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United States  
Department of  
Agriculture

Natural  
Resources  
Conservation  
Service

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**Part 631**  
**National Engineering Handbook**

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**Chapter 31**

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**Ground Water Investigations**

Issued draft April 2009

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# Preface

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The NRCS National Engineering Handbook (NEH), Part 631.31, Ground Water Investigations, is derived from NEH Section 18, Ground Water, released by the Soil Conservation Service (SCS), April 1968. NEH-18 was prepared by the following Service personnel (listed in alphabetical order):

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Note the following changes (the canceled documents are replaced by the new documents):

## **Canceled Documents**

- NEH, Section 18, Ground Water (June 1978)
- Technical Release No. 36, Ground-Water Recharge (June 1967)
- NEH, Part 631, Chapter 33, Investigations for Ground Water Resources Development (November 1998)

## **New Documents**

- NEH, Part 631 chapters
  - 631.30, Ground Water Hydrology and Geology
  - 631.31, Ground Water Investigations
  - 631.32, Well Design and Spring Development
  - 631.33, Ground Water Recharge



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**631.3100 Ground water investigations****(a) Introduction**

The intensity of ground water investigations depends on project purposes and scope, complexity of site conditions, and availability and accuracy of existing information and records. Recommendations must conform to State water and health laws.

**(b) Reconnaissance investigations**

A reconnaissance investigation is based on a review of existing information and an examination of surface features at the site.

The reconnaissance is made to acquaint the investigator with the nature and characteristics of surface features and conditions. From observation and examination, correlations with existing map information can be established. Tentative interpretations regarding subsurface materials and ground water conditions can be formulated. Any material or condition appearing to adversely affect project function, design, or construction should be located and referenced for further investigation.

Prior to making a reconnaissance of the site, the investigator should assemble and study topographic, geologic, and soil maps and literature and reports regarding geology and ground water applying to the area. Data from a field reconnaissance should contain general descriptions and locations of the surface features and conditions, including the following items:

- general geology of the project site
- geologic conditions that influence ground water movement and recharge
- surface features resulting from ground water movement, such as seeps, springs, and landslides
- general character of streams and valleys including volumes of flow, streambanks and bed, steepness of valley grades, and side slopes

- ground water development, yields, quality, and use
- water well logs
- ground water quality reports and data

Only limited interpretation of the available information should be done to characterize the ground water problem, subsurface conditions, materials, or yields. Interpretations may be made based on the data and conditions from areas of similar geologic and physical features. Limitations of such interpretations should be documented as initial estimates to be verified with additional investigation and data collection.

A written report should describe the site, provide interpretations or assumptions of the subsurface conditions, and any conclusions regarding project feasibility or need for additional studies. Copies of supporting maps, sketches, well logs, other data, and published references should be attached. Reports prepared for non-NRCS use shall contain only factual descriptions, observations, and remarks.

**(c) Preliminary investigation**

A preliminary investigation is made to determine characteristics of the subsurface material, ground water conditions, approximate yields, quality, and their geologic relationships. This will establish geologic feasibility of the project, be a basis for estimating project costs, or determine the need and intensities for further studies.

The preliminary ground water investigation consists of a review of the reconnaissance report, if available, and geologic literature of the area, a detailed surface study, and limited subsurface investigations at representative or critical locations. The nature and characteristics of subsurface materials, ground water conditions, yields, quality, and other pertinent features are established from existing logs and records and may be verified by geophysical surveys.

When starting a preliminary ground water investigation, all geologic, ground water, and well drilling data pertinent to the area should be reviewed including available well records.

### (1) Maps

A study of available resource maps is an excellent way to start a preliminary ground water investigation. Maps and other information may be obtained from State geological surveys, U.S. Geological Survey (USGS), local or county water management agencies, universities, and government agencies such as the Natural Resources Conservation Service (NRCS).

A geologic map of the United States on a scale of 1:2,500,000 was published by the USGS in 1974, accompanied by an explanatory text (King and Beikman, USGS Professional Paper 901). It is available from the USGS National Atlas series (<http://pubs.usgs.gov/atlas/geologic/>) and is shown in figure 31–1. State geologic maps are published by a variety of organizations, chiefly the State geological agencies, some by the USGS, and a few by professional societies or universities.

The USGS National Atlas of the United States contains many maps useful for general reference. Among these is the map showing productive aquifers and withdrawals from wells, reduced from a scale of 1:7,500,000 for inclusion in this handbook and other publications. USGS Circular 1323, Ground-Water Availability in the United States, provides updated ground water resources information, as well (<http://pubs.usgs.gov/circ/1323/>) (fig. 31–2). Detailed ground water maps are available from the USGS at <http://pubs.usgs.gov/ha/ha730/gwa.html>. Such a map for Texas is shown in figure 31–3.

Reports and maps by the various State geological surveys and the USGS provide basic data which can be used as a starting point for studies within a watershed area. In addition to their published data, unpublished reports and maps are kept on file at most State geological survey offices and at USGS offices.

USGS topographic maps are available in digital form and on paper at a scale of 1:62,500 to 1:24,000 and provide suitable base maps for a preliminary ground water investigation.

### (2) Imagery

Aerial photos can be used to make initial interpretations of geologic structure, landforms, potential recharge areas, springs, land use, and vegetation patterns. Satellite imagery, as well as Light Detection and Ranging (LIDAR) imagery, may also be used if avail-

able for the area of study. Figure 31–4 shows a comparison of LIDAR imagery with topographic maps.

### (3) Field study

In areas where stratified sedimentary rocks are exposed, the details of local structure and its relationship to possible aquifers in the geologic section must be determined. This is done by measuring and plotting the attitude (strike and dip) and elevation of the exposed strata on the map of the area. Aerial photo contact prints are very helpful and should be used wherever possible. Stereoscopic study of aerial photographs may show information about geologic features, such as faults, as well as losing and gaining streams (fig. 31–5). For field study of larger areas, USGS quadrangle sheets at scales of 1:62,500 to 1:24,000 and aerial photo mosaics or index sheets are useful base maps. A structure contour map can be constructed if well logs are available. Structure contour maps are especially useful in cross-bedded or indefinitely bedded sedimentary strata.

Where subsurface structure is not clearly indicated by outcrops, available well logs can be interpreted. Remote sensing technology, such as refraction seismograph or electrical resistivity equipment, can also be employed

Geologic features of importance to ground water occurrence in areas underlain by crystalline or metamorphic rocks include the depth of the weathered zone and the existence of fractures, joints, and fault zones, especially near the surface. Joint systems, faults, and the location and elevation of springs may be mapped.

In areas of extrusive igneous rocks, the thickness of flow or series of flows and the elevation of the water table should be observed in addition to the characteristics of jointing and the presence of faults and springs.

### (4) Mapping

A geologic map should always be prepared on the best available base map including:

- areal and surficial geology
- structure of bedrock, stratification, folding, schistosity, faults, or fractures
- surface ground water features including springs, seeps, swamps, and marshes

**Figure 31-1** Geologic map of the United States (from USGS National Atlas)

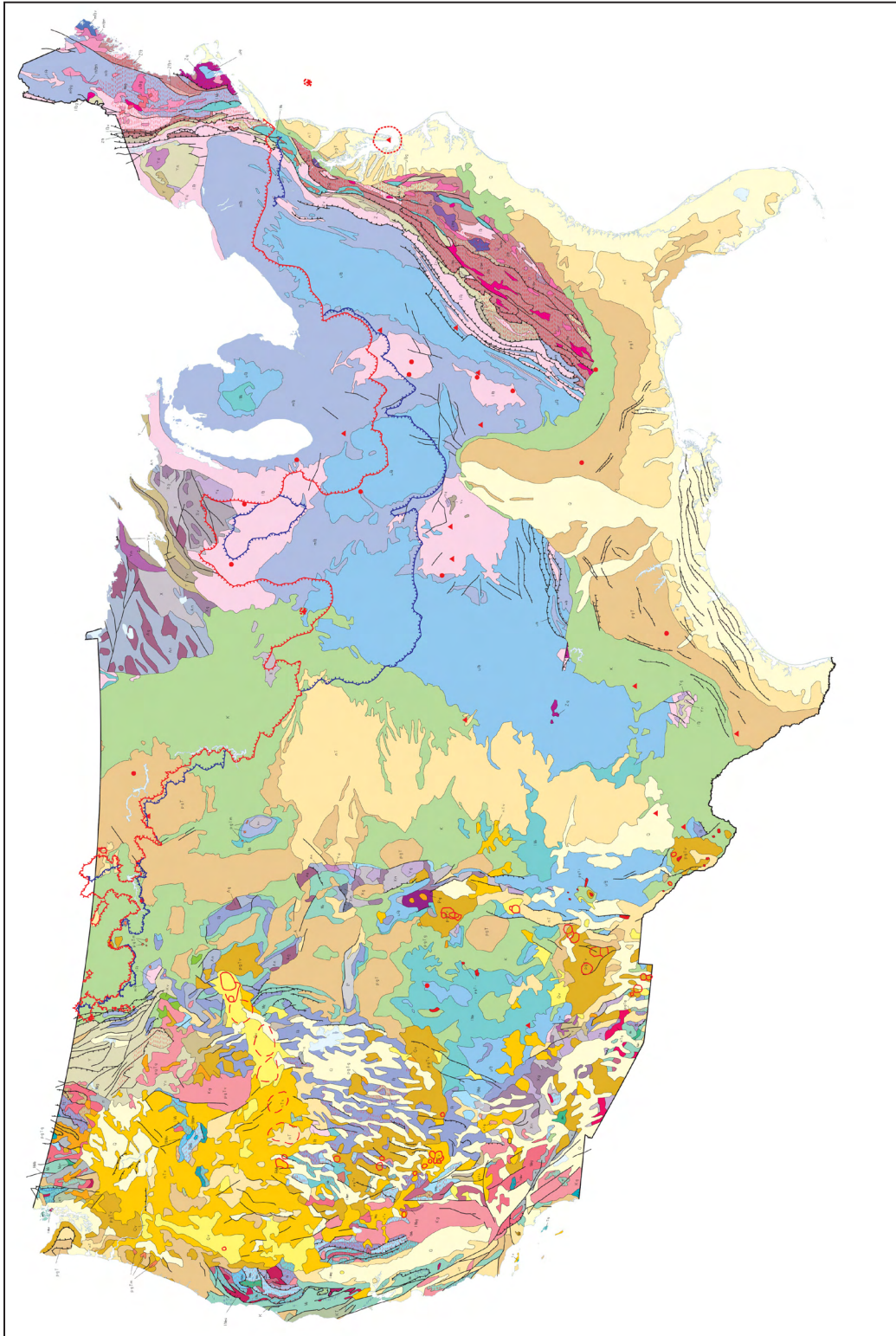
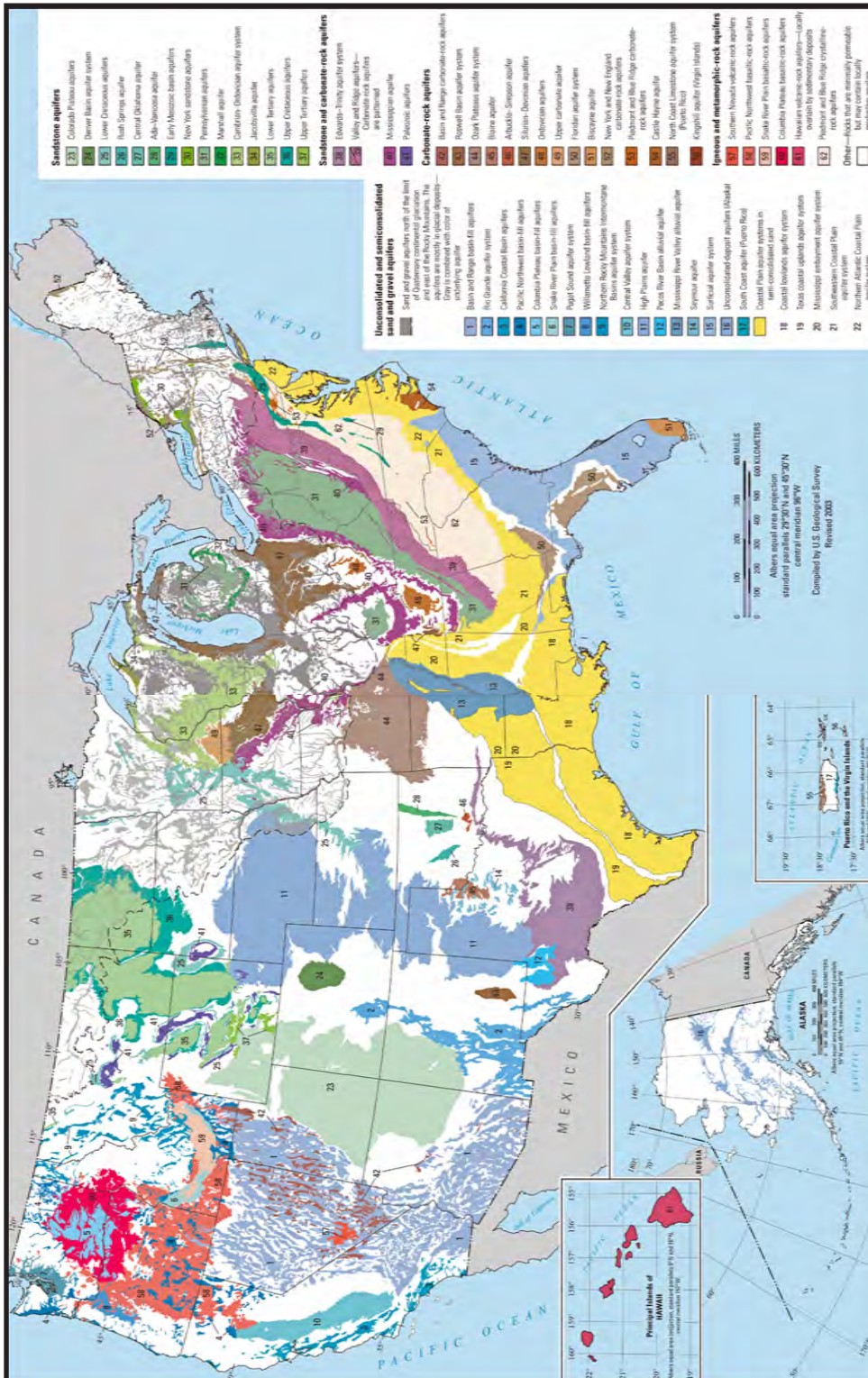
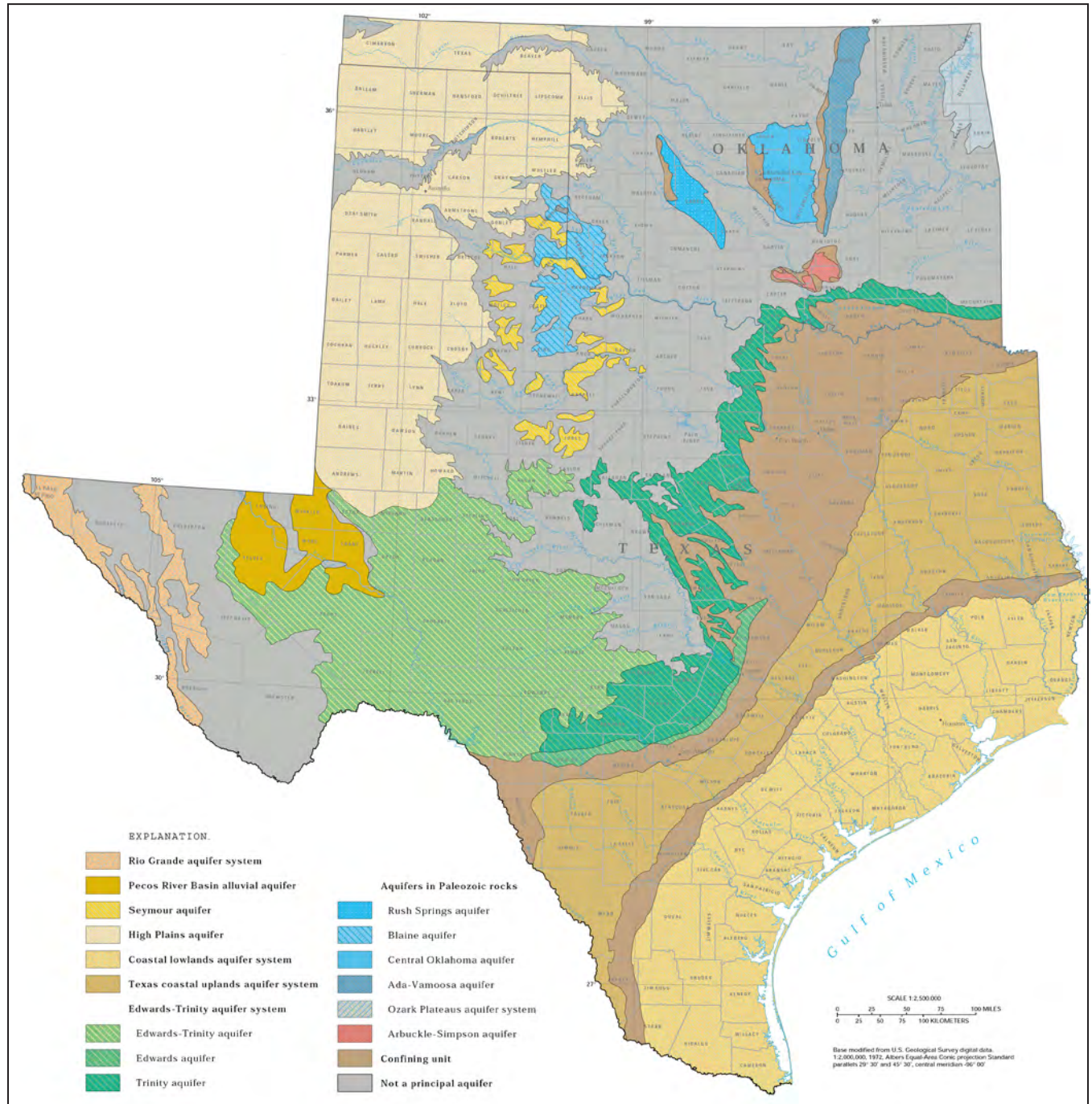


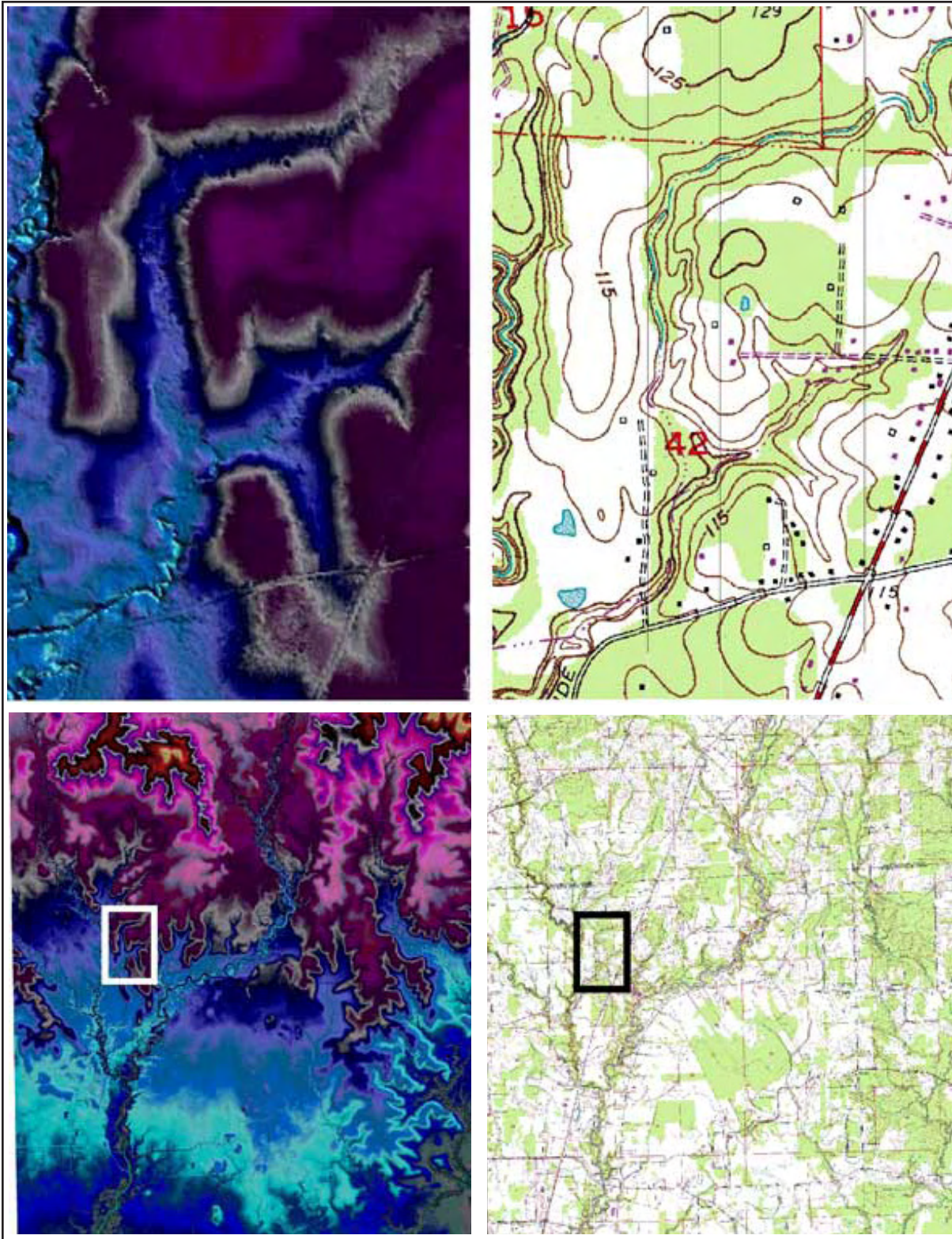
Figure 31-2 Principle aquifers of the United States (modified from Principal Aquifers, USGS 20)



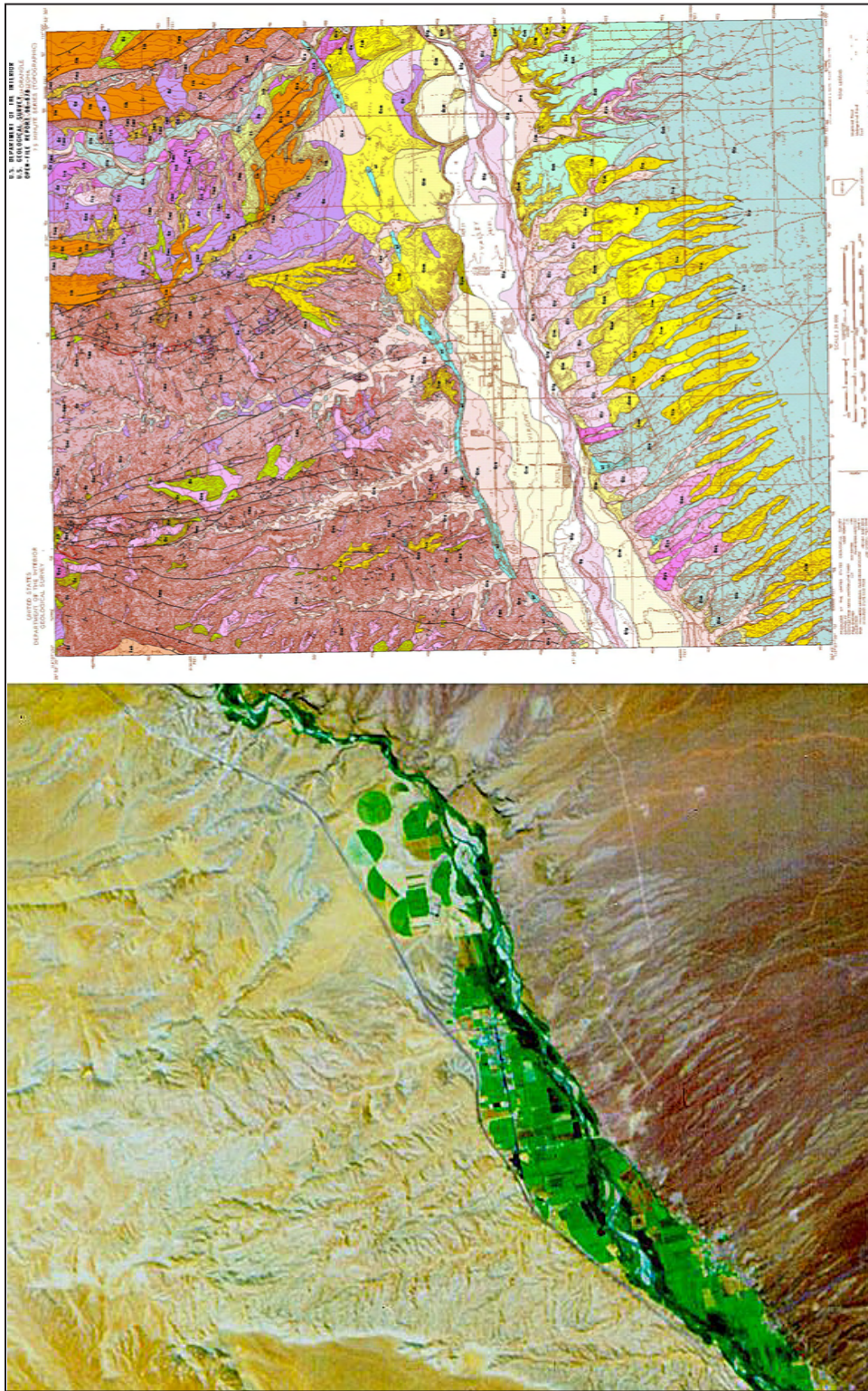
**Figure 31-3** Major aquifers of Texas and Oklahoma (USGS National Atlas)



**Figure 31-4** LIDAR imagery and topographic maps



**Figure 31-5** Satellite imagery used in geologic mapping



- sinkholes and disappearing or reappearing streams (in karst topography)
- legend listing all formations shown on map. This includes a brief description of characteristics of aquifers, aquicludes, and other pertinent information
- locations of wells. Well record data and logs will be included in reports

Specialized maps may also need to be prepared, based on the detail and type of information available and supplemented during the investigations. Structural contour maps or piezometric maps should be prepared when needed, based on field observations and well data.

### (5) Geologic sections

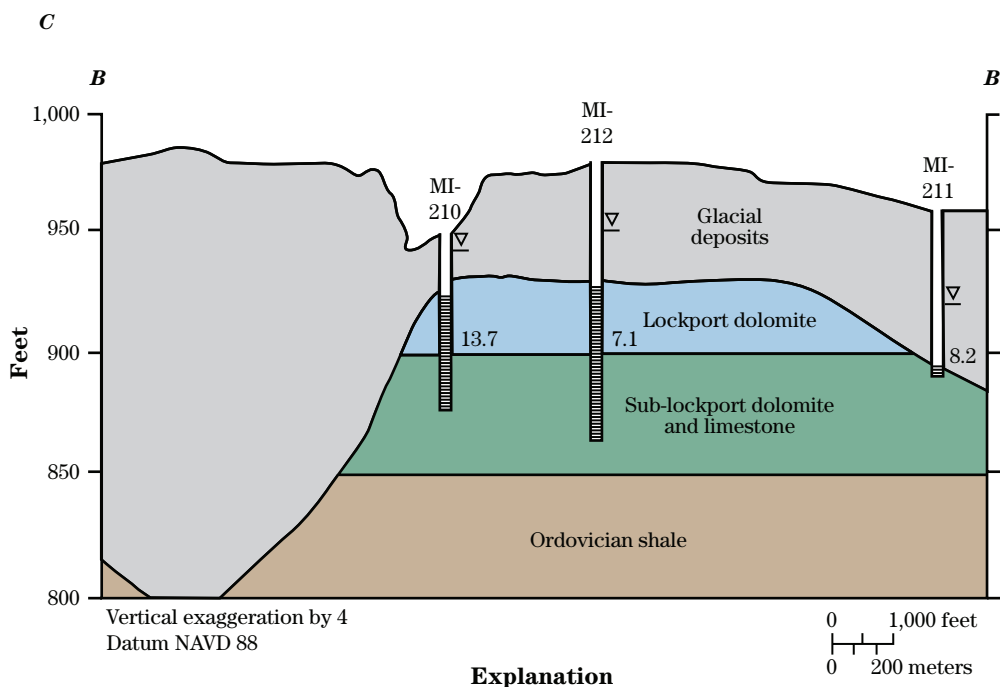
To complete and interpret the information on a geologic map, one or more geologic sections (fig. 31-6) and

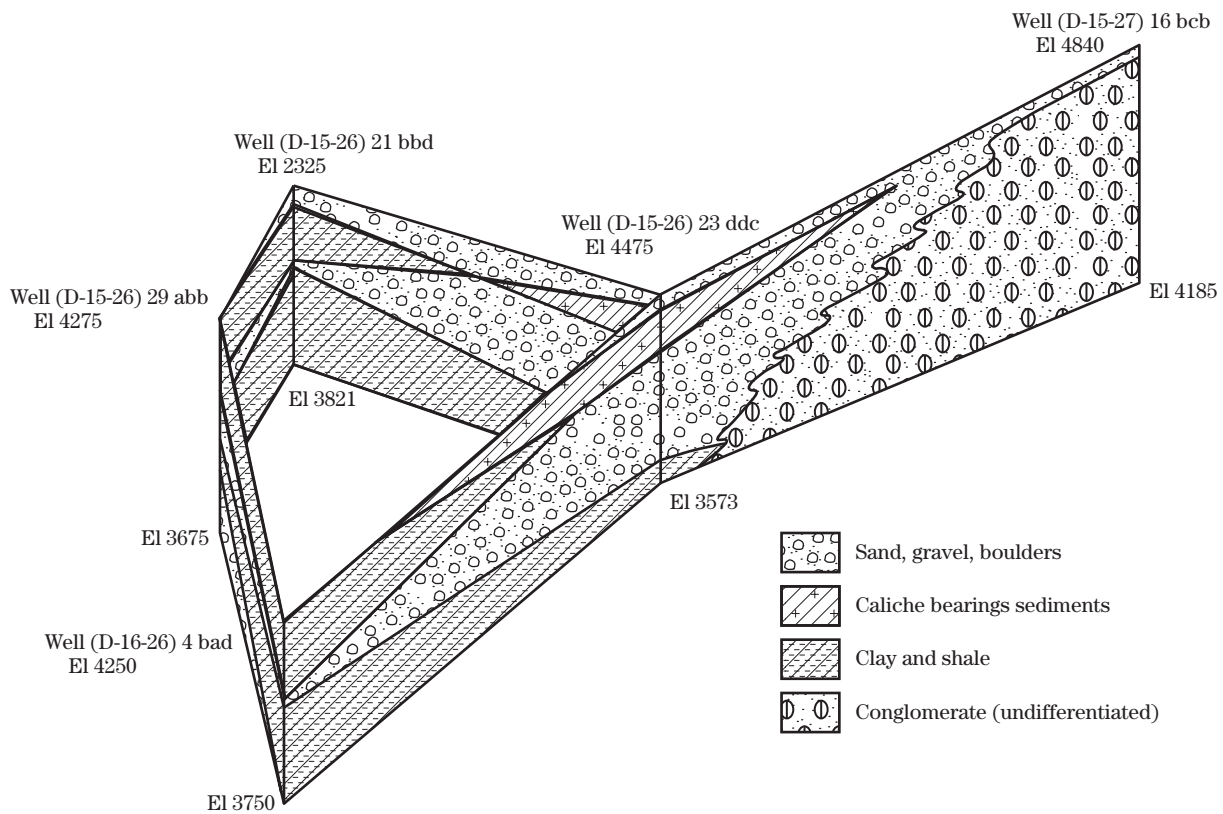
fence diagrams (fig. 31-7) should be prepared, based on logs of wells, test holes, geophysical studies, or other related information. The fence diagram is constructed in three-dimensional perspective from actual well logs to show geologic relationships.

### (6) Report of preliminary investigation

A geologic report generally following the outline at the end of this chapter should be prepared for a preliminary ground water investigation. The report should include a concise discussion of ground water conditions, interpretations, conclusions, and recommendations for solving any problems. The preliminary report should also include recommendations for methods to be used in making a detailed ground water investigation, where needed. Well records, log of borings, and other supporting data should be reviewed, interpreted, and included where applicable with the preliminary investigation report. Geologic maps and sections should be included.

**Figure 31-6** Generalized geologic section and water well information



**Figure 31-7** Fence diagram

### (d) Detailed investigations

A detailed investigation collects data for making sound geologic interpretations. Specific site materials and ground water conditions are documented to provide sufficient subsurface information for the design and construction of project measures.

Detailed investigations include a review of the information covered by the preliminary investigations, collection of additional data, preparation of a complete report, including logs, maps, geologic sections, fence diagrams, and results of field tests and the collection and laboratory analysis of samples.

Locations of wells, ambient and seasonal water levels, withdrawal areas, amounts of withdrawal, springs or other discharge areas, hydraulic gradients, and rate and direction of ground water movement should be determined. Seismic or electrical resistivity apparatus

and tracers may be used to determine flow directions and velocities. Drilling or the excavation of pits may be required to obtain more information, and to take samples of water and soil or rock materials. Field permeability tests, pumping tests, and pressure testing often are desirable. The installation of observation wells and piezometers may be advisable under some conditions.

Water quality should be determined to establish its potability for humans or livestock and its suitability for irrigation or other agricultural use. The risk of tapping saltwater zones or the possibility of permitting saltwater to enter and contaminate freshwater aquifers should be determined. An investigation may be required to determine the extent of saltwater intrusion and the feasibility of constructing reservoirs or boring wells to develop a freshwater barrier or trough to block the intrusion of saltwater.

Natural recharge areas should be determined, and the feasibility of artificial recharge should be studied. Recharge or underground disposal of surface water must not result in pollution of ground water.

In brief, detailed ground water investigations consist of:

- drilling, sampling, logging, describing, and classifying all strata that will influence ground water hydrology
- pressure testing for in-place permeability and seepage through fractured rock and voids in soluble strata where control of seepage is important
- ascertaining the influence of structural geology, faulting, folding, and fracturing on transmissibility of ground water
- installing piezometers or observation wells in hydrologically significant strata

### (1) Data collection

*Geophysical survey*—seismic or various types of electrical resistivity equipment can be used to determine depths to bedrock and depths to a water table, as well as fracture zones. Multiple-probe seismographs are useful in rapid analyses, especially using variable shock sources and postprocessing software. Portable electrical resistivity meters can be used to perform rapid surveys over long traverses. Table 31-1 shows six major geophysical methods for making remote-sensing interpretations of subsurface conditions.

*Test drilling*—detailed plans should be prepared showing locations and depths of wells desired to obtain sufficient information on the position, depth, gradient, and nature of the aquifer or underground cavernous or water storage area. Field permeability tests may be needed on the aquifer and overlying materials. Samples of water should be obtained to determine its quality.

All drill holes and surface exposures studied should be logged in detail to supply information relating to storage, transmissibility, or chemical conditions affecting ground water. The logging should include location, elevation, and depth of the hole or exposure, Unified Soil Classification System (USCS) classification of each horizon, stratification, density or consistency of materials, size range of the particles, cementation, chemical

composition, and estimates of pore space and permeability. Most of these features apply to both unconsolidated and consolidated materials, except that in consolidated materials the USCS classification should be replaced by the kind of rock and its characteristics regarding the storage and transmissibility of water. A Global Positioning System (GPS) receiver can be used for rapid mapping of locations, with lower accuracy on elevations.

Results of field tests such as pressure testing, slug testing (pumping in), yield (pumping out), well permeameter tests, and sieve analyses of aquifer materials should be recorded and summarized.

Observation wells and piezometers help define ground water movement, hydrostatic pressure, piezometric surface, unconfined water surface, seasonal fluctuations in water surface elevations, and the effects of flooding, withdrawal, or water levels in nearby streams or bodies of water. Piezometers usually are small diameter pipes with the bottom open, sealed at a specific depth, and are installed at shallow or moderate depths by driving or jetting methods.

Observation wells may be of any size, but often are 2- to 3-inch pipe with a screen attached at the bottom. They usually are installed by jetting or inserting in a hole bored by a rotary drill or continuous flight auger. The depths may vary from a few feet to hundreds of feet, depending on the depth that information is needed. The water levels may be measured by tape or simple sounding equipment or by mechanical or electrical recording devices which obtain continuous records.

*Sampling*—when drilling is done during the detailed investigation, samples should be collected to:

- determine gradation, storage capacity, chemical composition, and permeability rates of unconsolidated materials and rock formations
- assist in the correlation of horizons or rock formations
- determine the nature and extent of faulting, jointing, and cavernous conditions
- determine the possibility of surface subsidence or collapse of certain horizons

**Table 31-1** Characteristics of six geophysical methods

Method	Measures	Mode of measurement	Depth of penetration	Resolution	Raw data format
<b>Ground penetrating radar (GPR)</b>	Complex dielectric constant of soil, rock, pore fluids, and artificial objects	Continuous profile 0.4-km/h detail— 8-km/h reconnaissance (ground contact not necessary)	1–10 m typical—highly site specific; limited by fluids and soils with high electrical conductivity and by fine grain materials	Greatest of all six geophysical methods	Picture-like graphic display; analog tape; digital tape
<b>Electro-magnetics (EM)</b>	Bulk electric conductivity of soil, rock, and pore fluids (pore fluids tend to dominate)	Continuous profiles to 0.5–15 m depth; station measurements 15–60 m depth; some sounding capability (ground contact not necessary)	Depth controlled by system coil spacing of 0.5–60 m typical	Excellent lateral resolution; vertical resolution of two layers; thin layers may not be detected	Numerical values of conductivity from station measurements; stripchart and/or magnetic recorded data yields continuous profiling
<b>Resistivity sounding</b>	Bulk electrical resistivity of soil, rock, and pore fluids (pore fluids tend to dominate)	Station measurements for profiling or sounding (must have a ground contact)	Depth controlled by electrode spacing and equipment capabilities; limited by space available for array; instrument power and sensitivity become important at greater depth	Good vertical resolution of 3 to 4 layers; thin layers may not be detected	Numerical values of voltage, current and dimensions of array; can plot profile or sounding curves from raw data
<b>Seismic refraction</b>	Seismic velocity of soil or rock which is related to density and elastic properties	Station measurements (must have ground contact)	Depth limited by array length, energy source, and equipment capabilities	Good vertical resolution of 3–4 layers; seismic velocity must increase with depth—thin layers may not be detected	Numeric values of time and distance; can plot T/D graph from raw data
<b>Metal detector</b>	Electrical conductivity of ferrous and nonferrous metals	Continuous (ground contact not necessary)	Equipment dependent: single 55 gal drum up to 3 m; massive piles of 55 gal drums up to 6 m	Very good ability to locate targets	Relative response from audio/visual indicators (may record data)
<b>Magnetometer</b>	Magnetic susceptibility of ferrous metals	Continuous total field or gradient measurements; many instruments are limited to station measurements (ground contact not necessary)	Equipment dependent: single 55 gal drum up to 6 m; massive piles of 55 gal drums up to 20 m	Good ability to locate targets	Nonquantitative response from audio/visual indicators; quantitative instruments provide meter or digital display (may record data)

- determine the nature of an aquifer, its storage potential, productive capacity, and transmissibility of ground water

Disturbed samples may be taken from channels, dozer pits, or auger borings to determine grain size distribution or the potential for recharge. Undisturbed samples of unconsolidated materials may be secured from certain horizons to determine permeability rates, storage potential, or stability. Field permeability tests (mass test), however, are generally more reliable than laboratory tests (material test). Cores of representative rock formations may be needed to determine faulting, jointing, permeability, composition, and solubility.

*Tracers*—to use tracers in ground water investigations, the “upstream” or intake area must be accessible. If not, drill holes or test pits will need to be prepared. The discharge area also must be accessible, or holes or pits will be needed at a measured distance in the down-gradient direction where water samples can be quickly observed or tested.

The following dyes are the most common ones used: Fluorescein “B” (fig. 31–8), potassium permanganate, rhodamine “B” (fig. 31–9), methylene blue, aniline red, aniline blue, and auramine yellow. Caution is advisable in using any kind of tracers, especially if large amounts are used and they find their way into drinking water for humans or animals or into water used for fish and wildlife. Poisonous or objectionable tracers should not be used.

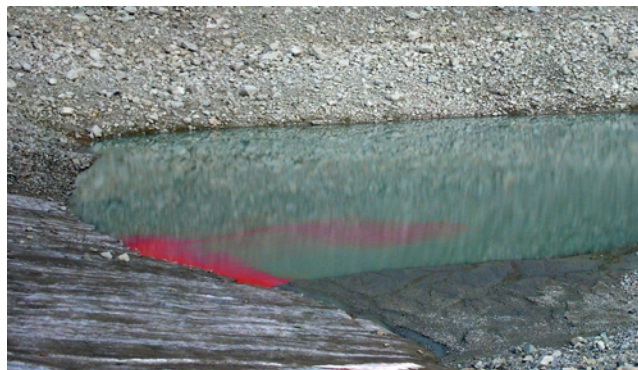
The volume of water, its acidity or alkalinity, and the distance covered by the test will determine the amounts or kinds of dyes to use. Also, the coloring ability of the dye and the strength of other tracers will determine the amount to use. Fluorescein “B” is probably the most powerful of these dyes. Photodegradation rates, as well as potential biological uptake, can affect the decision on whether or not to employ dye tracers.

The ion of chlorine applied in a concentrated solution of sodium chloride or ammonium chloride is detected in a down-gradient well by titration with silver nitrate or by the change in electrical conductivity of the

**Figure 31–8** Fluorescein “B” dye coming from spring



**Figure 31–9** Rhodamine “B” dye being used to trace flow direction



water. Tests of the chlorine ion concentration of the natural water must be made less than 24 hours prior to the tracer test, if the titration method is to be used. If the chlorine ion concentration is already high, this method will not give satisfactory results.

Injecting a fluid into an aquifer through a well will temporarily raise the water level adjacent to the well. This increases the hydraulic gradient and results in increased velocity of the fluid away from the well. For best results, the salt solution should be introduced through an injection well and the travel time of the solution measured between two observation wells located down gradient. A typical detection arrangement is shown in figure 31-10.

Radioactive tracers, such as Tritium and Iodine 131, can be detected in minute amounts and can be very effective in determining direction and velocity of ground water flow. Use of these tracers is not recommended, however, due to the complexity, safety, and permitting issues surrounding radioactive materials.

The velocity determined by any of these tracer methods tends to be the maximum velocity. This could

result in computed permeabilities that ground surface water table are generally greater than the average for the section of the aquifer tested.

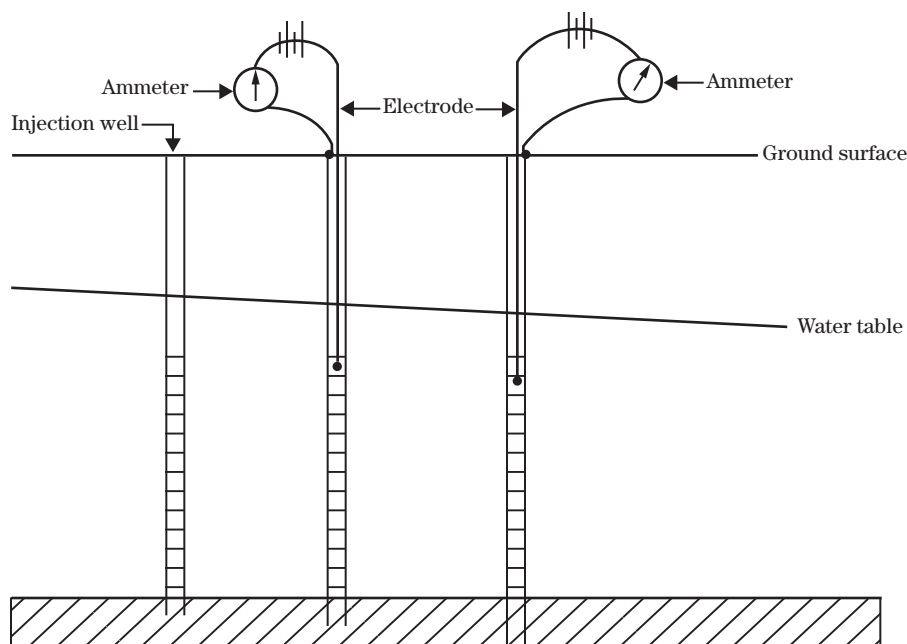
If seepage from a body of water is a problem, the tracer dye may be enclosed in a paper bag, tied to a weight or long pole, and placed in the area where the origin of the seepage is suspected. Successive tests may be made with the same or different colors at other locations.

In many localities, the public, through lack of understanding, strongly objects to the use of radioactive isotopes as tracers in ground water investigations. Public relations must be considered when using any tracer.

## (2) Correlation and interpretation

After reviewing the available information and completion of geophysical, drilling, and excavation investigations, detailed geologic sections and fence diagrams can be prepared and correlated. The data obtained should be complete enough to provide accurate correlation of geologic conditions and to supply the desired information on ground water, showing stratigraphic sequence, geologic age, thickness, character, and com-

**Figure 31-10** Typical salt detection arrangement



position of unconsolidated and consolidated strata. Continuity, confining or impervious strata, barriers or aquicludes, water-bearing formations, cavernous or fractured rock conditions, and water levels will be noted.

Maps of the area should be prepared showing extent of the aquifer, barriers, faults, caverns, confining strata, lines of equal pressure, recharge areas, withdrawal areas, springs, or other natural discharge areas. Geologic formations, geologic structures, structural contours, and any other features relating to ground water supply, movement, gradient, or storage should be mapped.

Figures 31–11 and 31–12 are typical examples of cross sections and water table contour maps.

### (3) Report of detailed investigation

A detailed investigation contains collected data on observations made and other information assembled during the investigation. The report also includes interpretations, conclusions, and recommendations made from these factual data.

*Factual data*—a narrative report is prepared describing the factual data obtained from published data or former investigations and the findings during the detailed investigations, including geology, correlation charts of unconsolidated and consolidated materials, and other facts relating to the problem being investigated. Columnar sections and maps showing areal extent of important materials or rock formations, locations of test holes, pits, rock exposures, natural recharge areas, springs or withdrawal areas, and locations of logged wells or other published data used for correlation purposes may also be included.

Log sheets will be prepared, if applicable, describing materials, encountered or observed, their classification, hardness, density, estimated gradation, and permeability. Facts regarding geologic structure, dip, faults, jointing, caverns, and barriers to ground water movement are shown on cross sections and discussed in this report.

Data on water levels are described or plotted. Whether water tables are static, perched, or under artesian pressure will be indicated, and the dates of observations will be shown. Records of pumping or permeability tests will be reported. If fluctuating or high water tables have adverse effects on agricultural use of the

land, the problem will be described including tables showing seasonal water tables and the cause of the adverse condition.

*Interpretation and conclusions*—estimates on storage potential, transmissibility, and rate of water movement may be given as based on Darcy's law, Hazen's approximation, or field permeability tests. Dye trace study results are also included.

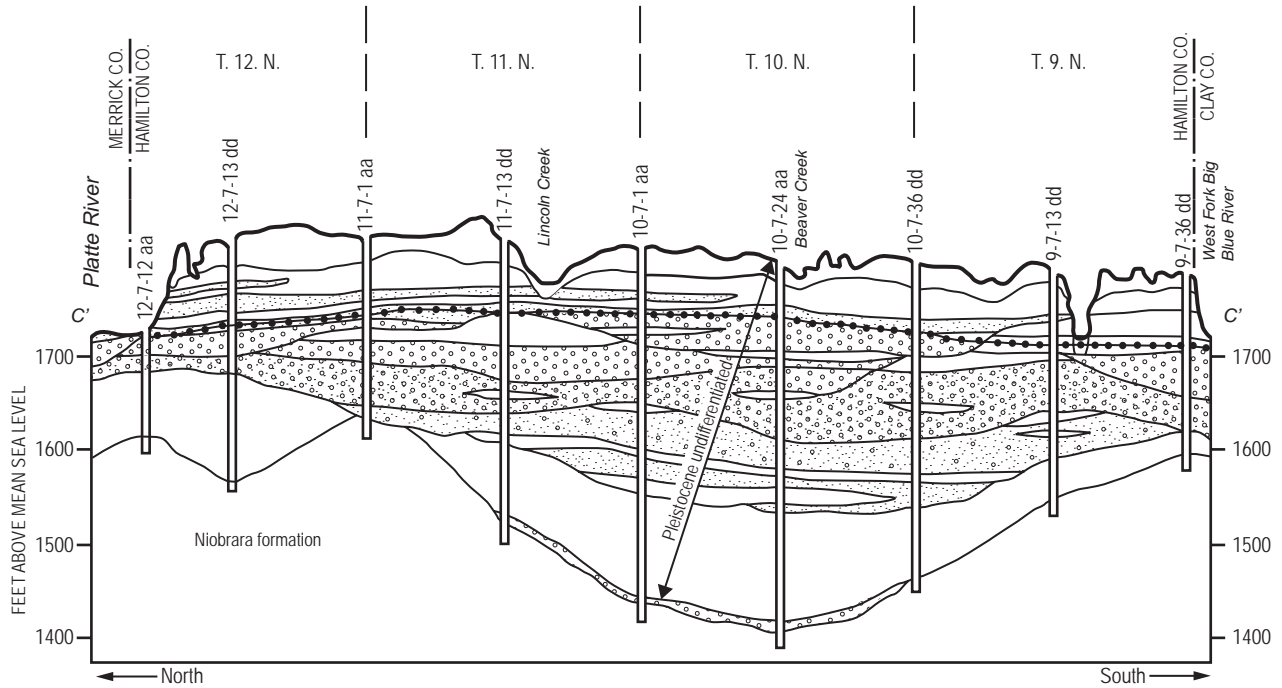
Potential for ground water recharge may be discussed, if applicable, and estimates made on storage and recovery of ground water and its potential uses.

If a high-water table is a problem, data are provided or estimates made on fluctuation of water levels and their effect on agricultural, cultural, industrial, or other uses of the land.

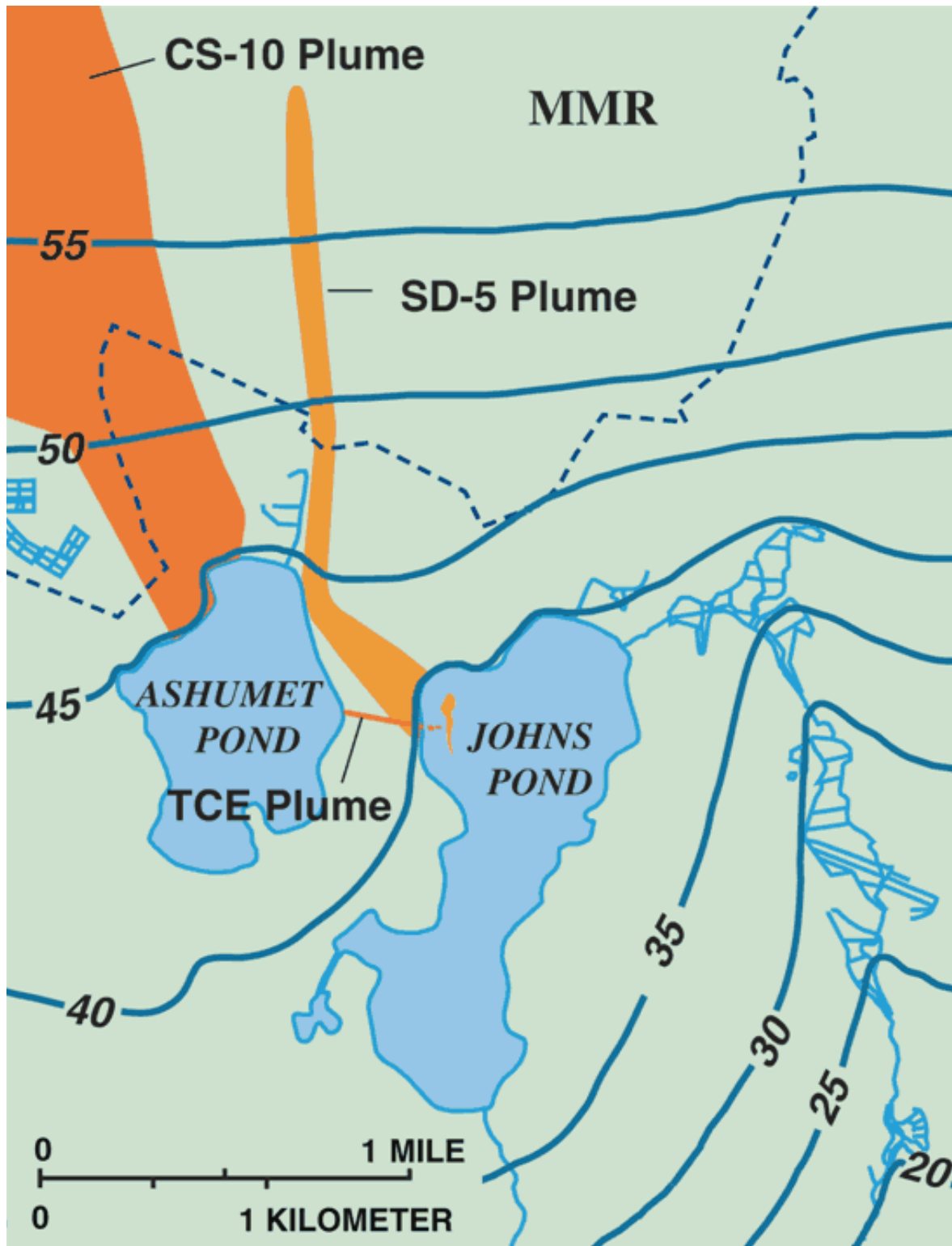
If the problem is stability, estimates will be made on water level fluctuations and their effect on subsidence, landslides, slumping or creeping of soil, seepage, levees, channel banks, and unstable foundations for dams, building, highways, railroads, or other structures.

Conclusions may indicate that the problem is the result of natural conditions such as excessive erosion, valley filling, stream piracy and glaciation or that the conditions are induced by natural causes or works of man such as channel aggradation, channel degradation, land movement, earth collapse, or formation of natural levees. Some of these conditions are excessive burning, deforestation, or other change in vegetative cover; water control structures (dams, drainage, stream diversion, irrigation, canals, and facilities for stream navigation); water disposal (either underground or in surface streams); excessive use and disposal of herbicides, detergents, or other chemical products and pollutants; and abandoned mines.

**Figure 31-11** Geologic section (from Ground-Water Resources of Hamilton County, Nebraska, by C.F. Keech, 1962, USGS Water-Supply Paper 1539-N)



**Figure 31-12** Water table contour map showing ground water gradients and pollution plumes



## (e) Outline for ground water investigation report

The following outline is provided as a guide for documenting results of ground water investigations. The outline may be modified as necessary, and only those items that are pertinent to the investigation and report should be used.

- I. Introduction
  - A. Name of watershed or designation of area covered by the report
  - B. Personnel making study and data
  - C. Purpose of study
  - D. Objectives
  - E. Methods
  - F. Sources of information
- II. Ground Water or Well Development
  - A. Source
  - B. Movement
  - C. Reservoir
    1. geomorphology
    2. structure
    3. stratigraphy
  - D. Aquifers
  - E. Aquicludes
  - F. Reservoir capacity
    1. total storage
    2. recharge rate
    3. safe yield
  - G. Well development
    1. well type and size
    2. elevation
    3. depth
    4. static water level
    5. pumping level
    6. production (gpm)
    7. specific capacity
    8. pump size
    9. power unit (type)
  - H. Cost data (indicate the estimated Federal and non-Federal costs for each item)
    1. drilling
    2. furnishing casing in place
    3. furnishing screen in place
    4. installing filter pack
    5. furnishing and installing pump
    6. furnishing and installing power unit
    7. development
    8. other costs
    9. total cost
10. comparison with cost of surface water supply, where available
- III. Water Table Control
  - A. Drainage
    1. agricultural
    2. engineering
      - (b) dewatering excavation; may be excavation for foundation, quarry, mine, etc.
      - (c) engineering subdrainage
- IV. Ground water Recharge
  - A. Recharge
    1. location and extent
    2. natural
    3. artificial
  - B. Surface drainage
    1. influent seepage
    2. effluent seepage
  - C. Subsurface movement
    1. interstices
    2. bedding planes, joints, fractures
    3. solution channels
  - D. Reservoir type
    1. monocline
    2. syncline
    3. sediment-filled valley or basin
    4. fault trap
    5. stratigraphic trap
    6. topographic control
  - E. Artificial recharge methods
    1. spreading
    2. injecting
    3. impounding
  - F. Reservoir capacity
    1. total storage
    2. recharge rate
    3. safe yield
- V. Problems
  - A. Ground water development
    1. reservoir
    2. pipeline
    3. watercourse
  - B. Drainage
  - C. Artificial recharge
  - D. Engineering structures
    1. effect on ground water regime
    2. effect on structural stability or functioning
- VI. Interpretations
- VII. Conclusions
- VIII. Recommendations

## 631.3101 Investigation methods and equipment

### (a) Introduction

Solutions to ground water resource problems are largely a function of the amount and kinds of information available. Existing published information or recently collected information may yield valuable insight to the nature and cause of ground water problems. Where information is still lacking, it may be necessary to collect additional information to pinpoint causes or sources of problems through active and focused data collection.

#### (1) Published maps and reports

Full use should be made of available geologic maps and reports related to ground water resources and investigations. Such maps should be sought from the USGS, State geological surveys, bureaus of mines, and universities and colleges. Bulletins and special publications of professional societies such as American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, American Water Well Association, Association of Engineering Geologists, Geological Society of America, and others are additional sources. Some State geological societies publish guide books, maps, and road logs for annual meetings. Following are some of the sources of information to identify and obtain:

- national or regional geological or physiographic maps (refer to the USGS National Atlas)
- tectonic maps
- ground water resource maps
- State geological maps
- State water resources investigations
- USGS Water Resources Investigations Reports
- State water well registration programs
- USGS topographic maps (digital and paper copy)
- aerial photos (especially in stereographic coverage, as well as of various years and times of year)

- satellite imagery
- LIDAR

Note that many sources of information are available for downloading or ordering from the Internet.

### (b) Ground water observations

Measurements of water levels, flows of springs and streams, and production of wells in an area all may be used to relate hydrology to geology and permit estimates of ground water occurrence, movement, and availability. Field observations of ground water are the basis for ground water maps, just as descriptions of surface exposures are for geologic maps.

#### (1) Elevation of water surface

Information regarding position of the water surface is essential to preparation of ground water maps. Elevations are used to draw contour maps of the water table or piezometric surface for confined aquifers, from which may be determined the direction of water movement, hydraulic gradient, relative aquifer permeabilities, and the position of ground water divides.

Under normal conditions, the elevation of the water surface fluctuates seasonally. It rises as a result of recharge by precipitation and streamflow and falls because of natural discharge and pumping from wells. This change may be enough to influence accuracy of the survey. Sufficient observations of water surface elevation should be made at streams, lakes, reservoirs, springs, and in wells to meet needs of the survey. Land surface elevations may be determined as described earlier.

*Water table measurement*—measuring depth to the water level in a well is fairly straightforward, but poorly collected readings may lead to inaccurate investigation results. Of primary importance is the selection of a stable reference point at the surface and whether the water table is perched. Water levels of flowing wells may be calculated by measuring the pressure developed when the well is closed or for low heads by connecting a short length of hose to the well and elevating the end until flow stops.

Some of the more common methods employed to measure depth to water in wells include:

- chalked tape
- tape and float
- tape and inverted cup-shaped weight
- electrical sounding devices
- air lines installed in wells

*Chalked tape*—the chalked tape method has been found to be the simplest and most satisfactory for rapid and accurate measurement in most wells. A steel tape is used with a small lead weight attached. The lower few feet are covered with carpenter's chalk, then wetted and drawn through the fingers to spread the chalk in an even film. The tape is lowered into the well until the weight is a few inches beneath the water surface. A reading is made at the surface and the tape quickly withdrawn and read at the water mark. Depth to the water level is obtained by subtraction. The tape should be held only momentarily at the surface measuring point because water tends to rise on the tape by capillarity in the chalk film. In place of chalk, a "water finder" paste may be used. The paste is spread on the tape or probe, and the part that dips into the water will turn red.

If chalk or paste on tape are to be used in a pumping well or one in which there is splash, tape must be inserted in a 1/2- to 3/4-inch pipe extending from ground surface deeper than the lowest water level to be measured.

*Electrical sounders*—an electric water level meter operates on a simple principle that the water completes the electrical circuit and indicates so via a light or meter. The electrical lead is calibrated to show the measured depth to water. Electric sounders are advantageous for deep wells and wells in which there is splash. In some instances, a continuously recording water level meter may be employed, which will provide a record of water levels in the well over time. Such information may be valuable in showing rapid changes in well levels.

*Air lines*—many wells are equipped with a pressure gage and an air line of known length. The air line is connected to a pressure gage (fig. 31-13). The lower end of tube or pipe is open. The pipe must be airtight, and it should extend 20 feet or more below the lowest pumping level. Depth to the lower end of the air line must be accurately known. Air pressure can be

furnished by an ordinary tire pump. The gage indicates pressure necessary to counterbalance the depth of water outside the air line. (This is the maximum pressure that can be attained).

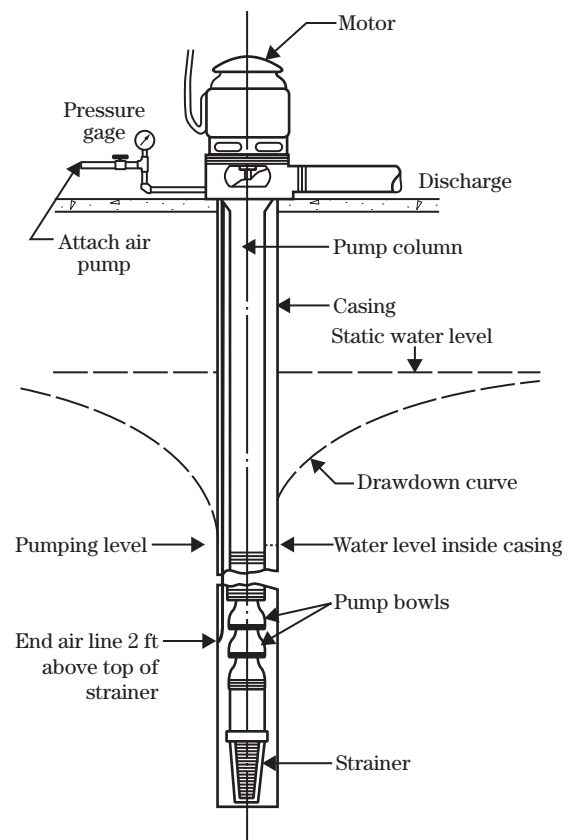
### (2) Observation well

Observation wells are simply vertical pipes or tubes that reveal the depth to the ambient water table. They are typically made of PVC pipe, with a slotted section to allow free flow from the aquifer.

### (3) Piezometers

Ground water piezometers are accurate, reliable, and inexpensive tools for determining hydrostatic pressure at particular depths or in selected layers of soil or rock. Piezometers typically consist of a filter head attached to a pipe. The materials vary, but the filter

**Figure 31-13** Air line for measuring depth to water level



head is typically porous plastic, and the pipe may be plastic or metal. Measurement of the pressure at the head is by pressure transducer or by inference from the depth of water measured in the tube. A simple piezometer may also consist of a pipe driven vertically into the ground to a definite elevation or stratum. The pipe is driven so that no leakage occurs, and ground water can enter only at the bottom. Measurement of the water in the tube reveals the water pressure at the bottom of the tube. Construction details of observation wells and piezometers and differences in design and conditions measured are shown in figure 31-14.

Because ground water moves from points of high hydrostatic pressure to points of lower pressure, it is possible by measuring pressure at a number of points to determine the movement of water. Results may be plotted in both plan and section and contours or equipotential lines drawn on the pressure surface indicated by the piezometer readings. Flow lines drawn perpendicular to the equipotential lines show direction of flow, hydraulic gradient, and areas of concentrated flow.

Piezometers, as well as being a principal tool in drainage investigations, are useful in planning development of confined ground water, in analyzing effect of engineering structures on local ground water conditions, determining need for and location of relief wells, and in measuring pore pressure in the foundation of structures.

Effective positioning of piezometers horizontally and vertically requires knowledge of underlying aquifers, preferably based on carefully logged borings. Piezometers may also be located in a grid pattern with a number of pipes of different length at each location depending on depths to aquifers. Piezometer locations should be referenced horizontally and vertically. Multiple piezometers may be set in a single bore hole, if desired, by carefully sealing each piezometer at its prescribed depth.

#### (4) Discharge of springs and streams

Flow from springs and streams provide important information on ground water conditions. In consolidated rocks, the location and alignment of springs is related to the location of joints, faults, or other structures influencing water accumulation. Springs in either bedrock or alluvium may be caused by bodies of perched ground water, water under artesian pressure, or outfall

of the main water table. Gains or losses in base flow of streams mark effluent (gaining) or influent (losing) reaches, resulting from ground water discharge or recharge.

In estimating small flows, it is helpful to visualize the time required for that flow to fill a 1-, 5-, or 50-gallon container. Flows of more than 100 gallons per minute may be estimated by measuring the average velocity of an object (e.g., an orange) floating in the stream and estimating or measuring the average cross-sectional area of flow.

Measurements of a few gallons per minute can be made rapidly and accurately by collecting the flow and timing the filling of known volume containers. Flows of over 100 gallons per minute may best be measured with a sharp-crested weir or Parshall flume.

#### (5) Production from wells

Production records or well yields show past performance and may indicate possibilities for additional production. The volume of water pumped and resultant drawdown indicate the capacity of aquifers at specific locations.

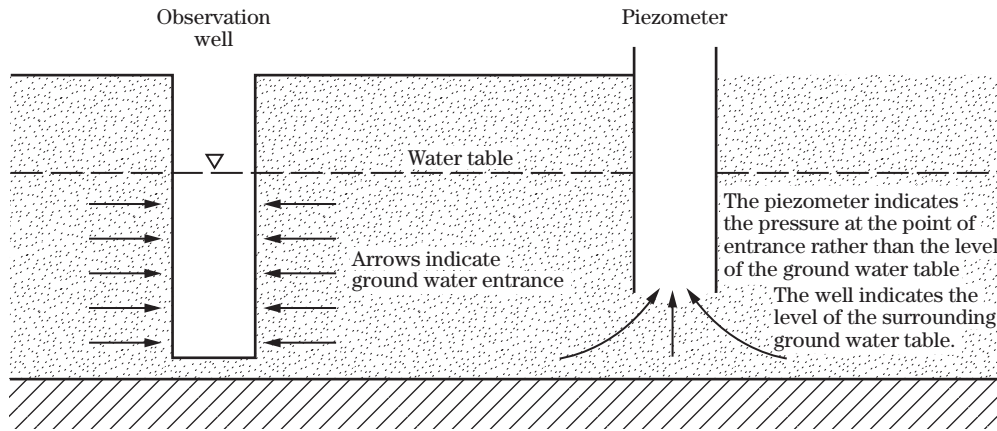
Data on production may be obtained from owners, lessees, drillers, pump agencies, well testing firms, power or gas companies, State engineer records, and USGS records.

Pipe orifices are commonly used to measure discharges ranging from 50 to 2,000 gallons per minute. If wells are in operation, their production may be estimated using nomographs for flow from pipes (figs. 31-15 and 31-16).

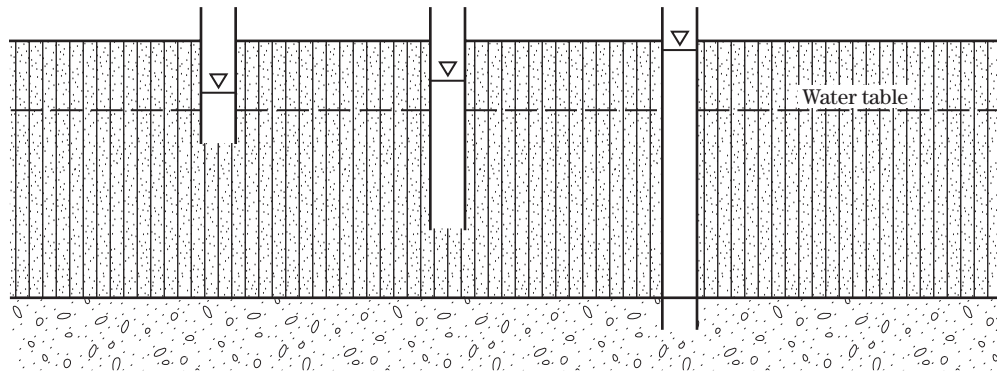
#### (c) Permeability investigations

Investigations of permeability are made to estimate the amount of water that may be obtained from a given aquifer, to estimate the safe yield of ground water reservoirs, and the time required to recharge such reservoirs after pumping has stopped. Several methods have been developed by a number of investigators during the past century. All are based on Darcy's law that velocity, when laminar or nonturbulent flow exists, is proportional to the hydraulic gradient and the coefficient of permeability. Relationship of the various methods for determining permeability is shown in figure 31-17.

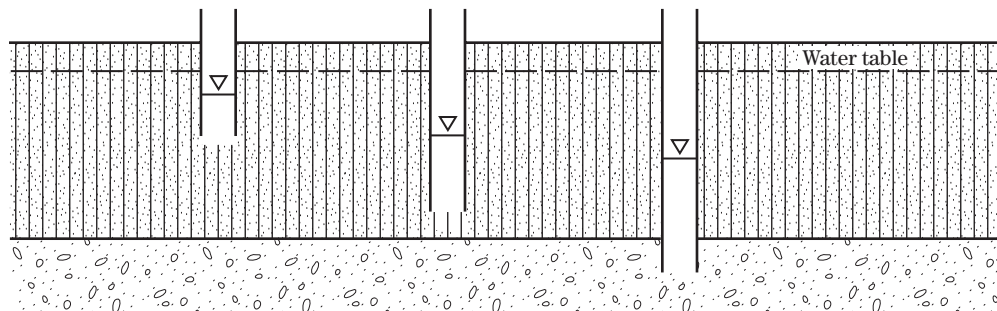
**Figure 31-14** Observation wells and piezometers



**A-Construction of observation wells and piezometers.**

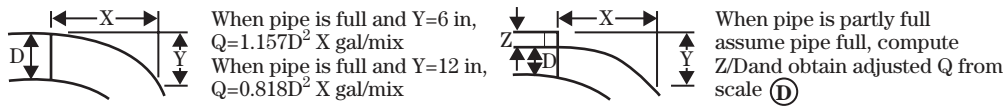


**B-Piezometers indicate water under artesian pressure in sand and gravel zone is leaking into overlying material.**

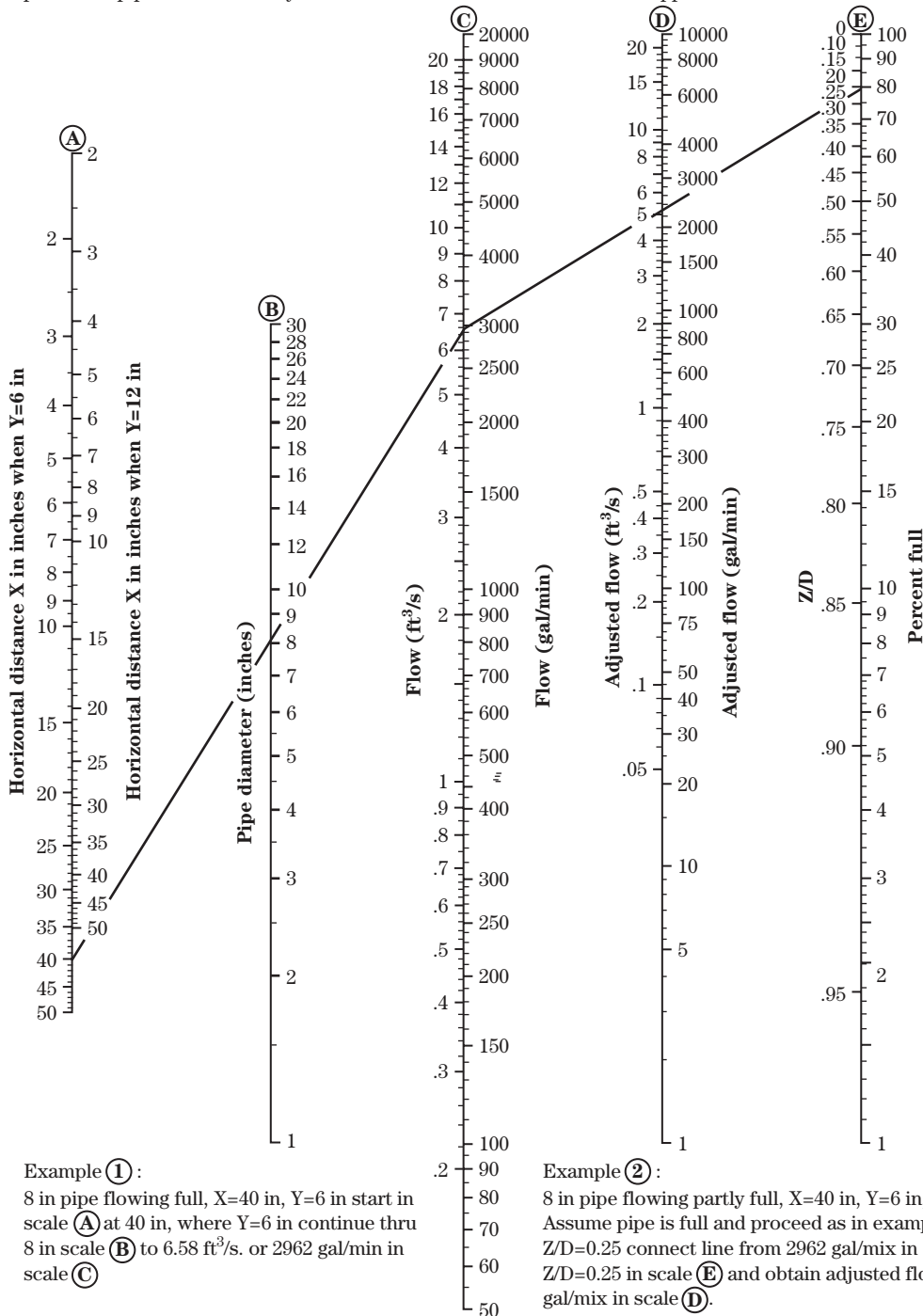


**C-Piezometers indicate a water table draining slowly into underlying sand and gravel.**

**Figure 31-15** Estimated flow from horizontal pipe



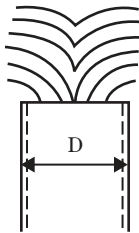
Use either folding rule or template with Y equal to 6 in or 12 in. For slightly inclined pipes, measure X parallel to pipe and Y vertically. Results obtained from this solution are approximate.



**Example ①:**  
8 in pipe flowing full, X=40 in, Y=6 in start in scale (A) at 40 in, where Y=6 in continue thru 8 in scale (B) to 6.58 ft<sup>3</sup>/s. or 2962 gal/min in scale (C)

**Example ②:**  
8 in pipe flowing partly full, X=40 in, Y=6 in, and Z= 2 in. Assume pipe is full and proceed as in example ①. Z/D=0.25 connect line from 2962 gal/mix in scale (C) to Z/D=0.25 in scale (E) and obtain adjusted flow equals 2382 gal/mix in scale (D).

**Figure 31-16** Estimated flow from vertical pipe

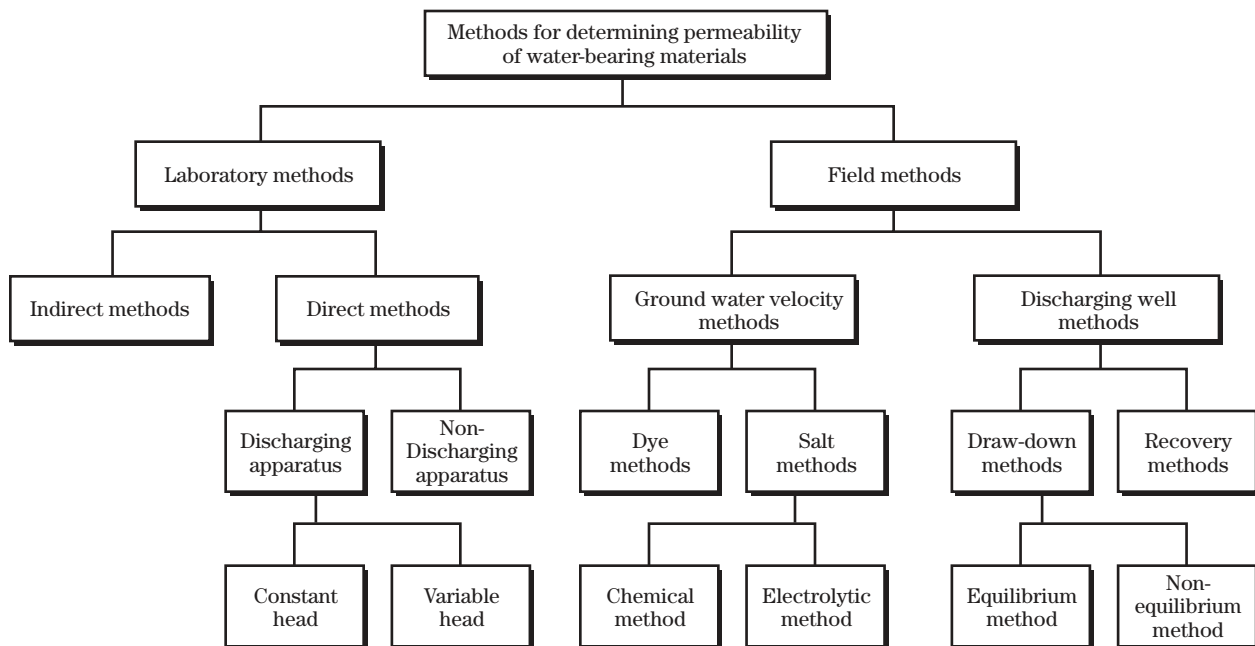


The approximate flow from vertical pipes or casings can be determined by measuring the maximum height (H) in inches to which the water jet rises above the pipe (D) in inches.

The flow in gallons per minute is given in the accompanying table for different sizes of standard pipe and different heights of the water jets.

Height (H) (in)	Nominal diameter (D) of standard pipe (in)				
	2	3	4	5	6
2	28	59	97	138	193
2.5	32	71	117	176	248
3	34	76	131	195	271
3.5	38	86	147	224	327
4	40	91	159	239	330
5	45	103	180	277	398
6	50	113	199	307	448
7	55	126	221	341	497
8	58	131	233	363	526
9	63	144	253	390	568
10	66	148	263	408	595
12	74	168	295	457	668
14	81	183	320	493	723
16	86	196	344	530	775
18	90	204	360	557	808
20	98	221	387	599	870

**Figure 31-17** Methods for determining permeability of water-bearing materials (from Wenzel 1942)



Laboratory methods are direct and indirect. The latter are based on analyses of samples for grain size and porosity developed by Hazen, Slichter, Terzaghi, Hulbert and Feben, and Fair and Hatch. Calculation of permeability on the basis of Hazen's effective or  $D_{10}$  size, using Slichter's porosity of material and temperature of fluid tables, holds for filter sands, and fine, clean, well-sorted sand (National Resources Committee 1939). This method should not be used indiscriminately, but for the materials mentioned, yields satisfactory preliminary results.

Direct methods consist of measuring flow of water through undisturbed samples using permeameters of various designs (Wenzel 1942). Laboratory permeability tests may reach a high degree of accuracy for a particular sample, but determinations must be made on a sufficient number to adequately represent the aquifer. This would amount to a considerable number for a thick and extensive alluvial aquifer. In gravelly sand and gravel, the taking of undisturbed samples is difficult and may require freezing of the materials.

Field methods include measurement of velocity by tracing dyes or salt solutions and observation of water levels in wells during and after drawdown. Timing the movement of colored or salted water between wells is subject to limitations and difficulties, but has given satisfactory results in very uniform materials. It has given very erroneous results in interbedded coarse and fine-grained materials. The latter is not adapted to use where ground water movement is slow because the heavier salt solution tends to sink.

The most satisfactory basis for aquifer permeability estimates is by pumping tests with wells. Estimates thus obtained represent average characteristics of materials throughout a considerable area. Discharging well methods have a definite advantage over laboratory methods because the materials remain in place. The formulas for calculating aquifer characteristics from well tests are based on assumption of some more or less ideal conditions. The absence of some conditions will prevent indiscriminate use of many formulas, but consistent results may be obtained by selection of a formula in close accord with geologic characteristics of the aquifer.

Discharging well methods present opportunities to obtain test data during both drawdown and recovery of water levels. It is recognized that a recovery test is

the reverse of a drawdown test. As the name implies, it involves shutting off a pumping well and observing water levels in nearby observation wells or the pumped well. Slichter and Muskat each developed formulas for calculating permeability from recovery data using the equilibrium method. Neither of these takes into consideration the length of time the well discharged prior to being shut off. The Theis formula for determining permeability from recovery data uses the nonequilibrium method (Wenzel 1942). The term "recovery" as used in the Theis formula means the difference between the water level in a well at any time after pumping is stopped and the water level that would have resulted if pumping has continued until that time.

An advantage of a recovery analysis of a pumped well is that it provides an easy check on pumping test results; also, it implies a constant discharge  $Q$ , which often is difficult to control accurately in the field.

Drawdown test data are used to determine aquifer characteristics by the equilibrium (Thiem) method and the nonequilibrium (Theis) method.

Important differences in requirements and results of the two methods are that the equilibrium method requires two or more observation wells, while the nonequilibrium method requires one or more observation wells. The nonequilibrium equation includes time as a factor and enables the computation of future pumping levels when the flow of ground water due to pumping does not approach an equilibrium condition.

### (1) Laboratory tests

Two types of permeameters are used to measure permeability in the laboratory: the constant head and variable head types. In the constant head type, the quantity of water flowing through a sample of known area and length in a given time can be measured. This type is applicable to relatively permeable materials. The variable head type of permeameter is adapted to relatively impermeable materials. In it, the quantity of water percolating through the sample is measured indirectly by observation of the rate of fall of water level in the standpipe above the specimen. All quantities are measured and the permeability is readily found by formulas in Wenzel (1942).

## (2) Aquifer tests

Aquifer pump tests are made to determine the transmissibility and, when using the nonequilibrium procedure, the coefficient of storage of an aquifer.

## (3) Equipment

Preliminary to the actual test is the installation of the testing equipment. Observation wells must be installed and ready to use. Equipment such as pumps, water-level measuring devices, timing watches, and well discharge measuring devices must be assembled and on the site. It is advisable to make a brief test run a few days before the actual aquifer test is to be made to be sure all equipment is in good operating condition and the personnel involved are familiar with their duties.

*Pumps*—the pump and power source to be used must be adequate to pump the required volume of water for a period of 21 to 72 hours. If the aquifer to be tested is artesian, an approximate 21-hour test is usually long enough. If it is an unconfined aquifer, at least a 72-hour test is desirable. Pumping for a short period of a few days prior to the test is helpful in determining if the pump is adequate to provide the drawdown required and all equipment is in good operating condition.

Provisions must be made to conduct all discharge water away from the site during the test. Recharge of the pumped water to the aquifer during the test will invalidate the test results.

*Observation wells*—the number of observation wells required to furnish adequate information depends on the geologic and hydrologic conditions present and the aquifer test method to be used.

For example, if boundary conditions are anticipated (recharge, impermeable, or less permeable boundary) the observation wells should be located to indicate these conditions. In this case, one or more observation wells should be located between the discharging well and the suspected boundary, and an additional well or wells should be located where boundary interference will be minimal. With this arrangement the effect of the boundary will be indicated. See Bentall (1963), Johnson (1975), and Todd (1959) for additional details.

If boundary conditions are not present and the aquifer is isotropic, the drawdown cone will be symmetrical. The observation wells can be located anywhere within the drawdown cone as long as the distance from the

discharging well is known. As stated previously, the minimum number of observation wells required for the Thiem equilibrium method is two, and the minimum number for the Theis nonequilibrium method is one. For limited water-level recovery calculations, no observation wells are required, but at least one is desirable.

The observation wells should be screened and at least lightly developed so they will respond quickly to water level fluctuations. The midpoint of the screens of the observation wells should be at about the same elevation as the midpoint of the screen in the discharging well and, if possible, in a coarse-grained zone in the aquifer. The observation wells should be located accurately with respect to the pumping well. The elevation of a point at the top of each well from which water level measurements will be referenced should be known to 0.01 foot.

## (4) Water level measurements

Exact timing during the test is necessary for an accurate test. The time the test starts and exact time of all measurements must be made. The time interval between readings is small when the drawdown is changing rapidly and greater as the drawdown changes more slowly.

Water level measurements must also be accurate and should be read to the nearest 0.01 foot. An electric sounder, wetted tape, or “popper” is preferred over the air line method for measuring the water level in the observation wells. When using the electric sounder, the electrode should be immersed to give the same deflection on the millimeter for each water-level reading. The popper method employs a steel tape and a weight. The bottom of the weight is cup shaped or hollow. When the weight strikes the water surface, it makes a popping noise. The popper and electric sounder do not have to be withdrawn from the well after every measurement; the chalked tape does. The air line method is not as accurate as the aforementioned techniques, but is adequate for use in the pumped well.

## (5) Discharge measurements

It is essential that the yield of the test well be measured accurately during a pump test and that the yield is constant. Pipe orifices are commonly used to measure discharges within a range of 50 to 2,000 gallons per minute. Parshall flumes or sharp crested weirs are used to measure larger flows.

A constant rate of discharge is required for pump tests. Governing the discharge by varying the pump motor speed is difficult. A gate valve installed in the discharge line is a very effective method. The valve is to be partially closed at the beginning of the test so it can be adjusted to maintain a constant yield from the well as drawdown increases during test.

*Discharging well method*—the information from pump tests should be tabulated as shown in figure 31-18, a through d.

The basic hydraulic equations for determining aquifer characteristics have been given in NEH631.01. An example of the application of these equations for equilibrium and nonequilibrium conditions will be given using data from the U.S. Bureau of Reclamation (1964).

*Equilibrium method*—the Thiem equilibrium equation is:

$$k = \frac{Q \log_e \left( \frac{r_2}{r_1} \right)}{2\pi m (s_1 - s_2)}$$

$$P = \frac{527.7 Q \log_{10} \frac{r_2}{r_1}}{m (s_1 - s_2)} \quad (\text{eq. 31-1})$$

These parameters are illustrated in figure 31-19.

This information is obtained from pump test data sheets, figure 31-18:

$$\begin{aligned} Q &= 50 \text{ ft} \\ &= 1210 \text{ gal/min} \\ r_1 &= 100 \text{ ft} \\ r_2 &= 200 \text{ ft} \\ r_3 &= 400 \text{ ft} \\ t &= 2,045 \text{ min} \\ s_1 &= 2.17 \text{ ft} \\ s_2 &= 1.65 \text{ ft} \\ s_3 &= 1.07 \text{ ft} \end{aligned}$$

Using data from observation wells 1 and 2:

$$P = \frac{(527.7)(1210) \left( \log_{10} \frac{200}{100} \right)}{50(2.17 - 1.65)}$$

$$= 7400 \text{ gal/ft}^2/\text{d}$$

Using data from observation wells 1 and 3:

$$P = \frac{(527.7)(1210) \left( \log_{10} \frac{400}{100} \right)}{50(2.17 - 1.65)}$$

$$= 7000 \text{ gal/ft}^2/\text{d}$$

Using data from observation wells 2 and 3:

$$P = \frac{(527.7)(1210) \left( \log_{10} \frac{400}{200} \right)}{50(1.65 - 1.07)}$$

$$= 6750 \text{ gal/ft}^2/\text{d}$$

Average P = 7050 gal/ft<sup>2</sup>/d

*Nonequilibrium method*—the Theis equation to determine aquifer characteristics under nonequilibrium conditions is:

$$s = \frac{114.6Q}{T} W(u) \quad (\text{eq. 31-2})$$

where:

- s = drawdown at a point r distant from a pumping well (ft)
- Q = discharge from the well (gal/min)
- T = coefficient of transmissibility (gal/d/ft)
- W(u) = exponential integral
- u =  $\frac{1.87r^2S}{Tt}$
- r = distance from pump well to point where drawdown s is determined (ft)
- S = coefficient of storage (dimensionless)
- t = time that pump well has been discharging (d)

If the coefficient of transmissibility and coefficient of storage are known, the drawdown on the cone of depression at any time and any distance from the well can be determined after the well starts discharging. This is done by substituting the known values of S and T and the desired values of t and r in the equation:

$$u = \frac{1.87r^2S}{Tt}$$

and the equation solved to determine u. The value of W(u) for u is read from table 31-2 and the equation:

$$s = \frac{114.6Q}{T} W(u)$$

is then solved for the drawdown, s.

**Figure 31-18** Pump test drawdown data sheet

(a)

Project:	Drawdown measured by:	1-foot Parshall Flume
Feature:	Discharge measured by:	Electrical sounder
Location:	Reference point:	North side of casing collar

## PUMP TEST NO. 1, PUMPING WELL

Date	Time	Depth to water (ft)	Drawdown, s (ft)	Gage reading (ft)	Discharge (gal/min)	Remarks
5-16	0840	60.99				
5-17	0830	61.01				
5-18	0845	61.00				
5-19	0820	60.98				
	0840	60.99 <sup>1/</sup>	0.0			Pump started
	0900	72.30	11.3	0.79	1,210	
	1000	72.60	11.6	0.79	1,210	
	1100	72.80	11.8	0.79	1,210	Pump off 5-21 at 0730
	1155	72.80	11.8	0.80	1,210	
	1255	72.80	11.8	0.80	1,215	Avg. Q = 121 gal/min
	1355	73.00	12.0	0.80	1,210	
	1455	73.20	12.2	0.80	1,210	
	1555	73.20	12.2	0.80	1,200	m = 50 ft
	1655	73.20	12.2	0.80	1,210	
	1800	73.20	12.2	0.80	1,210	
	1856	73.30	12.3	0.80	1,210	
	1948	73.40	12.4	0.80	1,210	
	2057	73.40	12.4	0.80	1,200	
	2203	73.40	12.4	0.80	1,210	
	2300	73.60	12.6	0.80	1,210	
	2358	73.50	12.5	0.80	1,210	
5-20	0104	73.60	12.6	0.80	1,210	
	0204	73.60	12.6	0.80	1,210	
	0259	73.60	12.6	0.80	1,210	
	0400	73.80	12.8	0.80	1,210	
	0501	74.00	13.0	0.80	1,210	
	0602	73.90	12.9	0.80	1,210	
	0702	73.90	12.9	0.80	1,210	
	0759	73.80	12.8	0.80	1,210	
	0855	73.80	12.8	0.80	1,210	
	0955	73.80	12.8	0.80	1,210	
	1055	73.80	12.8	0.80	1,210	

1/ Static water level

Continued but not reproduced

**Figure 31-18** Pump test drawdown data sheet—Continued

(b)

Project:	Drawdown measured by:	Electric sounder
Location:	Reference point:	North side of casing collar

PUMP TEST NO. 1, OBSERVATION WELL NO. 1,  $r = 100$  ft

Date	Time	Depth to water (ft)	Drawdown, s (ft)	t (min)	$r^2/t$	Remarks
5-16	0845	60.43				
5-17	0825	60.45				
5-18	0840	60.43				
5-19	0815	60.42				
	0841	60.42	0.00			Pump started at
	0845	60.50	0.08	5	2,000	0840
	0850	60.64	0.22	10	1,000	Pump off 5-21 at
	0855	60.74	0.32	15	670	0730
	0900	60.83	0.41	20	500	
	0905	60.90	0.48	25	400	
	0910	60.96	0.54	30	333	m = 50 ft
	0920	61.06	0.64	40	250	
	0930	61.14	0.72	50	200	
	0940	61.20	0.78	60	170	
	0950	61.27	0.85	70	140	
	1000	61.32	0.90	80	125	
	1010	61.36	0.94	90	110	
	1020	61.40	0.98	100	100	
	1030	61.44	1.02	110	91	
	1040	61.47	1.05	120	83	
	1140	61.62	1.20	180	56	
	1240	61.73	1.31	240	42	
	1340	61.83	1.41	300	33	
	1440	61.90	1.48	360	28	
	1540	61.96	1.54	420	24	
	1640	62.01	1.59	480	21	
	1740	62.05	1.63	540	19	
	1840	62.09	1.67	600	17	
	1940	62.14	1.72	660	15	
	2040	62.17	1.75	720	14	
	2240	62.26	1.84	840	12	
5-20	0040	62.31	1.89	960	10	
5-20	1845	62.59	2.17	2,045	4.9	

Continued but not reproduced

**Figure 31-18** Pump test drawdown data sheet—Continued

(c)

Project:	Drawdown measured by:	Electric sounder
Location:	Reference point:	East side of casing collar

## PUMP TEST NO. 1, OBSERVATION WELL NO. 2, r = 200 ft

Date	Time	Depth to water (ft)	Drawdown, s (ft)	t (min)	r <sup>2</sup> /t	Remarks
5-16	0835	58.41				
5-17	0820	58.39				
5-18	0820	58.40				
5-19	0810	58.41				
	0838	58.41 <sup>1/</sup>				Pump started at 0840
	0847	58.41	0.00	7	5,720	
	0852	58.44	0.03	12	3,332	Pump off 5-21 at 0730
	0857	58.48	0.07	17	2,352	
	0902	58.52	0.11	22	1,820	
	0907	58.56	0.15	27	1,480	m = 50 ft
	0912	58.59	0.18	32	1,252	
	0922	58.66	0.25	42	952	
	0932	58.72	0.31	52	768	
	0942	58.77	0.36	62	644	
	0952	58.81	0.40	72	556	
	1002	58.85	0.44	82	488	
	1012	58.89	0.48	92	436	
	0022	58.92	0.51	102	392	
	1032	58.95	0.54	112	357	
	1042	58.98	0.57	122	328	
	1142	9.12	0.71	182	220	
	1242	59.22	0.81	242	165	
	1342	59.30	0.89	302	132	
	1442	59.38	0.97	362	110	
	1542	59.44	1.03	422	94	
	1642,	59.49	1.08	482	83	
	1742	59.53	1.12	542	72	
	1842	59.57	1.16	602	66	
	1942	59.61	1.20	662	60	
	2042	59.64	1.23	722	55	
	2242	59.73	1.32	842	44	
5-20	0042	59.77	1.36	962	40	
5-20	1845	60.01	1.65	2,045	20	

1/ Static water level

Continued but not reproduced

**Figure 31-18** Pump test drawdown data sheet—Continued

(d)

Project:	Drawdown measured by:	Popper
Location:	Reference point:	East side of casing collar

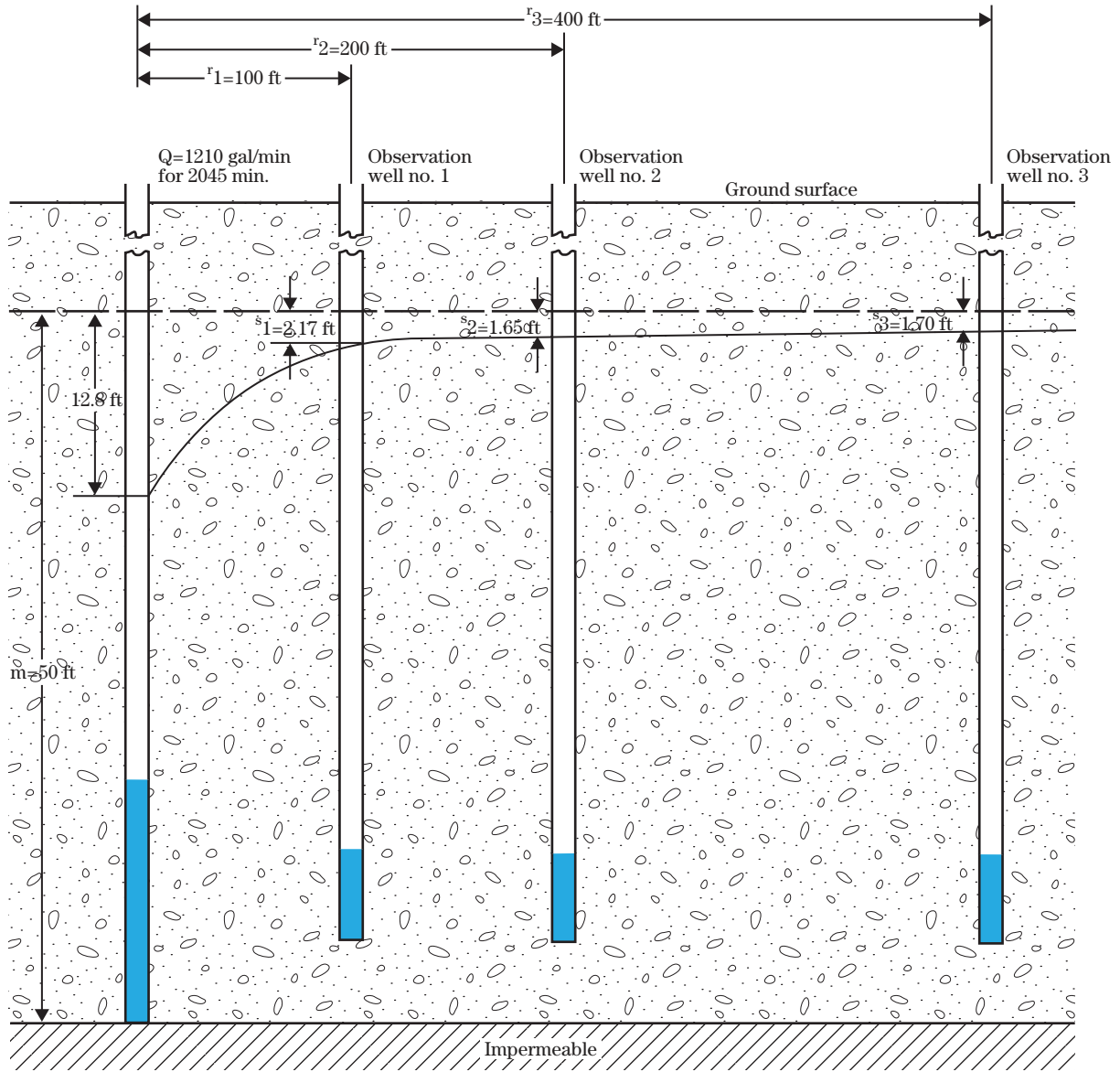
## PUMP TEST NO. 1, OBSERVATION WELL NO. 3, r = 400 ft

Date	Time	Depth to water (ft)	Drawdown, s (ft)	t (min)	r <sup>2</sup> /t	Remarks
5-16	0850	58.47				
5-17	0830	58.48				
5-18	0835	58.48				
5-19	0820	58.47				
	0838	58.47 <sup>1/</sup>				Pump on at 0840
	0855	58.47	0.00	15	10,720	Pump off 5-21 at
	0900	58.47	0.00	20	8,000	0730
	0905	58.47	0.00	25	6,400	
	0910	58.47	0.00	30	5,280	m = 50 ft
	0915	58.48	0.01	35	4,640	
	0920	58.49	0.02	40	4,000	
	0930	58.50	0.03	50	3,200	
	0940	58.52	0.05	60	2,720	
	0950	58.54	0.07	70	2,240	
	1000	58.55	0.08	80	2,080	
	1010	58.57	0.10	90	1,760	
	1020	58.59	0.12	100	1,600	
	1030	58.61	0.14	110	1,456	
	1040	58.62	0.15	120	1,328	
	1050	58.64	0.17	130	1,232	
	1150	58.73	0.26	190	848	
	1250	58.81	0.34	250	640	
	1350	58.87	0.40	310	512	
	1450	58.93	0.46	370	432	
	1550	58.98	0.51	430	368	
	1650	59.02	0.55	490	320	
	1750	59.06	0.59	550	288	
	1850	59.10	0.63	610	256	
	1950	59.12	0.65	670	240	
	2050	59.15	0.68	730	224	
	2250	59.22	0.75	850	192	
5-20	0050	59.27	0.80	970	160	
5-20	1845	59.54	1.07	2,045	78	

1/ Static water level

Continued but not reproduced

**Figure 31-19** Drawdown cone



The nonequilibrium equation can also be solved for transmissibility  $T$  and storage coefficient  $S$  if several values of drawdown  $s$  at times  $t$  are known for one distance  $r$  from the pumpwell or several values of  $s$  and  $r$  are known for one value of  $t$ . The solution requires the graphical determination of  $W(u)$ ,  $u$ ,  $s$ , and either  $r^2/t$  or the reciprocal of time ( $1/t$ ).

Figure 31-20 is a type curve of  $W(u)$  versus  $u$  and is plotted from the data in table 31-2.

In figure 31-21, test well data from figure 31-18 are plotted at the same scale on logarithmic paper as the type curve. Note that this data curve is plotted as  $s$  versus  $t$  instead of  $1/t$ . The logarithmic data curve, as plotted, is a mirror image of the curve that would be plotted as  $s$  versus  $1/t$ . The calculation of the reciprocal values of time is not necessary. The type and data curves are matched face to face (a light table is useful). Keep the axes parallel, pick a common point on a matched section of the two curves and obtain values of  $W(u)$ ,  $u$ ,  $s$ , and  $t$  for the common point.

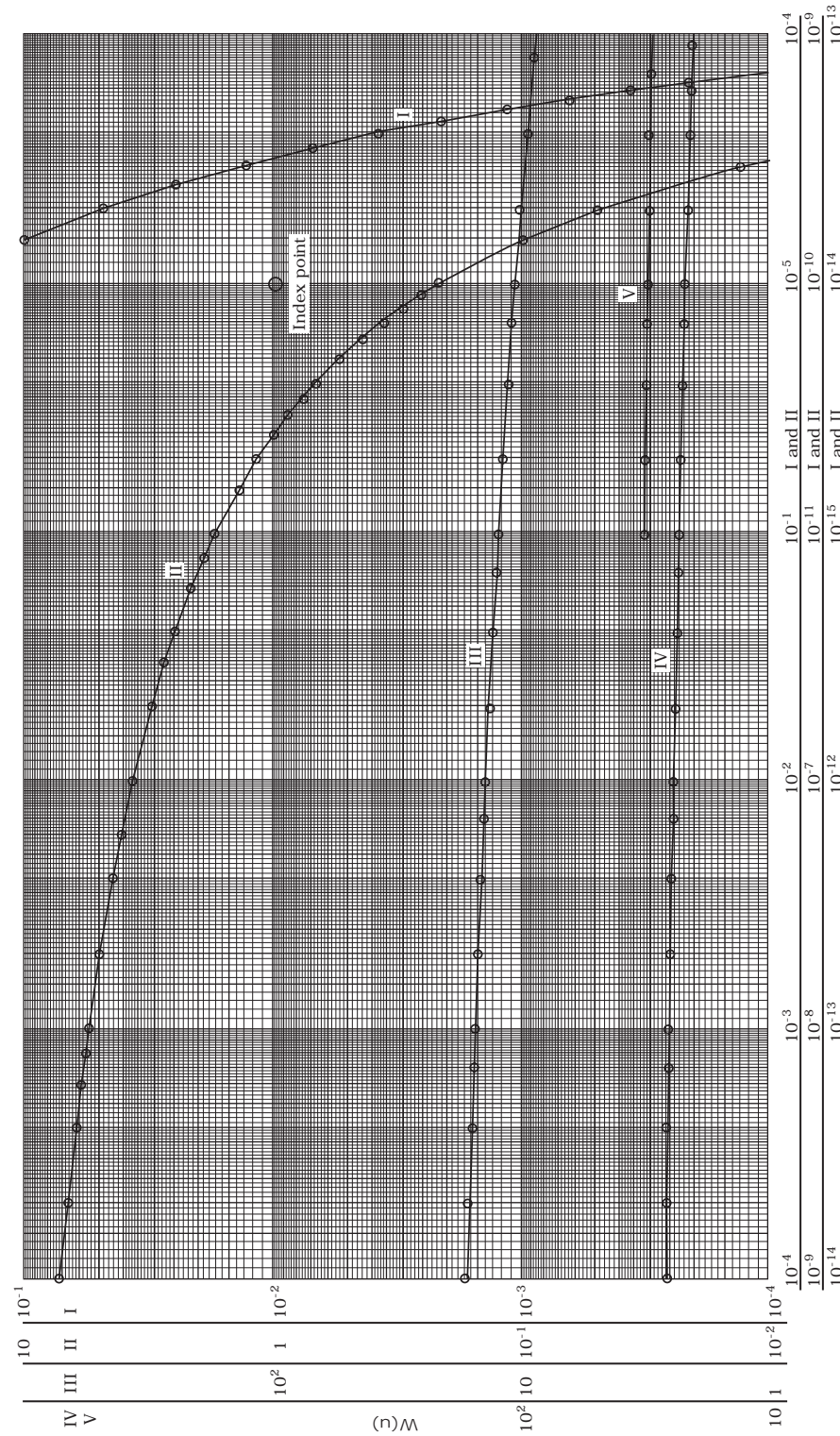
Since the curve fitting process is a measure of displacement of the data curve with respect to the type curve, a simplified procedure can sometimes be used. Move the curves, keeping the axes parallel until a fit is found. If the data curve fits section II of the type curve, select as a common point on the type curve  $W(u)$  and  $u$  equal one (1), and determine the value of  $s$  and  $t$  (or  $r^2/t$ ) for this point on the plotted curve.

Data from the three observation wells are plotted in figure 31-21 and matched to the type curve (figure 31-20). Values for  $W(u)$ ,  $u$ ,  $s$ , and  $t$  were obtained by picking a common point on the matched section of the fitted curves and for the common point at  $W(u)$  and  $u$  equal to one (1) when curves were fitted. As can be seen from the following calculations, both methods give approximately the same result. All values of time on the data curve are in minutes. To be consistent with the units in the equation, these time values must be divided by 1,440 to convert to days.

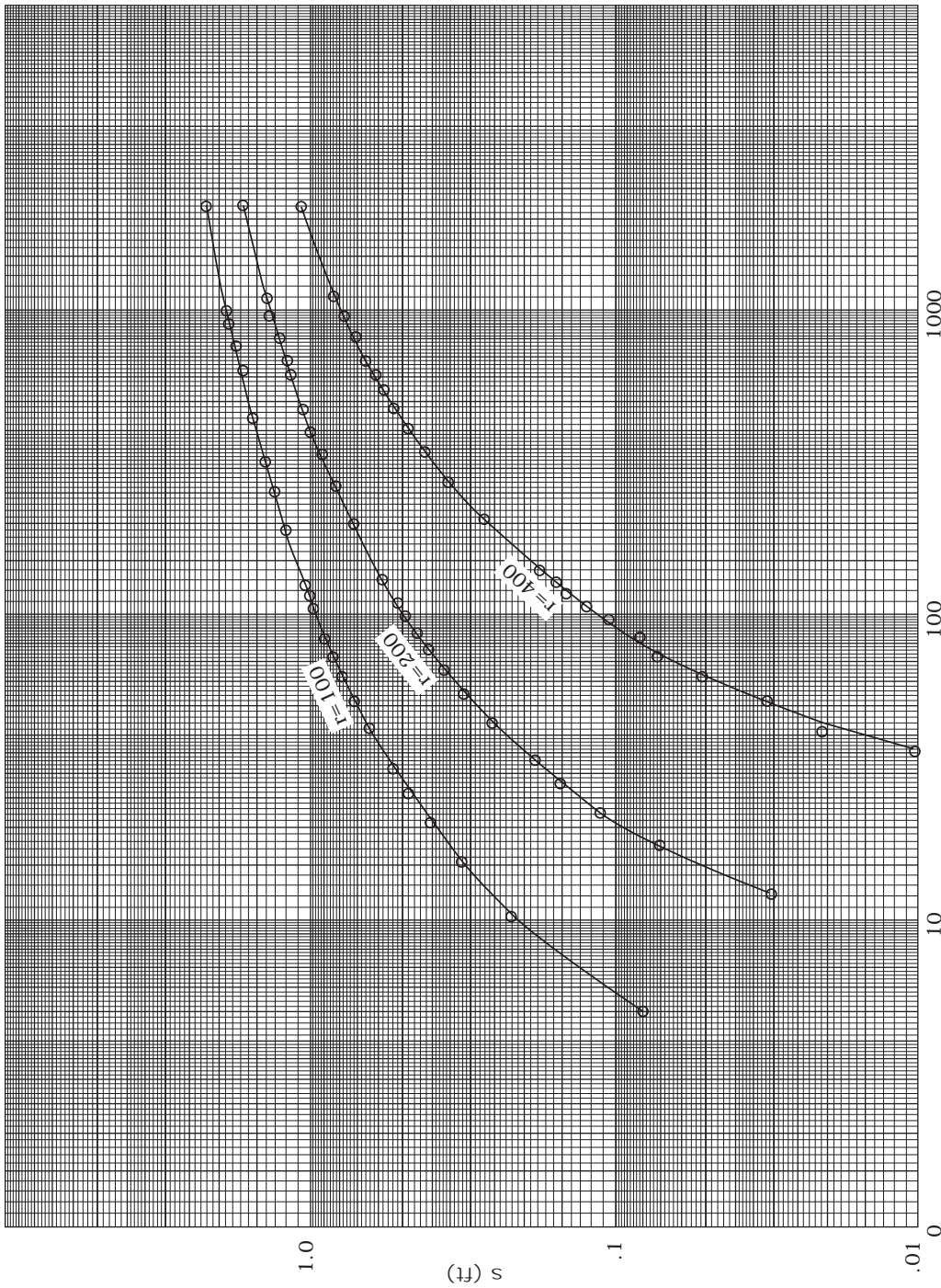
**Table 31-2** Selected values of  $u$  and  $W(u)$

$u$	$W(u)$	$u$	$W(u)$
9.5	0.0000072	0.01	4.04
6.0	0.00036	0.005	4.73
4.0	0.0038	$10^{-3}$	6.33
3.0	0.013	$10^{-4}$	8.63
2.0	0.049	$10^{-5}$	10.94
1.5	0.10	$10^{-6}$	13.24
1.0	0.22	$10^{-7}$	15.54
0.75	0.34	$10^{-8}$	17.84
0.5	0.56	$10^{-9}$	20.15
0.4	0.70	$10^{-10}$	22.45
0.3	0.91	$10^{-11}$	24.75
0.2	1.22	$10^{-12}$	27.05
0.1	1.82	$10^{-13}$	29.36
0.075	2.09	$10^{-14}$	31.66
0.05	2.47	$10^{-15}$	33.96
0.025	3.14		

**Figure 31-20** Type curve of  $W(u)$  versus  $u$



**Figure 31-21** Drawdown versus time curve



**Observation well no. 1**      **r=100 ft**

$$\begin{aligned}
 W(u) &= 2.4 & W(u) &= 1 \\
 u &= 5.5 \times 10^{-2} & u &= 1 \\
 t &= \frac{100}{1440} & t &= \frac{5.25}{1440} \\
 s &= .42 & s &= .42 \\
 \\
 T &= \frac{114.6Q}{s} W(u) & & \\
 &= \frac{(114.6)(1210)(1)}{0.42} & & = \frac{(114.6)(1210)(2.4)}{0.98} \\
 &= 330,000 & & = 340,000 \\
 \\
 s &= \frac{uTt}{1.87r^2} & & \\
 &= \frac{(1)(33 \times 10^5) \left( \frac{5.25}{1440} \right)}{(1.87)(100)^2} & & = \frac{(5.5 \times 10^{-2})(3.4 \times 10^5) \left( \frac{100}{1440} \right)}{(1.87)(100)^2} \\
 &= .064 & & = .069
 \end{aligned}$$

**Observation well no. 2**      **r=200 ft**

$$\begin{aligned}
 W(u) &= 1 & W(u) &= 1.22 \\
 u &= 1 & u &= 0.2 \\
 t &= \frac{20}{1440} & t &= \frac{100}{1440} \\
 s &= .40 & s &= .51 \\
 \\
 T &= \frac{114.6QW(u)}{s} & & \\
 &= \frac{(114.6)(1210)(1)}{.40} & & = \frac{(114.6)(1210)(1.22)}{.51} \\
 &= 346,000 & & = 330,000 \\
 \\
 s &= \frac{uTt}{1.87r^2} & & \\
 &= \frac{(1)(346,000) \left( \frac{20}{1440} \right)}{(1.87)(200)^2} & & = \frac{(0.2)(330,000) \left( \frac{100}{1440} \right)}{(1.87)(200)^2} \\
 &= .064 & & = .061
 \end{aligned}$$

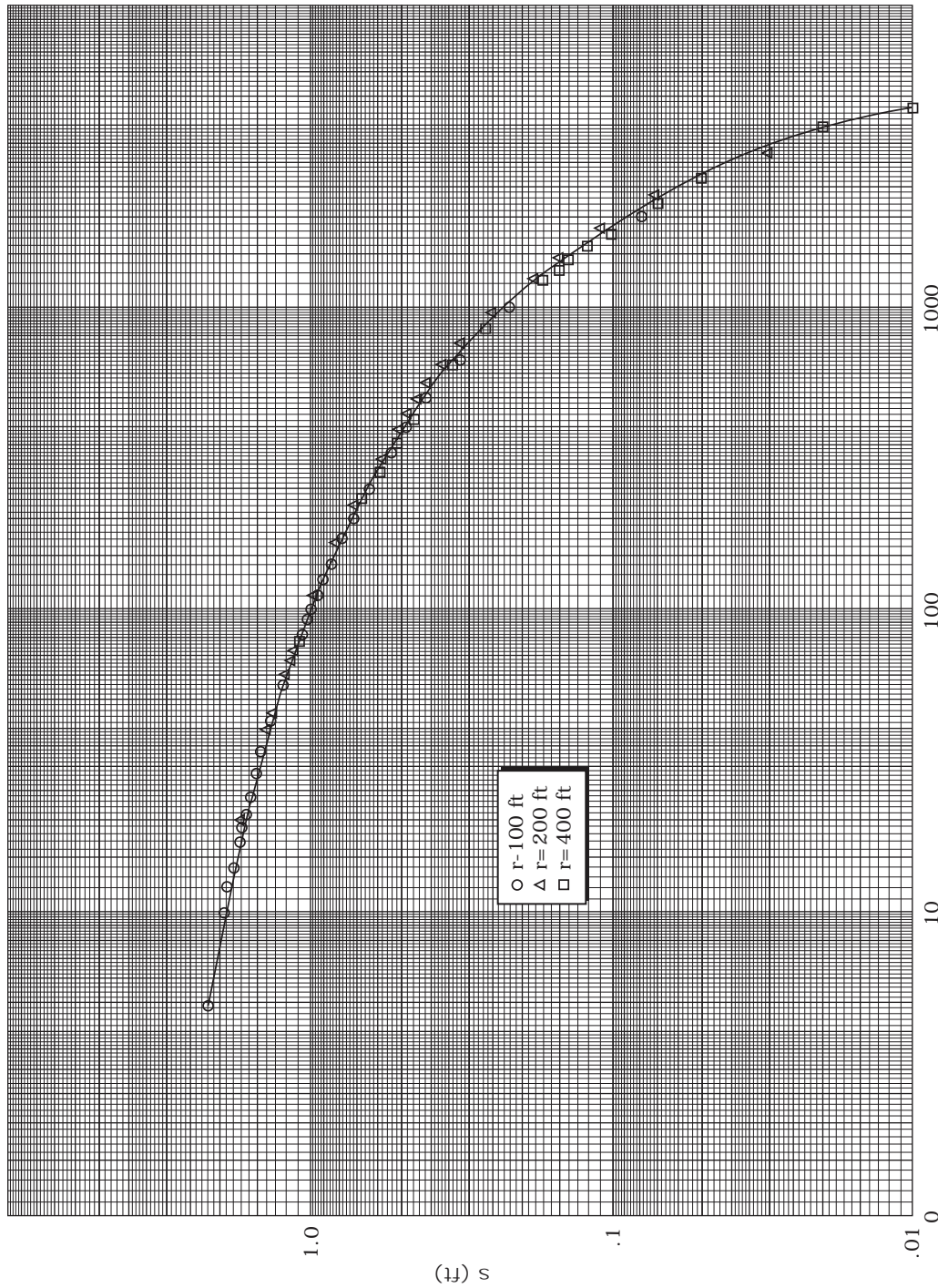
**Observation well no. 3**      **r=400 ft**

$$\begin{aligned}
 t &= \frac{86}{1440} & t &= \frac{86}{1440} \\
 \\
 T &= \frac{114.6QW(u)}{.096} & & \\
 &= \frac{(114.6)(1210)(1)}{.42} & & = \frac{(114.6)(1210)(.22)}{.096} \\
 &= 330,000 & & = 320,000 \\
 \\
 s &= \frac{uTt}{1.87r^2} & & \\
 &= \frac{(1)(330,000) \left( \frac{86}{1440} \right)}{(1.87)(400)^2} & & = \frac{(1)(320,000) \left( \frac{86}{1440} \right)}{(1.87)(400)^2} \\
 &= .066 & & = .064 \\
 \\
 \text{Average } T &= 335,000 & \text{Average } T &= 300,000 \\
 \text{Average } S &= .065 & \text{Average } S &= .065
 \end{aligned}$$

When plotting  $r^2/t$  versus  $s$  all points for the three observation wells fall on the same curve when plotted on logarithmic paper (fig. 31-22). This curve should also be plotted at the same scale as the type curve. Values of a common point on the type and plotted curve when fitted and the values of  $r^2/t$  and  $s$  when  $W(u)$  and  $u$  equal one (1) and the curves are fitted give essentially the same results for values of  $S$  and  $T$ . This is illustrated in the following example. In this example, also the time in minutes is divided by 1,440 to convert to days.

$$\begin{aligned}
 W(u) &= 1 & W(u) &= 1.22 \\
 u &= 1 & u &= 0.2 \\
 \frac{r^2}{t} &= 1950 & \frac{r^2}{t} &= 390 \\
 s &= 0.4 & s &= 0.5 \\
 \\
 T &= \frac{114.6QW(u)}{s} & & \\
 &= \frac{(114.6)(1210)(1)}{0.4} & & = \frac{(114.6)(1210)(1.22)}{0.5} \\
 &= 346,000 & & = 339,000 \\
 \\
 s &= \frac{uT}{1.87 \frac{r^2}{t}} & & \\
 &= \frac{(1)(346,000)}{(1.87)(1950)(1440)} & & = \frac{(0.2)(339,000)}{(1.87)(390)(1440)} \\
 &= .066 & & = .065
 \end{aligned}$$

**Figure 31-22** Drawdown versus  $r^2/t$  curve



Modified nonequilibrium method—there is, under certain conditions, a short-cut method for solving the Theis nonequilibrium equation. In the equation:

$$u = \frac{1.87r^2s}{Tt}$$

The value of  $u$  decreases when time  $t$  increases. When  $u$  becomes less than about 0.01, the equation:

$$s = \frac{114.6Q}{T} W(u)$$

Can be rewritten as:

$$s = \frac{264Q}{T} \log_{10} \frac{0.3Tt}{r^2S}$$

Solving this equation for transmissibility, it becomes:

$$T = \frac{264Q \log_{10} \frac{t_2}{t_1}}{s_2 - s_1}$$

where:

- $T$  = transmissibility
- $Q$  = pumping rate (gal/min)
- $s_1$  = drawdown (ft) at time  $t_1$
- $s_2$  = drawdown (ft) at time  $t_2$  in an observation well at  $r$  distance from the discharging well

This equation can be solved graphically by plotting on semi-logarithmic paper values of  $t$  (logarithmic) and  $s$  (arithmetic). These points will fall on a straight line when  $u$  becomes less than about 0.01 as  $t$  becomes large. The equation is solved for  $T$  by selecting values of  $t_1$ ,  $t_2$ ,  $s_1$ , and  $s_2$  from the straight line portion of the curve. If  $t_1$  and  $t_2$  are selected one log cycle apart the value of:

$$\log_{10} \frac{t_2}{t_1} = 1$$

and the equation becomes:

$$T = \frac{264Q}{\Delta s}$$

where:

$\Delta s$  =  $s_2 - s_1$  over one log cycle of time.

The equation:

$$s = \frac{264Q}{T} \log_{10} \frac{0.3Tt}{r^2S}$$

When solved for the coefficient of storage becomes:

$$S = \frac{0.3Tt_0}{r^2}$$

If the straight line portion of the semi-logarithmic curve is extended to intersect the zero drawdown axis, and  $t_0$  is the time in days where this intersection occurs, the coefficient of storage,  $S$ , can be determined from the above equation.

Following are calculations of  $S$  and  $T$ , using  $\Delta s$  and  $t_0$  values from figure 31–23.

For observation well no. 1 ( $r = 100$  ft)

$$\begin{aligned} \Delta s &= 0.90 \\ t_0 &= \frac{8}{1440} \\ T &= \frac{(264)(1210)}{0.90} = 355,000 \\ S &= \frac{(0.3)(355,000)(8)}{(100)^2(1440)} = 0.059 \end{aligned}$$

For observation well no. 2 ( $r = 200$  ft)

$$\begin{aligned} \Delta s &= 0.89 \\ t_0 &= \frac{28}{1440} \\ T &= \frac{(264)(1210)}{0.89} = 359,000 \\ S &= \frac{(0.3)(359,000)(28)}{(200)^2(1440)} = 0.052 \end{aligned}$$

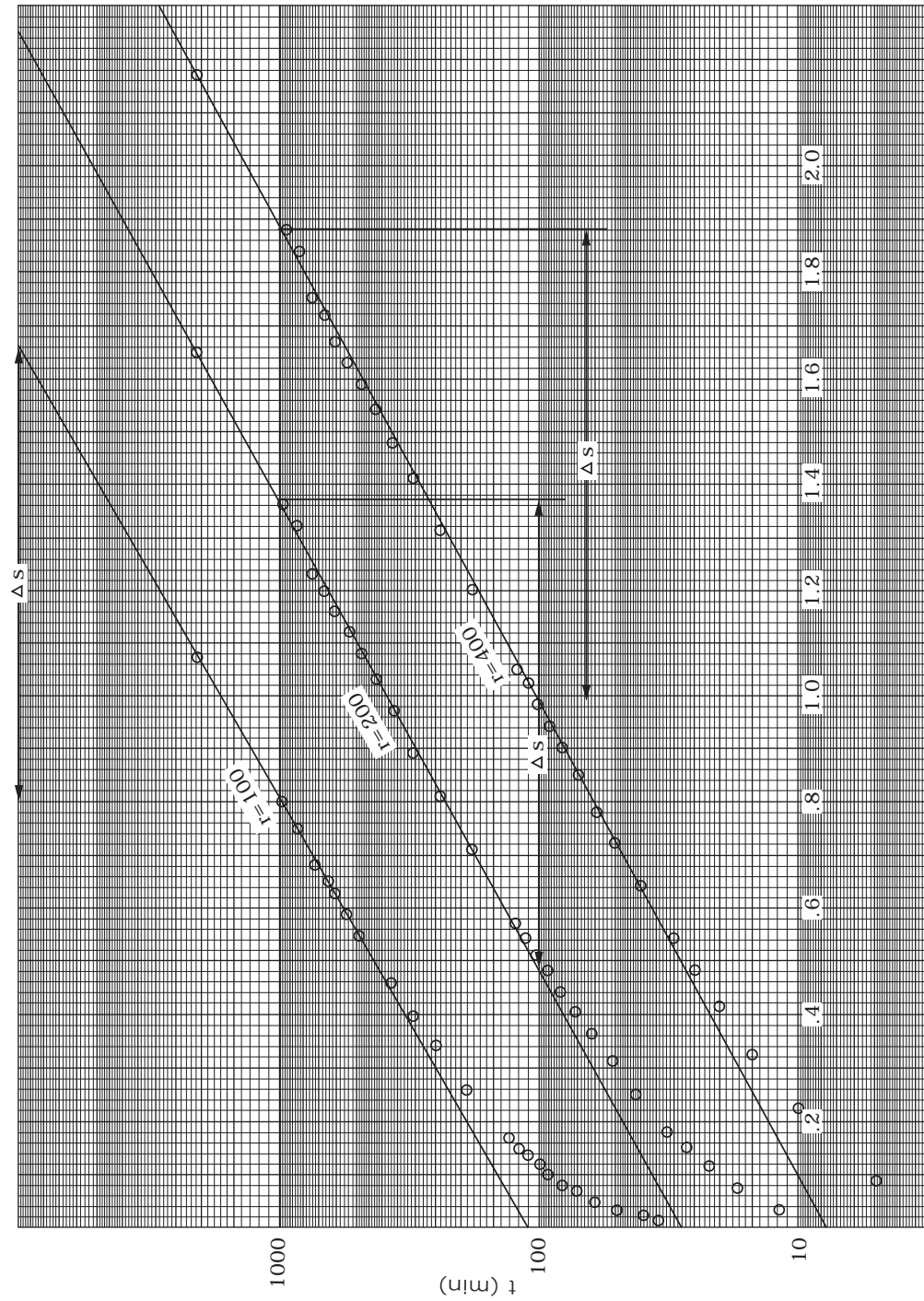
For observation well no. 3 ( $r = 400$  ft)

$$\begin{aligned} \Delta s &= 0.88 \\ t_0 &= \frac{115}{1440} \\ T &= \frac{(264)(1210)}{0.88} = 363,000 \\ S &= \frac{(0.3)(363,000)(115)}{(400)^2(1440)} = 0.054 \end{aligned}$$

Average  $T = 359,000$

Average  $S = 0.055$

**Figure 31-23** Time drawdown curves



**(6) Water level recovery method**

The water level recovery method is a useful check on the validity of the discharging well test results. Where no observation well is available limited calculations can be made of the coefficient of transmissibility of the aquifer, but not the coefficient of storage.

If a recovery test is to be made after the pump-out test, the exact time the pump is shut down is recorded. Water level recovery measurements are made and recorded in the same manner as in the pump-out test. These measurements are made at frequent intervals when recovery is rapid and less frequently as the rate of recovery decreases. See E.E. Johnson, Inc. (1975).

In the case where a recovery test is to be made without a pump-out test, the static water level is measured and recorded before starting the pump. The pump is then started, the exact time recorded, and the discharge maintained at a uniform rate. Measurements of drawdown are continued until the drawdown increases only slightly (0.1 ft/h or less) with time. The pump is then stopped, and water level recovery measurements are made as before. Figure 31-24 (from U.S. Bureau of Reclamation 2001) is an example of a water level recovery test data sheet when no observation well was available.

The coefficient of transmissibility can be determined using the straight line method by plotting residual drawdown versus  $\log t/t'$ . Residual drawdown is the difference in the water level before pumping began and at anytime after the pump has been stopped. Time  $t'$  is time since pumping was started, and  $t$  is the time since the pump was stopped (recovery started). The time can be measured in any consistent units (minutes, hours, days) because  $t/t'$  is a ratio and is dimensionless.

The coefficient of transmissibility can be determined from the straight-line equation:

$$T = \frac{264Q}{\Delta s}$$

where:

$\Delta s$  = residual drawdown over one log cycle of time ( $t/t'$ )

Figure 31-25 is the residual drawdown versus time ( $t/t'$ ) curve plotted from the data in figure 31-24. From this curve and data sheet we obtain:

$$Q = 1210 \text{ gal/min}$$

$$\Delta s = 0.93 \text{ ft}$$

$T$  is obtained by solving the equation:

$$\begin{aligned} T &= \frac{264Q}{\Delta s} \\ &= \frac{(264)(1210)}{0.93} = 343,000 \end{aligned}$$

**(7) Interpretation of aquifer test**

The results of the aquifer tests shown in the examples indicate it is essentially an isotropic aquifer of great extent.

Observation of the shape of the drawdown curves will indicate if boundary conditions are present in the aquifer. On the time drawdown curve (fig. 31-25), if as time increases the slope of the curve increases, showing greater drawdown, this would indicate an impermeable boundary at some distance from the well. If the slope of the drawdown curve decreases, showing less drawdown, this would indicate recharge to the aquifer is taking place; and if the slope of the line is flat, this would indicate recharge was equal to discharge.

Well interference, boundary conditions, leaky-roofed aquifers, image wells, and the many variations and ramifications encountered in aquifer pump tests are discussed in the extensive literature. Some of these references are E.E. Johnson, Inc. (1975), Wenzel (1942), Bental (1963), Lang (1961), Todd (1959), Bruin and Hudson (1961), and Walton (1962).

When the transmissibility and coefficient of storage of an aquifer are known, the drawdown at any distance from the discharging well can be predicted for a constant discharge for any period of time with the non-equilibrium equation. An example of this procedure follows.

From the preceding example of an aquifer test we know:

$$T = 335,000 \text{ gal/d/ft}$$

$$S = 0.065$$

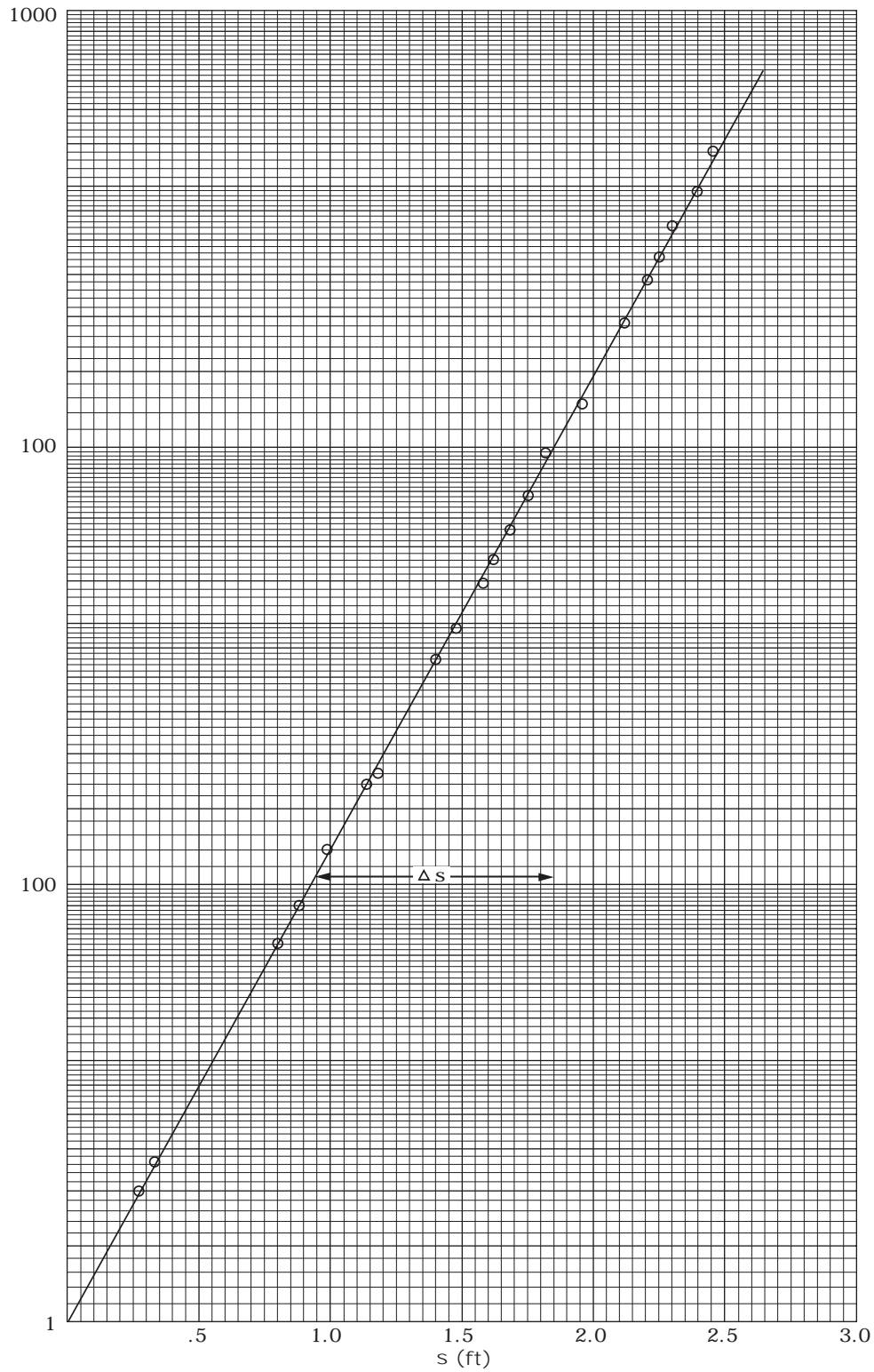
**Figure 31-24** Recovery measurement data sheet

Project:	Drawdown measured by:	Electrical sounder
Feature:	Discharge measured by:	Totalizing meter
Location:	Reference point:	Hole on north side of drive head

## TEST OF TOWN WELL NO. 1

Date	Time	Time since pumping stopped (min) t <sup>1</sup>	Depth to water (ft)	Drawdown, a s (ft)	Time since pumping started (min) t	Ratio t/t'	Remarks
10-5	2100		30.05	0			Pump on 10-5 at 2115
10-7	0515	0	41.50	11.45	1,920		Pump off 10-7 at 0515
	0516	1	26.00	-4.05	1,921	1,921	Discharge into reservoir
	0517	2	29.90	-0.15	1,922	961	Static water level on 10-5 at 2115 = 30.04 ft
	0518	3	32.50	2.45	1,923	641	Pumping level on 10-7 at 0515 = 41.50 ft
	0519	4	32.50	2.45	1,924	481	Meter reading on 10-5 at 2110 = 510 gal
	0520	5	32.44	2.39	1,925	385	Meter reading on 10-7 at 0515 = 2,323,800 gal
	0521	6	32.36	2.31	1,926	323	Total discharge = 2,323,290 gal
	0522	7	32.30	2.25	1,927	275	Time of pumping = 1,920 min
	0523	8	32.25	2.20	1,928	241	2,323,290 gal/1,920 min = 1,210 gal/min
	0524	9	32.20	2.15	1,929	214	
	0525	10	32.16	2.11	1,930	193	
	0530	15	32.00	1.95	1,935	129	
	0535	20	31.88	1.83	1,940	97	
	0540	25	31.80	1.75	1,945	78	
	0545	30	31.73	1.68	1,950	65	
	0550	35	31.67	1.62	1,955	56	
	0555	40	31.62	1.57	1,960	49	
	0605	50	31.53	1.48	1,970	39	
	0615	60	31.45	1.40	1,980	33	
	*	*	*	*	*	*	
	0705	110	31.23	1.18	2,030	18	
	0715	120	31.19	1.14	2,040	17	
	0815	180	31.04	0.99	2,100	12	
	0915	240	30.93	0.88	2,160	9	
	1015	300	30.85	0.80	2,220	7.4	
	*	*	*	*	*	*	
10-8	0215	1,440	30.38	0.33	3,360	2.3	
	0415	1,500	30.36	0.31	3,480	2.2	
	0615	1,680	30.35	0.30	3,600	2.1	
	0815	1,800	30.34	0.29	3,720	2.1	
	1015	1,920	30.33	0.28	3,840	2	

**Figure 31-25** Residual drawdown versus time ( $t/t'$ ) curve



What would be the drawdown 1,000 feet from the discharging well after it has been pumped at 1,000 gallons per minute for 10 days? In this case,

$$\begin{aligned} r &= 1,000 \text{ ft} \\ Q &= 1,000 \text{ gal/min} \\ t &= 10 \text{ d} \end{aligned}$$

$$\begin{aligned} u &= \frac{187r^2s}{Tt} \\ &= \frac{(187)(1000)^2(0.065)}{(335,000)(10)} \\ &= 3.5 \times 10^{-2} \end{aligned}$$

From table 31-2, the value of  $W(u)$  for  $u = 3.5 \times 10^{-2}$  is interpolated:

$$W(u) = 2.87$$

The drawdown is calculated from the formula:

$$\begin{aligned} s &= \frac{114.6QW(u)}{T} \\ &= \frac{(114.6)(1000)(2.87)}{335,000} \\ &= 0.98 \text{ ft} \end{aligned}$$

The same procedure,  $r$ , equaling the radius of the well, can be used to calculate the drawdown outside the well casing. What would be the drawdown outside a 14-inch (OD) well after it has been pumped at 1,000 gallons per minute for 10 days? The following data are used:

$$\begin{aligned} T &= 335,000 \text{ gal/d/ft} \\ S &= 0.065 \\ Q &= 1,000 \text{ gal/min} \\ t &= 10 \text{ d} \\ r &= 7 \text{ in} = 0.583 \text{ ft} \end{aligned}$$

$$\begin{aligned} u &= \frac{187r^2s}{Tt} \\ &= \frac{(187)(0.583)^2(0.065)}{(335,000)(10)} \\ &= 1.23 \times 10^{-8} \end{aligned}$$

Interpolating from table 31-2:

$$W(u) = 17.27$$

The drawdown outside the well casing is calculated from the formula:

$$\begin{aligned} s &= \frac{114.6Q}{T} W(u) \\ &= \frac{(114.6)(1,000)(17.27)}{335,000} \\ &= 5.92 \text{ ft} \end{aligned}$$

Since wells are not 100 percent efficient, the difference in drawdown inside and outside the casing depends on the efficiency of the well. A very good well will have an efficiency of 85 to 90 percent.

Whenever possible, wells should be spaced so their drawdown cone or radii of influence do not intersect, causing interference. When aquifer characteristics and pumping requirements are known, the above procedure can be used to locate wells to minimize interference between them. If drawdown cones intersect, drawdown is increased in the discharging wells for a given discharge. One of the factors in the cost of pumping water is the lift height (depth). Increasing the drawdown in a well therefore increases the cost of pumping.

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- Bentall, R. 1963. Methods of collecting and interpreting ground water data: U.S. Geol. Surv. Water Supply Paper 1544–H.
- Bruin, J., and J.E. Hudson, Jr. 1961. Selected methods for pumping test analysis. Ill. State Water Surv. Rpt. of Inves. 25.
- Darcy, H. 1856. Les Fontaines Publiques de la Ville de Dijon, Dalmont, Paris.
- Fetter, C.W., Jr. 1980. Applied Hydrogeology. Charles E. Merrill Publishing Company. Columbus, OH.
- Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, NJ.
- Johnson Drillers Journal. 1963. Radioactive tracers assist ground water studies. Edward E. Johnson, Inc. St. Paul, MN. September-October.
- Johnson, E.E., Inc. 1975. Ground water and wells. Johnson Division, UOP, Inc. Saint Paul, MN.
- Keech, C.F. 1962. Ground water resources of Hamilton County, Nebraska: U.S. Geol. Surv. Water Supply Paper 1539–N.
- Lang, S.M. 1961. Methods for determining the proper spacing of wells in artesian aquifers. U.S. Geol. Surv. Water-Supply Paper 1945–B.
- Legget, R.F. 1962. Geology and Engineering. McGraw-Hill, New York, NY.
- Meinzer, O.E. 1923. The occurrence of ground water in the United States. U.S. Geol. Surv. Water-Supply Paper 489.
- National Resources Committee. 1939. Low dams. U.S. Govt. Printing Office. Washington, DC.
- Rice, C.M. 1951. Dictionary of geological terms. Edward Bros, Inc. Ann Arbor, MI.
- Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Trans. Amer. Geophys. Union, 2, pp. 519–524.
- Thiem, G. 1906. Hydrologische Methoden. Gebhardt, Leipzig.
- Todd, D.K. 1959. Ground water hydrology. John Wiley and Sons, Inc. New York, NY.
- Tolman, C.F. 1937. Ground Water. McGraw-Hill, New York, NY.
- U.S. Bureau of Reclamation. 1964. Ground water engineering techniques and standards (tentative). Denver, CO.
- U.S. Department of Agriculture, Natural Resources Conservation Service. 1963. Section 8, Engineering Geology. National Engineering Handbook. Washington, DC.
- U.S. Bureau of Reclamation. 1998. Earth Manual, Third Edition, Earth Sciences and Research Laboratory, Geotechnical Research Technical Service Center. Denver, CO.
- U.S. Bureau of Reclamation. 1998. Engineering Geology Field Manual. U.S. Government Printing Office, Washington, DC.
- U.S. Bureau of Reclamation. 2001. Water Measurement Manual in cooperation with USDA–ARS and USDA–NRCS, Superintendent of Documents, U.S. Government Printing Office, Washington, DC. ([http://www.usbr.gov/pmts/hydraulics\\_lab/pubs/wmm/index.htm](http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/index.htm))
- U.S. Geological Survey. 2008. Circular 3123, Ground-Water Availability in the United States. (<http://pubs.usgs.gov/circ/1323/>).
- U.S. Geological Survey. 2005. National Atlas (<http://pubs.usgs.gov/atlas/geologic/>).
- Walton, W.C. 1962. Selected analytical methods for well and aquifer evaluation: Ill. State Water Surv. Bull. 49.
- Wenzel, L.K. 1942. Methods for determining permeability of water bearing materials: U.S. Geol. Surv. Water-Supply Paper 887.