C

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.

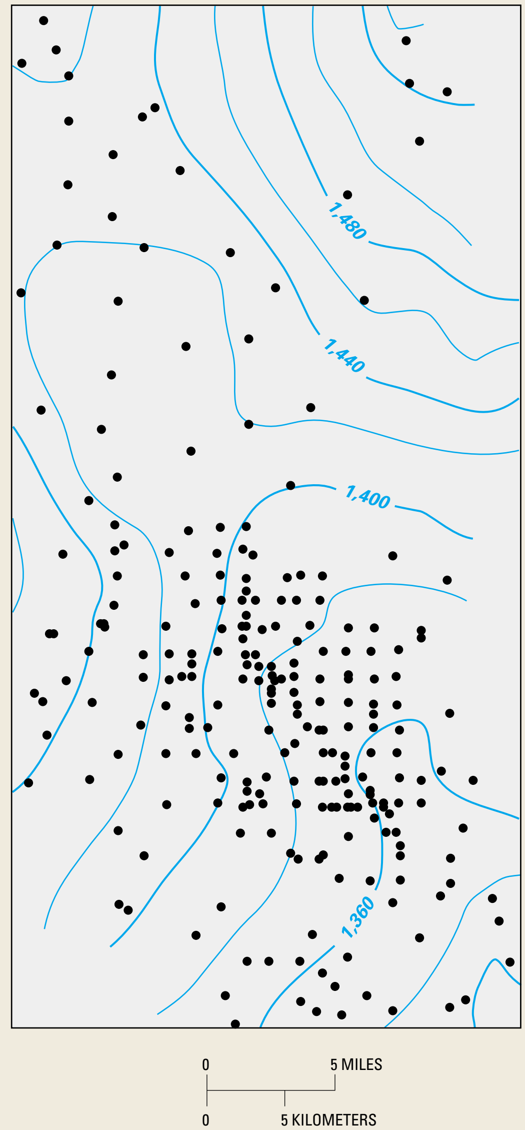

Figure C–1. *Water-table elevation in the Equus Beds aquifer, based on data from network of 244 observation wells. Circles show locations of observation wells. (Modified from Olea, 1984.)*

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.

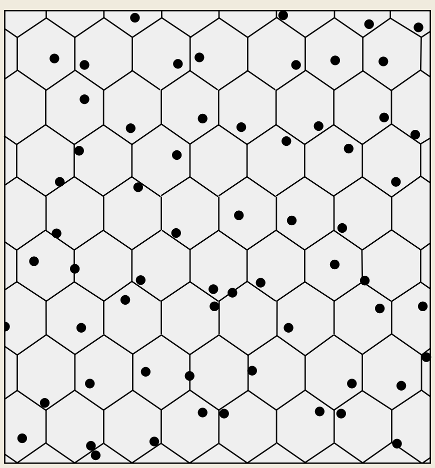

Figure C–2. *Example of hexagonal sampling. Olea (1984) found the hexagonal pattern to be more efficient than a square pattern for selecting wells.*

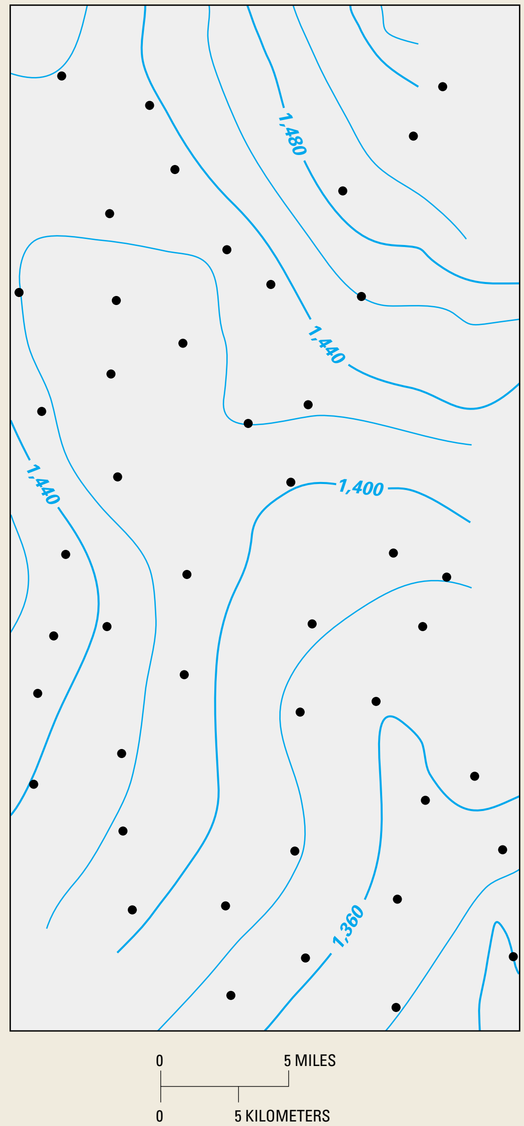

Figure C–3. *Water-table elevation in the Equus Beds aquifer, based on data from network of 47 wells selected using 16-square-mile hexagons. Circles show locations of observation wells. (Modified from Olea, 1984.)*

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

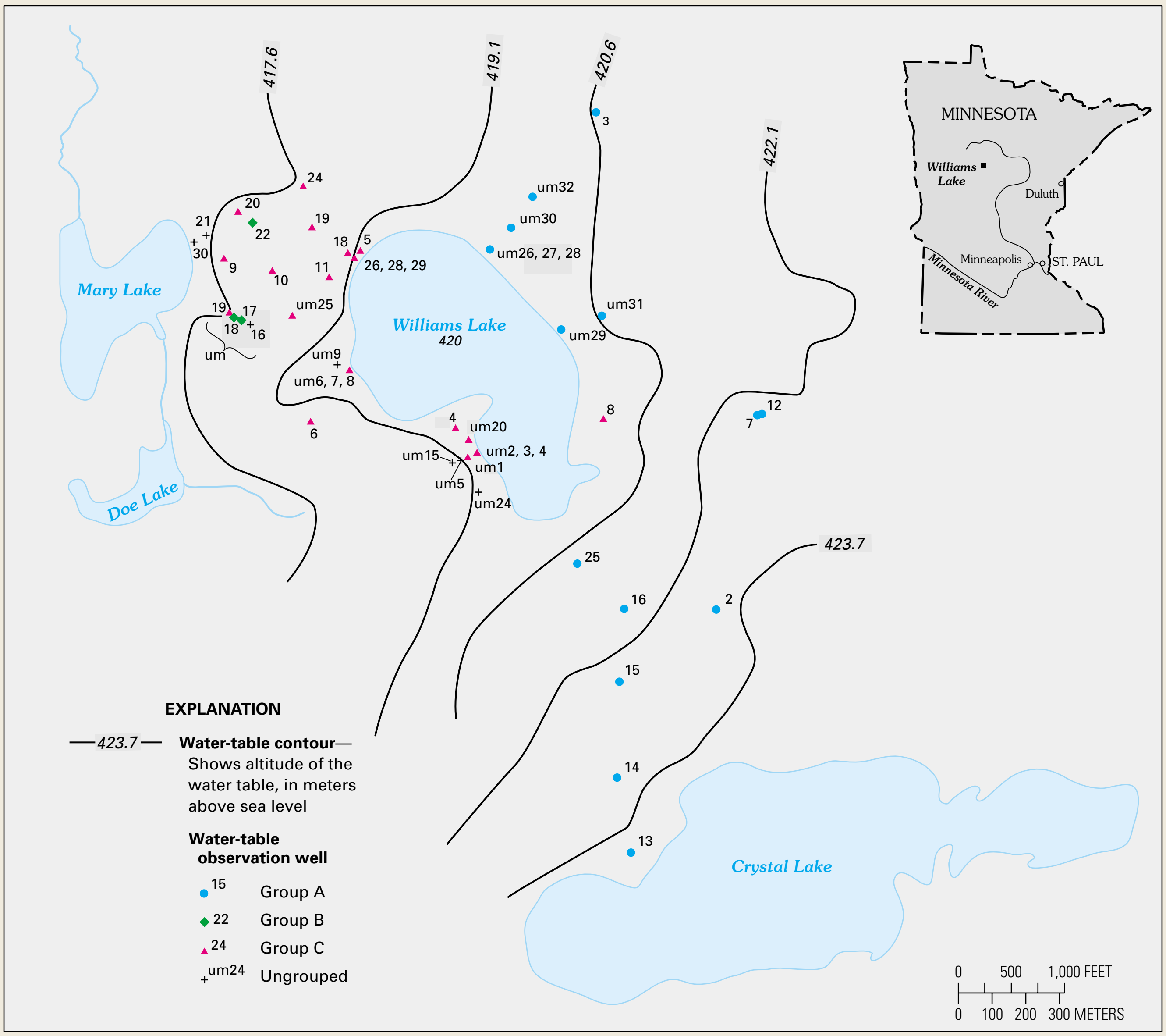

Figure C–4. *Location of observation wells near Williams Lake in Minnesota. Well groups are based on the delineations shown in Figure C–6 and discussed in the text. (Modified from Winter and others, 2000.)*

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

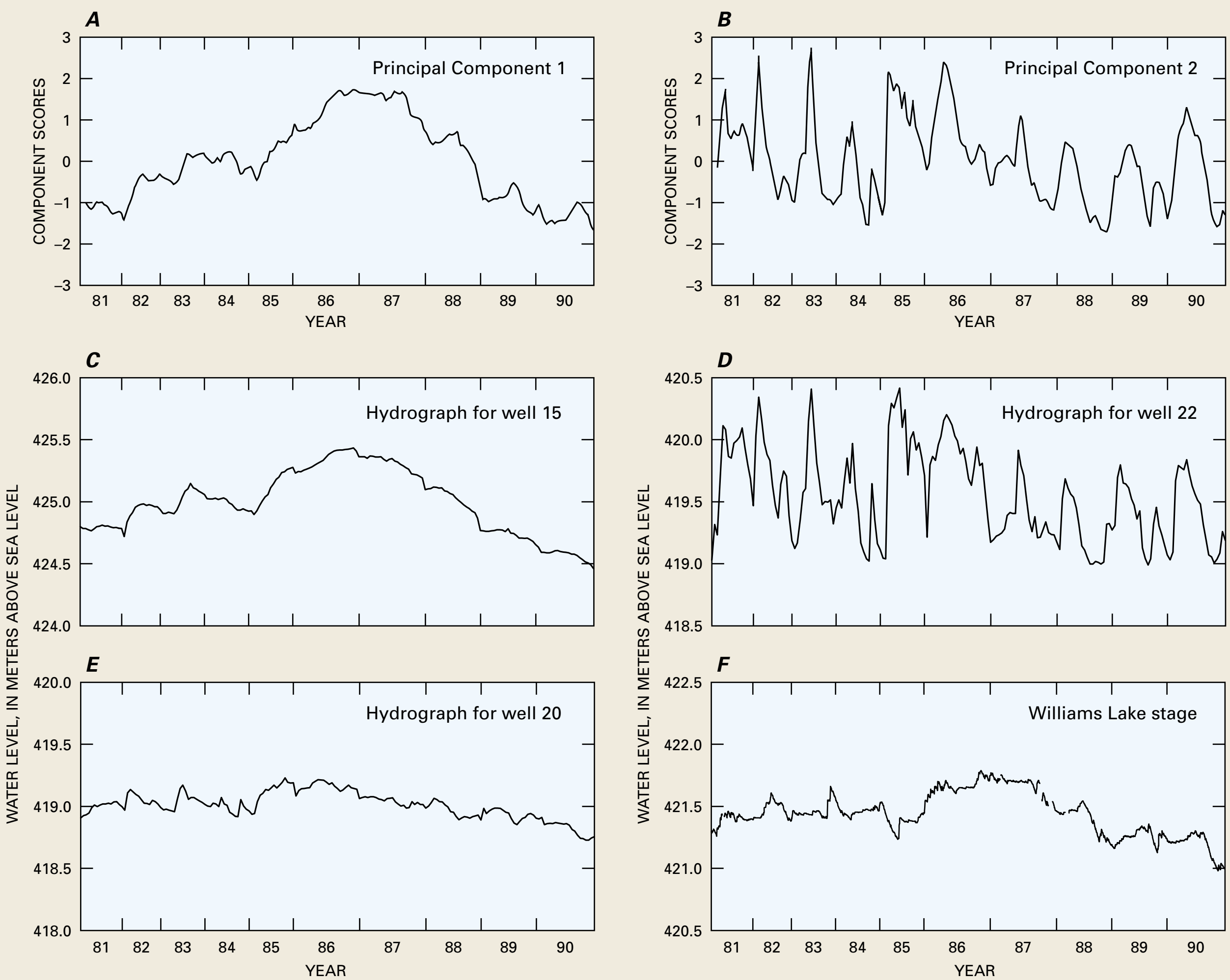

Figure C–5. *Selected graphs for the Williams Lake area of Minnesota, including (A) component scores for principal component 1, (B) component scores for principal component 2, (C) water level in well 15, (D) water level in well 22, (E) water level in well 20, and (F) stage of Williams Lake. The variable 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.

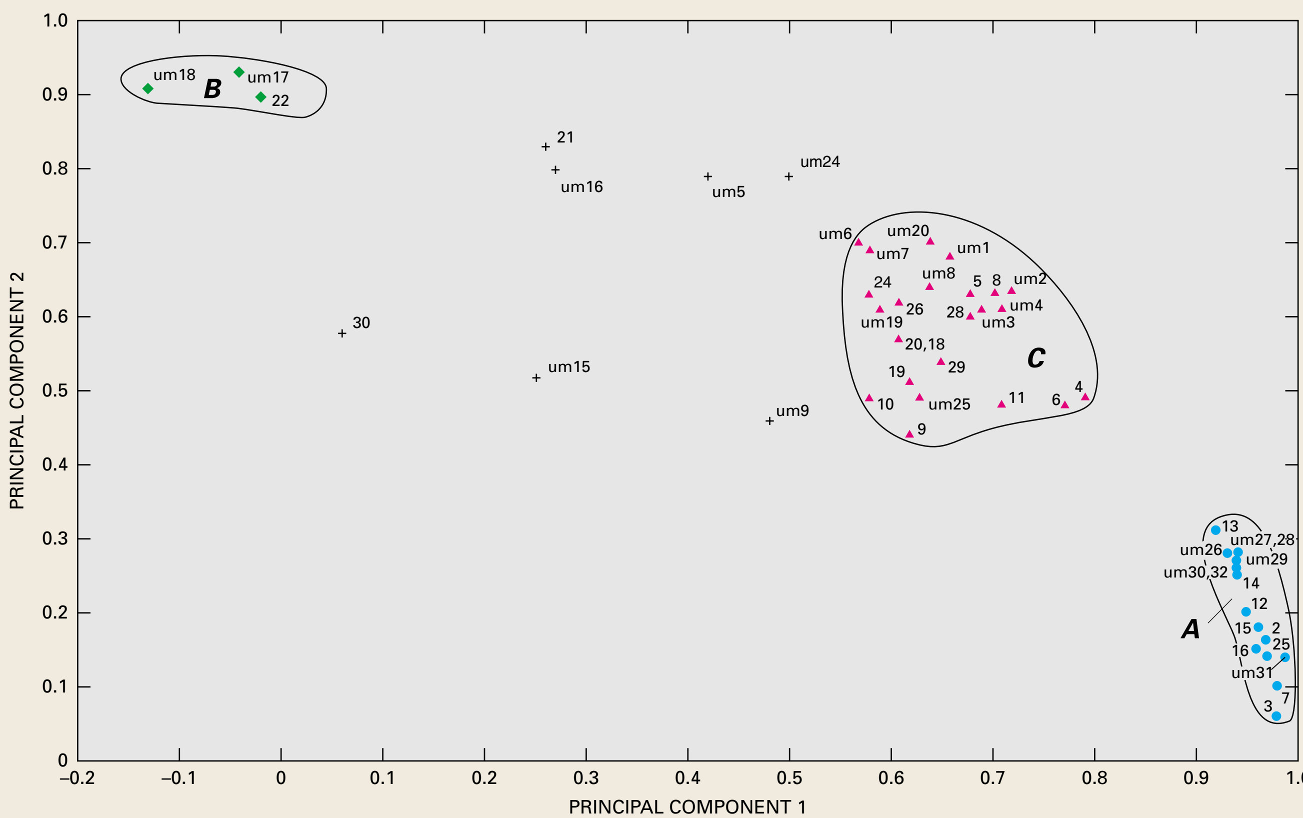

Figure C–6. *Plot of component loadings for principal component 1 versus principal component 2 for wells in the Williams Lake area. (Modified from Winter and others, 2000.)*

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).

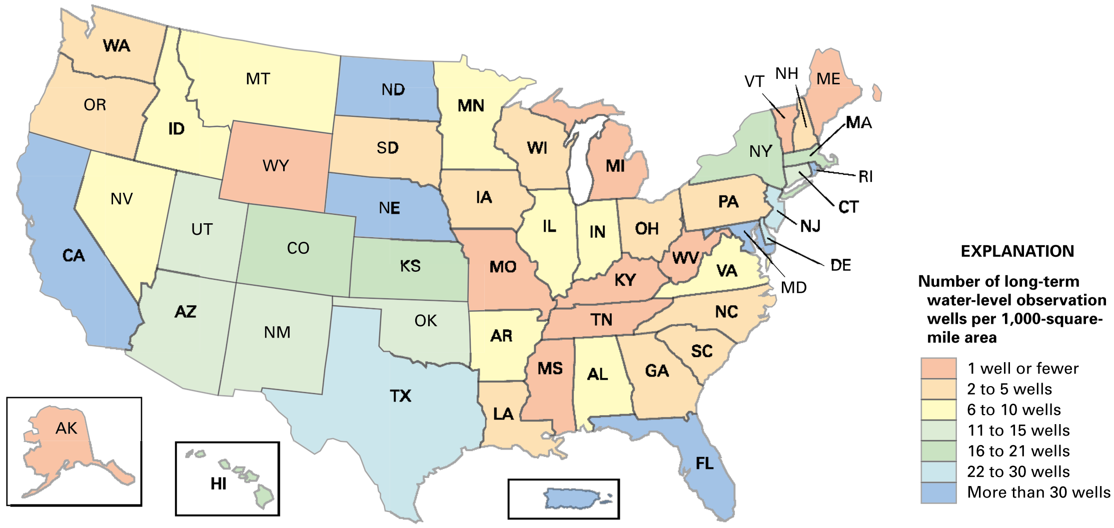

Figure 27. *Number of long-term water-level observation wells per 1,000-square-mile area in each State and in Puerto Rico.*

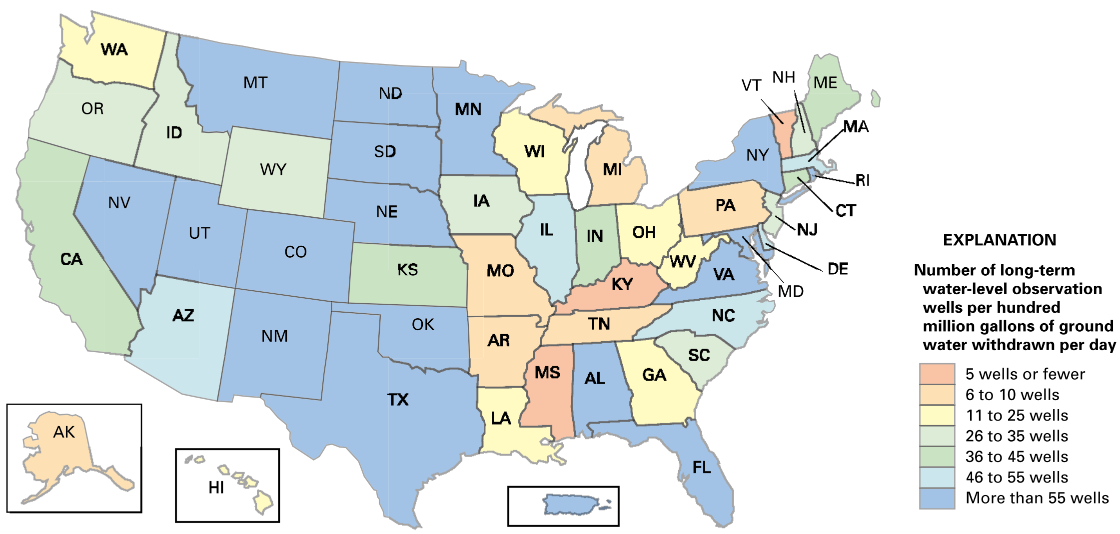

Figure 28. *Number of long-term water-level observation wells per hundred million gallons of ground water withdrawn per day in each State and in Puerto Rico.*

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

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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.

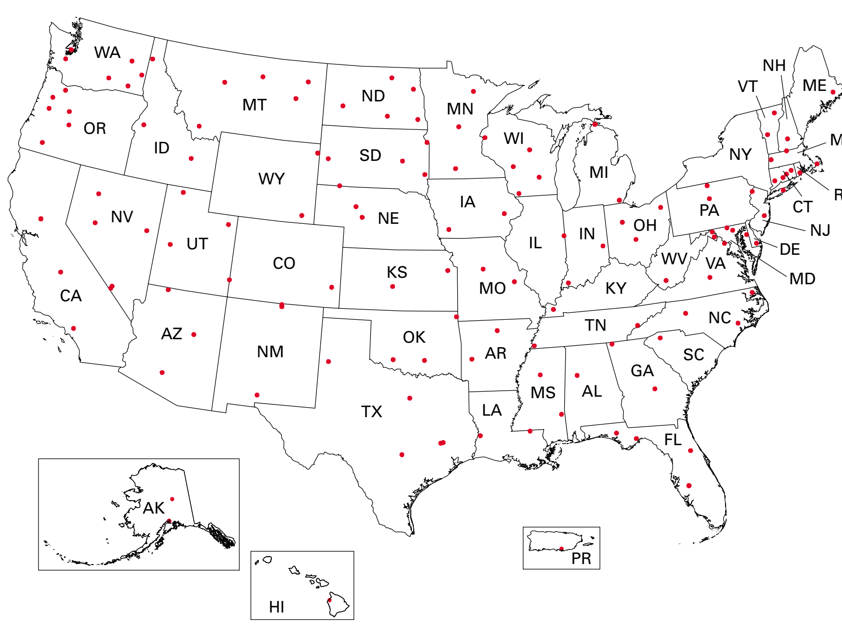


Figure 29. *Location of observation wells in the USGS national climate-response ground-water-level network.*

D

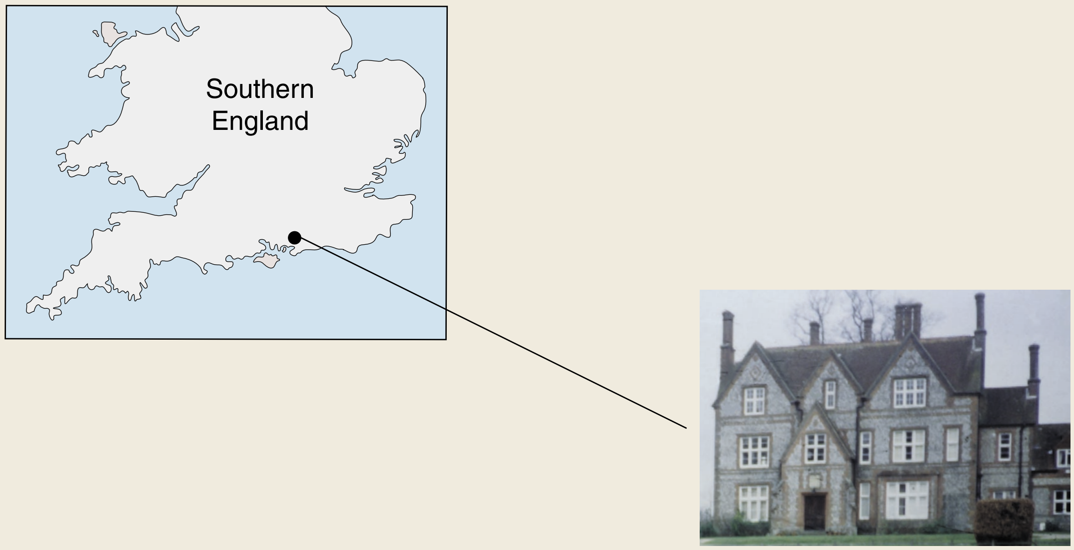
Ground-Water-Level Monitoring in the 1930's, 1950's, and Today

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.

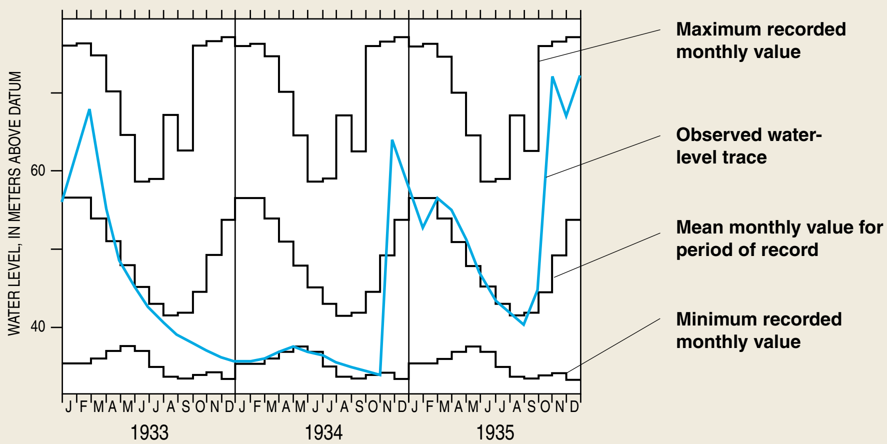
1930's—In 1933, about 3,000 observation wells were being measured periodically by the USGS and by State agencies, and about 115 of these wells were equipped with automatic (continuous) water-level recorders. Records of water levels covering many years were available for only a few areas, notably southern 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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