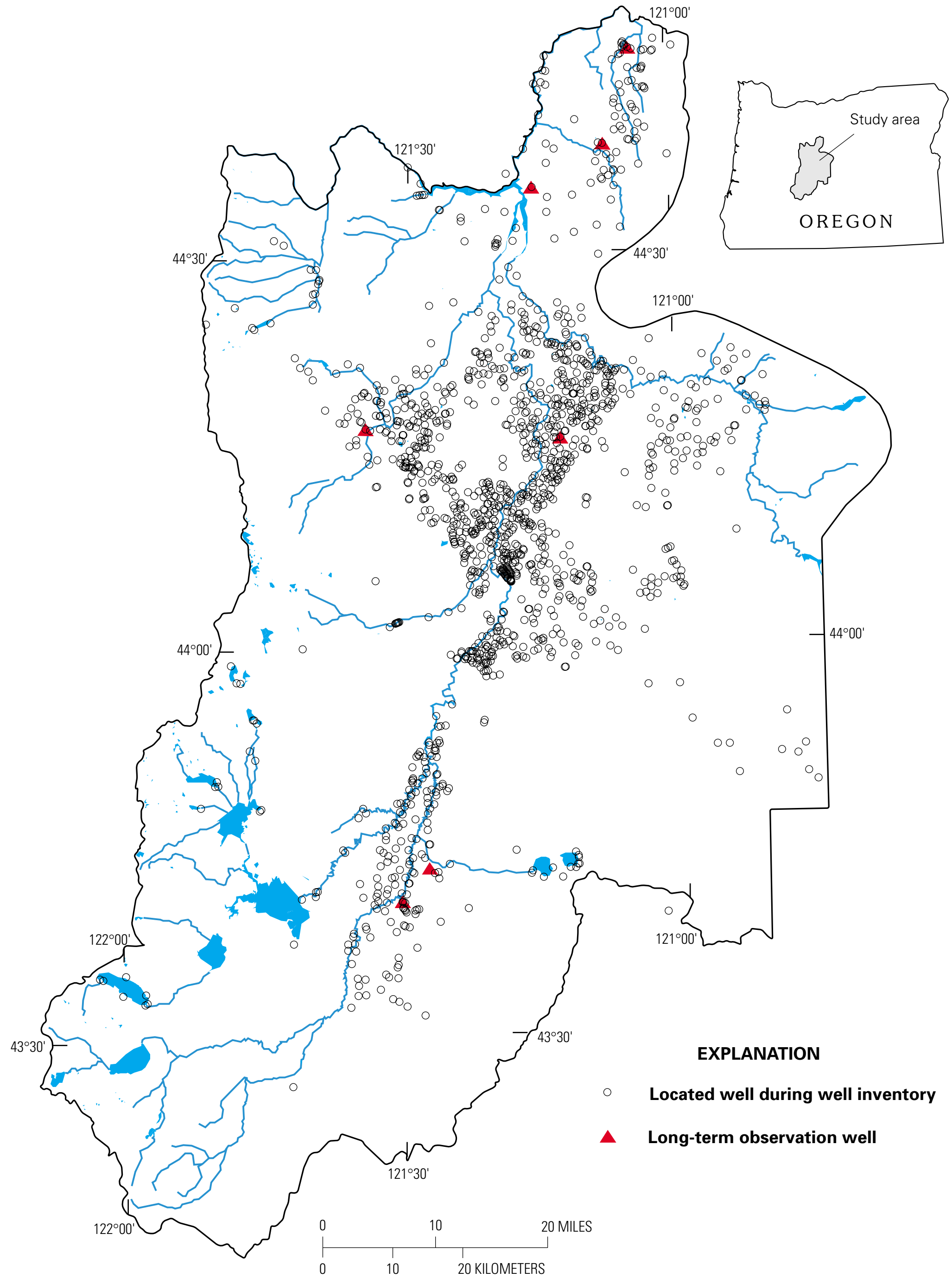


Figure 16. *Location of field-located wells in upper Deschutes Basin study area, Oregon. (Modified from Caldwell and Truini, 1997; Gannett and others, 2001.)*

about 100 cubic feet per second into permeable lava. Stream-gaging data show that the rate of loss is proportional to the river stage. The well closer to the river is near the gaging station. The well farther from the river is about 4 miles downstream from the station. Water levels in both wells respond to changes in river stage, and the effect is attenuated and delayed with distance from the river.

Figure 19 shows the relation between the static water level in a 690-foot well and the stage in an irrigation canal about one-half mile away. Canal leakage is a significant source of local recharge in the more arid areas of the basin. The canals commonly operate during the irrigation season from April through the beginning of October and also are used periodically at other times to fill stock ponds and other storage facilities. Isotopic evidence (Caldwell, 1998) substantiates that the canal (and possibly the Deschutes River from which this and other canals originate) is likely the predominant source of water to this well and other wells in areas traversed by irrigation canals.

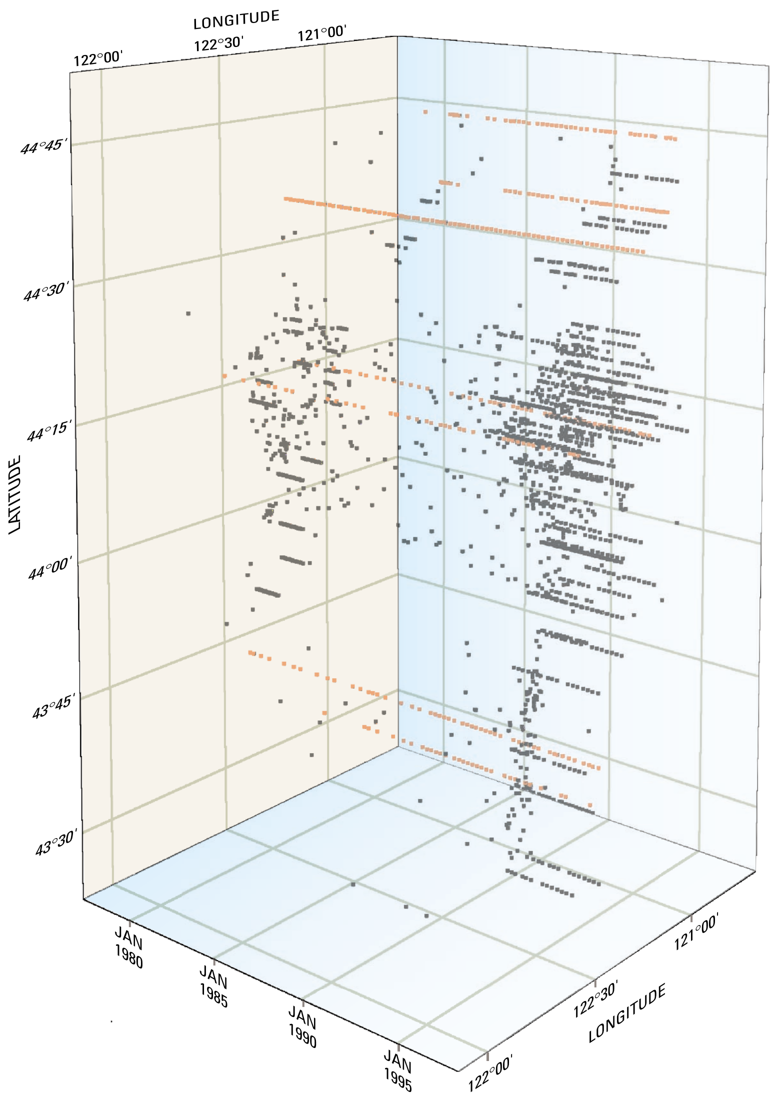


Figure 17. *Plot showing location of measured wells in upper Deschutes Basin, Oregon, and times of water-level measurement, 1977–98. Measurements from long-term observation wells are shown in red. (M.W. Gannett, U.S. Geological Survey, written commun., 2000.)*

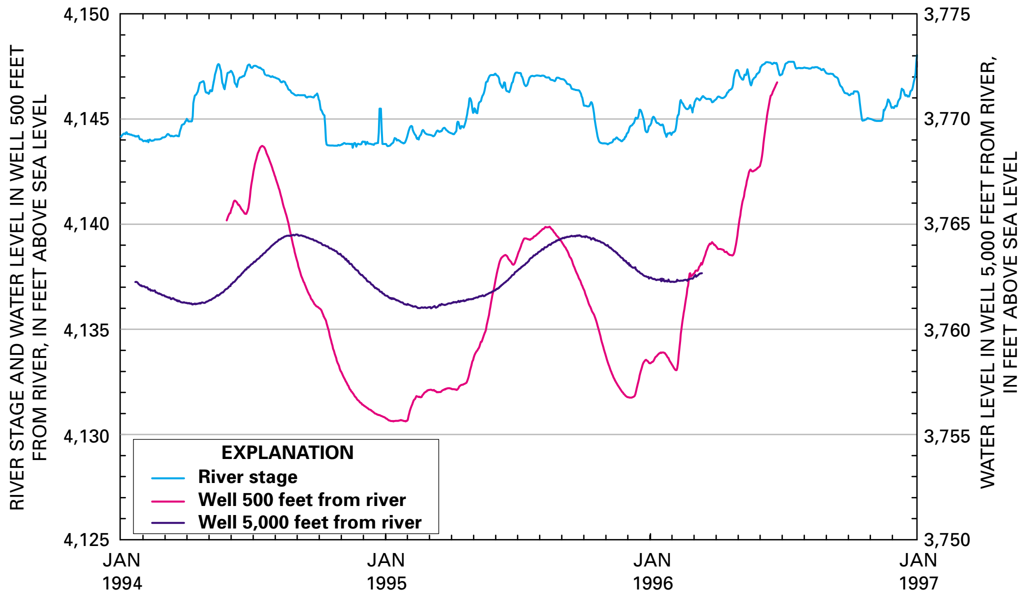


Figure 18. *Hydrographs of the stage of the Deschutes River at Benham Falls and water levels in wells 500 and 5,000 feet from the river. (Gannett and others, 2001.)*

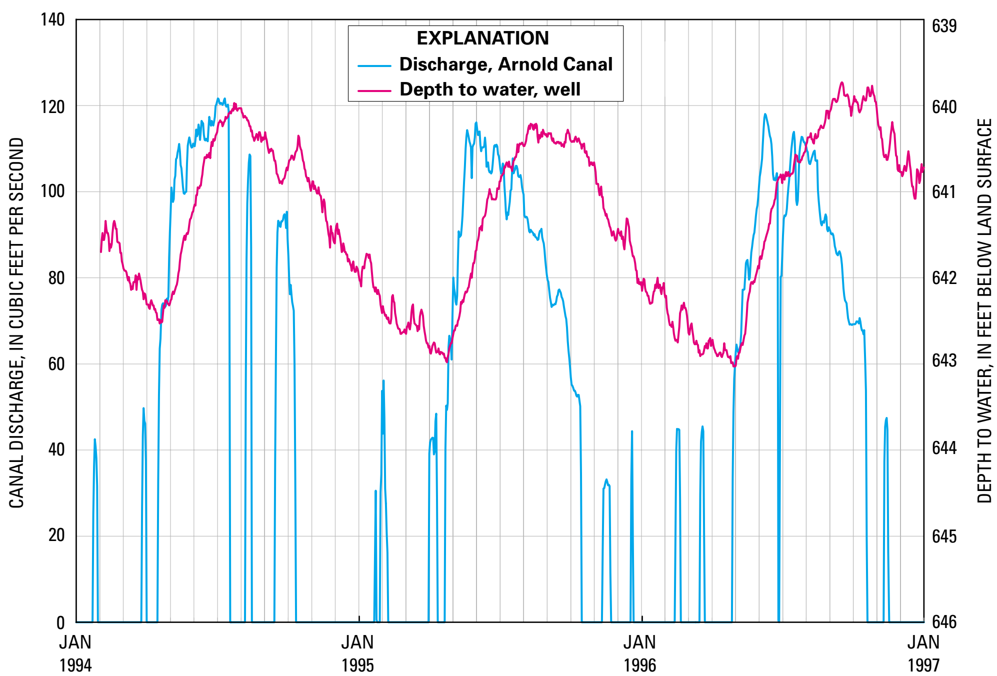


Figure 19. *Relation between the static water level in a well in upper Deschutes Basin, Oregon, and the stage in an irrigation canal about one-half mile away. Although over 600 feet below land surface, the water level in the well starts to rise shortly after the canals start flowing and starts to drop soon after they are shut off for the season. The water level also responds to periodic short-term operation of the canal. (Gannett and others, 2001.)*

Wetland Hydrology in Michigan

Wetlands provide many beneficial functions such as flood control, water-quality modification, and habitat for wildlife. Increasingly, artificially constructed wetlands are used in flood mitigation and for treatment of acid-mine and wastewater discharges. While they are often thought of only in the context of surface water, most wetlands are ground-water-discharge areas. The storage of water is crucial to wetland ecology and hydrologic functions (Carter, 1996). In many wetlands, the depth to ground water and ground-water-level fluctuations largely control the capacity for water storage. Moreover, ground-water levels are often important in maintaining the physical and chemical conditions in the root zone that promote healthy and stable growth of wetland plants (Hunt and others, 1999).

Because of the complex interaction between surface and ground water in wetlands, ground-water discharge and storage commonly are difficult components of the wetland hydrologic system to characterize. Restoration of former wetlands or construction of functional artificial wetlands requires knowledge of ground-water-flow gradients and the natural range in seasonal fluctuations in the water table. One example of the need for water-level data to assess the efforts required to restore a wetland is

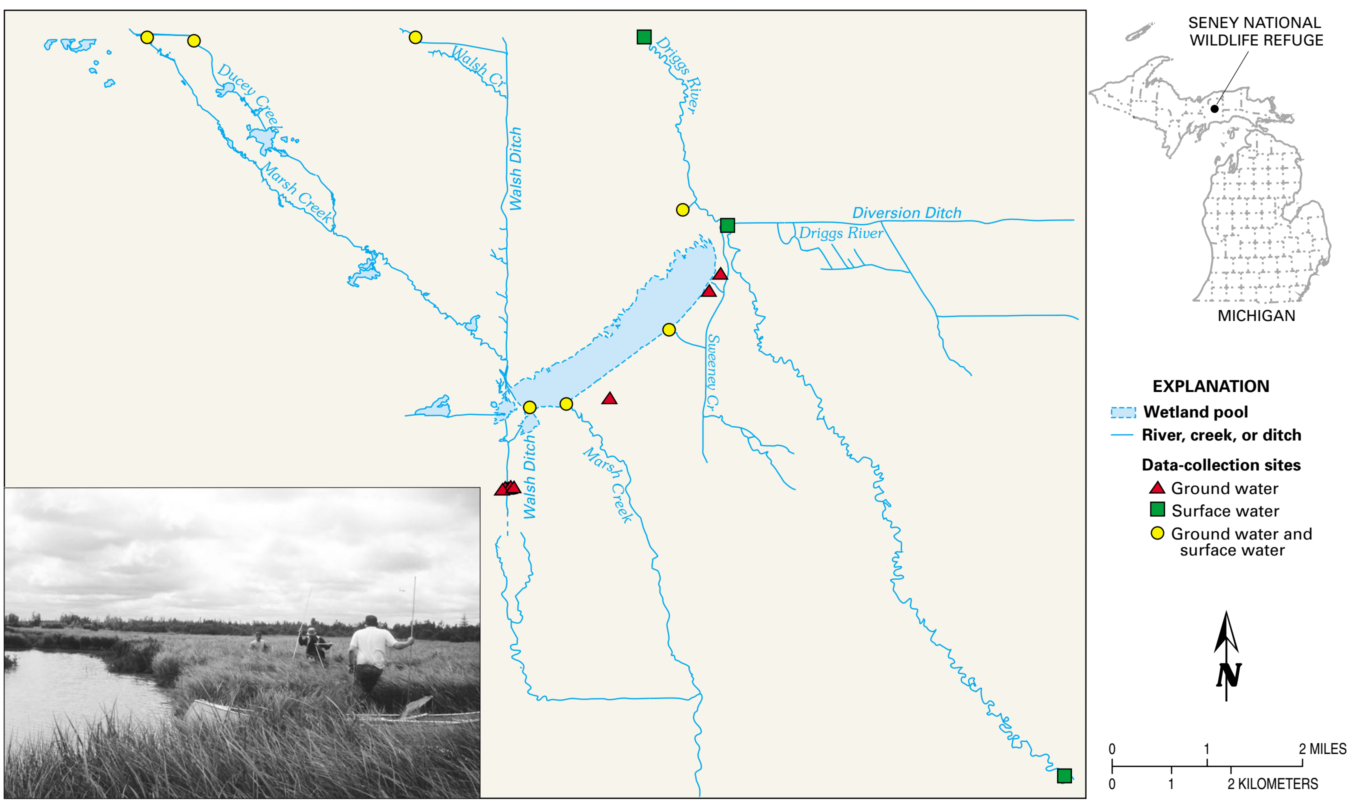


Figure 20. *Ground-water and surface-water observation stations in the watershed management area of the Seney National Wildlife Refuge wetlands, in the Upper Peninsula region, Michigan. Photograph shows hydrologists making flow measurements in a perennially flooded pool in the wetland area at the refuge. (Courtesy of "People, Land, and Water," October 1998, published by U.S. Department of the Interior, Washington, D.C.)*

highlighted by a project underway in the Seney National Wildlife Refuge, in the Upper Peninsula region of Michigan (Figure 20). Wetlands in the wildlife refuge were drained in 1912 in a failed attempt to convert the land to agricultural use. Research began in 1998 to evaluate the potential for restoration of the wetland ecosystem in approximately 33,500 acres of the refuge (Sweat, 2001). Engineering controls will be used to rehydrate wetland soils and increase the altitude of the water table. However, the natural range of ground-water-level fluctuation within the wetland area is not known. If ground-water levels decline significantly or are subject to severe seasonal fluctuations, wetland ecosystems can be disrupted and the function and sustainability of the wetland can be impaired.

Because available water-level data were not sufficient to determine seasonal trends and the range of ground-water-level fluctuations, investigators have installed 11 long-term ground-water observation wells and 7 combined ground-water and surface-water gaging stations (Figure 20). Data collected at these sites will be used to assess the average range of water-level fluctuations under the existing conditions, to determine how much ground-water levels need to be raised to support wetland ecologic functions, and to manage wildlife habitat and flood control in a perennially flooded pool in the wetland.

Downloading data from automatic water-level recorder. Photograph by Michael D. Unthank, U.S. Geological Survey.

Relevance of Water-Level Data to Ground-Water Quality Issues

The role of water-level data in the investigation of ground-water quality or contamination problems is sometimes underappreciated. To a large degree, predictions about the speed and direction of movement of ground-water contaminants are based on determination of the gradient (slope) of the water table or potentiometric surface in the affected aquifer. While the data needed for these determinations typically are obtained by synoptic water-level surveys, longer term water-level measurements are often needed to develop an understanding of how ground-water contaminants migrate from their sources through the ground-water system. For example, an examination of water-level hydrographs and graphs of contaminant concentrations over time may reveal a relation between the occurrence of event-related or seasonal changes in ground-water recharge and fluctuations in the contaminant concentrations.

Increasingly, computer-based solute-transport models are used to simulate subsurface migration and behavior of ground-water contaminants. Water-level data of sufficient duration and frequency of measurement are needed to calibrate and evaluate the reliability of the flow component of these models before realistic simulations of contaminant transport can be made.

Many ground-water-quality problems develop over long periods due to human-induced changes in hydraulic heads and resultant changes in the dynamics of a ground-water-flow system. Degradation of freshwater aquifers by the intrusion of saline water is a particularly common ground-water-quality problem of this type.

The use of long-term water-level data to address saline-water intrusion is presented in two examples here. These are followed with an example related to concerns about ground-water degradation from residential development.

The role of water-level data in the investigation of ground-water quality or contamination problems is sometimes underappreciated.

SALINE WATER INTRUSION IN NEW JERSEY

The relation between the intrusion of saline water and declining hydraulic heads due to extensive aquifer development is well illustrated by the aquifers in the Coastal Plain of New Jersey (Lacombe and Rosman, 1997). Since the 1800's, the principal source of public-water supply in the Coastal Plain of New Jersey has been ground water obtained from wells in 10 major confined aquifers. The aquifers are arranged in a dipping, layered ground-water system similar to that of the Gulf Coastal Plain aquifer system. Because of large ground-water withdrawals, regional cones of depression have developed in each of the aquifers. By 1978, the potentiometric surfaces of most of the aquifers had been lowered below sea level, and natural flow directions in some areas were reversed. Consequently, saline water that is naturally present in the deeper parts of the aquifers was induced to migrate toward pumping centers, and chloride and dissolved-solids concentrations increased significantly in parts of these aquifers.

As an example, pumping by public-supply wells completed in the Upper Potomac-Raritan-Magothy aquifer near the New Jersey coastline resulted in a decline in hydraulic heads to more than 40 feet below sea level (Schaefer and Walker, 1981). The development of this large cone of depression in the potentiometric surface in the aquifer also resulted in the landward reversal of ground-water flow and migration of saline water. Throughout the 1970's, ground water in parts of the aquifer became progressively degraded by sharply rising chloride concentrations, as shown for the Union Beach well field in Figure 21. Although pumping was curtailed in the 1980's, degradation of the aquifer by saline water was sufficiently extensive that the well field was later abandoned and replaced by wells farther inland.

Because of the continued potential threat of degradation of the freshwater parts of the aquifers, ground-water withdrawals are carefully monitored and regulated by the New Jersey Department of Environmental Protection (NJDEP). In addition, the NJDEP and USGS have developed a cooperative program to monitor changes in water levels and chloride concentrations at 5-year intervals in each of the confined aquifers. As part of this

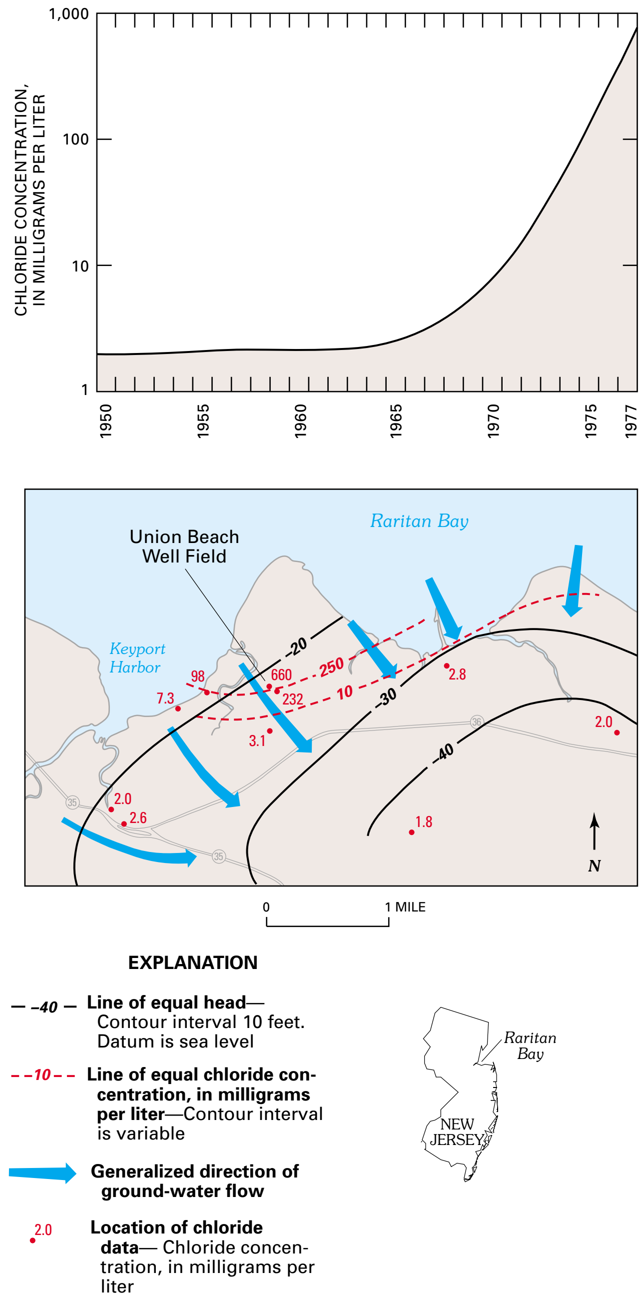


Figure 21. *Relation between reductions in heads from pumping and chloride concentrations in the Upper Potomac-Raritan-Magothy aquifer, New Jersey, 1977. Chloride concentrations shown in the graph are a composite of concentrations in water samples from wells screened at about the same depth in the Union Beach well field. (Modified from Schaefer and Walker, 1981.)*

monitoring program, water-level hydrographs are prepared from continuous measurements collected in 99 long-term observation wells and used to assess seasonal trends in ground-water recharge and storage. Water-level measurements are made in approximately 1,000 additional observation wells and used to construct potentiometric maps showing any significant changes in the size of the cones of depression developed in the aquifers. Water samples are collected from selected observation wells for analysis of chloride and dissolved-solids concentrations, and these data are compiled to monitor changes in the relation between hydraulic heads, ground-water-flow directions, and ground-water quality. Using this combined water-level and water-quality monitoring program, the NJDEP can evaluate the effects of water-management decisions on the aquifers and carefully monitor the improvement or further degradation of water quality in the aquifers.

UPWELLING OF SALINE WATER IN UTAH

Chloride contamination also can occur in noncoastal areas where the freshwater aquifer is invaded by saline water or brines upwelling from deeply buried sedimentary rocks. Spangler and others (1996) documented an example of this problem in a study of the quality of water in the Navajo aquifer in southeastern Utah.

The Navajo aquifer, composed of the Entrada and Navajo Sandstone formations, is one of several aquifers separated by confining units within a large sedimentary basin that underlies San Juan County, Utah (Figure 22). Within the basin, the top of the Navajo aquifer averages about 550 feet below land surface, and the thickness of the aquifer generally ranges from 750 to 1,000 feet. The Navajo aquifer is recharged mainly by infiltration where the sandstones crop out at the surface along several mountain ranges that surround the basin. The Navajo aquifer is confined above by the Wanakah Formation and below by the Chinle-Moenkopi Formation. Artesian pressures are so great in parts of the aquifer that ground water discharges naturally at the land surface from open, flowing wells.

Much of the sedimentary basin that contains the Navajo aquifer has been explored and developed for oil and gas. Several oil fields were developed in the basin in the 1950’s, and exploration and production generally have increased since then. The main oil-producing zones in the basin are in carbonate rocks of the Paradox Formation, at depths ranging from 5,000 to 6,000 feet below land surface. Over time, as oil was extracted and oil-field pressures declined, the technique of water flooding—the injection of freshwater from alluvial aquifers along the San Juan River to flush residual oil—was used to boost production in the Paradox Formation oil wells. This practice began in the late 1950’s and continues to the present. Brine water, obtained from the Paradox Formation as a by-product of the water flooding and oil recovery process, was reinjected into deep wells completed in the oil-producing zones for disposal.

Water-quality problems associated with increased chloride concentrations in wells drilled into the Navajo aquifer began to be reported in the 1950’s. A review of historical water-level records indicated that hydraulic heads in the Navajo aquifer had declined by as much as 178 feet since the early 1950’s because of increased development. The decline in hydraulic heads in the Navajo aquifer had resulted in an increased upward hydraulic gradient between the upper Paleozoic aquifer and Navajo aquifer (Figure 23). This indicated that ground water from the upper Paleozoic aquifer could provide recharge to the Navajo aquifer in locations where the Chinle Formation confining unit was breached by fractures or by improperly sealed wells.

The information from historical water-level measurements was used to guide water-quality sampling needed to identify the source of the chloride contamination in the Navajo aquifer. Water samples were collected from wells completed in the Navajo aquifer, the upper Paleozoic aquifer, the Paradox Formation, and other deep aquifers (Spangler and others, 1996). Samples of the brine water being reinjected at producing oil wells also were collected. Detailed chemical analyses of these water samples indicated that the degradation of water quality in wells completed in the Navajo aquifer was caused primarily by the upwelling and mixing of saline water from the upper Paleozoic aquifer. The brine water reinjected into the Paradox Formation was determined to be an unlikely source of the chlorides in the Navajo aquifer. The oil and gas production activities may have contributed indirectly to the water-quality problem, however, as a review of well-construction logs identified over 200 active and abandoned oil wells that may be inadequately cased or sealed. These wells could provide conduits by which ground water migrates upward from the upper Paleozoic aquifer and intermingles with ground water in the Navajo aquifer.

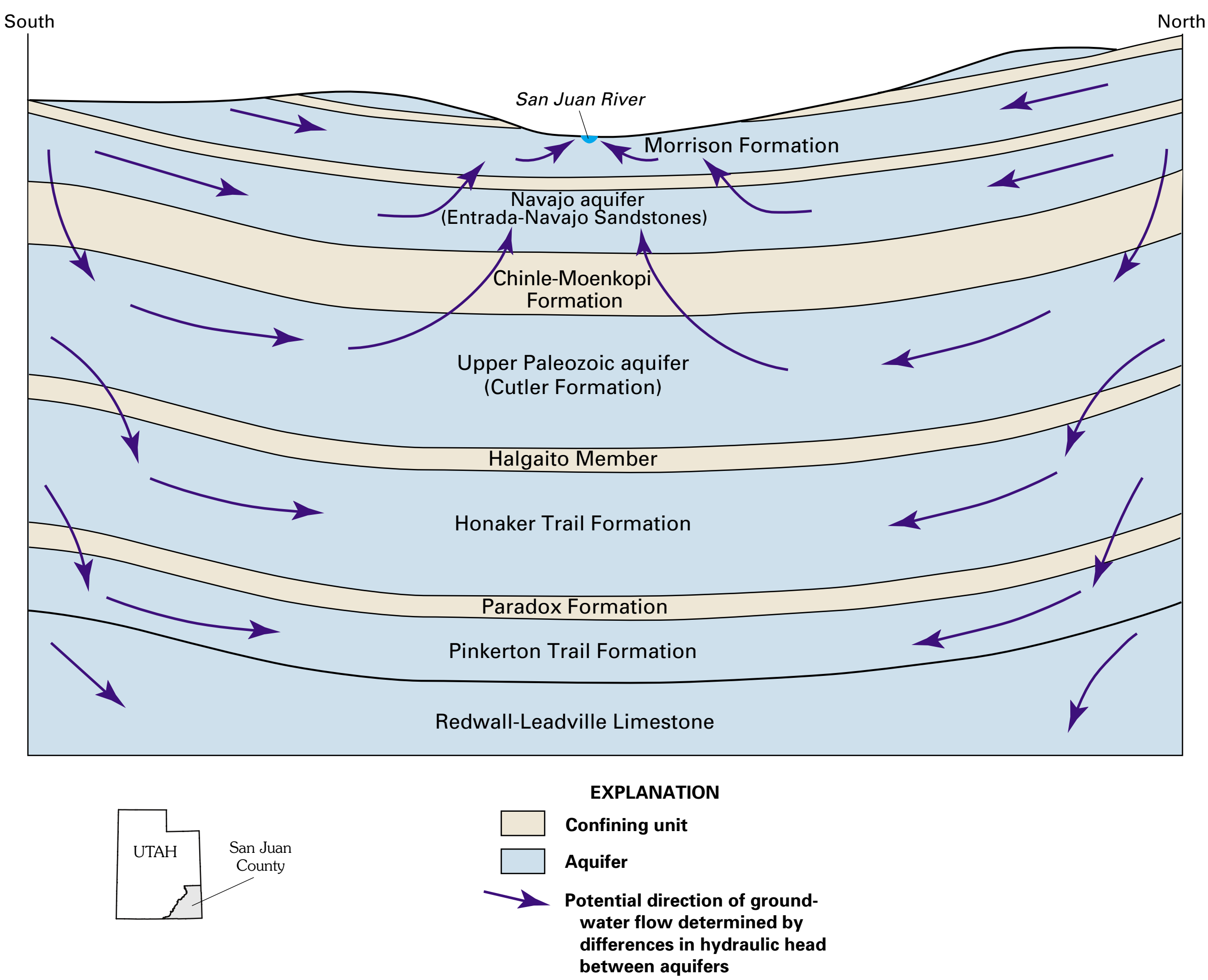


Figure 22. *Geologic section showing the stratigraphic relations and movement of ground water between the Navajo aquifer, upper Paleozoic aquifer, and other major aquifers and confining units, San Juan County, southeastern Utah. (Modified from Spangler and others, 1996.)*

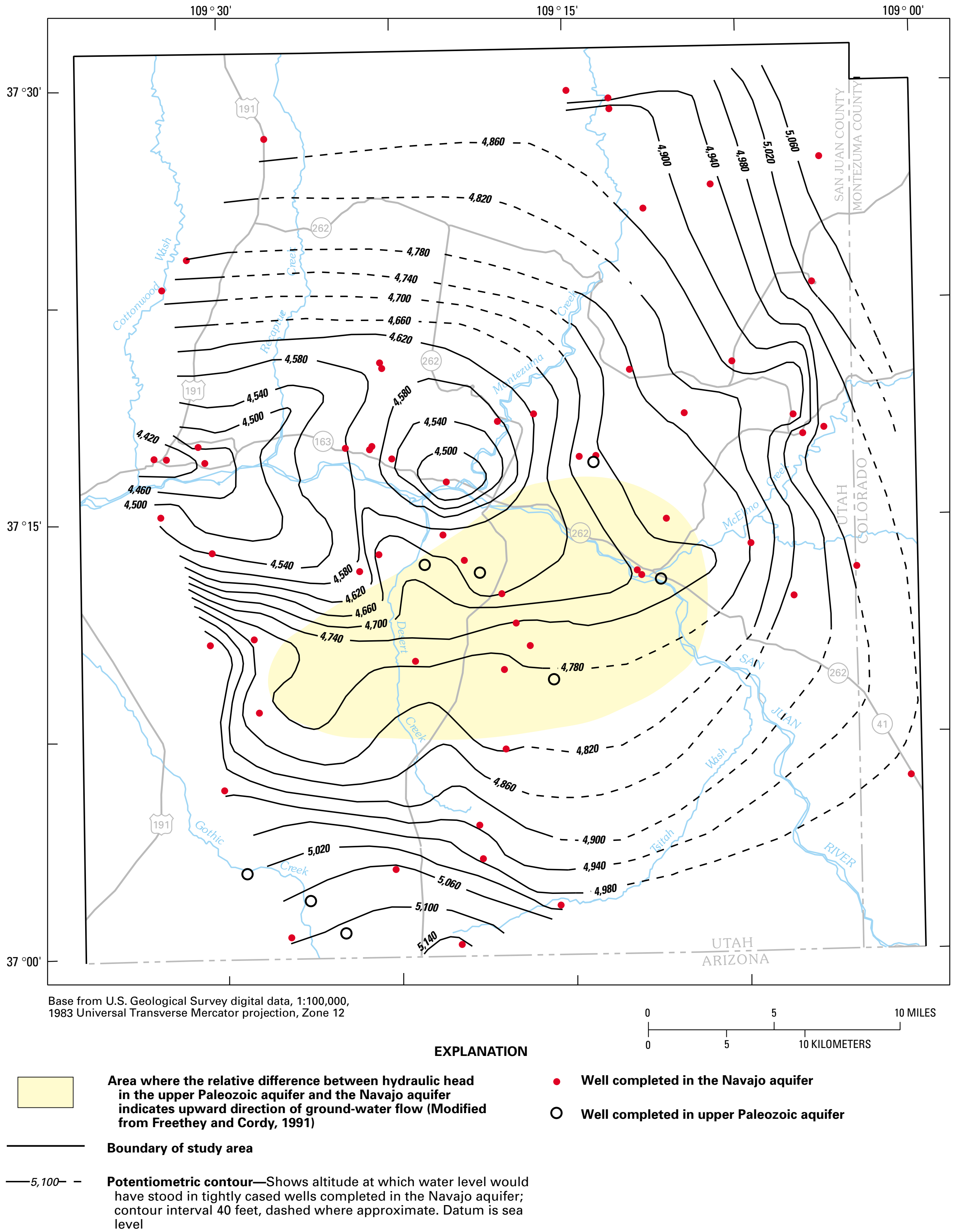


Figure 23. *Potentiometric map of the Navajo aquifer showing locations of wells used for water-level measurements and the inferred area of upward ground-water flow from the upper Paleozoic aquifer, San Juan County, southeastern Utah. (Modified from Spangler and others, 1996.)*

EFFECTS OF RESIDENTIAL DEVELOPMENT IN MONTANA

The early stages of land or aquifer development is an opportune time to establish a combined water-level and water-quality monitoring network that can define baseline conditions and track important changes with time in the quantity and quality of the resource. Examples are provided for the Gallatin and Helena areas in southwestern Montana, which are among many parts of the Western United States where rapid changes in land development have the potential to affect ground-water resources.

The Gallatin Valley is an intermontane basin that consists of an alluvial plain flanked by higher elevation benches (Figure 24). The alluvial plain is used primarily for irrigated agriculture and the benches for dryland farming. In recent years, residential and commercial development has replaced considerable areas of farmland on both the alluvial plain and the benches. Much of the population increase has been outside of established cities and towns, in areas where each home has its own well and septic system. The residential development has raised concerns regarding the potential effects of infiltrating septic wastewater on the quality of ground water. In response, the Gallatin Local Water Quality District (GLWQD) was established in 1995, and efforts were undertaken to monitor the quality of ground water and surface water.

Long-term water-level measurements are needed to provide information on trends or variations in annual recharge that may affect either the amount of dilution or the additional loads of contaminants that may be introduced to the ground-water system from the septic wastewater. Since the late 1940's, periodic surveys have been made of water levels in the valley, but only two wells have been measured consistently from year to year. Both wells are near or within the flood plain of the Gallatin River. Water levels in the two wells primarily represent recharge from the river or from local diversions of river water for irrigation. Little water-level monitoring has been done for the aquifers underlying the benches (Kendy, 2001). To help address these issues, in 1997 the USGS designed a long-term water-level monitoring network in cooperation with the GLWQD that consists of 101 wells. An attempt was made to include as many previously monitored wells as possible and to expand the network to represent all developed aquifers in the GLWQD.

Like Gallatin Valley, the Helena, Montana, area has experienced marked growth in recent years. Public concerns about depletion or contamination of ground water in the bedrock areas surrounding the Helena Valley led to a hydrologic

The early stages of land or aquifer development is an opportune time to establish a combined water-level and water-quality monitoring network that can define baseline ground-water conditions and track important changes with time in the quantity and quality of the resource.

study by the USGS in cooperation with the Lewis and Clark County Water Quality Protection District (Thamke, 2000) that is similar to the study described previously for the Gallatin area.

Monthly measurements of water levels in 112 wells from 1993 to 1998 were an important part of the Helena bedrock area study, and water-level measurements currently (2001) continue to be made in 25 wells. Again, few long-term water-level monitoring wells existed prior to the study. Water-level data available for two wells from 1976 to 1998 are shown in Figure 25 and illustrate the value of longer term measurements. The hydrograph for well 60 shows that though the period 1992–98 was one of generally rising water levels for this well, water levels in the well generally declined during the full period (1976–98). For well 174, the long-term trend is more difficult to determine because of relatively large gaps for some parts of the record. Water-level trends in the Helena bedrock are likely to vary across the area as a result of differences in precipitation, human influences, and the heterogeneous character of the bedrock aquifer. Thus, a network of long-term monitoring wells is needed to develop an overall perspective on the ground-water resources.

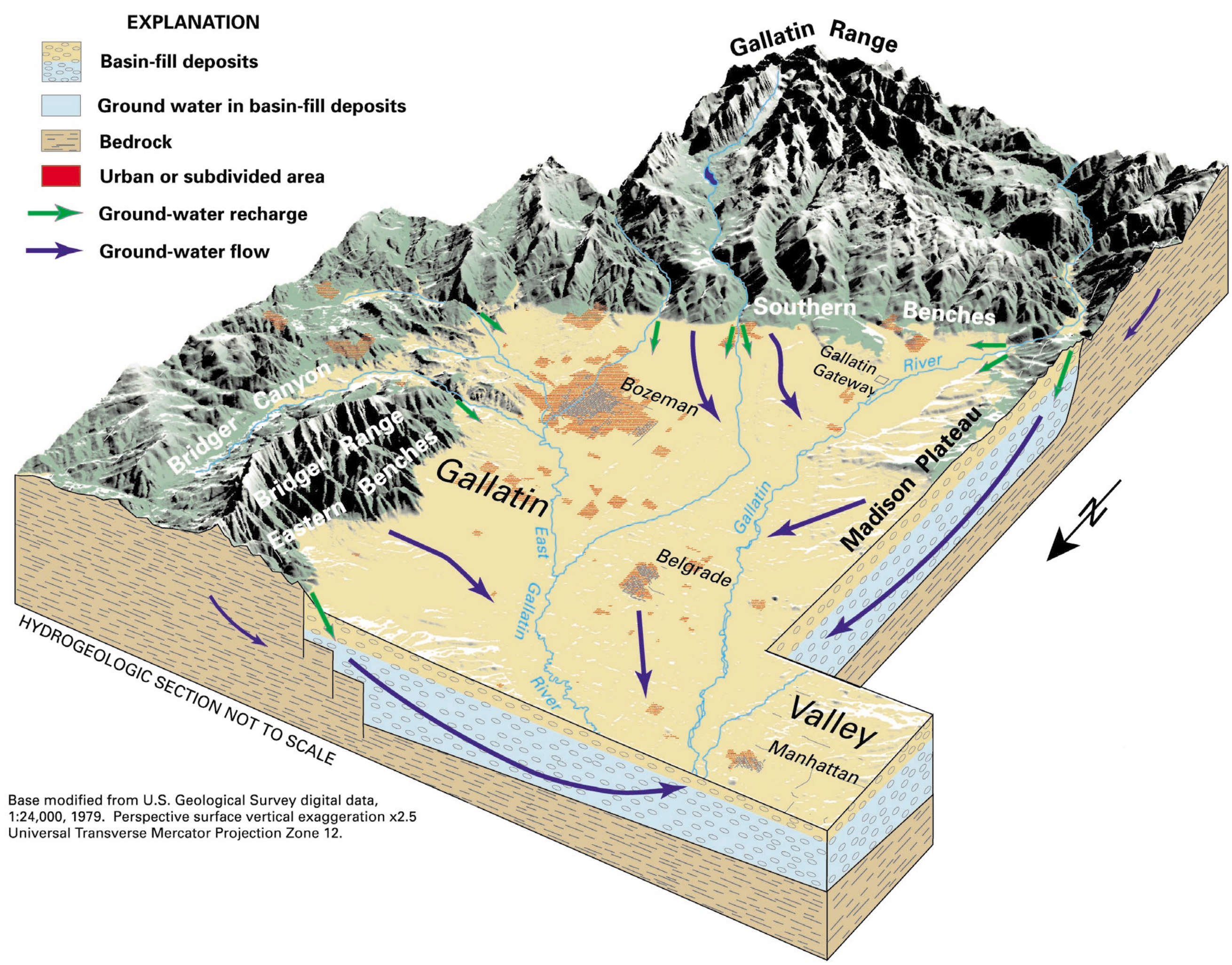


Figure 24. *Perspective block diagram of the Gallatin Local Water Quality District, Montana, showing areas of urban and residential development. (Modified from Kendy, 2001.)*

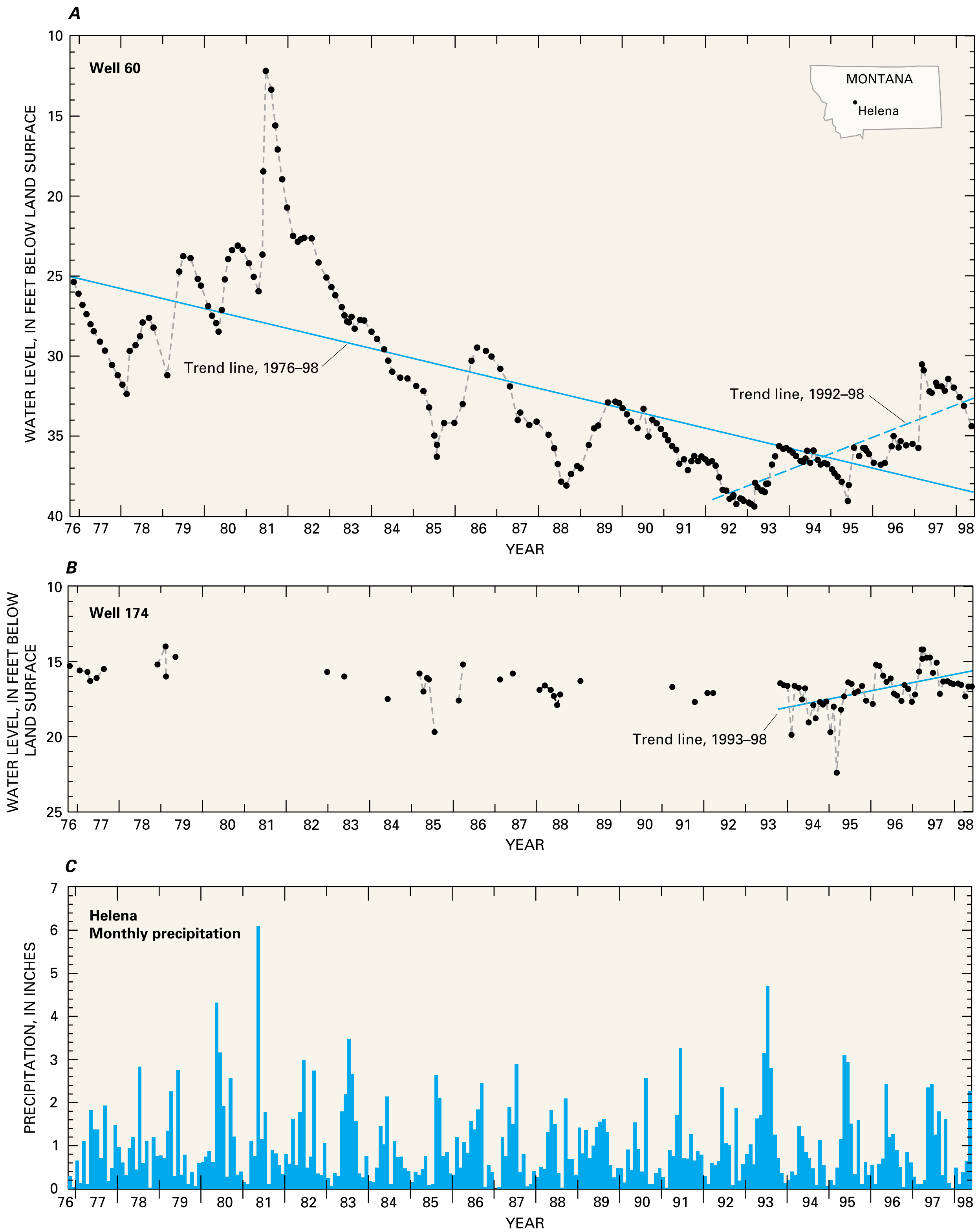


Figure 25. *Long-term hydrographs for two wells in the Helena bedrock area and corresponding monthly precipitation at Helena, Montana. Trend lines are based on simple linear regression between water level and time. (Modified from Thamke, 2000.)*

Innovative and Emerging Applications

Several innovative uses of long-term water-level monitoring have been proposed in addition to the more conventional uses described thus far. For example, van der Kamp and Schmidt (1997) demonstrated a method in which the soil-moisture balance for a relatively large area was determined on the basis of water levels in wells completed in a thick clay layer. After removing the effects of barometric loading and Earth tides, the remaining changes in water pressure (water levels) represent changes in loading on a relatively large scale resulting from the balance between infiltration of precipitation and losses by evapotranspiration. Separately, Narasimhan (1998) emphasized that valuable insights about the dynamic attributes of ground-water systems can be gained by long-term passive monitoring of responses of ground-water systems to barometric changes and earth tides.

The use of geophysical techniques in combination with water-level data can enhance delineation and interpretation of water-level changes over a region. For example, microgravity methods can be used to measure extremely small gravitational changes resulting from changes in ground-water storage over an area. An example of the combined use of water-level measurements and microgravity measurements is shown in Figure 26 for the Tucson Basin in Arizona. The patterns of changes in ground-water storage based on microgravity measurements (Figure 26*A*) and patterns of changes in water levels (Figure 26*B*) are similar. Differences between the two maps result from the different locations of measurement, spatial variations in specific yield, and water stored in the unsaturated zone that is measured by microgravity measurements but not by the water-level measurements.

A second geophysical technique, Interferomic Synthetic Aperture Radar (InSAR), is proving to be a powerful new tool that uses repeat radar signals from space to measure land subsidence at high degrees of measurement resolution and spatial detail (Galloway and others, 1999). The combination of InSAR information with long-term water-level data from different locations and depths provides a means to map land subsidence as well as evaluate its causative factors.

Scientist making microgravity measurement as part of study to determine aquifer storage changes near Tucson, Arizona. Photograph by Alice Konieczki, U.S. Geological Survey.

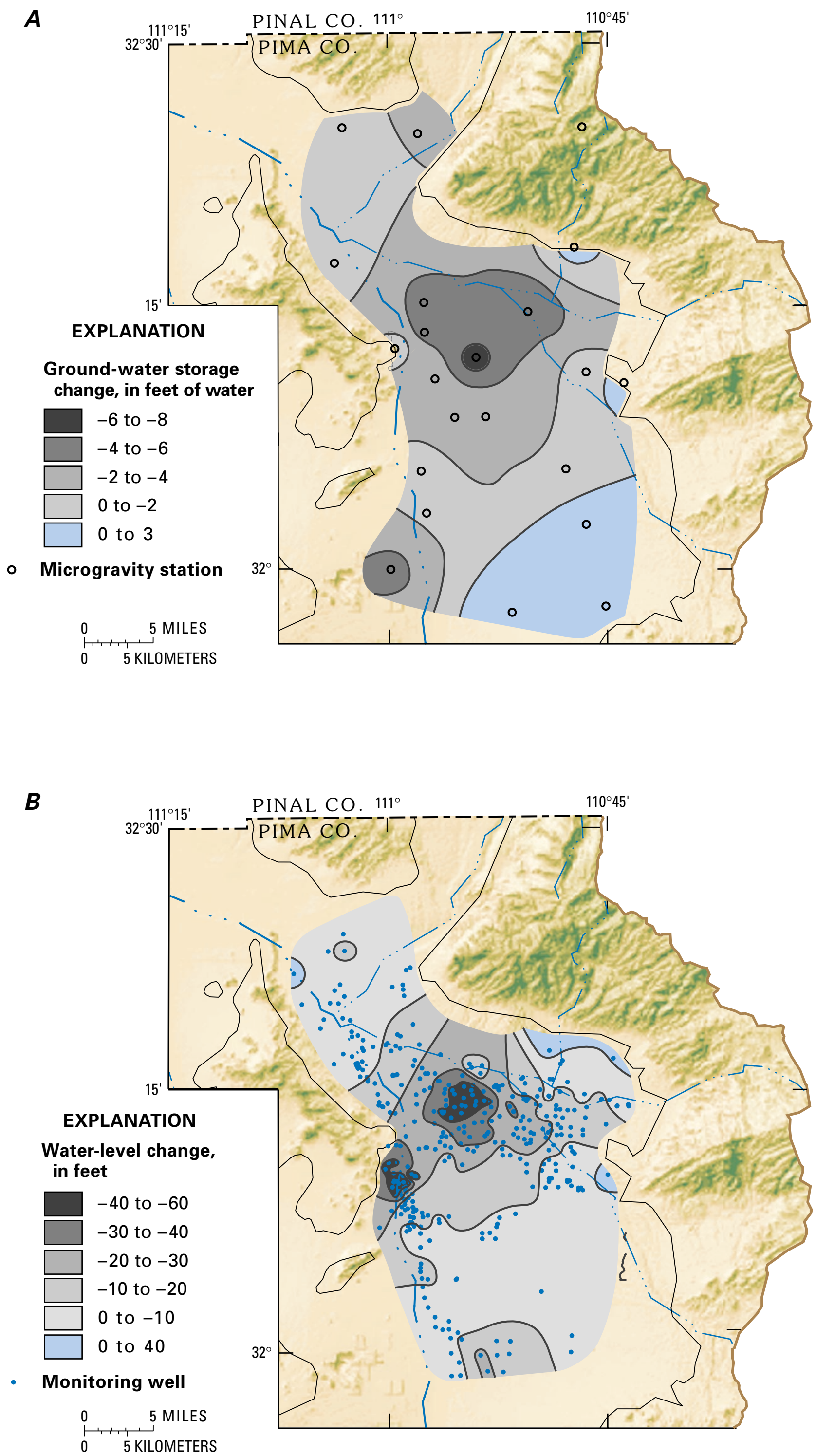


Figure 26. *Estimated changes from 1989 to 1998 in the Tucson Basin in (A) ground-water storage based on microgravity survey data, and (B) ground-water levels based on measurements in monitoring wells. (Modified from Pool and others, 2000.)*

Statistical Design of Water-Level Monitoring Networks

Statistical techniques have found limited application to the design of water-level monitoring networks for several reasons. First, sufficient data are needed to reliably estimate the parameters required by the techniques. Second, water-level monitoring networks typically have multiple objectives, some of which are difficult to express quantitatively. Despite these limitations, statistical analysis of data from existing networks can provide useful guidance in evaluating these networks and a firmer basis for network modifications. Examples of the use of two well-known statistical techniques, geostatistical analysis and principal-components analysis, are described here.

GEOSTATISTICAL ANALYSIS

Geostatistics encompasses a set of probabilistic techniques aimed at determining estimates of spatial data (in this case, water levels) at unmeasured locations as combinations of nearby measured values. The method provides estimates of uncertainty that can be used to aid network design.

A typical application of geostatistics is to evaluate the relation between the number or density of monitoring wells and the uncertainty of a potentiometric map. Olea (1984) presented an example of this type of application for the Equus Beds aquifer, an intensively used aquifer in central Kansas. A map of the water-table elevation in the Equus Beds aquifer, based on data from the existing network of 244 observation wells, is shown in Figure C–1. Note that the density of monitoring wells in Figure C–1 is not homogeneous—about 80 percent of the wells are located in the southern half of the area. From this network, Olea (1984) identified a reduced network of 47 wells by laying a regular hexagonal pattern (Figure C–2) over the area and randomly selecting from among the existing monitoring wells in each hexagon.
A map of water-table elevation based on the revised network of 47 wells is shown in Figure C–3 and is similar to the map shown in Figure C–1. About 95 percent of the values in the two contour map grids differ by less than 5 percent. From the geostatistical analysis, the estimated average standard error of the water-table elevations increased about 20 percent from 10 feet for the map of Figure C–1 to 12 feet for the map shown in Figure C–3.

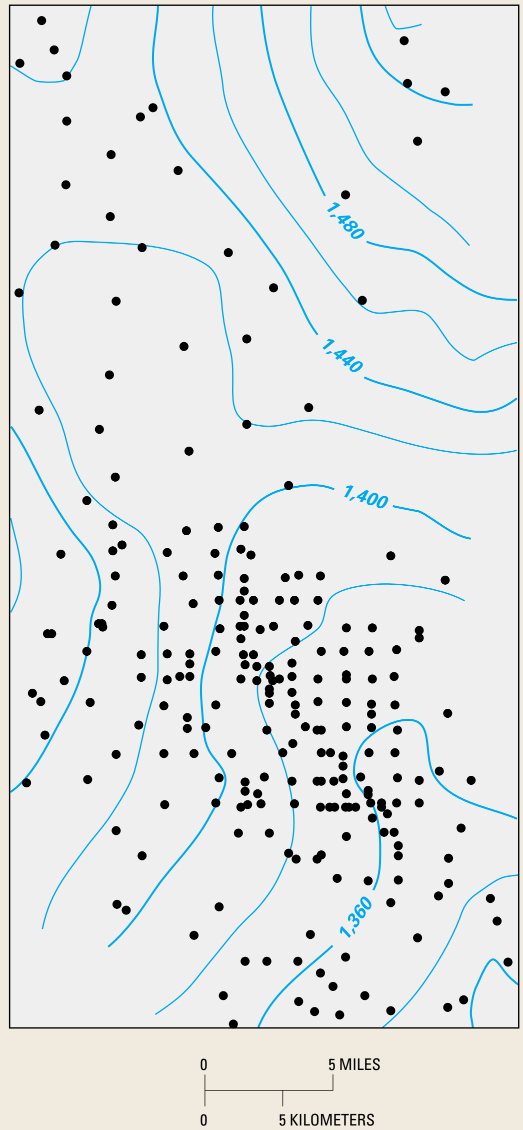


Figure C–1. *Water-table elevation in the Equus Beds aquifer, based on data from network of 244 observation wells. Circles show locations of observation wells. (Modified from Olea, 1984.)*

Information provided by the previously described type of analysis may lead to reductions in the number of monitoring wells in some areas. The savings can be used to establish additional monitoring wells in areas with less adequate coverage, to increase the frequency of measurement, or to otherwise upgrade the network. The limitations of this type of analysis should be kept fully in mind, however, in that the analysis focuses on the overall ability to accurately represent a regional potentiometric surface. Other objectives of the network might need to be factored into any decisions about network design, such as objectives to quantify drawdowns in particular areas, to identify possible flow paths for water-quality analysis, or to evaluate the interactions of ground water and surface water. Likewise, geostatistical analysis assumes that further ground-water development will not greatly alter the estimated spatial correlations.

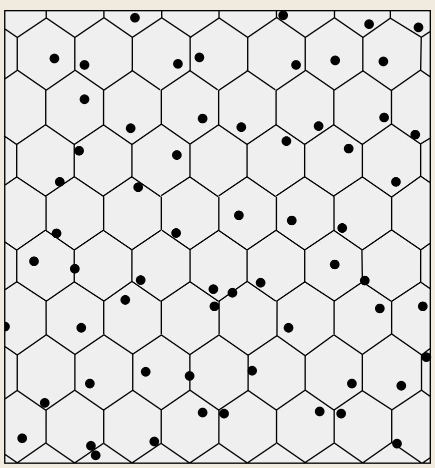


Figure C–2. *Example of hexagonal sampling. Olea (1984) found the hexagonal pattern to be more efficient than a square pattern for selecting wells.*

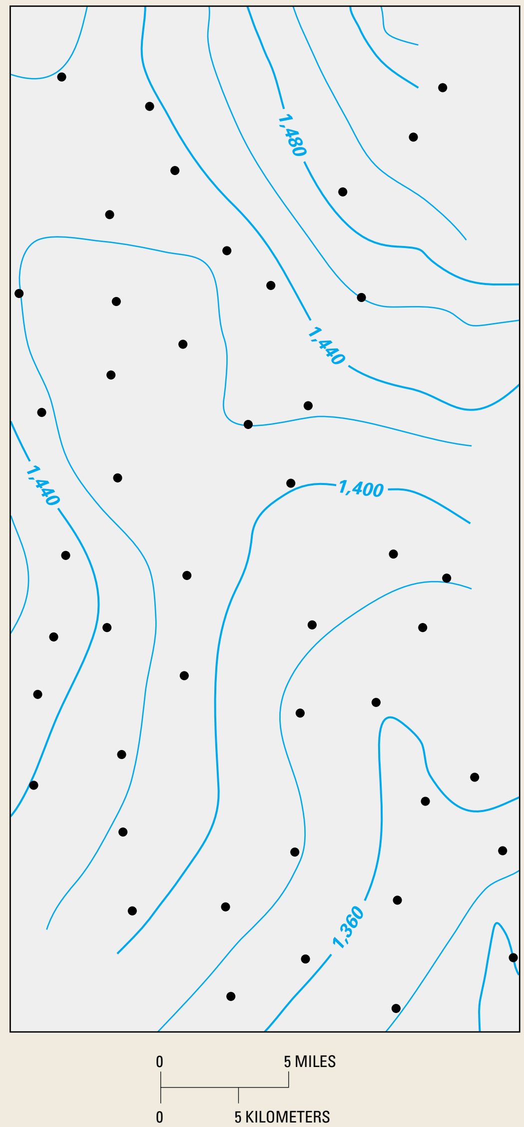


Figure C–3. *Water-table elevation in the Equus Beds aquifer, based on data from network of 47 wells selected using 16-square-mile hexagons. Circles show locations of observation wells. (Modified from Olea, 1984.)*

PRINCIPAL-COMPONENTS ANALYSIS

Principal-components analysis (PCA) is a data transformation technique used to search for structure in multivariate data sets. The goal of PCA is to determine a few linear combinations (principal components) of the original variables that can be used to summarize the data without losing much information. An example of PCA applied to water-level measurements near Williams Lake in Minnesota is discussed here (Winter and others, 2000).

Williams Lake is located in the glacial terrain of northern Minnesota. More than 300 measurements of water levels were made at each of 50 wells surrounding the lake (Figure C–4). In applying PCA to these data, the first two principal components (PC–1 and PC–2) were found to mimic basic patterns of water-level fluctuations in the wells and together accounted for 93 percent of the variance (variability) in the water-level data. For example, in Figure C–5, compare

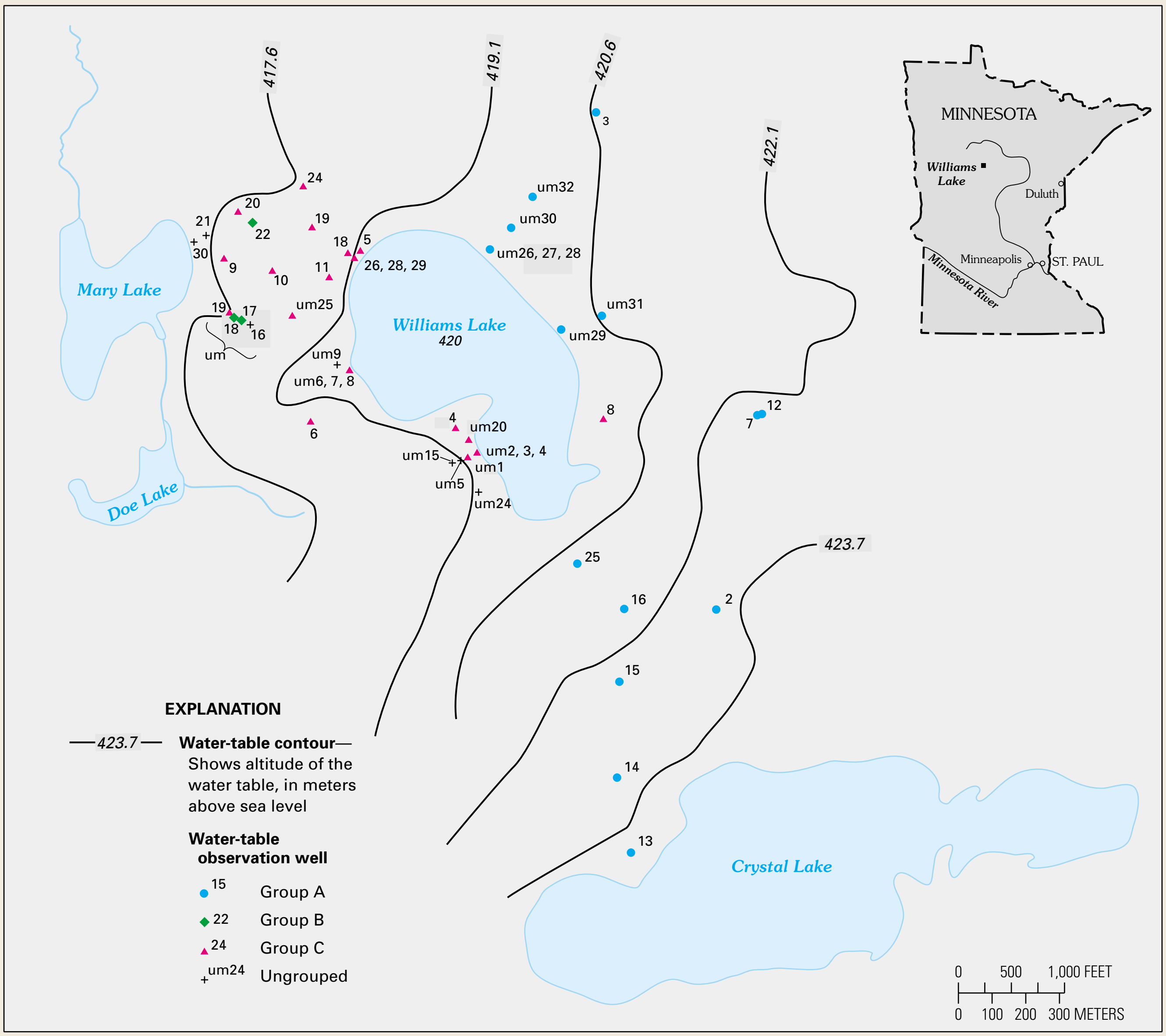


***Figure C–4.** Location of observation wells near Williams Lake in Minnesota. Well groups are based on the delineations shown in Figure C–6 and discussed in the text. (Modified from Winter and others, 2000.)*

the hydrograph of water levels for well 15 with the graph of component scores for PC–1. Likewise, compare the hydrograph of water levels for well 22 with the graph of component scores for PC–2. A third hydrograph, for well 20, appears to be a mixture of PC–1 and PC–2.

The relative weighting of the water-level patterns represented by PC–1 and PC–2 for a well are reflected in the principal-component loadings. The component loadings are the correlation coefficients between the water-level measurements for the well and each principal component. A plot of the component loadings for each well with respect to PC–1 and PC–2 (Figure C–6) indicates that most wells fall into three groups. A large number of wells have high loadings on PC–1 and low loadings on PC–2 (Group A). At the other extreme, a few wells have high loadings on PC–2 and low loadings on PC–1 (Group B). Many wells have relatively high

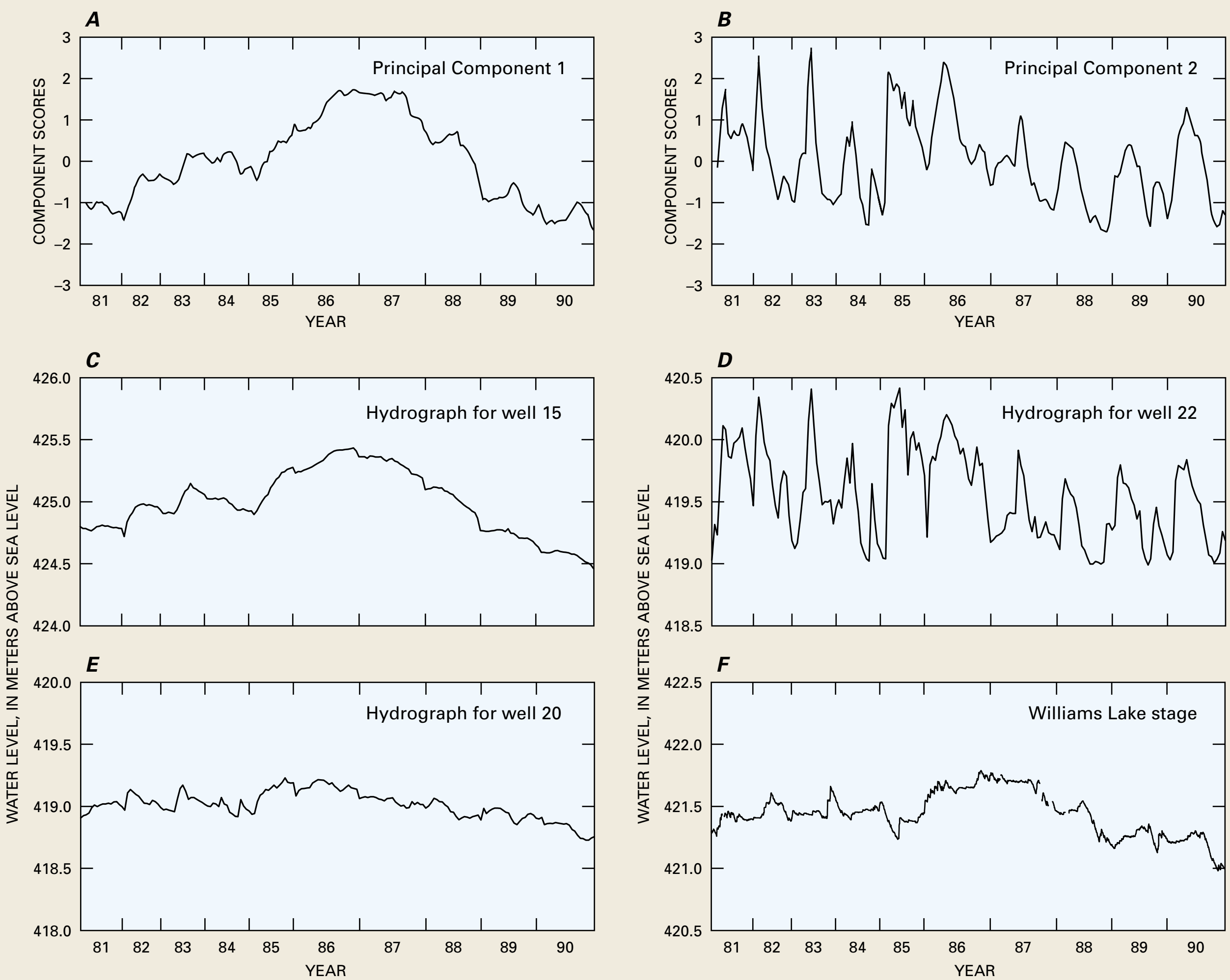


Figure C–5. *Selected graphs for the Williams Lake area of Minnesota, including (A) component scores for principal component 1, (B) component scores for principal component 2, (C) water level in well 15, (D) water level in well 22, (E) water level in well 20, and (F) stage of Williams Lake. The variable spacing for each year on the x-axis reflects the number of measurements made for the year at each site. Principal-components analysis requires that measurements be made for all wells for each date used in the analysis, but the number of measurements per year can vary. (Modified from Winter and others, 2000.)*

loadings on both PC–1 and PC–2 (Group C). Wells 15, 22, and 20, whose hydrographs are plotted in Figure C–5, are examples of wells from Groups A, B, and C, respectively.

The three patterns of water-table fluctuations reflect variations in recharge as related to the depth to the water table and whether the wells are upgradient or downgradient from the lake. For example, all Group A wells are upgradient from Williams Lake, and the water table is relatively deep at these wells. In contrast, the water table is very shallow at the three Group B wells. All but one of the Group C wells are downgradient from Williams Lake, and the pattern of water-table fluctuations shows some similarity to the stage of Williams Lake (Figure C–5).

The results of the PCA thus provide some basic insights into the similarities and dissimilarities in patterns of water-level fluctuations among the wells and might be useful in selecting wells for long-term monitoring. For example, a first consideration might be to select wells from each of the three groups. In addition, wells that fall outside the three groups might be individually reviewed to consider whether they represent critical hydrologic settings for long-term monitoring not represented by wells in the three groups.

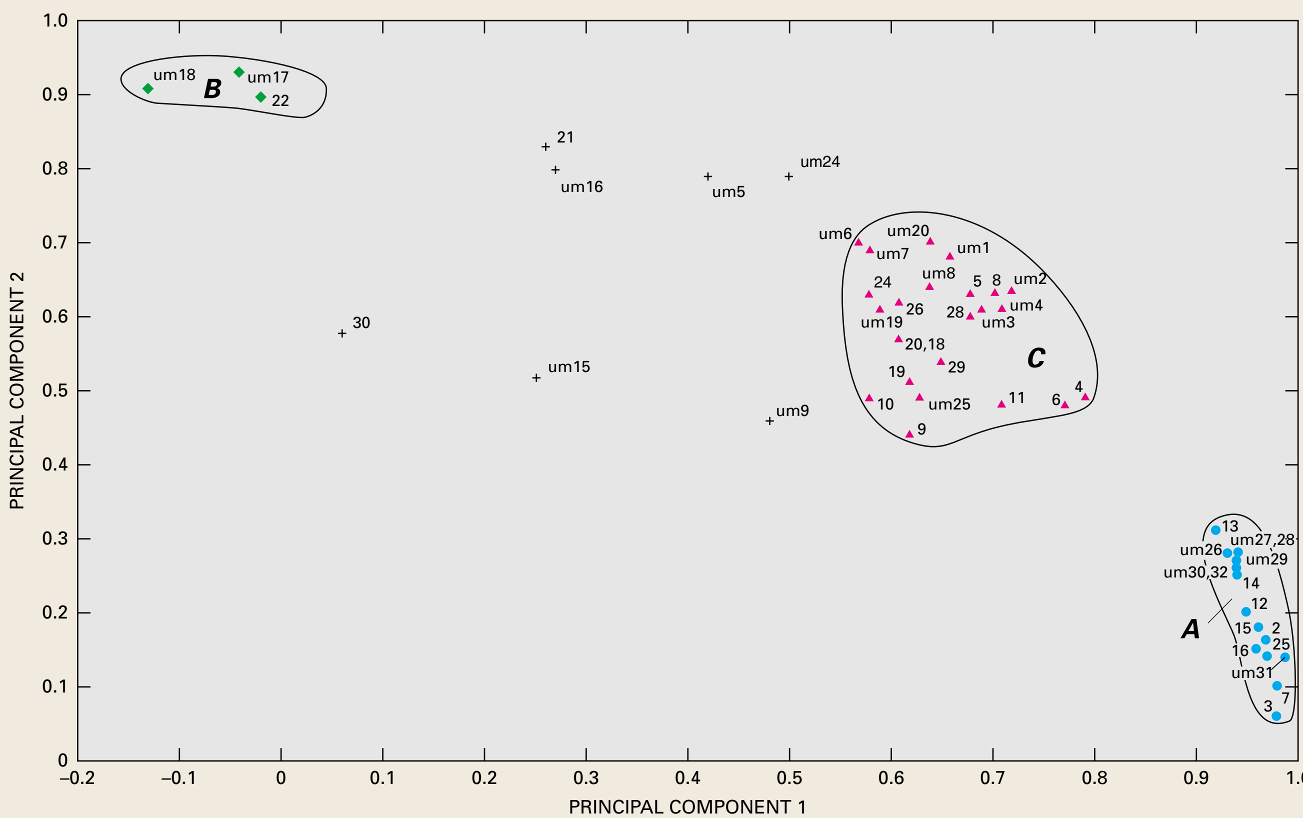


Figure C–6. *Plot of component loadings for principal component 1 versus principal component 2 for wells in the Williams Lake area. (Modified from Winter and others, 2000.)*

STATUS OF WATER-LEVEL DATA-COLLECTION PROGRAMS

To aid in preparation of this report, State and local water-resources agencies and USGS District offices were asked to provide information about the design, operation, and history of long-term ground-water observation wells in their respective State. "Long term," as defined here, refers to any well being used to collect water-level measurements for 5 years or more, or having at least 5 years of hydrologic record. It is worth repeating that water-level measurements typically must be collected from an observation well without interruption over one or more decades in order to compile a hydrologic record that represents the potential range of natural water-level fluctuations and tracks trends over time. Five years is therefore a relatively short period for water-level data collection, but it is at least sufficient to provide a record of several seasons of ground-water-level fluctuations.

Sixty-two State and local water-management or regulatory agencies provided information, as did USGS offices in all 50 States and Puerto Rico. A surprising revelation from the results was how difficult it is to obtain information about the actual number of observation wells monitored, the frequency of water-level measurements, the average period of hydrologic record, and changes in the monitoring program over time. The reasons for this varied, but often the ability of the respondents to provide information was hindered by a lack of formal documentation about the design of the observation-well networks, limited "institutional memory," and the lack of an accessible database. Another common problem encountered was that responsibilities for collecting water-level data are not always clearly defined.

The level of effort in collecting long-term water-level data varies greatly throughout the United States. Although difficult to define precisely, the information collected indicated that there are on the order of 42,000 long-term (5 or more years of record) observation wells distributed throughout the United States. Approximately 11,000 (less than one-third) of the reported number of long-term observation wells are presently monitored through the USGS Cooperative Water Program. This number is significantly less than the 18,300 long-term observation wells reported in a 1997 inventory of hydrologic monitoring stations operated under the Cooperative Water Program (Lew, 1998). The difference between the two numbers, in part, reflects a difference in the definition of "long-term" observation wells. However, a continuing decrease in the number of long-term observation wells monitored under the USGS Cooperative Water Program is consistent with the national trends noted in the 1997 inventory and in tracking USGS data-collection activities.

In many States, a lack of sufficient financial resources impedes the construction of new observation wells in areas of need. To eliminate costs incurred by drilling and well construction, most agencies use private water wells or existing monitoring wells for the collection of water-level data. These "wells of opportunity" are often useful as long-term observation wells, but a problem reported by many States is the difficulty in locating suitable existing wells in specific aquifers or geographic locations. Limitations in funding and staffing also impair observation-well maintenance, upgrades to water-level-monitoring equipment, and consistency in water-level monitoring activities conducted from year to year.

A proper evaluation of the suitability of existing observation-well networks is best done at the State and regional level, where the diversity in topographic, climatic, and geologic settings, ground-water use, and other factors can be properly considered. Two indicators of the status of observation-well networks are presented here that may be useful in comparing the approximate magnitude of long-term observation-well networks by State or region. The first indicator, observation-well density, is the ratio of the reported number of long-term observation wells in each State to the area (in 1,000 square miles) enclosed within State boundaries (Figure 27). The second indicator, which relates water-level data collection to ground-water use, is the ratio of the reported number of long-term observation wells to the total amount of ground water withdrawn (in 100 million gallons per day) from each State (Figure 28).

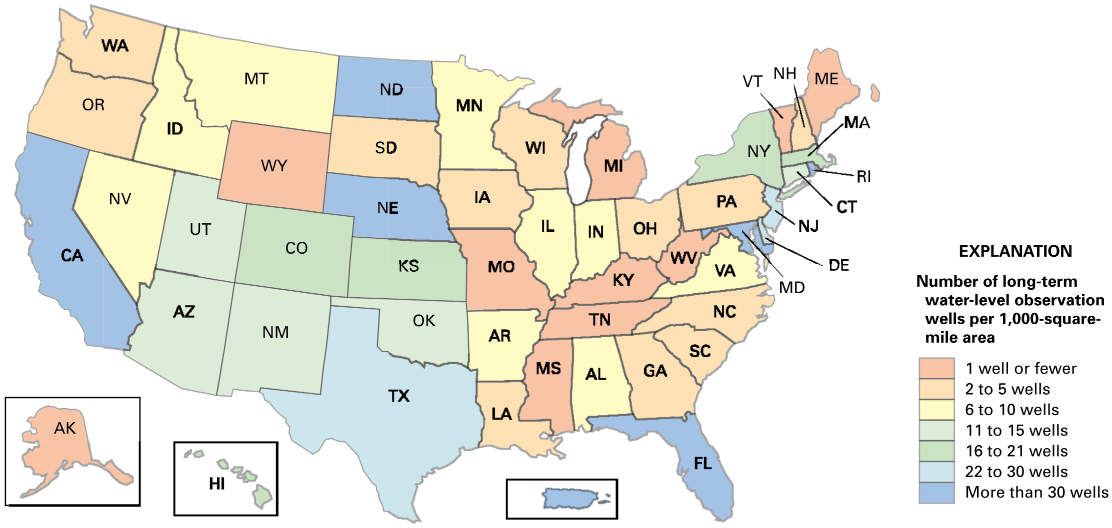


Figure 27. *Number of long-term water-level observation wells per 1,000-square-mile area in each State and in Puerto Rico.*

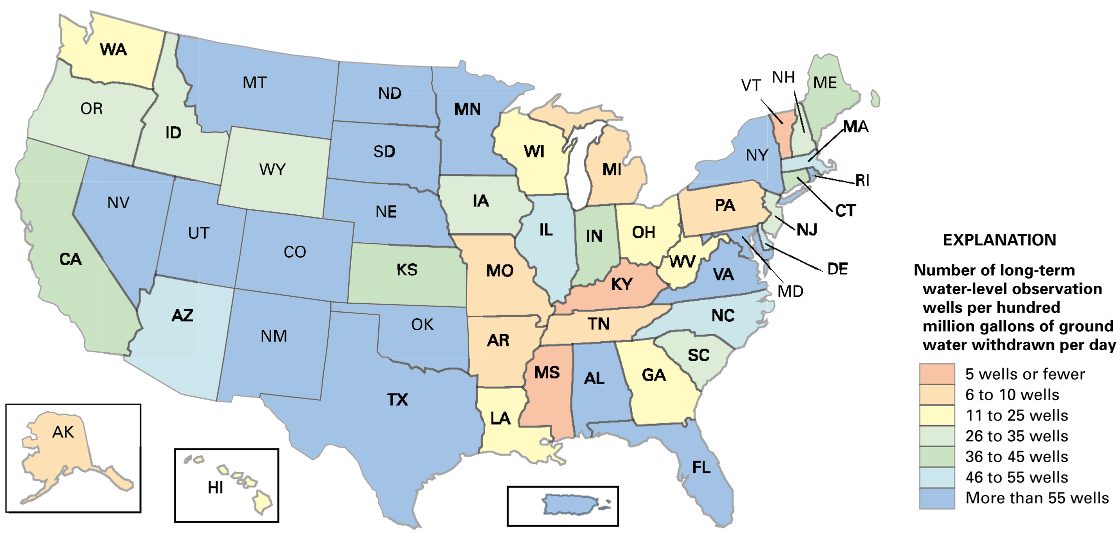


Figure 28. *Number of long-term water-level observation wells per hundred million gallons of ground water withdrawn per day in each State and in Puerto Rico.*

The information presented by the maps in Figures 27 and 28 provides some indication of the relative magnitude of long-term ground-water-level data collection in various parts of the Nation. The data do not indicate the degree to which observation wells are distributed geographically and among aquifers in any particular State. Large observation-well networks in States having comparatively high values of one or both indicators may be good candidates for network evaluation designed to determine if monitoring sites may be reduced or redistributed to enhance data collection or reduce operational costs (see Box C). Conversely, comparatively low values of one or both indicators generally reflect a sparse number of wells relative to geographic area or to ground-water use in the indicated State. In these cases, in particular, a larger number of observation wells may be needed to ensure that sufficient water-level data are being collected, at a minimum, where ground-water withdrawals are concentrated or where sensitive environmental areas are located.

As with streamflow and precipitation data, ground-water-level data become increasingly valuable with length and continuity of the records. Yet, unlike streamflow and meteorological records, ground-water-level records in most parts of the Nation are less than 40 years in length. Forty-four percent of agencies reported having observation-well networks in which the typical hydrologic record was 25–40 years, 31 percent reported having observation-well networks in which the typical hydrologic record was 10–25 years, and 2 percent reported having networks in which the typical hydrologic record was less than 10 years. Twenty-two percent of the agencies reported that observation wells in their networks had periods of hydrologic record too varied to characterize.

In recent years, the USGS and many State and local agencies have experienced difficulties in maintaining long-term water-level-monitoring programs because of limitations in funding and human resources. Where fiscal or personnel constraints have forced agencies to revise priorities for environmental data collection, preference typically has been given to water-quality monitoring, often at the expense of basic ground-water-level monitoring. Although water-level and ground-water-quality monitoring are complementary activities, these two types of data commonly are treated as mutually exclusive, and separate agencies commonly are responsible for each. Greater attention is needed to the long-term value of water-level data collected as part of water-quality monitoring and to the potential synergies between water-quality and water-level-monitoring networks.

In many States, observation wells tend to be concentrated in areas where aquifers are heavily developed. Few long-term observation wells are intentionally located away from the influence of pumping, irrigation, and other human activities to allow for monitoring of the natural effects of climate variability and to provide baseline data against which ground-water levels monitored during short-term investigations can be better evaluated in a longer term climatic perspective. The U.S. Geological Survey presently operates a sparse

Greater attention is needed to the long-term value of water-level data collected as part of water-quality monitoring and to the potential synergies between water-quality and water-level-monitoring networks.

Increased numbers of climate-response observation wells and long-term monitoring of naturally occurring fluctuations in ground-water levels are needed to develop more complete ongoing assessments of droughts and the cumulative effects of other climatic phenomena.

national network of about 140 climate-response wells (Figure 29), and a few States have drought-monitoring networks that include climate-response observation wells, such as previously noted for Pennsylvania. Increased numbers of climate-response observation wells and long-term monitoring of naturally occurring fluctuations in ground-water levels are needed to develop more complete ongoing assessments of droughts and the cumulative effects of other climatic phenomena (Alley, 2001). During drought conditions, the effective management of ground-water resources, and monitoring of ground-water availability and ground-water and surface-water interaction, require the ability to rapidly collect water-level measurements and track trends. Therefore, more efforts should be made to construct climate-response and other observation wells capable of collecting "real-time" water-level measurements, and to make all collected water-level data more rapidly and readily accessible through electronic transmittal.

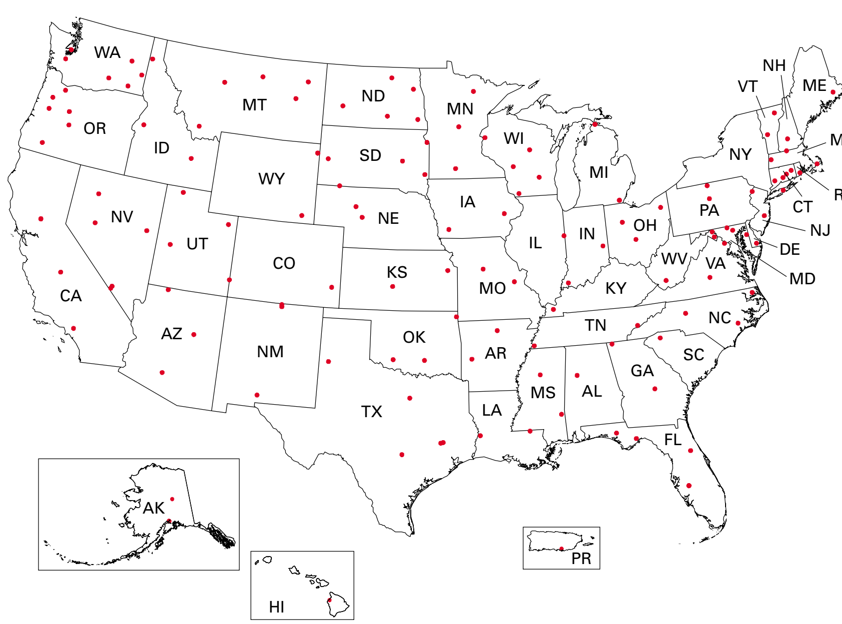


Figure 29. *Location of observation wells in the USGS national climate-response ground-water-level network.*

D

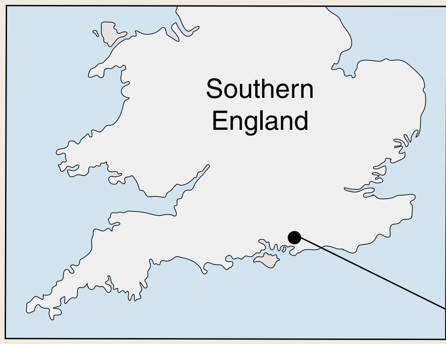
Ground-Water-Level Monitoring in the 1930's, 1950's, and Today

The severe drought of the 1930's in much of the United States created widespread concern that declining water levels in wells and diminished flow of springs may be warnings of the eventual exhaustion of the Nation's ground-water supplies. During the drought years of the 1930's, considerable interest arose in the establishment of systematic programs for monitoring water levels in observation wells. It is instructive to compare the status of water-level monitoring during the 1930's, during the 1950's (a second severe drought period), and today at the beginning of the 21st century.

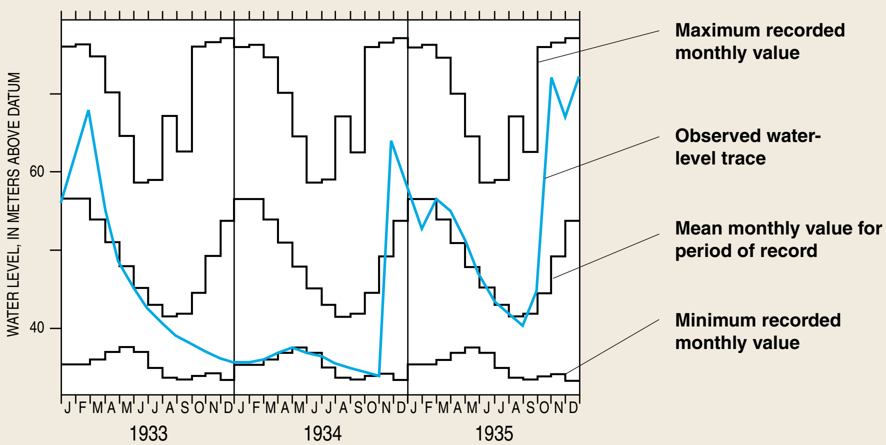
1930's—In 1933, about 3,000 observation wells were being measured periodically by the USGS and by State agencies, and about 115 of these wells were equipped with automatic (continuous) water-level recorders. Records of water levels covering many years were available for only a few areas, notably southern California, Honolulu, the Roswell Basin in New Mexico, and Long Island, New York. Other areas of heavy withdrawals had more sporadic water-level records. In 1936, the USGS released the first annual report on the fluctuations of ground-water levels and artesian pressures in the United States (Meinzer and Wenzel, 1936). This report was envisioned "as a step in the realization of a nationwide program of water-level records." At the time, it was noted that the availability of water-level records was dependent upon ongoing investigations and that some of the most valuable records were in danger of being discontinued because of lack of funds for the projects that supported the monitoring. The need also was expressed for more observation wells outside of areas of major ground-water withdrawals to provide information on the effects of climatic variations on water levels. In addition, increased automatic monitoring of water levels was recommended.

1950's—Ground-water levels at the end of 1954 were at or near record lows throughout most of the southern two-thirds of the United States, creating renewed concern about the possible exhaustion of the Nation's ground-water supplies (Fishel, 1956). Federal, State, and local agencies measured water levels in about 20,000 long-term observation wells across the country with records for many of the observation wells dating back to the 1930's. Fishel (1956) used water-level records from nine States to illustrate how in most areas the low water levels were largely a function of the dry climate conditions and would recover after the drought ended. Fishel also noted that significant water-level declines in some areas, including "some of the best and most important aquifers," were caused by large ground-water withdrawals, and that water-level declines in these areas would likely persist or worsen after the drought ended.

Today (2001)—There are on the order of 42,000 long-term observation wells in the United States with 5 or more years of water-level record. These wells are distributed throughout all States, and the level of effort varies greatly among States. No nationwide, systematic water-level monitoring program exists. Observation wells are still largely selected from existing wells that are part of specific studies, and the continuity of records is difficult when studies draw to a close. The ease of making data available on the Internet enhances the value of automatic water-level monitoring beyond that of the previous decades, but automatic measurement of water levels in long-term observation wells remains limited (for example, less than 10 percent of USGS long-term monitoring wells have continuous monitoring). Relatively little long-term monitoring takes place outside of major withdrawal areas. Concerns about the exhaustion of ground-water supplies exist for parts of the United States, but no longer for the Nation as a whole. Concerns about the effects of pumping on surface-water bodies, about water quality, and about the effects of possible climate change on ground-water and surface-water resources are much greater than in the 1930's and 1950's.



Chilgrove House



Ground-water levels have been measured from 1836 to the present on an almost continual basis at the Chilgrove House well in the south of England (Monkhouse and others, 1990). The well is completed in a chalk aquifer, and the hydrologic record for the well represents the longest period of measurement for any well in the United Kingdom. Snapshots of the water-level record for this well show the intensity of drought conditions from 1933 to 1935 in the context of the more than 160 years of record at the site. (Photograph by Terry J. Marsh, Centre for Ecology and Hydrology, Wallingford, England.)

CHALLENGES AND FUTURE OPPORTUNITIES

The focus of this report has been to illustrate the importance of systematic, long-term collection of water-level data. Such data are crucial to the investigation and resolution of many complex water-resources issues commonly faced by hydrologists, engineers, water-supply managers, regulatory agencies, and the public. To ensure that adequate water-level data are being collected for present and anticipated future uses, observation-well networks and water-level monitoring programs at the local, State, and Federal level need to be evaluated periodically. In the course of these evaluations, several questions might be asked. Are data being collected from areas that represent the full range in variation in topographic, hydrogeologic, climatic, and land-use environments? Are plans to ensure long-term viability of observation-well networks and data-collection programs being made? How are the data stored, accessed, and disseminated? Who are the principal users of water-level data, and are the needs of these users being met?

To ensure that adequate water-level data are being collected for present and anticipated future uses, observation-well networks and water-level monitoring programs at the local, State, and Federal level need to be evaluated periodically.

Careful planning and design are required to ensure the collection of high-quality water-level data over the period of time needed to compile a useful hydrologic record of water-level changes. A further challenge is to supplement the long-term monitoring wells as hydrologic conditions in aquifers evolve. A comprehensive monitoring program should consider aquifers substantially affected by ground-water pumping, areas of future ground-water development, surficial aquifers that serve as major areas of ground-water recharge, and links with water-quality and surface-water monitoring.

A commitment to long-term monitoring is needed to avoid data gaps resulting from an inadequate distribution of observation wells or periods of no measurements in a hydrologic record. Many agencies lack formalized written plans for the design and operation of ground-water-level networks, and many agencies have difficulty maintaining funding and program continuity necessary to ensure long-term collection of water-level data. Disruptions in the hydrologic record provided by water-level data collection and the gaps in data coverage can hinder the ability of water-resources managers to make sound resource-management decisions. Where water-level data are not available, hydrologic information needed to address critical ground-water problems may be impossible to obtain. Much recent effort has been made in the application of computer modeling techniques to forecast future ground-water levels. However, the successful application of even these advanced methods requires that sufficient water-level data are available.

More effort is needed to increase the amount of ground-water-level data stored in electronic databases, to increase the compatibility between databases, and to improve access to ground-water-level data on the Internet. Although some water-level databases can be accessed in this way, detailed and complete records of historical water-level data usually are limited or unavailable. In many agencies, large backlogs of historical ground-water-level data have not been entered into electronic databases, let alone made available on the Internet. Consequently, potentially useful data are residing in paper files where accessibility and utility are very limited.

Finally, to increase the collection and accessibility of water-level data, agencies need to examine ways to increase interagency coordination in constructing and maintaining observation-well networks, collecting water-level measurements, and sharing and disseminating data. Greater interagency cooperation will help ensure that data-collection efforts are sufficient to address issues relevant to the greatest variety of local, State, regional, and national water-resources issues.

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Members of State and Federal agencies and local citizens group discuss results of ground-water-level monitoring at a landfill research site in Connecticut. Photograph by Susan Soloyanis.

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