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Design of Ground-Water Level Observation-Well Programs

by Ralph C. Heath

Reprinted from the March-April 1976, Volume 14, Number 2 issue of *Ground Water*

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ABSTRACT

Data obtained from observation-well programs are used to determine (1) the effect of withdrawals on recharge and natural discharge conditions, (2) the hydraulic characteristics of ground-water systems, and (3) the extent and degree of confinement of aquifers. Wells in these programs can usefully be divided into three networks: (1) a hydrologic network which includes wells needed to determine the extent of aquifers and changes in storage, (2) a water-management network which includes wells needed to determine the effect of withdrawals and hydraulic characteristics, and (3) a baseline network which includes wells needed to determine the response of ground-water systems to natural changes such as those related to climate.

INTRODUCTION

Measurements of the position of the water level in wells has long been an important part of ground-water investigative programs. A survey of observation wells in use in the United States in 1968, conducted by the Office of Water-Data Coordination of the U.S. Geological Survey, revealed 28,964 such wells (Pauszek, F. H., 1972). Clearly, a large amount of effort is being devoted to the collection of data on fluctuations of ground-water levels.

The data obtained in this program are used for a variety of purposes. Possibly the most important use, at least in terms of the number of wells involved, is for determining seasonal and long-term changes in ground-water storage. Other uses include determining (1) the effect of withdrawals (stresses) on recharge and natural discharge conditions, (2) the hydraulic characteristics of ground-water systems, (3) their degree of confinement, and (4) their areal extent. All of these uses relate to the basic objective of most ground-water studies—that is, the determination of how much water can be withdrawn from the ground. Data from observation wells are also used in various research projects not directly related to determining the yield of ground-water systems. These include studies of land-surface subsidence, the prediction and prevention of earthquakes, and the effect of modifications of the natural environment on ground-water systems.

In view of the existence of observation-well programs in every State in the United States and in most other countries, a logical question at this point might be whether to review the existing program or, as suggested by the title of this paper, design a new program. It can be argued that a rational and critical review of existing programs can be made only after designing a new program. That is, before determining the adequacy of an existing program, it is first necessary to (1) identify the objectives of the program and (2) determine in fairly definite terms what wells are needed to meet these objectives. Once these two requirements are met it is relatively simple to determine which wells in the existing program are providing useful data.

In an effort to encourage a critical review of existing observation-well programs, in accordance with the principle discussed in the preceding paragraph, the remainder of this paper will be devoted to a brief discussion of program objectives and the observation-well networks needed to meet these objectives.

It should be noted at this point that this paper deals only with water-level observation programs.

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Discussion open until August 1, 1976.

The fact that chemical quality, temperature, and other types of data may be collected from observation wells is not considered. I should also note that some of the objectives of observation-well networks can be met with other types of ground-water data, but this fact is also not considered in this article.

OBJECTIVES OF OBSERVATION-WELL PROGRAMS

The objectives of observation-well programs mentioned above are listed in Table 1 along with the types of water-level fluctuations that must be observed to meet these objectives. The numbers in the table refer to the kinds of water-level observations needed to observe the different types of fluctuations. Each of the objectives listed in the Table are discussed in the following sections.

Status of Storage

In the arid parts of the western United States, a sizable proportion of ground-water withdrawals is from storage. In these areas, periodic observation of the status of ground-water storage and determination of the rate at which it is being depleted are of considerable importance. Figure 1 shows the decline in ground-water levels in an area in Arizona, as determined from observation-well data. So far as is known, ground-water storage is not being progressively depleted in any area in the eastern part of the country. However, ground-water levels are progressively declining in the Cretaceous aquifers in parts of the Atlantic Coastal Plain but analyses have not yet been made to determine how much of the decline is due to increasing withdrawal and how much to delay of the system in establishing a new equilibrium.

Where depletion of storage is an important problem, wells, more or less randomly spaced over the affected area, are selected for annual or more frequent measurements.

Effect of Stresses on Recharge and Discharge Conditions

Theis (1937) has pointed out that unless and until withdrawals are balanced by an increase in recharge or a reduction in natural discharge, water will be removed from storage and water levels will decline. Therefore, the rate at which water can be removed from a ground-water system for an indefinitely long period (i.e., what some hydrolo-

Table 1. Objectives of Observation-Well Programs and Types of Water-Level Fluctuations Normally Observed (1. Single Measurements at Many Points, Repeated at Intervals of Months or Years; 2. Measurement at Daily, Weekly, or Monthly Intervals for Long Periods; 3. Continuous Measurements for Short to Medium Periods; and 4. Continuous Measurements for Long Periods)

Objectives of observation-well programs	Types of water-level fluctuations											
		Short-period phenomena (0.01-1.0 days)				Medium-period phenomena (1.0-100 days)			Long-period phenomena . (more than 100 days)			
	Periods without fluctuations	Earthquakes	Atmospheric pressure	Earth and ocean tides	Man-controlled loading	Cyclical withdrawal or injection	Precipitation	Stream and lake fluctuations	Seasonal changes in climate	Long-term changes in climate	Progressive changes in withdrawals	Unanticipated changes in withdrawals
Status of storage	1								2	2	2	
Effect of stresses on recharge and discharge conditions	1					3	2-3	3	2-3	2	2	
Hydraulic characteristics:												
Transmissivity	1			3		3		3				
Storage coefficient						3	3	3				
Degree of confinement		3	3	3	3	3	2-3	3			2	4
Areal extent of aquifers	1					3					2	4
Research				Depends on objective of research								

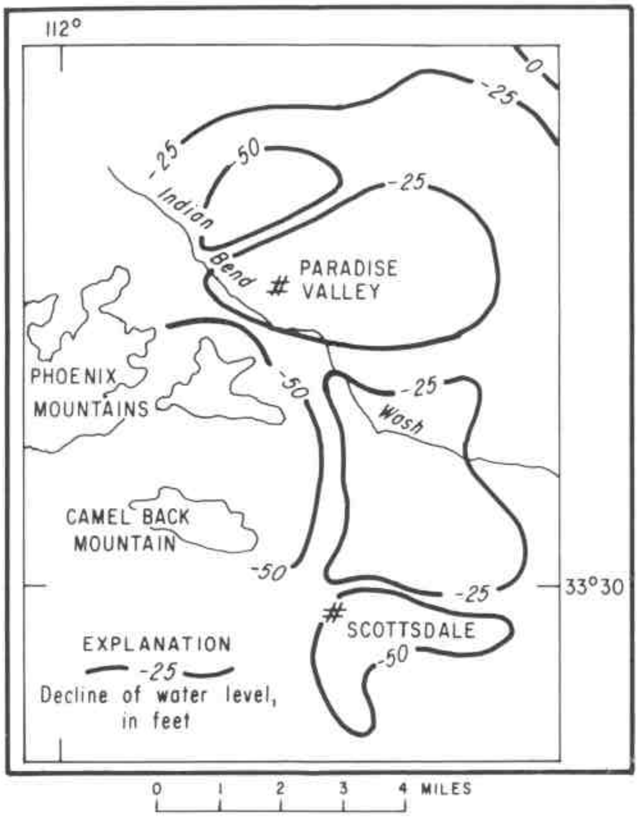

Fig. 1. The depletion of ground-water storage is an important problem in the arid parts of the West. This Figure shows the decline in ground-water level in a part of the Paradise Valley in Arizona (adapted from Arteaga and others, 1968).

gists would call the perennial yield) depends on the extent to which withdrawals affect recharge and natural discharge conditions. We can reliably predict this effect for relatively few systems at this time. For the remainder, we must continue to observe and analyze their response to imposed stresses.

Records of ground-water levels related to two different pumping situations are particularly important in predictions of long-term yields. The first is a record of the change in drawdown with time in response to a large and relatively constant withdrawal. The second, and more important, is the change in drawdown resulting from a gradual or stepwise increase in withdrawals. Crain (1966) effectively used data of the latter type to predict the yield of a glacial outwash aquifer near Jamestown, New York (see Figure 2).

In order to identify the change in water level resulting from withdrawals, it is necessary, in many cases, to be able to correct for water-level changes due to other causes such as seasonal and longer-term variations in climate. In this regard, it is also important to note that seasonal and long-term changes in climate constitute natural stresses on ground-water systems which provide useful clues on how the systems will respond to the stresses of large withdrawals.

Determining the response of ground-water systems to stress is by far the most important objective of an observation-well program.

Hydraulic Characteristics of Ground-Water Systems

The most important hydraulic characteristics of a ground-water system are its capacity to transmit water (its transmissivity) and its capacity to store water and to release water from storage (its storage coefficient). Knowledge of transmissivity is essential for nearly all predictions of well and aquifer yields and is one of the parameters that must be included in digital and analog models. The storage coefficient affects the rate of response of a ground-water system to stress. Knowledge of it is essential in predicting drawdowns under transient conditions.

Both transmissivity and storage coefficient are most often determined by pumping tests made for that purpose. However, they may also be determined from data collected during routine operations of an observation-well program. These are indicated in Table 1 and include the analysis of water-level maps prepared from a "simultaneous" series of measure-

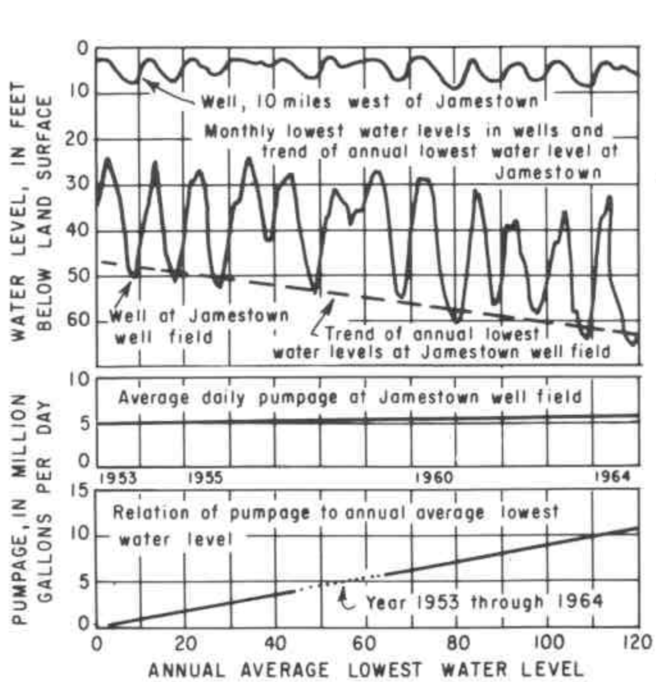

Fig. 2. Drawdowns resulting from increasing withdrawals are invaluable in understanding how aquifers respond to stress and thus are an essential element in predicting long-term yields. This Figure shows how water-level data for the Jamestown area, New York, was used to predict future yields. (Adapted from Crain, 1966, Figure 30.)

ments made in observation wells throughout an area and an analysis of continuous records showing fluctuations due to tides, cyclical pumping, or any other pulse induced in the hydrologic system.

Degree of Confinement

The response of an aquifer to stress depends to a large extent on whether it is unconfined or confined and, if confined, on the hydraulic conductivity of the confining beds. The degree of confinement of an aquifer is quantitatively indicated by its storage coefficient. It is qualitatively indicated by the response of water levels to short-period phenomena such as earthquakes, changes in barometric pressure, tides, and the passage of railroad trains or other heavy loads. It may also be apparent from fluctuations caused by cutting pumping wells on and off, from the rise of water levels resulting from individual rains, and from fluctuations caused by changes in stream and lake stages.

An indication of the degree of confinement is the minimum information that should be obtained from any observation well. In order to obtain this it is necessary in most cases to operate a graphic recorder on the well at least for a month or two. It is desirable to insert a word of caution at this point relative to interpreting the degree of confinement from changes in ground-water levels. For example, barometric fluctuations are sometimes observed in unconfined aquifers overlain by an unsaturated zone containing extensive clay layers. Such fluctuations are also observed during the winter in cold regions when the soil zone is frozen.

Areal Extent of Aquifers

The yield of a ground-water system depends on the areal extent of the aquifers comprising the system and the hydrologic nature of their boundaries. The extent of some aquifers—for example, an alluvial or a glacial outwash aquifer—may be readily apparent from surface observations or from geologic or topographic maps. The extent of other aquifers—for example, aquifers such as those underlying the Atlantic and Gulf Coastal Plains—may not even be obvious from detailed stratigraphic maps. The most practical way to determine the extent of such aquifers is to observe the regional continuity of water levels. Classic examples are the water-table map of Long Island and the map of the potentiometric surface of the Floridan aquifer (see Figure 3). Water-level data showing regional cones of depression around major pumping centers provide similar information.

Determination of the regional continuity of water levels requires water-level measurements made over a relatively short period in large numbers of wells (so-called "mass measurements") or, when this is not possible, the adjustment to a base period of water-level measurements made at different times. The extent of aquifers (or what might more properly be called their uninterrupted hydraulic continuity) may also be determined from data collected at widely-spaced observation wells, as Leggette (1937) demonstrated for the artesian system on Long Island when he observed the drawdown and recovery of the water level in an observation well more than seven miles from a pumping well.

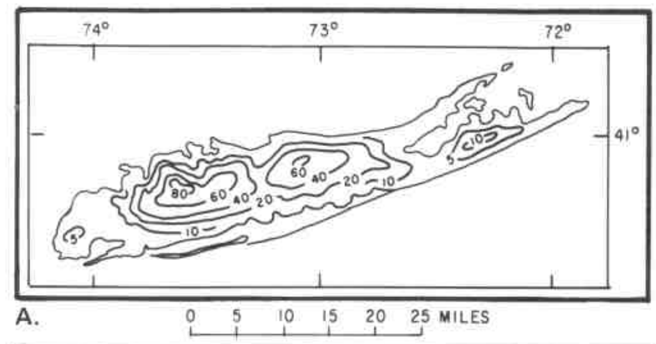

Fig. 3. The areal extent of aquifers is indicated by water-table and potentiometric-surface maps. Such maps are also invaluable in predicting the response of aquifers to stresses and in analysis of changes in ground-water storage.

A. Map of Long Island, New York, showing the altitude and configuration of the water table. Contours are in feet above sea level; interval is variable.

B. Map of Florida showing the potentiometric surface of the Floridan aquifer. Contours are in feet above sea level; contour interval is variable.

Research

Data from observation wells are also used in various research projects not directly related to determining the yield of ground-water systems. As noted earlier, these include studies of land-surface subsidence, the prediction and prevention of earthquakes, and the effect of modifications of the natural environment on the ground-water system.

COMPONENTS OF OBSERVATION-WELL PROGRAMS

How can the objectives described above be used in the design of an observation-well program? The objectives are not exclusive so that the same well or group of wells will satisfy more than one. From the standpoint of program design, it is useful to think of the first two objectives as of primary importance and the remainder, with the possible exception of research, as of secondary importance. Primary, as used here, is an objective that cannot normally be satisfied except with an observation-well program. A secondary objective is one that may be satisfied either by wells operated for a primary objective or by other means. For example, data on the hydraulic characteristics of aquifers and on their degree of confinement and their extent may be obtained from aquifer tests.

Wells needed to meet program objectives consist of the three networks listed in Table 2 and described in the following sections.

Hydrologic Network

Relative to the status of storage, this is generally determined by comparing two water-table or potentiometric-surface maps based on measurements separated by a significant period of time, such as a year or several years. Such maps are usually prepared only for extensive aquifers that are either already heavily developed or are undergoing rapid development.

For convenience, we can refer to wells used to periodically determine the status of storage as a *hydrologic network.* Such a network would consist of wells more or less randomly spaced over the area to be mapped, which may range in size from a part of a county to several States. The position of the water level with respect to mean sea level or some other datum, would be measured "simultaneously" in all the wells.

The density of wells—that is, the number of wells per unit of area—needed in a hydrologic network would depend on the complexity of the system and the level of detail desired. It may range from more than 100/1,000 mi^2 for a complex area to be mapped in considerable detail to 2/1,000 mi^2 for a large area in which only the major features are mapped. The first time the water-table or potentiometric-surface in an area is mapped, it is desirable to obtain the maximum possible amount of information. Good network management after this should be concerned with identifying those

Table 2. Summary of Observation-Well Networks

Network	*Objectives*	*Products*
Hydrologic	(a) Status of storage	(a) Regional water-table and/or potentiometric-surface maps
	(b) Areal extent of aquifers	(b) Maps showing net change in water levels or storage over a selected period
Water-Management	(a) Effect of stresses on recharge and discharge conditions	(a) Local water-level maps
	(b) Hydraulic characteristics of aquifers	(b) Hydrographs showing change in water levels with time
	(c) Degree of confinement	(c) Graphs of water levels versus pumping rates
Baseline A	(a) To define effect of climate on ground-water storage	(a) Hydrographs showing "natural" changes in storage in different aquifers and topographic situations in each climatic zone
B	(a) To define effect of topography and geology on climatic response	

wells not needed in the preparation of future maps.

Needless to say, it is essential that all wells in a hydrologic network are open to the same aquifer or water-bearing zone.

Water-Management Network

The second primary objective—that of determining the effect of stresses on recharge and discharge conditions—requires a network of wells located near pumping centers, recharge wells, deep-well waste injection sites, etc. Such a network might appropriately be referred to as a *water-management network* because it not only provides information on the responses of ground-water systems to stresses but also provides water-level data needed for water-management decisions. The observation-well programs in all States undoubtedly include some wells that meet the requirements of this network.

The number of wells needed in the water-management network will differ from place to place, depending on the nature of the ground-water system and the number and magnitude of the points of stress. As a minimum, at least one observation well should be located near every major pumping center. "Near," as used here, means that the well is located close enough to the pumping center to show the composite drawdown but not so close to any one pumping well that its intermittent operation obscures the effect of the more distant wells. "Major," as used here, cannot be precisely defined but implies a rate of withdrawal large enough to produce drawdowns over an area of at least several square miles. In Florida, major may mean withdrawals in excess of 25 M gal/d (million gallons per day). In the glacial-outwash aquifers in upstate New York it may mean withdrawals in excess of 5 M gal/d.

Instead of being overly concerned about the meaning of words like "near," and "major," it would be more useful to think in terms of objectives of the water-management network. First and foremost, the objective is to measure the response of ground-water systems to stress because, as we have noted, this is essential in predicting their long-term yields. A second, and directly related, objective is to provide information essential to water management, including warnings of overdevelopment.

The observation wells near major pumping centers should include wells open to the producing zone at different distances from the center of pumping. They should, ideally, also include wells open to both overlying and underlying permeable zones in order to measure the three-dimensional response of the ground-water system to the withdrawals (see Figure 4).

With respect to the length of time over which observations should be continued, it is useful to note that most pumping centers fall into one of two groups: (1) those at which the rate of withdrawal remains relatively constant over a long period of years, and (2) those at which the rate of withdrawal is being gradually or intermittently increased. Where withdrawals have been constant, and are likely to remain so, there is little need to continue observations past the point at which drawdowns have stabilized. Where withdrawals are increasing or decreasing it is essential that observations be continued for an indefinite period.

Baseline Network

The two networks discussed previously—the hydrologic network and the water-management network—are needed to observe man's impact on ground-water systems. The hydrologic network would show the composite, regional effect of withdrawals from numerous, widely dispersed pumping wells. The water-management network would show the effect of concentrated withdrawals from groups of relatively closely spaced pumping wells (well fields).

To obtain maximum benefit from these networks, a third network, referred to here as the *baseline network,* is needed. This network would consist of observation wells located in areas not significantly affected by withdrawals or other major artificial stresses. Data from this network is intended to show the response of the ground-water

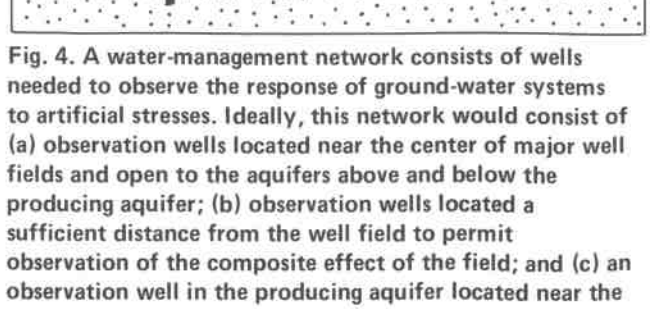

Fig. 4. A water-management network consists of wells needed to observe the response of ground-water systems to artificial stresses. Ideally, this network would consist of (a) observation wells located near the center of major well fields and open to the aquifers above and below the producing aquifer; (b) observation wells located a sufficient distance from the well field to permit observation of the composite effect of the field; and (c) an observation well in the producing aquifer located near the outer limit of the cone of depression.

system to variations in climate and other natural phenomena and thus provide the baseline data needed in the interpretation of data from both the hydrologic network and the water-management network.

It may be useful to think of a baseline network as being composed of subnetworks A and B. Subnetwork A would consist of wells that show only the effect of areal variations in climate on ground-water storage. In other words, wells in this subnetwork must be of nearly identical construction and must be located in nearly identical geologic and topographic situations. Subnetwork B would consist of wells that show how climatic effects are modified by different geologic and topographic situations.

Specifically, the characteristics of wells in subnetwork A ideally might be as follows:

1. They are open to the permeable, unconfined, surficial aquifer that responds most directly to climatic effects.

2. The depth to the water table below land surface is roughly the same in all the wells in order to permit ready comparison of the data from different wells without having to correct for travel time across the unsaturated zone.

3. The topographic position of the different well sites is similar in order to eliminate the effect of topography.

4. The casing diameter and length of screen or open hole is the same in all wells.

Baseline subnetwork B would include wells needed in the evaluation of the effect of both topography and geology on the response of aquifers to climate. Wells in this subnetwork would be located near some or all of the wells in subnetwork A, but in different topographic situations and/or open to deeper aquifers. For example, if the wells in subnetwork A are located in valleys, some of the wells in subnetwork B would be located on nearby hilltops and hillsides. Some of the wells would also be located in the valleys adjacent to the wells in subnetwork A but in deeper aquifers.

CONCLUSIONS

The data obtained from networks of ground-water level observation wells are essential to efficient development and effective management of ground-water systems. A large amount of effort is now devoted to observation-well programs. This effort would be more productive if each well met a clearly defined network objective. The solution of this problem lies in the identification of objectives, both for the program as a whole and for individual wells, and a critical review of existing networks in terms of these objectives.

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