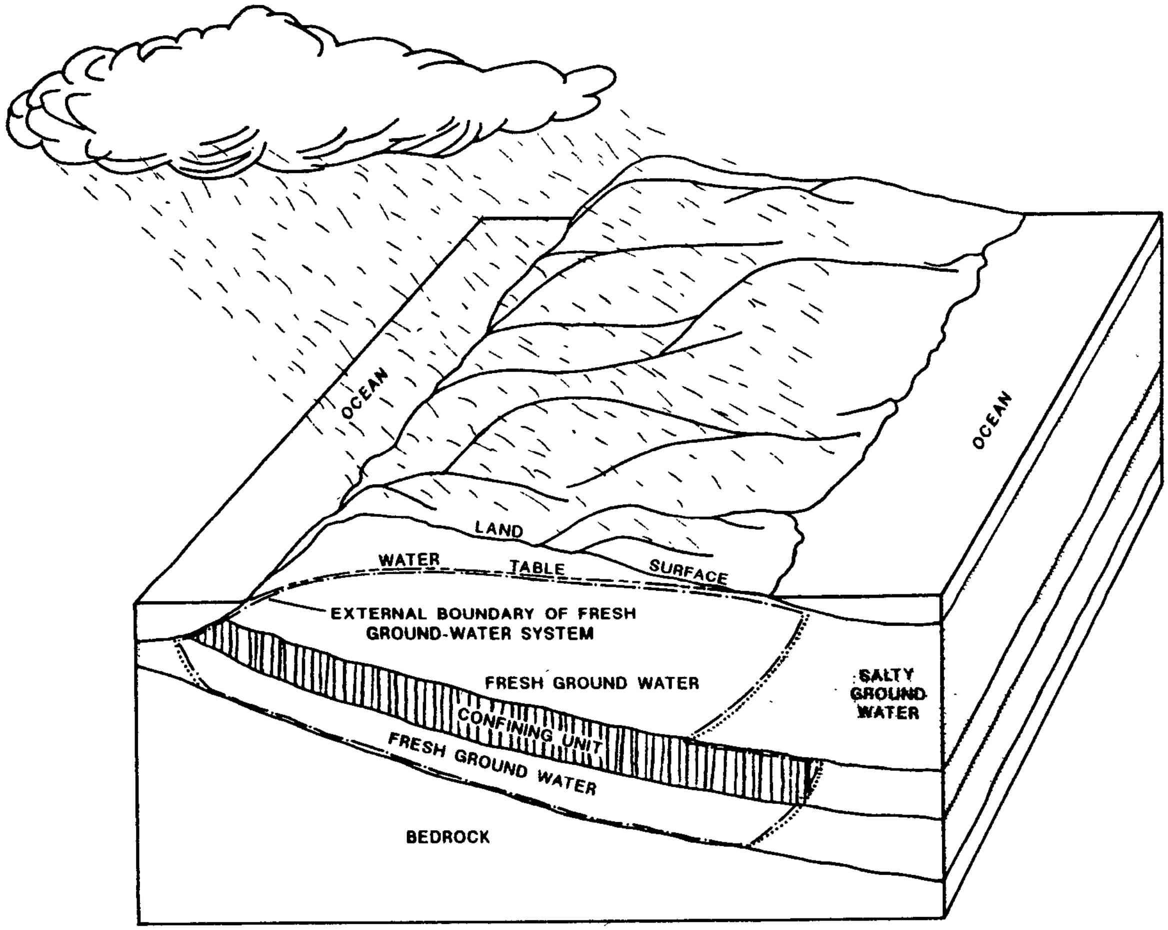
STUDY GUIDE FOR A BEGINNING COURSE IN GROUND-WATER HYDROLOGY: PART I -- COURSE PARTICIPANTS



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SECTION (3)--DESCRIPTION AND ANALYSIS OF GROUND-WATER SYSTEMS

The first three subsections below--system concept, information required to describe a ground-water system, and preliminary conceptualization of a ground-water system--introduce the system concept as it is applied to ground-water systems. The system concept is exceedingly useful in ground-water hydrology. It provides an organized and technically sound framework for thinking about and executing any type of ground-water investigation and is the basis for numerical simulation of ground-water systems, the most powerful investigative tool that is available. Although the system concept usually is not developed in a beginning course in ground-water hydrology to the extent that it is here, its fundamental importance, particularly as a framework for thinking about a ground-water problem, warrants this emphasis.

An example of the need for "system thinking" in practical problems is the "site" investigations of ground-water contamination from point sources, a major activity of hydrogeologists at this time. Many of these studies suffer irreparably from the investigators' failure to apply "system thinking" by not placing and studying the local "site" in the context of the larger ground-water system of which the "site" is only a small part.

System Concept

Assignment

*Study Note (3-1)--System concept as applied to ground-water systems.

In Note (3-1), attend particularly to the list of features that characterize a ground-water system. Although these features may seem to be abstract at this time, the reasons for this formulation will become evident as we proceed.

Note (3-1).--System Concept as Applied to Ground-Water Systems

The word system occurs frequently in ground-water literature in combinations such as hydrologic system and ground-water system. The following comments on the system concept and a distillation of those aspects of the concept relevant to a definition of a ground-water system may be used to establish a general framework for ground-water resource evaluation.

A general definition of a system is an orderly combination or arrangement of parts or elements into a whole, especially such combination according to some rational principle giving it unity and completeness. In thermodynamics, a system is a portion of the universe defined by a closed mathematical surface. The rest of the universe is referred to as the surroundings or the environment of the system. To be useful, this definition must be supplemented by additional information describing the physical properties of the enclosing surface (the walls or boundaries of the system)--whether these boundaries are impermeable, permeable, or selectively permeable to the flow of matter and (or) energy across them. These additional considerations lead to the following definitions:

open system--system constantly exchanges both matter and energy with its environment and is maintained by this exchange;

relatively closed system--system constantly exchanges energy but not matter with its environment;

absolutely closed (isolated) system--system exchanges neither energy nor matter with its environment.

In general, ground-water systems are open systems because they exchange both matter (water) and heat energy obtained from the sun or the interior of the earth with their surrounding environment. A simple, schematic representation of a system with its accompanying input and output is shown below.

Flow of matter
and (or) energy
and (or) information

Input -----> System -----> Output
(or stress) (or response)

Depending on the investigator's objectives and point of view, a natural ground-water flow system may be defined in various ways. In this discussion, the term "flow system" refers to the part of the ground-water regime that has been isolated for study, and implies the following:

1. the three-dimensional body of earth material under consideration is saturated with flowing ground water;

2. the moving ground water is bounded by a closed surface--the boundary surface of the flow system;

3. under natural conditions, heads and flows associated with specific locations or parts of the system vary with time, normally oscillating around a mean condition;

4. for the flow system to operate continuously through time, water input (continuous or intermittent) to the system and water output (continuous) from the system must occur through at least part of the boundary surface.

A common example of an input to (or stress on) the ground-water system is areal recharge to the water table, which ultimately is derived from precipitation. Short-term fluctuations or longer-term changes in natural recharge due to variations in precipitation or other climatic variables also may be regarded as a stress on the ground-water system. Other stresses on a ground-water system include pumping of ground water, any other mechanism of artificial withdrawal such as an infiltration gallery, and any form of artificial recharge--for example, injection wells, spreading basins and leaking pipe networks.

The most commonly measured response to stress is a change in head in one or more aquifers comprising the ground-water system. These changes in head are an indirect manifestation of changes in flow (as well as changes in storage) either into or out of various parts of the system. Changes in flow in the ground-water system sometimes can be measured directly by monitoring through time increases or decreases in base flow in selected reaches of a stream.

Information Required to Describe a Ground-Water System

Assignments

*Study Fetter (1988), p. 533-534; or Freeze and Cherry (1979), p. 67-69, 534-535.

*Study Note (3-2)--Information necessary to describe a ground-water system.

In these and other study assignments concentrate particularly on all the available information about the boundary conditions used in ground-water hydrology (name, properties, and physical occurrence in real ground-water systems). This is the most important new information in this section and also the most difficult to apply to specific problems.

Note (3-2).--Information Necessary to Describe a Ground-Water System

Quantitative analysis or simulation of a ground-water system entails the solution of a boundary-value problem--a type of mathematical problem which has been studied extensively and which has applications in many areas of science and technology. The flow of ground water in the general case is described by partial differential equations. A ground-water problem is "defined" by establishing the appropriate boundary-value problem; solving the problem involves solving the governing partial differential equation in the flow domain while at the same time satisfying the specified boundary and initial conditions. In ground-water problems, the solution usually is expressed in terms of head (h); that is, head usually is the dependent variable in the governing partial differential equation. The solution to a simple boundary-value problem in ground-water flow is given by Franke and others (1987, Appendix 1).

The information necessary to describe a ground-water system is summarized in table 3-1. This information is in fact the same information that is needed to formulate a boundary-value problem expressed in ground-water hydraulic terminology. Of the four types of information listed, we will consider at this time only (1) external and internal geometry of system, (2) boundary conditions, and (4) distribution of hydraulic conducting and storage parameters. Item (3), initial conditions, will not be discussed in this course.

Table S-1.--Information necessary for quantitative definition of a ground-water flow system in context of a general system concept

Input ---------------->>	System -------------->>Output	
Input or stress applied to ground-water system	Factors that define the ground-water system	Output or response of ground-water system
(1) Stress to be analyzed: - expressed as volumes of water added or withdrawn - defined as function of space and time	(1) External and internal geometry of system (geologic framework) - defined in space (2) Boundary conditions -defined with respect to heads and flows as a function of location and time on boundary surface (3) Initial conditions -defined in terms of heads and flows as a function of space (4) Distribution of hydraulic conducting and storage parameters - defined in space	(1) Heads, drawdowns, or pressures[1] -defined as function of space and time

[1] Flows or changes in flow within parts of the ground-water system or across its boundaries sometimes also may be regarded as a dependent variable. However, the dependent variable in the differential equations governing ground-water flow generally is expressed in terms of either head, drawdown, or pressure. Simulated flows across any reference surface can be calculated when the governing equations are solved for one of these variables, and flows in real systems can be measured directly or estimated from field observations.

The list of factors in table 3-1 may be clarified by considering the specific example of an island hydrologic system illustrated in figure 3-1. We already have encountered the idea of defining a specific volume of saturated earth material or reference volume for study in previous discussions of water budgets and the system concept. The external geometry of the ground-water system is the position in space of the outer bounding surface of this reference volume. In figure 3-1, the trace of this outer bounding surface is depicted by a broken line and dots. Note that this line in figure 3-1 defines a continuous closed curve.

The internal system geometry or geologic framework refers to lithologic units or combinations of units within the reference volume that can be differentiated in the subsurface and which often exhibit marked differences in hydraulic conductivity. When contrasts in hydraulic conductivity are large (several orders of magnitude), and the higher conductivity units can provide water to wells, we distinguish between aquifers and confining units. In figure 3-1 units (1) and (3) are aquifers, and unit (2) is a confining unit.

Often, some part of the boundary surface of a ground-water system corresponds to identifiable hydrologic features at which some characteristic of ground-water flow is described easily in hydraulic terms, such as heads acting on or flows through that part of the surface; examples are a body of surface water, an almost impermeable surface, a water table, and so on.

First, consider the contact surface between a fresh surface-water body such as a lake or stream and the saturated ground-water reservoir (for example, the streambed of a gaining stream). From a previous discussion (see last part of exercise on ground-water head) we know that the hydraulic head acting on this contact surface is equal to the water-level elevation of the surface-water body above it, irrespective of the configuration of the contact surface. The usual way of defining the "boundary condition" of the ground-water system along such a contact surface is as a "constant-head" boundary condition. If the surface elevation of the surface-water body changes with location, as would generally be the case for streams, then the hydraulic head acting on the contact surface would also change as a function of location.

Second, consider the contact surface between nearly impermeable bedrock and an overlying hydrogeologic unit whose hydraulic conductivity is several orders of magnitude larger (for example, the surface between unit (3) and the underlying bedrock represented by line FG in figure 3-1). If we assume that the bedrock is effectively impermeable compared to the overlying units, then the contact surface between the underlying effectively impermeable unit and the overlying relatively permeable unit represents hydraulically a stream surface; that is, ground-water flowlines move parallel to this surface but not across it. This type of boundary is known as a "no-flow" or streamline boundary.

Third, consider a water table (line AB in figure 3-1) that is subject to intermittent areal recharge through the unsaturated zone by water derived from precipitation at the land surface. Under these hydraulic conditions this upper boundary of the saturated ground-water system often is considered to be a "flux" boundary; that is, the volume of water entering the saturated ground-water system at the water table per unit area per unit time is

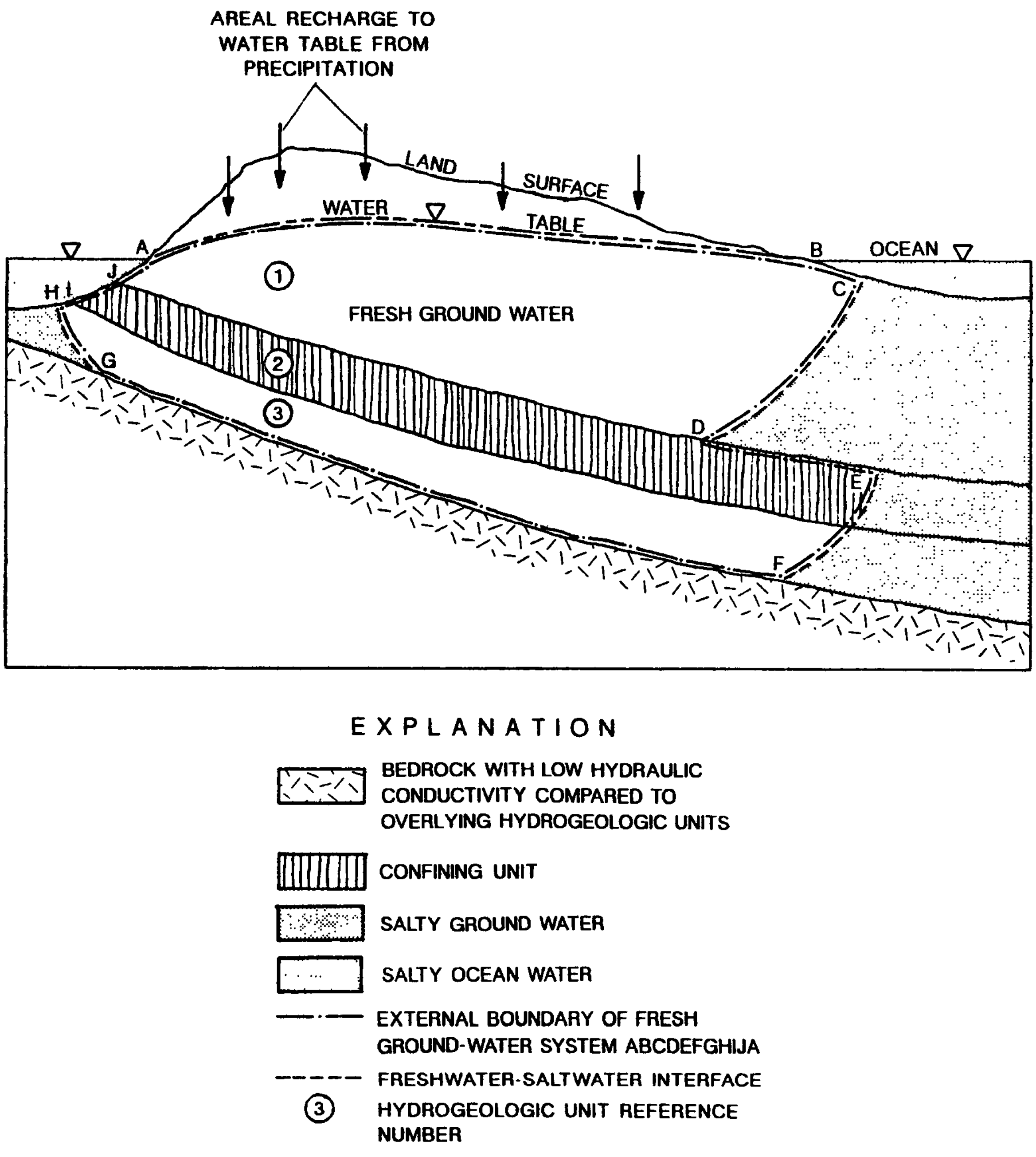

Figure 9-1.--Vertical section through an island ground-water system surrounded by salty surface-water bodies and underlain by nearly impermeable bedrock.

specified. This value of specified flux may vary as a function of location and time.

The preceeding three examples represent common hydrologic features of ground-water systems, and their representations in terms of boundary conditions--(1) constant head, (2) streamline or "no flow", and (3) specified flux--are equally common. Further discussion of these and other boundary conditions utilized in analyzing ground-water systems is provided by Franke and others (1987).

Before concluding this brief introduction to boundary conditions, two additional comments are appropriate. (1) As noted previously, the broken line with dots in figure 1 designates the external bounding surface of the ground-water system. Specifying the boundary conditions of the ground-water flow system, as required to define a ground-water-system boundary-value problem (table 3-1), means assigning a boundary type (for example, one of the types discussed above) to every point on the boundary surface. (2) The "mathematical" boundary conditions that are used to describe hydraulic conditions in terms of heads and flows at the bounding surface of the ground-water system generally are greatly simplified representations of the hydraulic conditions that actually exist in nature at these boundaries.

A principal activity of ground-water hydrologists is to determine by various techniques the spatial distribution of hydraulic properties of earth materials which include both conductivity (horizontal and vertical hydraulic conductivity and transmissivity) and storage (storage coefficient, coefficient of specific storage) parameters (item (4) in table 3-1). A ground-water system such as the one depicted in figure 3-1 would exhibit not only possibly significant differences in "average" hydraulic properties of the three designated hydrogeologic units (two aquifers separated by a confining unit), but also possibly significant areal variations in hydraulic properties within each unit.

A clear understanding of the factors that define a ground-water system as listed in table 3-1 is an essential prerequisite for both the descriptive and quantitative study of these systems.

Preliminary Conceptualization of a Ground-Water System

<u>Assignments</u>

*Study Note (3-3)--Preliminary conceptualization of a ground-water system.

*Work Exercise (3-1)--Refining the conceptualization of a ground-water flow system from head maps and hydrogeologic cross sections.

*Refer to figure 1-7 of Note (1-1) on head in which three pairs of observation wells are depicted, each pair showing a different relationship between shallow heads and deeper heads. Based on your study of the ground-water system in Exercise (3-1), where would you expect to find each pair of observation wells in a "typical" ground-water system, irrespective of the scale of that system?

After finishing the assignments, note that (a) our conceptualization of a ground-water system is based on what we know about that system at any particular time and must be revised continually as new information becomes available; and (b) a system conceptualization that bears little resemblance to the real system under study may lead to quantitative analyses of that system that are grossly in error because, in essence, the "wrong" system is being analyzed.

Note (3-3).--Preliminary Conceptualization of a Ground-Water System

A conceptual model of a ground-water system is a clear, qualitative, physical representation of how the system operates. A hydrologist's conceptual model of the ground-water system under study at any specific time determines the direction, focus, and specific content of the progressing investigation. If the hydrologist's operating conceptual model bears little resemblance to the operation of the natural ground-water system, then the results of the investigation will be at best misleading and at worst grossly in error. Steps for developing a conceptual model, which in essence describe a sequential thought process, are listed in table 3-2.

The first four steps listed in table 3-2 were mentioned previously in notes and exercises on water budgets and the systems concept as applied to ground-water systems. Thus, table 3-2 is both a summary to this point and a qualitative extension of the system concept that may be used to guide the study of any ground-water system. In the context of this course, table 3-2 serves as a guide to the detailed study of two simple ground-water systems described in subsequent exercises.

With reference to item (5) in table 3-2, ground-water flowlines must join boundary areas of inflow to boundary areas of outflow, assuming that no internal sources or sinks exist within the ground-water system; in addition, "no-flow" system boundaries define the location of locally bounding system flowlines. Coupling this information with the fact that flowlines cannot cross one another often enables the investigator to sketch a crude but conceptually useful flow pattern within the ground-water system. The inclusion of geologic framework information, particularly the spatial distribution of aquifers and confining layers, and heads depicted on head maps and vertical cross sections, further refines the resulting physical picture. As part of this process, it is also useful to think about not only the general pattern of flow within the ground-water system but also the gross distribution of flow in the various parts of the system, to the extent that available information permits.

The response of a ground-water system to a "large" stress ultimately depends on the type and areal extent of system boundaries and their location relative to the stress (item (6) in table 3-2). Further discussion of item (6) follows the exercise on the source of water to a pumping well (Exercise 3-3).

Table 3-2.--Steps in developing a conceptual model of a ground-water system

(1) Isolate for study an appropriate three-dimensional body of saturated earth material (ground-water system), which is equivalent to the reference volume for the water budget of the ground-water system.

(2) Delineate areas where water enters (recharges) and leaves (discharges from) the boundary surface of the reference volume defined in (1), as well as boundary areas across which little or no flow occurs.

(3) Describe the hydraulic conditions in terms of heads and flows on the various boundary surface areas delineated in (2). Assign mathematical boundary conditions to these areas based on their associated hydraulic descriptions.

(4) Depict the spatial distribution and hydraulic characteristics of the principal aquifers and confining beds in the ground-water system by means of hydrogeologic maps and sections.

(5) Conceptualize an approximate ground-water flow pattern within the ground-water system on the basis of the results obtained in (2), (3), and (4), associated head maps, and related information.

(6) Evaluate qualitatively the response of the ground-water system to (further) development--that is, to stresses of different magnitude and location within the system.

Exercise (S-1)--Refining the Conceptualization of a Ground-Water Flow System from Head Maps and Hydrogeologic Sections

by Herbert T. Buxton and Debra E. Bohn[1] ¢

The first stage of any ground-water-system analysis includes the development of a clear concept of the structure and operation of the system under investigation. This concept includes an evaluation of (1) the system's hydrogeologic framework (geometry), (2) its hydrologic boundaries, and (3) the distribution of water-transmitting properties within the system. Early in the investigation of actual ground-water systems this concept often is highly oversimplified because of a lack of hydrologic data. Continuing analysis accompanied by additional hydrologic data gradually increases the understanding of the ground-water system and refines the initial concept.

Flow patterns in natural ground-water systems are characteristically three-dimensional and complex at the local scale. The pattern of flowlines through a system is controlled by the distribution of flow entering and leaving the system and the distribution of water-transmitting properties within the system. Recharge to and discharge from a ground-water system is controlled by the location and characteristics of its natural hydrologic boundaries, which often are conceptualized in a mathematical sense by identifying an associated boundary condition. The distribution of water-transmitting properties at the system scale is defined by its internal hydrogeologic geometry, which usually is depicted as a sequence of aquifers and confining units, each with distinct hydrologic properties.

The hydrologist often approximates ground-water flow patterns from the distribution of hydraulic head throughout the ground-water system. In general, hydraulic head varies in three dimensions throughout the flow domain. Practical problems arise, however, in the attempt to depict equipotential surfaces and hydraulic gradients in three dimensions. Head distributions typically are represented on plan-view maps and (or) cross sections which must be constructed in a manner that 1) properly represents our concept of the structure and operation of the ground-water system, and 2) accurately depicts the three-dimensional features of the ground-water system and the head distribution within it.

The purpose of this exercise is to demonstrate (1) how an accurate depiction of the three-dimensional distribution of hydraulic head in a system can be described on a series of maps and sections derived from (a) pertinent hydrologic data, (b) knowledge of the physics of ground-water flow, and (c) a preliminary concept of the structure and operation of a ground-water system, and (2) how this depiction of the head distribution confirms and (or) modifies our initial conceptualization of the system.

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A description of a hypothetical ground-water system is provided, followed by data from a synoptic water-level measurement of a ground-water observation-well network in that system. A step-by-step procedure for mapping the three-dimensional distribution of hydraulic head in the system is presented. A similar procedure is used to depict the change in head distribution caused by (1) the introduction of a pumped well to the system and (2) a hypothetical change in the internal geometry of the system. The "observed" data presented for each of these exercises were obtained from numerical models of these hypothetical systems.

Description of Hypothetical Ground-Water System

The hypothetical ground-water system represented in figure 3-2(A) shows a rectangular glacial valley approximately 56,000 ft wide (east-west) by 40,000 ft long (north-south). The valley was eroded in consolidated bedrock and subsequently filled with alluvium. A large lake lies south of the valley. A small tributary stream drains the valley and flows into the lake.

Sections A-A' and B-B' (figs. 3-2(B) and 3-2(C)) depict the hydrogeologic framework of the ground-water system. An initial concept of the hydrogeologic framework of this system is provided to facilitate the head-mapping exercise. In an actual field investigation, undoubtedly, development of this initial concept would require data collection and analysis.

The system is bounded laterally on three sides and on the bottom by bedrock and on the top by the water table. The hydraulic conductivity of the bedrock is assumed to be negligible compared to that of the aquifer units in the alluvium. To the south the water-table aquifer is bounded by the lake. The lower aquifer, which initial hydrogeologic data indicate is confined, appears to pinch out abruptly several miles offshore, south of the map and sections shown in figure 3-2.

The water table, generally, is a subdued replica of the valley topography. Inflow to the ground-water system occurs as areal recharge at the water table derived from precipitation; and ground water discharges to the stream and lake at the stream bed and lake bottom, respectively. The water table configuration approaches and intersects the downstream portion of the stream surface as shown in figure 3-2(C). Along this reach ground-water seeps into the channel, which acts as a ground-water drain. Discharge measurements verify that this stream is a gaining stream; its base flow increases continuously downstream. Seasonal and annual changes in areal recharge affect the altitude and configuration of the water table, thereby changing the quantity and temporal distribution of base flow in the stream and the point at which flow in the stream channel begins (start-of-flow).

The internal geometry of the system consists of two aquifers separated by an approximately 40-ft-thick confining unit (fig. 3-2(B) and 3-2(C)). Data available from previous studies indicate that the water-transmitting properties of the hydrogeologic units are approximately as follows: the water-table aquifer has a hydraulic conductivity of about 300 ft/d and a horizontal to vertical anisotropy of about 100:1; the confining unit has a vertical hydraulic conductivity of approximately 0.002 ft/d, and the confined aquifer has a hydraulic conductivity of about 100 ft/d (no data on its anisotropy are available.

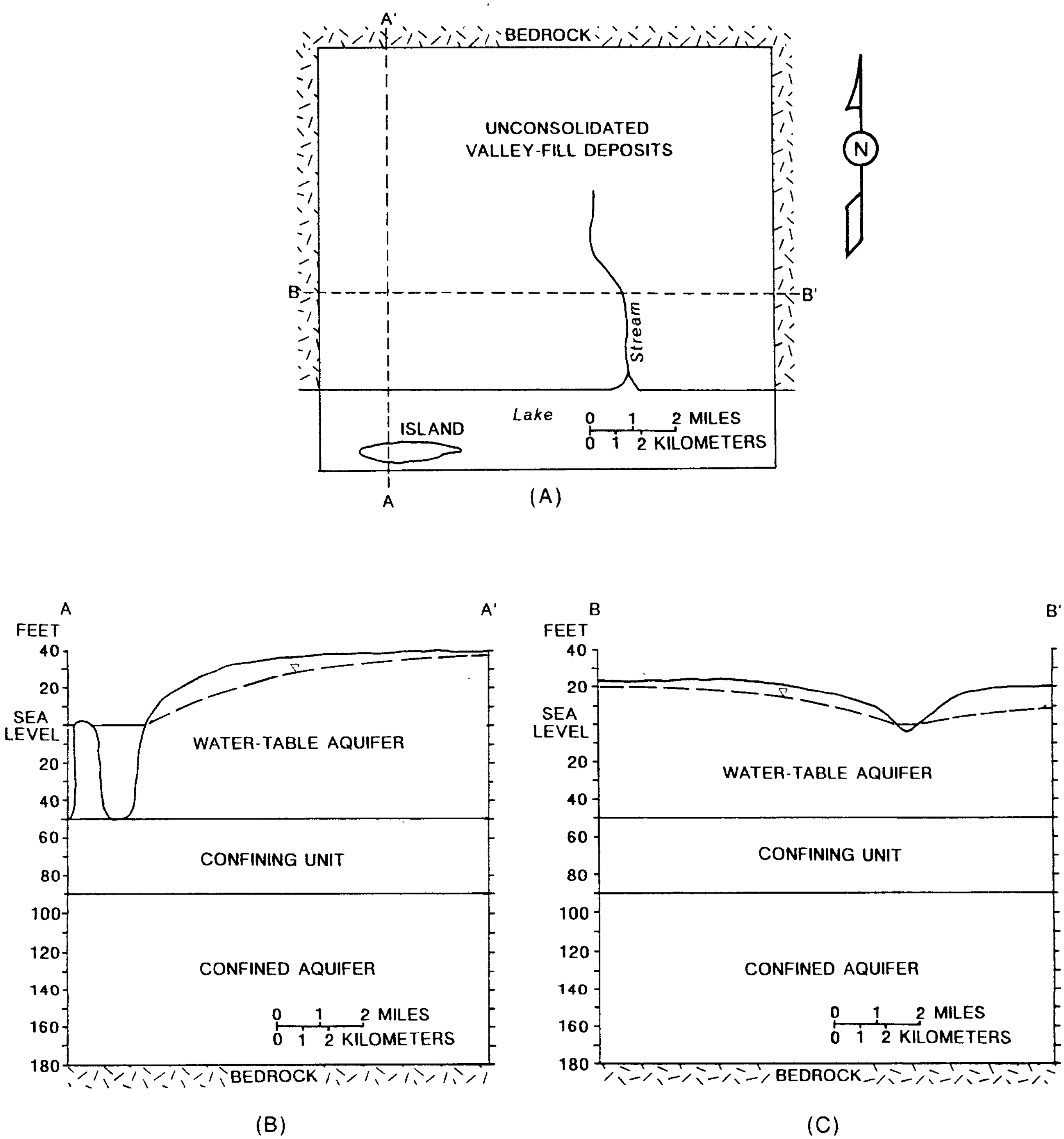


Figure 3-2.--Hydrogeologic framework of hypothetical ground-water system: (A) plan view, (B) north-south-trending section, (C) east-west trending section.

Question 1.--From the preceding description, assign a physically reasonable boundary condition to each of the system boundaries shown on figures 3-2(A), 3-2(B), and 3-2(C) (e.g. constant-head, no-flow, and so on.) A discussion of boundary conditions in ground-water systems is provided by Franke and others (1987).

Observation-Well-Network Design in Hypothetical Ground-Water System

An observation-well network installed to monitor hydrologic conditions in this system is illustrated in figure 3-3. Doublet and triplet wells indicated in figure 3-3 mark sites where multiple wells were installed and screened at different altitudes. This observation-well network was designed to permit the definition of the three-dimensional head distribution using a limited number of point observations. Observation wells are piezometers that measure hydraulic head at the point of opening to the system (well screen). One-foot-long screens were installed in these wells so that subsequent measurements could be assigned to a unique location in space.

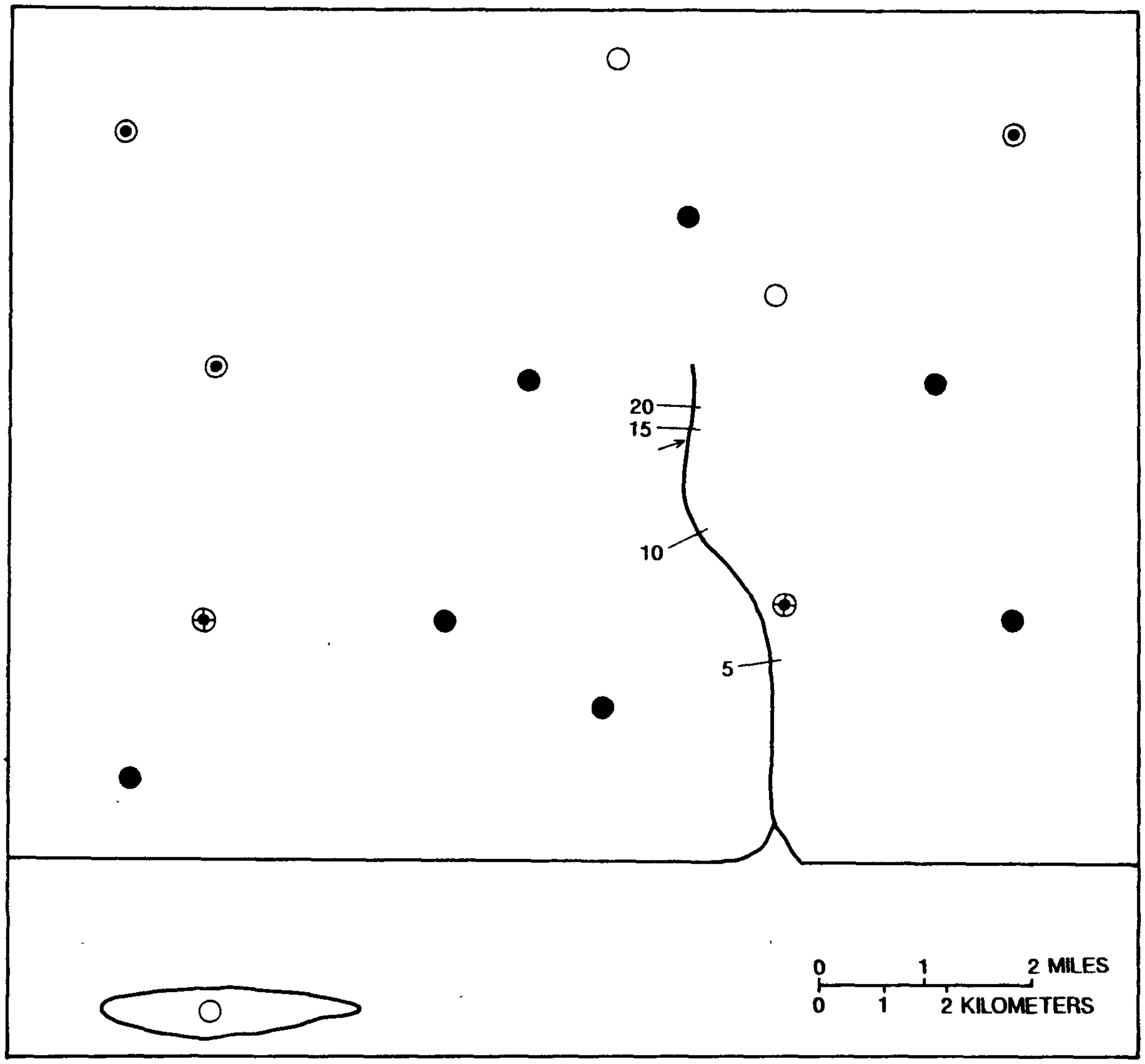
In order to define the head distribution within the ground-water system, well locations must be chosen with a measure of hydrologic insight--for example, anticipating areas of large hydraulic gradients and selecting surfaces on which head maps or sections will be constructed. Some wells, screened at or near the water table, are intended to be used primarily for construction of maps that describe the configuration of the water-table surface. Other wells, screened near the base of the water-table aquifer, are intended to indicate the magnitude of the vertical component of head gradients within the aquifer. The remaining wells were screened in the confined aquifer and are intended to be used for construction of maps of the potentiometric surface of the confined aquifer.

The numbers marked along the tributary stream in figure 3-3 indicate streambed altitudes, taken from topographic maps, which closely approximate the actual stage in this shallow stream.

Mapping Hydraulic Head in a Layered Ground-Water System: Water-Table Map

Head and related data from a synoptic measurement of the observation-well network are plotted on several maps and cross sections. Water-table altitude, streambed altitudes, and the start-of-flow point in the tributary stream are plotted in figure 3-4. The start-of-flow point of this ground-water-fed stream marks the upstream limit of intersection between the water-table surface and the stream-channel surface. Downstream from the start-of-flow point the stream surface defines the water-table altitude; upstream from the start-of-flow point the streambed is dry because the water-table altitude is below the streambed altitude. Because the water table is depressed near a gaining stream, equipotential lines form "V"s that point upstream, indicating that ground water flows toward the stream channel.

A number of additional hydrologic facts and principles are useful in constructing head maps of this system. The head distribution within a ground-water system is a continuum in three-dimensional space; therefore, contour lines should be smooth and subparallel to one another. The shape and changes in spacing of contour lines indicate changes in hydraulic gradients. Kinks or jogs in contour lines indicate changes in direction of flow (usually



EXPLANATION

LOCATION OF OBSERVATION WELL SCREENED:

● NEAR THE WATER TABLE

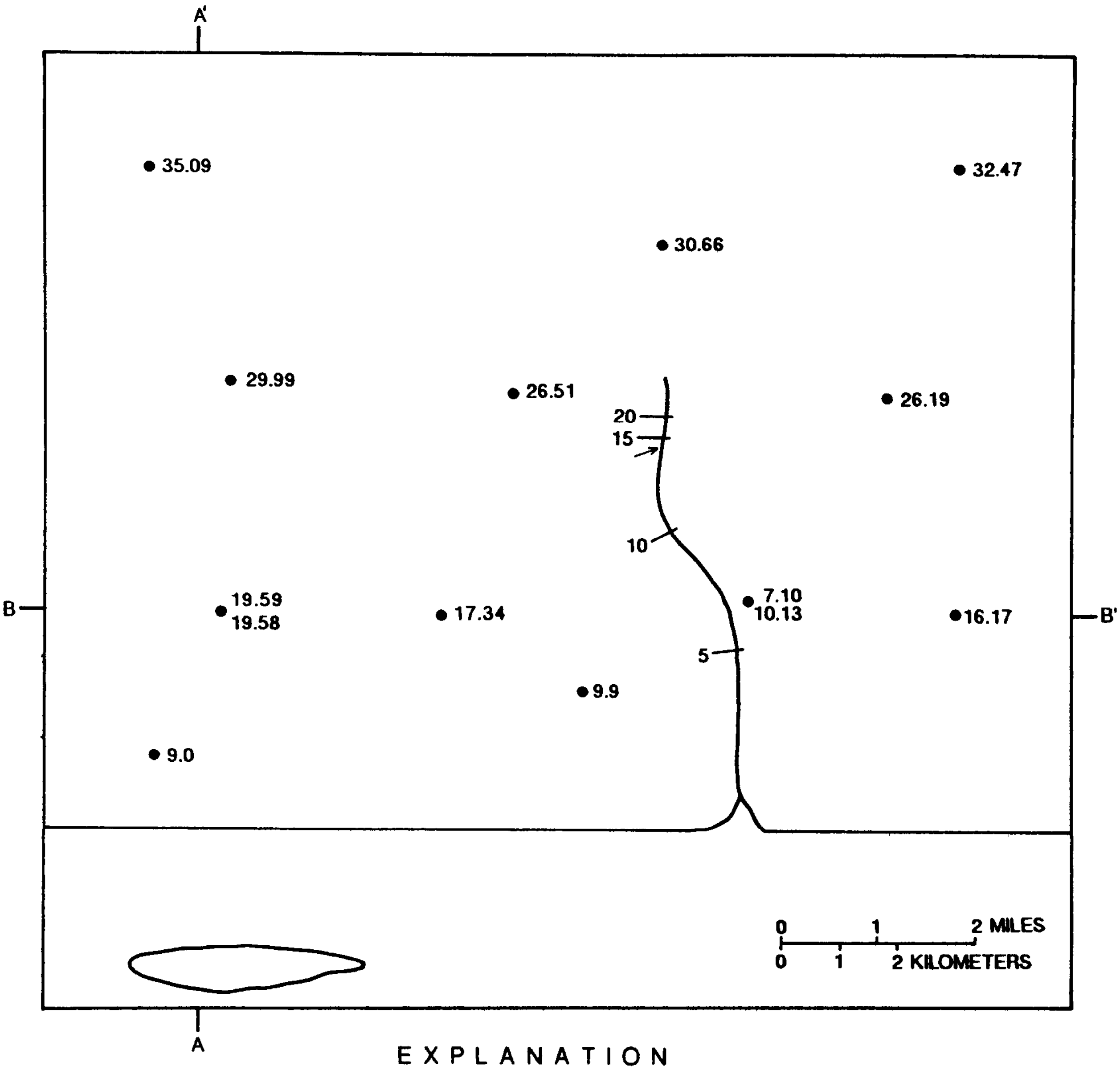
⊕ AT BASE OF WATER-TABLE AQUIFER

○ IN CONFINED AQUIFER

5 STREAMBED ALTITUDE, IN FEET ABOVE SEA LEVEL

POINT OF START OF FLOW OF STREAM

Figure 3-3.--Observation-well network and streambed altitudes for hypothetical ground-water system.



EXPLANATION

- • 9.9 — WATER-TABLE OBSERVATION WELL -- Number is altitude of water level, in feet above sea level
- 5 — STREAMBED LEVEL -- Number is altitude of streambed, in feet above sea level
- ← — POINT OF START OF FLOW OF STREAM
- A-A' — TRACE OF SECTION

Figure 8-4.--Water-table heads obtained during a synoptic measurement of water levels in observation wells.

convergent or divergent flow); irregular spacing indicates changes in gradients caused either by changes in flow rates or variations in transmissivity.

The shape of equipotential lines near hydrologic boundaries is affected by the boundary type. The configuration of equipotential lines in the vicinity of impermeable, constant-head, and water-table boundaries in a homogeneous and isotropic system is shown in figure 3-5. Equipotential lines typically are perpendicular to no-flow boundaries, are parallel to constant-head boundaries, and represent the altitude of the water-table surface. Freeze and Cherry (1979, p. 168-170) describe these features in greater detail.

Recharge enters this ground-water system at the water table and moves generally toward the discharge boundary (lake shore), resulting in a progressively greater volume of water flowing through the system as one approaches the discharge boundary. In addition, because this aquifer is unconfined, its saturated thickness decreases toward the shoreline. Both of these reasons cause a continuous increase in the hydraulic gradient toward the shore; equipotential lines, therefore, become progressively closer to one another in this direction.

Question 2.--Based on your knowledge of the operation of this system and an understanding of the physics of ground-water flow, draw a contour map of the water-table surface using the data set plotted in figure 3-4 and taking into account the hydrologic principles discussed above. Use a 5-ft contour interval.

Mapping Hydraulic Head in a Layered Ground-Water System: Potentiometric-Surface Map

A potentiometric-surface map depicts the distribution of hydraulic head throughout a confined aquifer. We typically assume (not always correctly) that vertical gradients within the confined aquifer are negligible. Therefore, the head in a well screened in a confined aquifer defines a point on the potentiometric surface of that aquifer.

The confined aquifer shown in figure 3-6 is recharged by slow downward leakage through the confining unit. Heads in tightly cased wells screened in this aquifer are above the altitude of the top of the aquifer.

The potentiometric surface of the confined aquifer in this system is a subdued replica of the water-table configuration. Intuitively, we know that ground water must flow downward from the water-table aquifer into the confined aquifer in the north, and upward out of the confined aquifer to the water-table aquifer in the south, where heads in the water-table aquifer decrease rapidly near the lake and stream.

Question 3.--Use your present knowledge of the ground-water system under consideration to draw the potentiometric surface of the confined aquifer. Use the map and data presented in figure 3-6. Keep in mind the same hydrologic factors that were used to construct the water-table map, and the additional factors noted above. Use a 5-ft contour interval. Overlay this map on the water-table map using a light table. Changes in spacing between nearby equal-valued contours in these two maps indicate changes in vertical

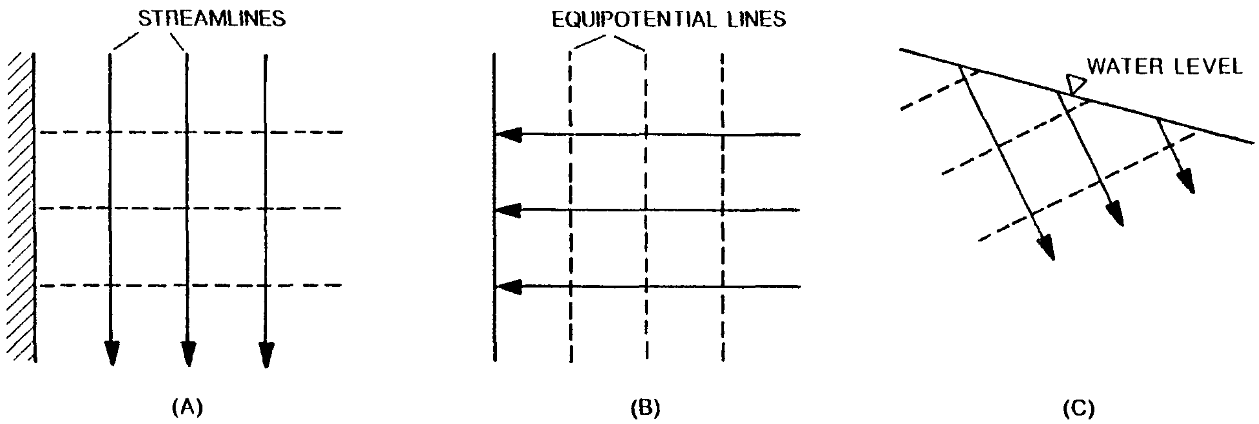
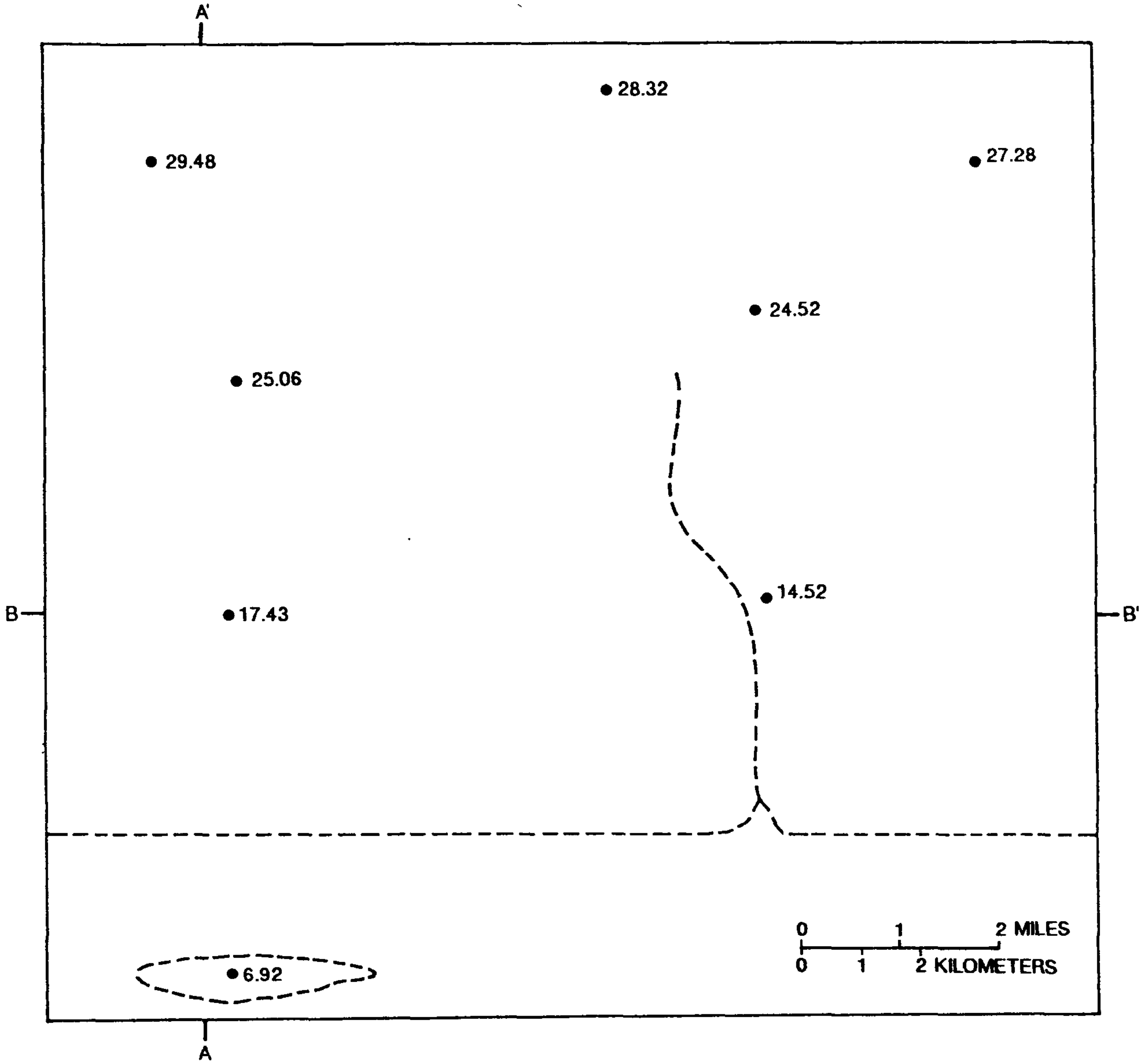


Figure 3-5.--Ground-water-flow pattern in the vicinity of (A) an impermeable boundary, (B) a constant-head boundary, and (C) a water-table boundary. (From Freeze and Cherry, 1979, fig. 5.1.)



EXPLANATION

● 6.92 OBSERVATION WELL SCREENED IN THE CONFINED AQUIFER -- Number is altitude of water level, in feet above sea level

A-A' TRACE OF SECTION

Figure 9-6.--Heads in the confined aquifer obtained during a synoptic measurement of water levels in observation wells.

gradients. Modify either or both contour maps if inconsistencies in the magnitude and areal distribution of vertical gradients occur. Together these maps provide a picture of the continuous distribution of hydraulic head in the system.

Mapping Hydraulic Head in a Layered Ground-Water System: Hydrogeologic Sections

Hydrogeologic sections typically depict the vertical distribution of aquifers and confining units along with vertical variations in head within the ground-water system. They allow correlation between heterogeneities in hydrogeologic geometry and the vertical distributions of hydraulic head and flow. Measurements of head at the well screens are plotted for wells along sections A-A' and B-B' in figures 3-7 and 3-8. To review: an observation well is a piezometer--a pressure- and head-measuring device. The well's measuring point is the midpoint of the well screen, which represents the point in three-dimensional space at which the pressure and head is observed. The assumption is that the well screen is sufficiently short to preclude connecting volumes of aquifer with significantly different heads and, therefore, does not transmit a volume of water through the screen and well bore that is sufficient to affect heads locally in the flow system.

All the hydrologic factors discussed previously that are considered in the construction of both water-table and potentiometric-surface maps also are useful in drawing head contours in section. For example, rules that govern the shape of equipotential lines near hydrologic boundaries such as constant-head, streamline, and the water-table boundaries in maps also are true in section (fig. 3-5). The distribution of head in hydrologic sections of natural systems, however, generally is more complicated than in head maps, because the distribution in sections is more likely to reflect the heterogeneity and anisotropy of the aquifers and confining units in the ground-water system.

Heterogeneous Systems.--Vertical heterogeneities (sequences of aquifers and confining units) often depicted in hydrogeologic sections include stratigraphic boundaries between units which exhibit large contrasts in hydraulic conductivity. Flow and equipotential lines refract in a predictable manner as they cross these boundaries (fig. 3-9). The angle of refraction at a boundary for both sets of lines can be calculated from the angle of incidence and the ratio between the hydraulic conductivities of both units (Fetter, 1988, p. 139-141). In an intuitive way, we can consider the changes in the ground-water flow pattern that are necessary to maintain flow from a more permeable to a less permeable region. Given that the flow in any stream tube (the flow conduit between any two streamlines) in figure 3-9 remains constant, it is evident that: (1) streamlines refract toward the vertical when entering a less permeable region, thereby increasing the cross-sectional area of flow within stream tubes; and (2) equipotential lines refract away from the vertical and decrease their spacing, thereby increasing the hydraulic gradient within stream tubes. In accordance with these principles vertical gradients within aquifers often are small in comparison to vertical gradients across confining units, resulting in equipotential lines that are nearly vertical in aquifers and nearly horizontal in confining units.

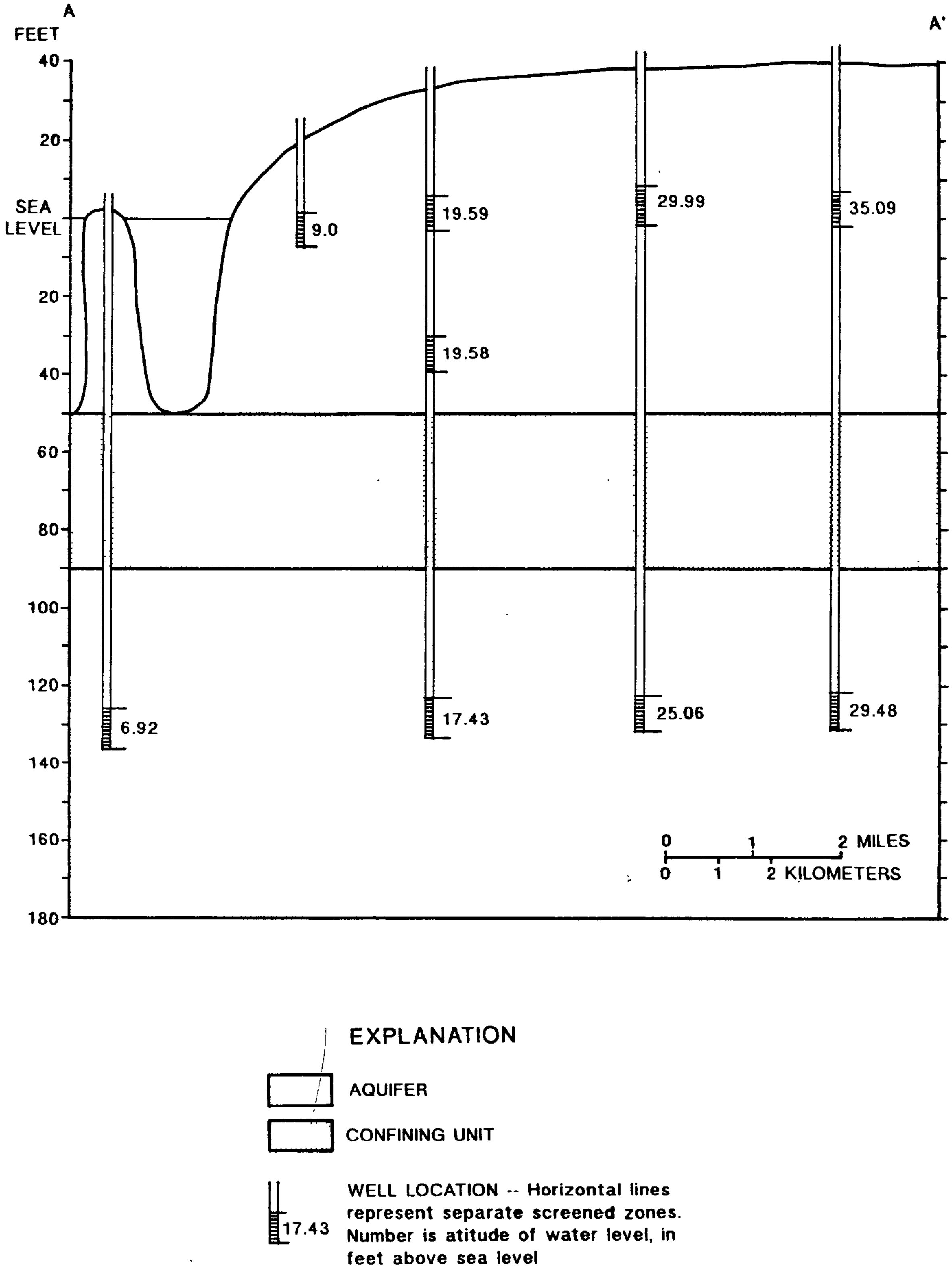


Figure 3-7.--North-south-trending hydrogeologic section showing heads obtained during synoptic measurement of water levels in observation wells. (Location of section A-A' is shown in fig. 3-2.)

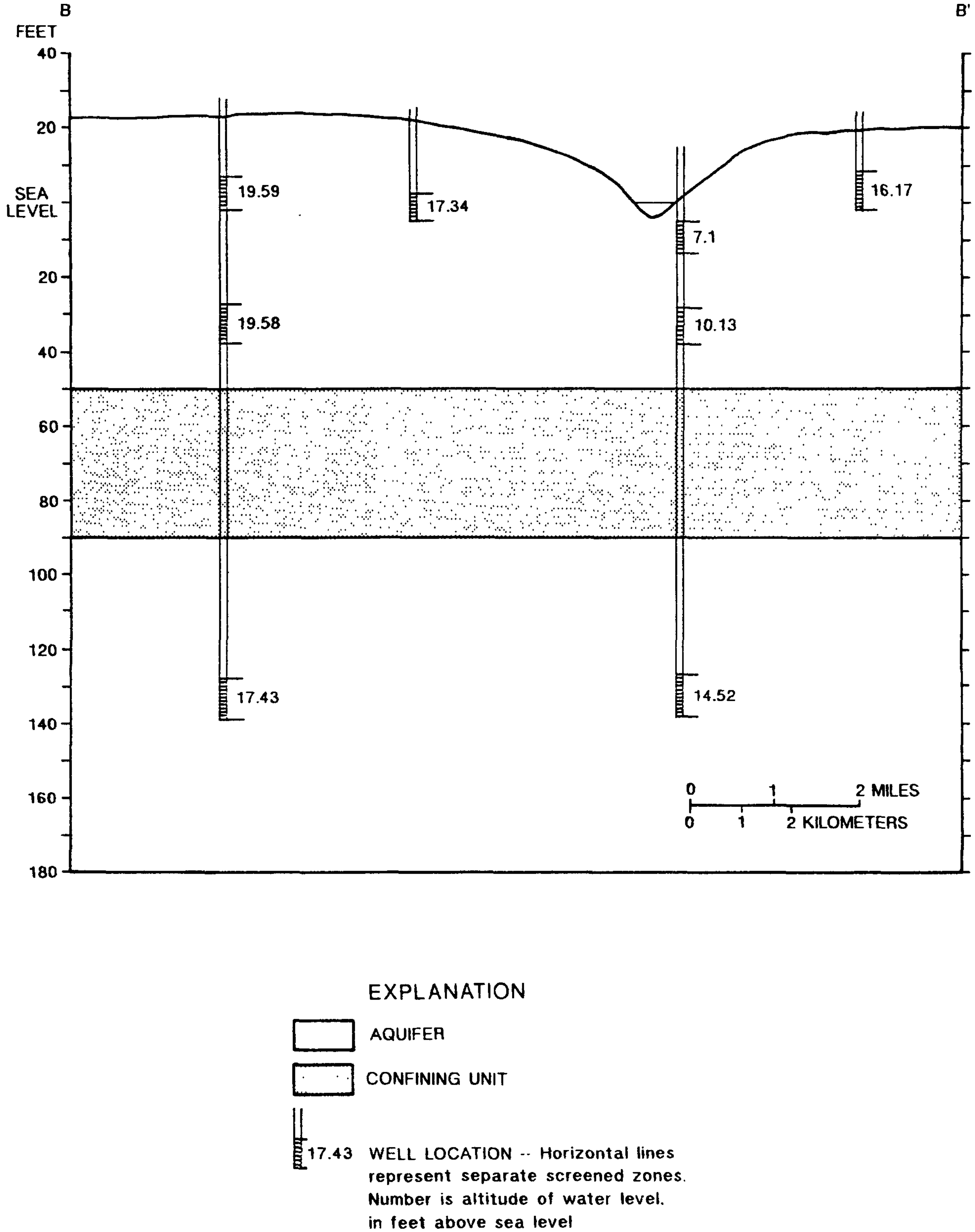


Figure 3-8.--East-west-trending hydrogeologic section showing heads obtained during synoptic measurement of water levels in observation wells. (Location of section B-B' is shown in fig. 3-2.)

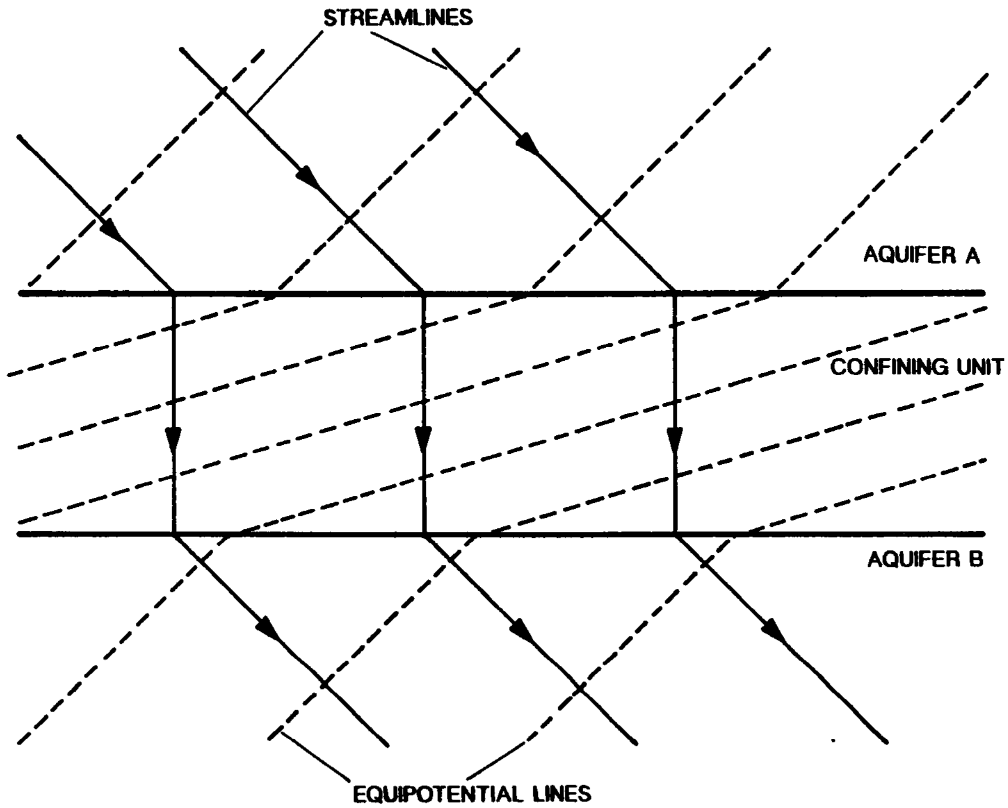


Figure 3-9.--Pattern of streamlines (flowlines) and equipotential lines passing through units with highly contrasting isotropic hydraulic conductivities.

Alignment of Flowlines and Equipotential Lines.--Although many hydrogeologic units are effectively isotropic in plan view, the layered deposition of geologic strata causes most hydrogeologic units to exhibit different values of hydraulic conductivity in directions normal and parallel to planes of deposition. In general, most hydrogeologic units are deposited in nearly horizontal beds, and as a result, horizontal hydraulic conductivity is usually greater than vertical hydraulic conductivity. The most significant result of vertical anisotropy in ground-water systems is its effect on the vertical distribution of flow within a system. In anisotropic systems, flowlines and equipotential lines are not orthogonal; their angle of intersection depends on the relation between the direction of the hydraulic gradient and the orientation of the axes of maximum and minimum hydraulic conductivity. Thus, vertical anisotropy also affects the distribution of head within a system and complicates the interpolation of head contours between points of measured head in a vertical section despite a general knowledge of the ground-water flow pattern. A more detailed discussion of this topic is found in Freeze and Cherry (1979, p. 174-178).

The relation between flowlines and equipotential lines is additionally complicated by the fact that hydrogeologic sections usually are constructed with a vertical exaggeration that may be as high as several hundred. Vertical exaggeration skews or distorts both flowlines and equipotential lines in the vertical axis direction and changes their apparent angle of intersection. As a consequence, although equipotential lines may appear to be vertical on a section, indicating horizontal flow, significant vertical flow components may be present.

Question 4.--Use your present knowledge of this ground-water system and the hydrologic factors discussed above to draw equipotential lines on both sections A-A' and B-B' (figs. 3-7 and 3-8). A good starting point is to locate the position of each contour line on the section from both the water-table and potentiometric-surface maps. Plot the water-table surface on both sections using these data. Remember that contour lines on the water-table map show the altitude of the water-table surface and should be marked on the section at the water-table surface. Assume that vertical gradients within the confined aquifer are negligible; that is, contour lines are effectively vertical in that aquifer.

Constructing hydrogeologic sections can result in an improved understanding of the head distribution and general flow pattern in the ground-water system. While contouring, either the water-table or the potentiometric-surface map can be refined to reflect an improved concept of the system. Upon completion, the maps and sections should represent a consistent picture of the three-dimensional distribution of hydraulic head within the system.

Sketch arrows across equipotential lines to indicate general flow directions based on observed gradients. Keep in mind that flowlines and equipotential lines are perpendicular only in isotropic systems, and that even in isotropic systems they do not appear to be perpendicular on sections in which the vertical dimension is exaggerated.

Question 5.--Use the completed set of maps and sections produced in Questions 2, 3, and 4 to delineate the regions in which ground water flows upward and downward between aquifers. Draw a dashed line on the water-table map (fig. 3-3) that marks the transition between these regions. Again, use a light table for an accurate comparison of the head in each aquifer. Also mark the position of this transition on both sections (figs. 3-7 and 3-8). If this demarcation line on the water-table map is not a smooth curve or its pattern is not consistent with the concept of the flow system developed previously, then changes should be made in the position of head contours on those maps and cross sections that will improve the configuration of this demarcation line. Our concept dictates that vertical flow is generally downward in the north and reverses to upward in the south, near the lake. The line of demarcation also is affected to some extent by the gaining tributary stream, which has depressed the water-table surface locally.

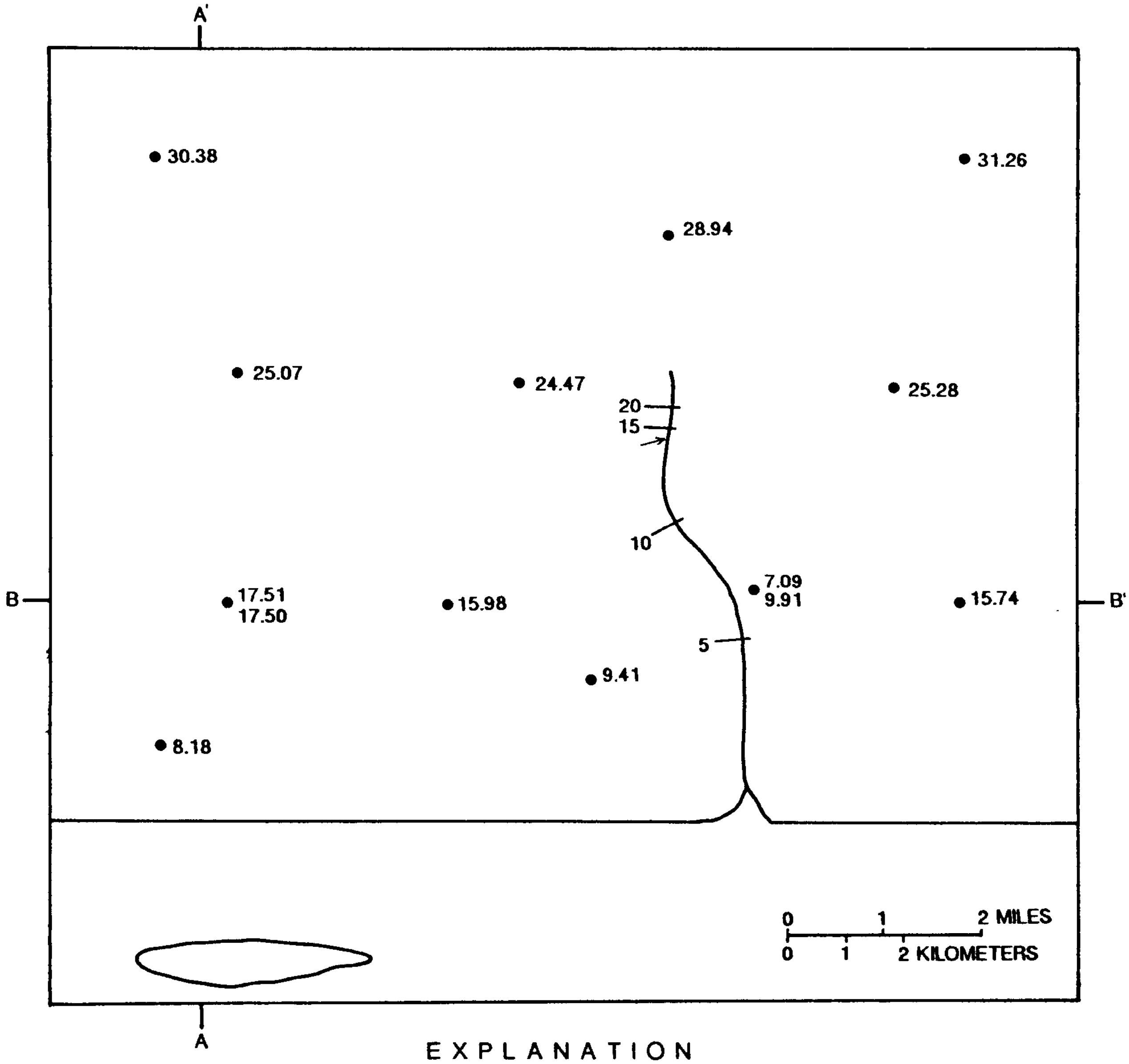
Mapping Hydraulic Head in a Layered Ground-Water System with a Pumping Well

The ground-water system discussed in this section is identical to the one discussed previously. However, a pumping well has been introduced to the system, and ground-water levels have achieved a new equilibrium condition in response to pumping. The well is located in the northwest corner of the system, 17,500 ft south of the northern boundary of the ground-water system and 12,500 ft east of the western boundary of the system. It is screened in the bottom 25 ft of the water-table aquifer.

Although the major features of the system are the same, hydrologic conditions in the system have changed, requiring a revision to our initial concept of the flow system's operation before additional analysis. The well is pumped at a rate of approximately 1.66 Mgal/d (million gallons per day). The recharge rate for this ground-water system is estimated to be approximately 0.475 ft/yr (feet per year). To indicate the magnitude of the pumping stress relative to total inflow to the system, calculate the total rate of recharge to the system, in million gallons per day, and the percent of the total flow in the system that is pumped. In a budget sense, how will the pumping affect the inflow and outflow at system boundaries?

The pumping well affects this system by "rearranging" ground-water flow paths to divert a fraction of the flow through the system to the well. The areal extent of the cone of depression (or the area in which head changes) in response to the discharging well extends to the boundaries of the system. The area of flow diversion (or the area in which all flowlines terminate at the well, also known as the capture area) is such that the recharge entering this area equals the quantity of water discharged by the well. Head data obtained during a synoptic measurement under steady pumping conditions are shown in figures 3-10, 3-11, and 3-12. These data indicate that ground water still discharges to the lake and stream, and no inflow from the lake has been induced.

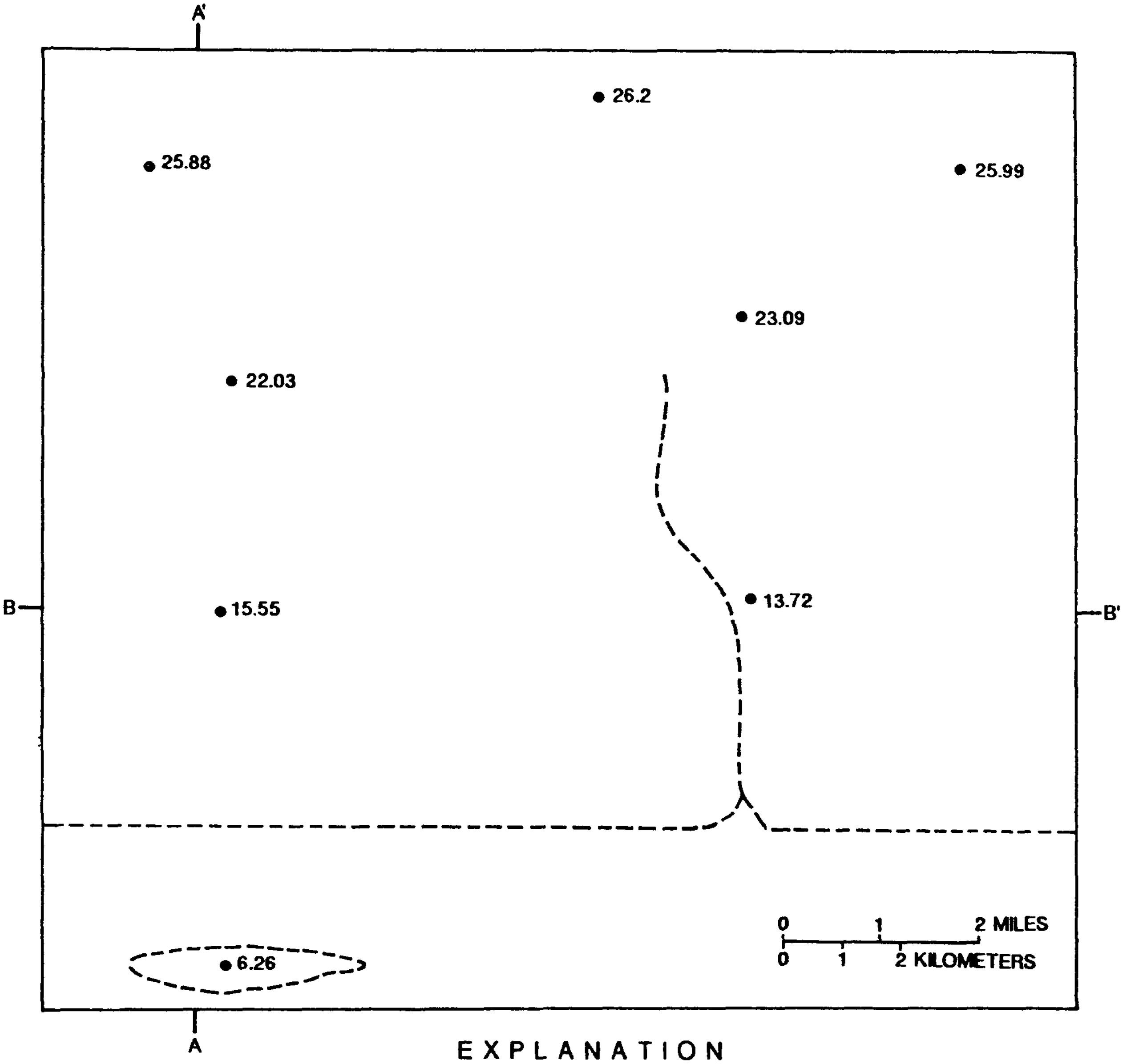
Keep in mind that measured heads in observation wells reflect the effect of the pumping stress on the head distribution at known points within a system, and that the location of the stress actually is the pumping-well screen. Because the pumping-well screen is the destination of flow in the area that surrounds the well, it is, locally, the point of lowest head. Mark the location of the pumping well on figure 3-10 and sketch in the pumping well and screen on section A-A' (fig. 3-12) before the mapping exercise.



EXPLANATION

• 8.18	WATER-TABLE OBSERVATION WELL -- Number is altitude of water level, in feet above sea level
5	STREAMBED LEVEL -- Number is altitude of streambed, in feet above sea level
	POINT OF START OF FLOW OF STREAM
A-A'	TRACE OF SECTION

Figure S-10.--Measured heads in the water-table aquifer in response to steady pumping from a well screened in the lower part of the water-table aquifer.



EXPLANATION

● 6.26 OBSERVATION WELL SCREENED IN CONFINED AQUIFER -- Number is altitude of water level, in feet above sea level

A-A' TRACE OF SECTION

Figure 3-11.--Measured heads in the confined aquifer in response to steady pumping from a well screened in the lower part of the water-table aquifer.

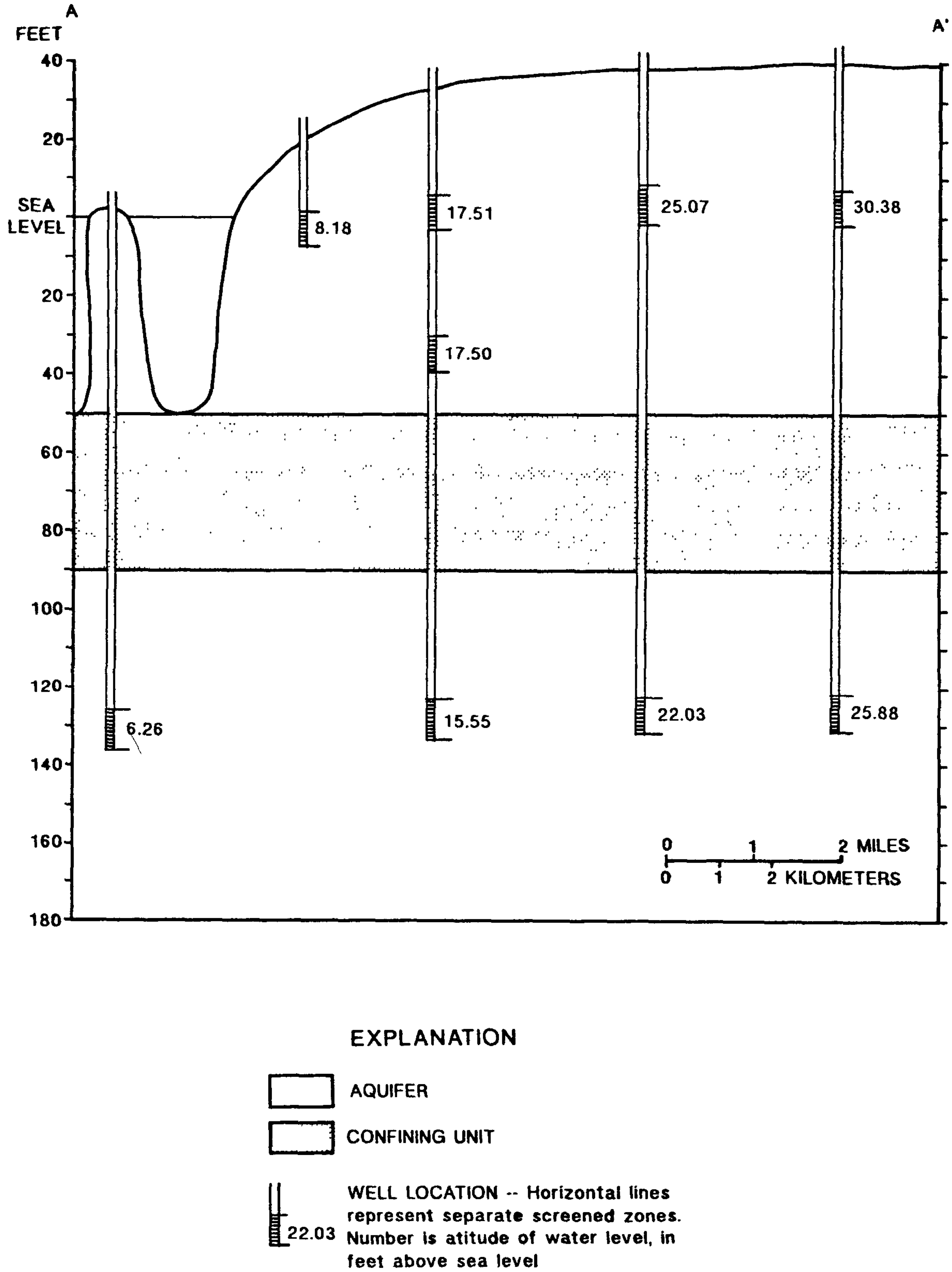


Figure 3-12.--North-south-trending hydrogeologic section showing measured heads in response to steady pumping. (Location of section A-A' is shown in fig. 3-2.)

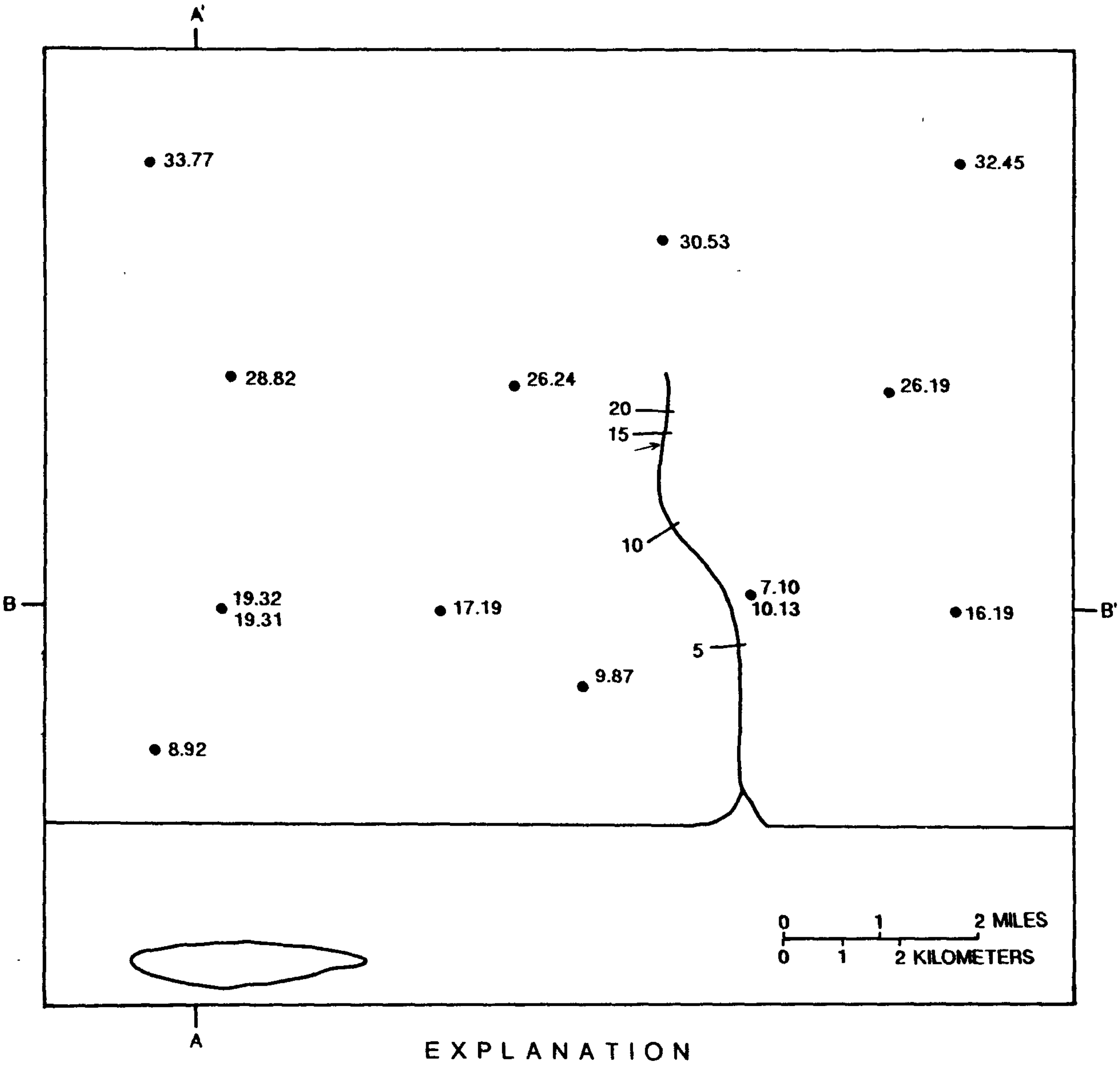
The mapped distribution of head in the unstressed system may be used as a guide to mapping head in the stressed system. Because the key hydrologic features, recharge and lake stage, have not changed, the head at any point in the stressed system is measurably less than or almost equal to the corresponding head in the unstressed system. Furthermore, the difference between the two head distributions is equal to the drawdown caused by pumping, about which some general deductions may be made. The cone of depression is greatest at the pumping-well screen. The cone of depression is assymmetric because of its proximity to impermeable boundaries to the west and north and to constant-head boundaries to the south and east; the drawdown at a given distance from the pumping well is greater near the impermeable boundaries than near the constant-head boundaries. (See Freeze and Cherry, 1979, p. 330 for a discussion of bounded aquifers.)

Question 6.--Using your knowledge of this system and its operation under pumping conditions, construct a set of maps and sections that depict the three-dimensional distribution of head in the system. First construct potential maps using 5-ft contour intervals of the water table and confined aquifers on figures 3-10 and 3-11. Draw equipotential lines at 5-ft intervals on section A-A' (fig. 3-12). Draw a dashed line on figure 3-12 to indicate the water-table surface under unstressed conditions, then include the water-table surface under stressed conditions. Insert small arrows on the completed section to indicate approximate directions of flow. Locate the line of transition between regions of downward and upward flow between the aquifers. Draw a dashed line on figure 3-10 that indicates the transition line under unstressed conditions. A small zone of upward flow may exist in the immediate area of the pumping well, but the data are insufficient to verify this possibility. Compare the line of transition for the stressed conditions with that for the unstressed conditions. Describe the differences, and what this means in terms of the flow within the system.

Mapping Hydraulic Head in a Layered Ground-Water System with a Discontinuous Confining Unit

The head data presented in this section (figs. 3-13 and 3-14) were obtained during a synoptic measurement of observation wells in a ground-water system similar to the one described previously in this exercise. Although initial concepts of the geologic framework and hydrologic features of these two ground-water systems may have been identical, observed head data indicate some difference between these systems. Compare the data set presented in figures 3-13 and 3-14 in this section with that presented earlier in figures 3-4 and 3-6.

The major difference between the two data sets is the absence of vertical gradients between water-table and confined aquifers in the northwest part of the system. The difference in head at the well doublet in the extreme northwest is only 0.01 ft (33.77 ft minus 33.76 ft), and the difference in head at the doublet directly to the south is 0.04 ft (28.82 ft minus 28.78 ft); both differences are much smaller than the corresponding head differences in the original system. In other areas vertical gradients are considerably larger than in the original system; for example, the well doublet in the northeast corner of the modified system shows a 6-ft head difference. Hypothesize a modified concept of the ground-water system that would explain these new observed head data.



EXPLANATION

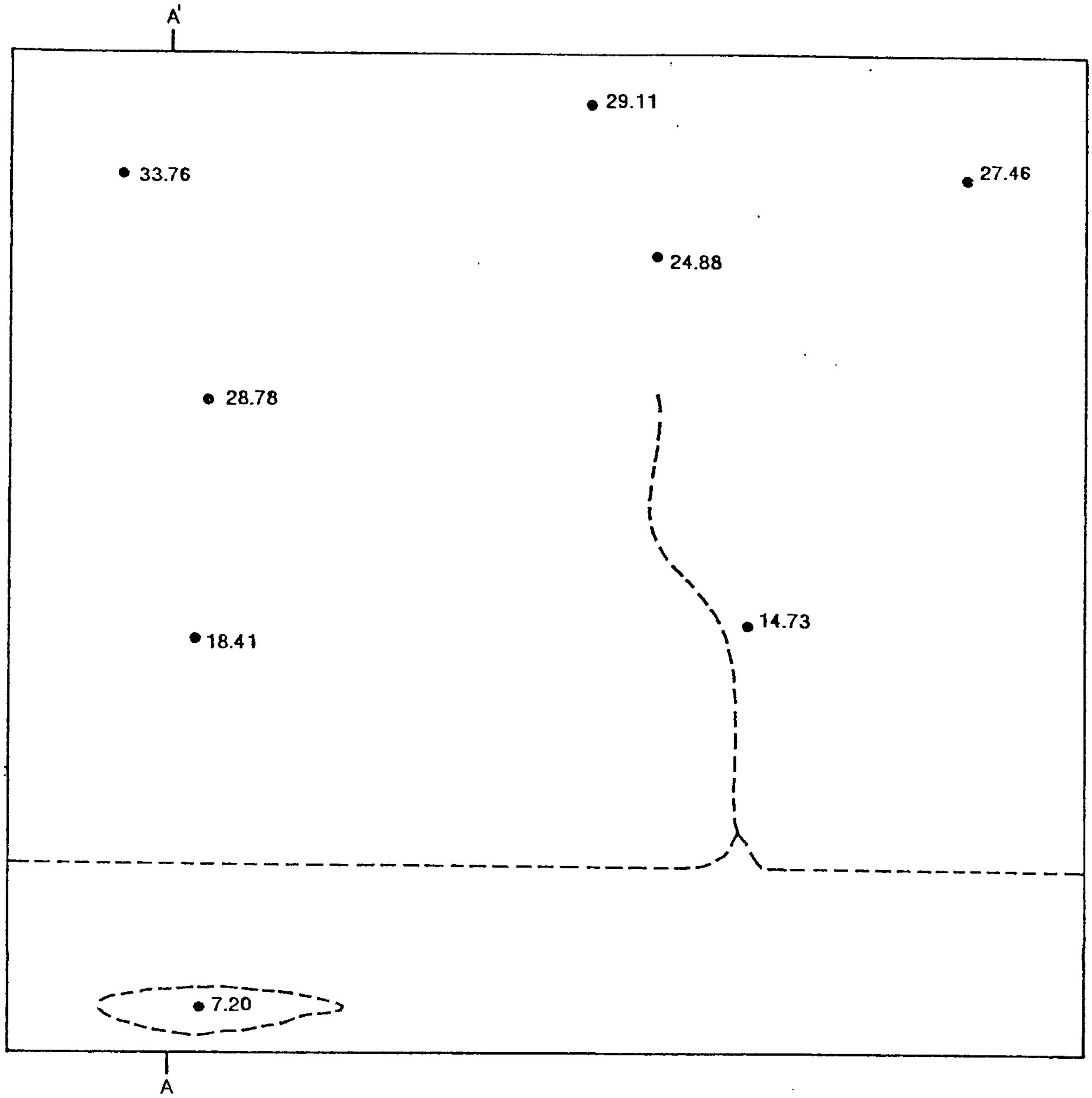
● 8.92 WATER-TABLE OBSERVATION WELL -- Number is altitude of water level, in feet above sea level

5 STREAMBED LEVEL -- Number is altitude of streambed, in feet above sea level

POINT OF START OF FLOW OF STREAM

A-A' TRACE OF SECTION

Figure 3-13.--Measured heads in the water-table aquifer in a ground-water system with a discontinuous confining unit.



EXPLANATION

● 14.73 OBSERVATION WELL SCREENED IN THE CONFINED AQUIFER -- Number is altitude of water level, in feet above sea level

A-A' TRACE OF SECTION

Figure 3-14.--Measured heads in the confined aquifer in a ground-water system with a discontinuous confining unit.

Further field investigation of this phenomenon reveals an irregular hole in the confining unit in the northwest corner of the area (fig. 3-15). This hole results in a direct hydraulic connection locally between the water-table and confined aquifers. Although the vertical gradient between the aquifers is least in the area of the hole, the flux between the aquifers probably is greatest there. An additional effect of this hole on the flow system might be that, to a limited degree, water converges above the hole in the water-table aquifer, flows through the hole, and disperses (flowlines diverge) within the confined aquifer.

Question 7.--Using your current understanding of the structure and operation of this ground-water system, construct a set of maps that depict its three-dimensional head distribution. Construct maps for the water-table and potentiometric surfaces and section A-A' (figs. 3-13, 3-15, and 3-16. Draw equipotential lines at 5-ft intervals.

Locate the line of transition between regions of downward and upward flow between aquifers, and mark it as a dashed line on figure 3-15. Compare this transition line with the one determined in question 5 (for unstressed conditions with continuous confining unit); also compare the head maps constructed for both scenarios. What does this comparison indicate about the effect of the hole in the confining unit on the operation of this system?

Analysis of Ground-Water Systems Using Flow Nets

Assignments

*Study Fetter (1988), p. 137-141, 218-229; Freeze and Cherry (1979), p. 168-185; or Todd (1980), p. 83-93.

*Study Note (3-4)--Introducton to discretization.

*Work Exercise (3-2)--Flow net beneath an impermeable wall.

*Study Note (3-5)--Examples of flow nets.

Flow nets depict a selected number of accurately located flowlines and equipotential lines in the flow system, which provide in total a quantitatively useful, graphical representation of the ground-water flow field. In fact, problems that involve ground-water flow often can be considered as solved if an accurate flow net is developed. Flow nets can be applied conveniently only in two-dimensional flow problems, and the technique is particularly useful in analyzing vertical sections of flow systems that are oriented along a regional "streamline" (actually, stream surface).