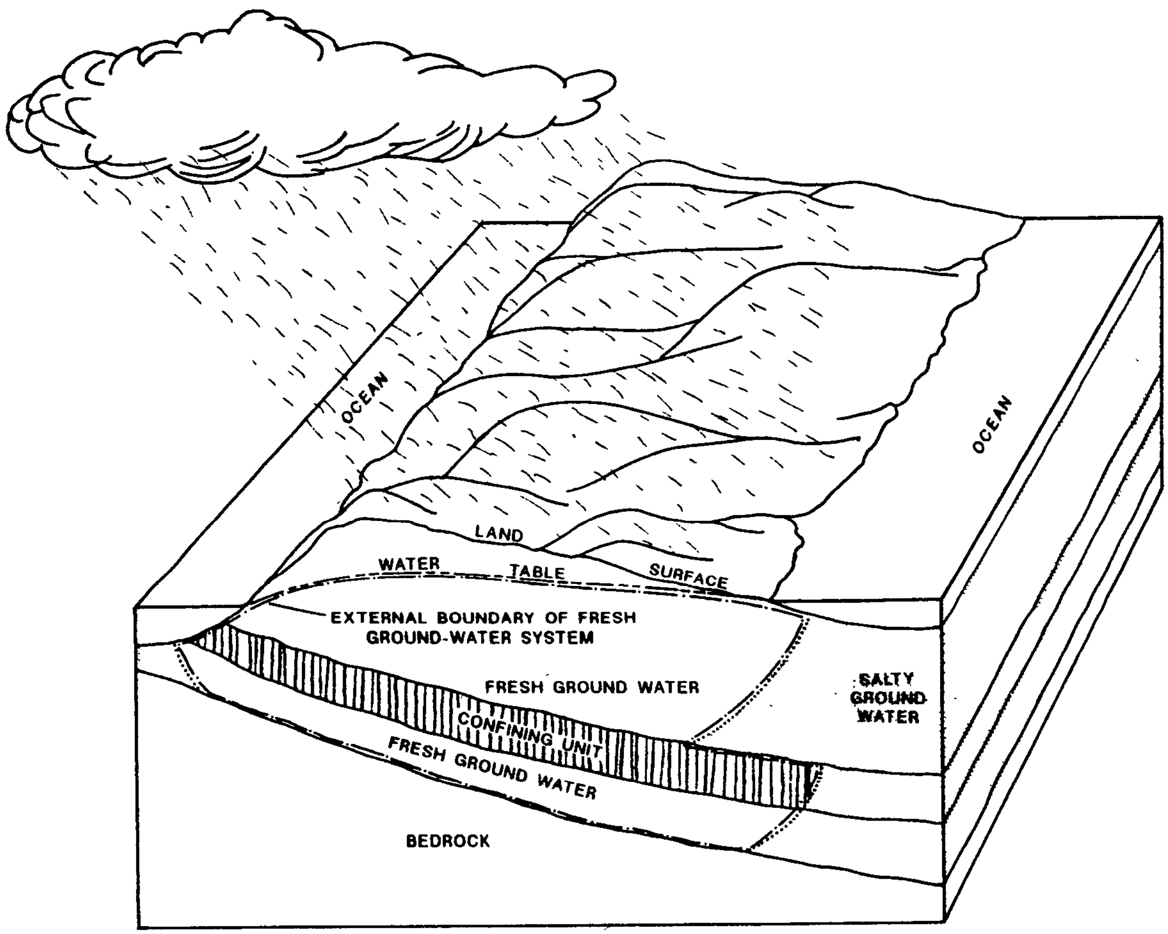
STUDY GUIDE FOR A BEGINNING COURSE IN GROUND-WATER HYDROLOGY: PART I -- COURSE PARTICIPANTS



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

by O. Lehn Franke, Thomas E. Reilly, Ralph J. Haefner, and Dale L. Simmons

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DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply inch-pound units	by	To obtain SI (metric units)
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
foot per year per square mile [$(ft/yr)/mi^2$]	0.7894	meter per year per square kilometer [$(m/yr)/km^2$]

PREFACE

The principal purpose of this study guide is to provide a broad selection of study materials that comprise a beginning course in ground-water hydrology. These study materials consist primarily of notes and exercises. The notes are designed to emphasize ideas and to clarify technical points that commonly cause difficulty and confusion to inexperienced hydrologists and may not receive adequate treatment in standard textbooks. Some of the exercises are more extensive than those usually found in textbooks to provide an additional level of detail and to focus on concepts that we consider to be particularly important. Detailed answers to exercises with explanatory comments are available in a companion publication.

The most important and unique technical feature of this course is the emphasis on the concept of a ground-water system. Generally, this concept is first developed extensively in a more advanced rather than a beginning course in ground-water hydrology. We believe that it is highly desirable to introduce this concept early in a hydrologist's education because it provides the best possible conceptual framework for analyzing and guiding all phases of any investigation related to ground water.

The study guide is divided into five sections: (1) Fundamental concepts and definitions, (2) Principles of ground-water flow and storage, (3) Description and analysis of ground-water systems, (4) Ground-water flow to wells, and (5) Ground-water contamination. Each section is subdivided into a number of subtopics, and each subtopic is followed by an appropriate "assignment" and comments on the topic or study materials. The "assignment" consists of a list, in preferred order of study, of readings in Applied Hydrogeology (Fetter, 1988), or readings in either Freeze and Cherry (1979) or Todd (1980), specially prepared notes, and exercises. The notes and exercises are numbered separately and sequentially in each major section of the study guide and are found immediately after the assignment and comments in the subsection in which they are listed.

If the user of this guide is participating in an intensive, short-term workshop, the material in the readings should be covered in lectures and discussion. In this case the readings can function as preparation for the workshop or a review and extended coverage of material afterwards. If a person is engaged in self-study, the readings are an essential part of the study sequence.

The ideal minimum technical background for users of this study guide is (a) 1 year of basic college physics, (b) 1 year of calculus, and (c) one semester of physical geology. Of course, additional background in any or all of these subject areas is highly desirable. A person with a technical background in a subject other than geology will benefit greatly from reading selected parts of basic texts in physical geology, stratigraphy, and structural geology. In addition, although we do not attempt to cover this subject area in the outline, basic chemistry and geochemistry are fundamental to the broad field of ground-water hydrology. Finally, we have taught beginning ground-water hydrology successfully to individuals with less technical background than that outlined above--perhaps the most important prerequisite for learning a new subject is the motivation of the prospective learner.

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INTRODUCTION

Background

Professional expertise in ground-water hydrology is required by a number of Federal agencies. Because such expertise is now generally in short supply, these agencies are faced with the prospect of providing basic training in this discipline to current employees with diverse academic backgrounds. Recognizing that appropriate courses commonly are either not available or inconveniently scheduled at local schools, one possible training option is to use the most knowledgeable in-house ground-water professionals as course instructors.

Purpose and Scope

The purposes of this study guide are to (1) provide a broad selection of study materials that comprise a beginning course in ground-water hydrology and (2) support in-house training by assembling these materials in a form that can be used easily by competent ground-water professionals who may not be experienced teachers to provide technically sound instruction in ground-water hydrology with a minimum of preparation.

The study guide for a beginning course in ground-water hydrology consists of two parts under separate cover. The first part is for course participants and consists of specially prepared notes and exercises, instructions on how to proceed and comments on the material, as well as appropriate readings keyed to three well-known textbooks in ground-water hydrology--Applied Hydrogeology (Second Edition) by C. W. Fetter (1988), Groundwater by R. A. Freeze and J. A. Cherry (1979) and Ground-Water Hydrology by D. K. Todd (1980). Any one of these three textbooks, as well as other available textbooks, are appropriate to use with this study guide. However, for continuity and because of the specific content and manner of presentation, particularly in the introductory chapters, we have adapted the notations and equations used in the book by Fetter (1988) in this study guide.

As implied in the previous paragraph, this study guide is not designed to stand alone, but is designed to be used in conjunction with a textbook in ground-water hydrology. However, for the most part, the notes and exercises in the study guide do stand alone and may be used to advantage individually in training courses without reference to the study guide.

The second part of the study guide under separate cover, "A Study Guide for a Beginning Course in Ground-Water Hydrology: Part II--Instructor's Manual," is for course instructors. It provides completely worked answers to problems, additional comments on the course materials, and additional references keyed to the specific topics in the outline.

The study guide is designed primarily for an intensive 1-week course or workshop (minimum 40 hours); between 30 and 50 percent of this time will be devoted to exercises and the remainder to lectures or reading by participants. Because all the material in the study guide probably cannot be covered in one week, the instructors will be required to make a discretionary selection of material. Additionally, this study guide can provide the basis for longer or shorter workshops, and the instructor can emphasize further an existing topic or add other specialized topics if desired. The study guide also is appropriate for self-paced instruction by highly motivated individuals with a minimum of assistance from a knowledgeable ground-water professional.

Two additional features of this study guide are the notes and exercises. The notes are designed to emphasize ideas and to clarify technical points that frequently cause difficulty and confusion to inexperienced hydrologists and may not receive adequate treatment in standard textbooks. Some of the exercises are more extensive than those usually found in textbooks to provide an additional level of detail and to focus on concepts that we consider to be particularly important.

The most important and unique technical feature of this study guide is the emphasis on the concept of a ground-water system. Generally, this concept is first developed extensively in a more advanced rather than a beginning course in ground-water hydrology. We believe that it is highly desirable to introduce this concept early in a hydrologist's education because it provides the best possible conceptual framework for analyzing and guiding all phases of any investigation related to ground water.

Technical Qualifications for Users of the Study Guide

The ideal minimum technical background for users of this study guide is (a) 1 year of basic college physics, (b) 1 year of calculus, and (c) one semester of physical geology. Of course, additional background in any or all of these subject areas is highly desirable. A person with a technical background in a subject other than geology will benefit greatly from reading selected parts of basic texts in physical geology, stratigraphy, and structural geology. In addition, although we do not attempt to cover this subject area in the outline, basic chemistry and geochemistry are fundamental to the broad field of ground-water hydrology. Finally, we have taught beginning ground-water hydrology successfully to individuals with less technical background than that outlined above--perhaps the most important prerequisite for learning a new subject is the motivation of the prospective learner.

ANNOTATED LIST OF SELECTED REFERENCES IN GROUND-WATER HYDROLOGY

Professionals beginning their career in ground-water hydrology generally are interested in starting their own technical library. The available literature in hydrology is overwhelming in volume and scope. The annotated list below consists of three well-known textbooks, and several publications produced by Federal agencies, primarily the U.S. Geological Survey. These publications are characterized by their technical relevance and generally high technical quality, modest cost, and ready availability.

Textbooks

Fetter, C. W., 1988, Applied hydrogeology: Columbus, Ohio, Merrill Publishing Company, 592 p.

Freeze, R. A., and Cherry J. A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, 604 p.

Todd, D. K., 1980, Ground-water hydrology: New York, John Wiley and Sons, 535 p.

Although there is a large measure of overlap in these three textbooks, as would be expected, the texts complement each other in their coverage of technical topics. In general, the treatment of solute transport and geochemistry in the text by Freeze and Cherry is more extensive than in the other two texts.

Federal Publications

Bennett, G. D., 1976, Introduction to ground-water hydraulics: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Chapter B2, 172 p.

An excellent introduction to basic mechanics of ground-water flow; ideal for supplementary study in conjunction with this study guide.

Bureau of Reclamation, 1977, Ground water manual: U.S. Department of the Interior, Bureau of Reclamation, 480 p.

Useful as a source of information on field studies--their design, field measurements and procedures.

Environmental Protection Agency, 1987, Handbook of ground water: EPA/625/6-87/016, 212 p.

Useful compilation of ground-water information, particularly information related to ground-water contamination; not organized as a textbook in ground-water hydrology.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, 174 p.

Authoritative introduction to theory and application of aquifer tests and image-well theory.

Franke, O. L., Reilly, T. E., and Bennett, G. D., 1987, Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems--an introduction: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Chapter B5, 15 p.

A concise introduction to boundary conditions used in ground-water hydrology; essential reading for anyone involved in computer simulation.

Haeni, F. P., 1988, Application of seismic-refraction techniques to hydrologic studies: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 2, Chapter D2, 86 p.

Heath, R. C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Concise explanations of and figures illustrating basic ground-water concepts; useful supplementary source of information for this course.

Heath, R. C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78 p.

Concise overview of ground-water "regions", based on regional geology, in the United States.

Hem, J. D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 264 p.

An indispensable reference for all ground-water hydrologists; included in this list even though geochemistry is not discussed in this beginning course in ground-water hydrology.

Keys, W. S. 1988, Borehole geophysics applied to ground-water hydrology: U.S. Geological Survey Open-File Report 87-539, 305 p.

Lohman, S. W., 1972a, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Useful as a reference, particularly for radial-flow problems.

Lohman, S. W. (editor), 1972b, Definitions of selected ground-water terms--revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

The most authoritative glossary of ground-water terms that is available.

Rantz, S. E., 1982, Measurement and computation of streamflow: Volume 1. Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Reed, J. E., 1980, Type curves for selected problems of flow to wells in confined aquifers: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Chapter B3, 106 p.

A well documented compilation of analytical solutions for confined radial-flow problems, with associated tables of function values, plotted type curves, and computer programs for calculating function values.

Reilly, T. E., Franke, O. L., and Bennett, G. D., 1987, The principle of superposition and its application in ground-water hydraulics: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Chapter B6, 28 p.

Concept of superposition simply and thoroughly explained; clear discussion of the applications and advantages of using superposition in the simulation of ground-water systems.

Reilly, T. E., Franke, O. L., Buxton, H. T., and Bennett, G. D., 1987, A conceptual framework for ground-water solute-transport studies with emphasis on physical mechanisms of solute movement: U.S. Geological Survey Water-Resources Investigations Report 87-4191, 44 p.

A practical and readable discussion on how to approach and design a field study involving solute transport.

Shuter, E., and Teasdale, W. E., 1989, Application of drilling, coring, and sampling techniques to test holes and wells: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 2, Chapter F1, 97 p.

Stallman, R. W., 1971, Aquifer-test design, observation, and data analysis: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Chapter B1, 26 p.

Basic reference on aquifer-test design.

Zohdy, A. A. R, Eaton, G. P., and Mabey, D. R., 1974, Application of surface geophysics to ground-water investigations: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 2, Chapter D1, 116 p.

DETAILED OUTLINE WITH NOTES AND EXERCISES

The study guide is divided into five major sections (see Contents, p. 1): (1) Fundamental concepts and definitions, (2) Principles of ground-water flow and storage, (3) Description and analysis of ground-water systems, (4) Ground-water flow to wells, and (5) Ground-water contamination. Each section is subdivided into a number of subtopics, and each subtopic is followed by an appropriate "assignment" and comments on the topic or study materials. The "assignment" consists of a list in preferred order of study of readings in Applied Hydrogeology (Fetter, 1988), or readings in either Freeze and Cherry (1979) or Todd (1980), specially prepared notes, and exercises. The notes and exercises are numbered separately and sequentially in each major section of the study guide and are found immediately after the assignment and comments in the subsection in which they are listed.

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SECTION (1)--FUNDAMENTAL CONCEPTS AND DEFINITIONS

This section of the study guide provides a background in earth materials, selected hydrologic concepts and features, and physical principles that are sufficient to begin the quantitative study of ground-water hydrology in Section (2).

Dimensions and Conversion of Units

Assignment

*Work Exercise (1-1)--Dimensions and conversion of units.

Conversion of units is a painful necessity in everyday technical life. Tables of conversion factors for common hydrologic variables are found in Fetter (1988), both in the inside cover and several appendixes; Freeze and Cherry (1979), p. 22-23, 29, 526-530, and front inside cover; or Todd (1980), p. 521-525, and back inside cover.

Exercise (1-1)--Dimensions and Conversion of Units

The capability of executing unit conversions accurately, both within the inch-pound system of units and between the inch-pound and metric systems, is a necessity for any professional in a technical field. The purpose of this exercise is simply to serve as a reminder of this fact. Most beginning textbooks in any technical field address this topic. In addition, all engineering handbooks include extensive treatments of dimensions, units, and unit conversions.

Ground-water hydraulics is a specialty within the general field of mechanics. Variables in mechanics possess some combination of three fundamental dimensions--mass (M), length (L), and time (T). Careful analysis of dimensions is a valuable first step in becoming acquainted with unfamiliar variables and (or) formulas.

Below is a list of several conversions to be calculated. Before performing the calculations, test whether the two sets of units are dimensionally compatible. (One or more examples are not compatible.) To perform this test, write a general dimensional formula for each set of units in terms of mass (M), length (L), and time (T). For example, velocity has a general dimensional formula of (LT^{-1}), and force has a general dimensional formula of (MLT^{-2}). As part of the calculations, write out all conversion factors.

(1) 15 ft/d (feet per day) to (a) in/hr (inches per hour), (b) cm/s (centimeters per second)

(2) 200 gal/min (gallons per minute) to (a) ft^3/d, (b) cm^3/s

(3) 500 gal/d•ft^2 to (a) ft^2/d, (b) m^2/d

(4) 250 ft^2/d to (a) gal/d•ft, (b) cm^2/s

(5) 500,000 gal/d•mi^2 to (a) in/yr, (b) cm/d.

Water Budgets

Assignments

*Study Fetter (1988), p. 1-12, 15-24, 446-448; Freeze and Cherry (1979), p. 203-207, 364-367; or Todd (1980), p. 353-358.

*Work Exercise (1-2)--Water budgets and the hydrologic equation.

The preparation of an approximate water budget is an important first step in many hydrologic investigations. Unfortunately, the only two budget components that we can measure directly and do measure routinely are precipitation and streamflow. Evapotranspiration, the "great unknown" in hydrology, can be estimated by various indirect means, and estimates of subsurface flows also usually are subject to considerable uncertainty. The reasons for the uncertainty in subsurface-flow estimates are addressed later in this course.

In Exercise (1-2) and the accompanying discussion on water budgets, the following points are emphasized: (a) the differentiation between inflows and outflows from a basin as a whole and flows within the basin, (b) the possible specific inflow and outflow components of the saturated ground-water part of the hydrologic system, and (c) the necessity of defining clearly a reference volume when a water budget that focuses on the saturated ground-water part of the system is undertaken. This reference volume will be discussed again in later sections of the report that focus on the development of concepts specifically related to ground-water systems.

Exercise (1-2)--Water Budgets and the Hydrologic Equation

The following notes and problems assume previous reading and (or) discussion on the continuity principle, as represented in hydrology by the "hydrologic equation" or "water-budget equation"--that is,

$$\text{Inflow} = \text{Outflow} \pm \Delta\ \text{Storage}$$

(where Δ means "change in")--and the various components of the hydrologic cycle. The continuity principle will be encountered again later in this course as the starting point for developing the basic differential equation of ground-water flow. The focus here is the application of this principle to the preparation of water budgets for hydrologic systems. It is conceptually useful to note, however, that the continuity principle is applicable at all physical scales, not only in hydrology, but also in other fields of science and technology.

The purpose of a water-budget analysis is to quantify, to the extent that data and time permit, the various fluxes[1] to, from, and within the hydrologic system. Many of the budget components or fluxes can be only roughly approximated in most systems (for example, ground-water evapotranspiration), and even the best "estimates" (for example, ground-water contribution to streamflow, which involves a base-flow separation) may involve considerable uncertainty. The best results are achieved by estimating each component in as many different ways as possible and, by continuous checking and comparisons, establishing ranges of uncertainty for each estimate and making certain that the estimates for the different components are consistent with one another. Usually, average water budgets for several years are prepared, as opposed to a water budget for a single year, so that changes in storage in the hydrologic system are small relative to other budget components and need not be considered. This approach implies use of the steady-state or equilibrium form of the hydrologic equation,

$$\text{Inflow} = \text{Outflow}.$$

Flow diagrams for the hydrologic system of central and eastern Long Island, New York under predevelopment and developed conditions are shown in figures 1-1 and 1-2, respectively. Although these diagrams were prepared for Long Island, they can be modified easily to accommodate local conditions. In these diagrams the "boxes" (atmosphere, land surface, zone of aeration) represent sites within or components of the hydrologic system, and the lines with arrows between boxes represent some of the major flow paths of water between the various sites. Most of these sites represented by boxes are also hydrologic storage sites; that is, some quantity of water is nearly always in storage at these sites. This quantity of stored water changes with time.

In figures 1-1 and 1-2, a larger rectangle encloses a number of boxes and flow lines. This larger rectangle represents the boundaries of the hydrologic system that has been isolated for study. In map view, boundaries of hydrologic systems usually are defined by the topographic drainage areas of streamflow-measuring stations. In terms of water budgets, a distinction is made between budgets for a river basin "as a whole" and water-budget components within the river-basin hydrologic system. In water budgets for the basin "as a whole", inflow components generally consist of precipitation, and outflow includes total evapotranspiration, surface-water outflow, and

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[1] The term flux refers to the rate of flow or transfer of some entity such as water, heat, electricity, mass, number of particles, and so on; more specifically, it is the quantity that crosses a unit area of a given surface in a unit of time. For example, heat flux might have the units of calories/$cm^2 \cdot s$ (calories per square centimeter per second); mass flux might have the units of $g/m^2 \cdot d$ (grams per square meter per day). In hydrology we often refer to the transfer or movement of water as a flux. A flux of water can be expressed as a volume flux with possible units, for example, of $ft^3/ft^2 \cdot d$ (cubic feet per square foot per day) or $m^3/m^2 \cdot s$ (cubic meters per square meter per second. Thus, a volume flux has the units of length divided by time. Sometimes, we refer loosely to a volumetric flow rate with units of volume divided by time as a flux. Often, in such cases, an area across which this volumetric flow rate is transferred is implied but not defined or taken into account explicitly.

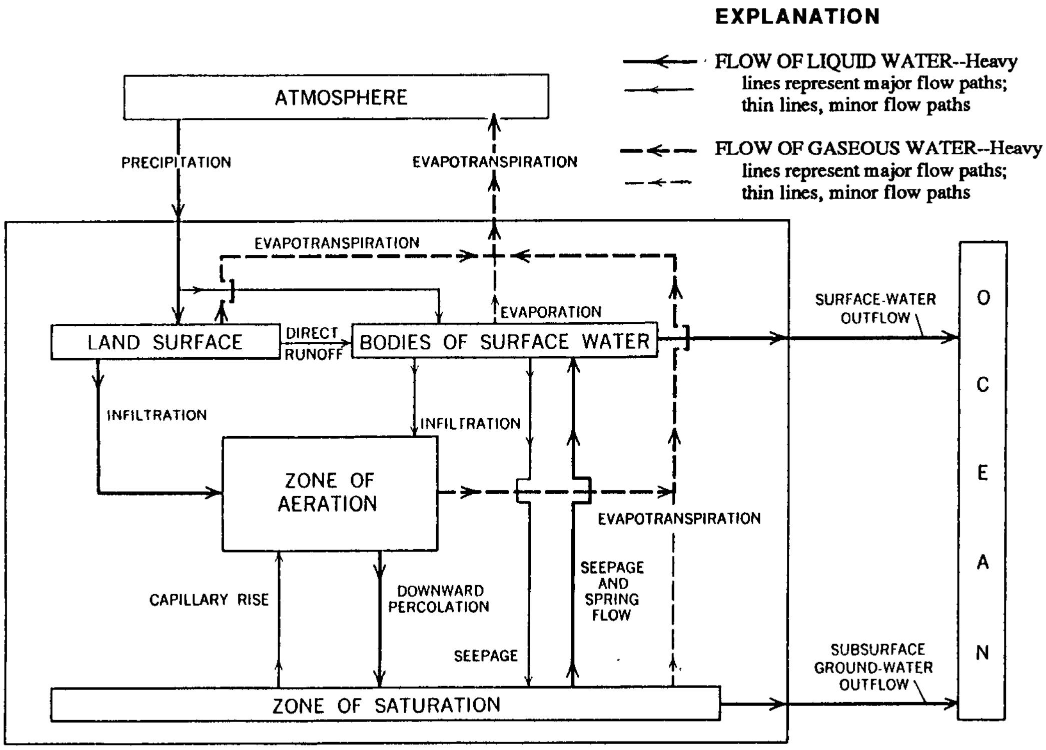

Figure 1-1.--Flow diagram of the hydrologic system, Nassau and Suffolk Counties, Long Island, New York, under predevelopment conditions. (From Franke and McClymonds, 1972, fig. 13.)

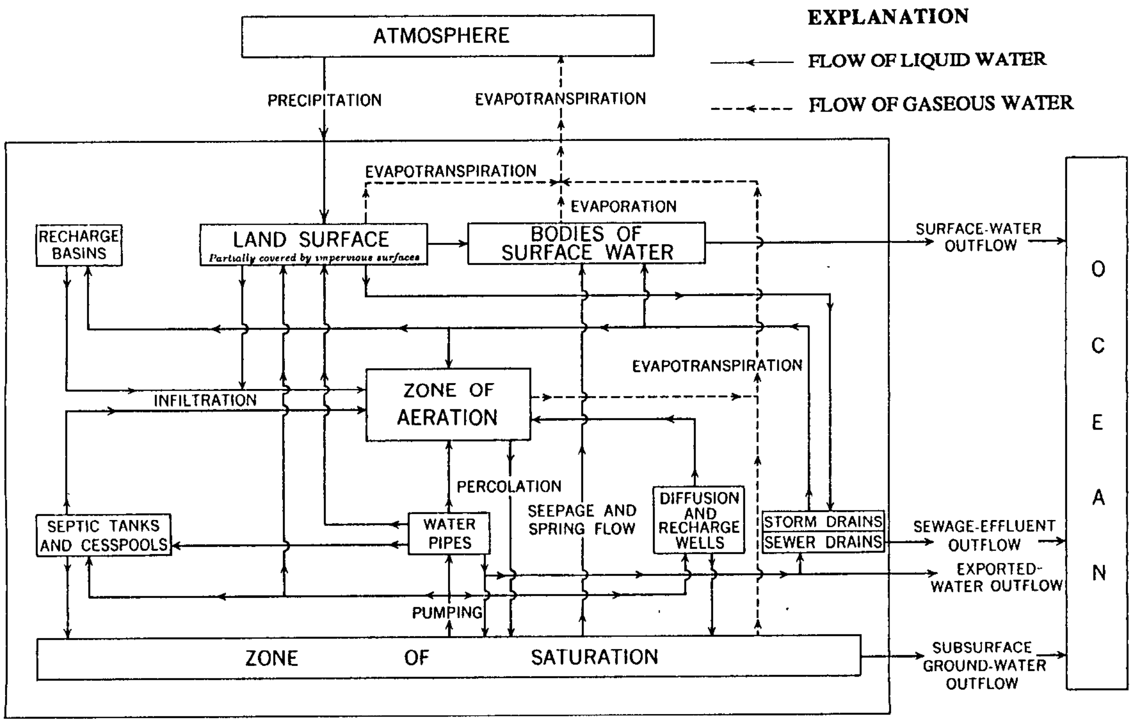

Figure 1-2.--Flow diagram of the hydrologic system, Nassau and Suffolk Counties, Long Island, New York, after noticeable influence from human activities. (From Franke and McClymonds, 1972, fig. 33.)

subsurface ground-water outflow (fig. 1-1), whereas ground-water flow to surface-water bodies, for example, occurs within the boundaries of the water-budget reference volume. This internal contribution to surface water becomes a part of the total measured surface-water outflow from the basin "as a whole" (fig. 1-1).

As implied in the previous discussion, preparation of a water budget requires the careful definition of a reference volume. Inflows and outflows of water occur across the surfaces of this reference volume and changes in storage occur within it. As noted above, however, in many basin studies water budgets are related to the area of the basin. This approach is valid only when most of the ground-water inflow occurs locally as recharge from precipitation, when ground-water outflow occurs as local discharge to streams, and when both flows occur within the basin boundaries. An explicit reference volume must be defined as the initial step in a water-budget analysis whenever (1) inflow and outflow of deeper percolating ground water represent a significant quantity of water relative to other water-budget components, or (2) the ground-water system is the focus of the investigation. In ground-water studies, delineation of an appropriate volume of saturated earth material for study (the ground-water system) is required not only for the preparation of water budgets but also for carrying out additional study elements including computer simulation. How the boundaries of this volume of saturated earth material are delineated comprises one of the most important decisions in the entire investigation.

To this point we have considered long-term average water budgets for which changes in storage between the beginning and end of the water-budget period are so small relative to total inflow and outflow for the water-budget period that we may assume Inflow = Outflow. Generally, however, inflow will not equal outflow in drainage-basin water budgets except fortuitously for water-budget periods of 1 year or less. The transient water-budget equation is written conveniently in the form

$$\text{Inflow} - \text{Outflow} = \pm \Delta \text{ Storage}$$

We will clarify the meaning of + or -change in storage on the right-hand side of the budget equation by means of a hypothetical numerical example. Let us assume that inflow = 10 units and outflow = 8 units, that is, inflow is greater than outflow. Then 10 units -8 units = +2 units change in storage. If we remember that estimates of water-budget components relate to a reference volume,

Inflow -----> Reference Volume -----> Outflow

then we can interpret the +2 units change in storage as an increase in water storage within the reference volume. Similarly, as long as the change in storage term is written on the right-hand side of the budget equation, a minus (-) change in storage means a decrease in water storage within the reference volume, that is, inflow is less than outflow.

Because the focus of this study guide is ground water, possible fluxes to and from the saturated zone under natural conditions are summarized in table 1-1 for reference.

Table 1-1.--Summary of possible fluxes to and from the saturated zone under natural conditions

Inflow ------------------------->	Saturated Zone[1]	Outflow ---------------------------->
(1) From unsaturated zone--through-flow of "gravity" water to water table (intermittent areal recharge) (2) From bodies of surface water-- (a) recharge from losing streams (b) recharge from surface water bodies in flood stage (increase in bank storage)		(1) To bodies of surface water--streams, lakes, or saltwater bodies (bays, estuaries, or oceans) and springs (a) steady release of ground water in (relatively) long-term storage (b) relatively rapid, short-term release of ground water in bank storage caused by rapid fluctuations in stage of surface-water bodies (2) To atmosphere--ground-water evapotranspiration (plants derive moisture from capillary fringe)

[1] Changes in storage in the saturated zone are manifested by changes in ground-water levels. See later section on ground-water storage.

Exercise on Water Budgets

The following data refer to a hypothetical river basin in a coastal plain with a drainage area of 250 mi^2 (square miles). The data represent long-term average annual values and are assumed to be exact (never the case in the real world). Before answering the questions below, enter the known budget values next to the appropriate "flow" line between boxes on figure 1-1. If a water budget doesn't balance, what missing information might account for the discrepancy?

Data

Precipitation, 45 in/yr (inches/year); ground-water recharge, 20 in/yr; direct runoff, 1 in/yr; subsurface outflow, 8 in/yr; total evapotranspiration, 25 in/yr; streamflow, 12 in/yr; ground-water contribution to streams (base flow), 11 in/yr.

Questions

(1) Prepare a water budget for the basin as a whole using the principal inflow and outflow components. List inflow and outflow components in separate columns accompanied by long-term average quantities of water.

(2) Prepare a water budget for the streams (surface-water bodies). What possible budget components are neglected?

(3) Prepare a water budget for the ground-water reservoir (saturated zone). What possible budget components are neglected?

(4) What is the average volume of precipitation during one year over the whole basin, in ft^3 (cubic feet)?

(5) Express the average volume of precipitation for one year in (4) as a rate, in ft^3/s (cubic feet per second) and as a rate per unit area, in Mgal/d (millions of gallons per day) per square mile.

(6) For the same basin in a given year the following water budget figures are assumed to be correct: Precipitation, 35 in.; total evapotranspiration, 20 in.; streamflow, 10 in.; subsurface outflow, 7 in.. Write a formal water-budget equation using these figures. Write the water-budget equation in words and then a second time using the available numbers. What is the probable cause of the discrepancy and how must this factor be included in the water-budget equation?

Characteristics of Earth Materials Related to Hydrogeology

Assignments

*Study Fetter (1988), p. 63-73; Freeze and Cherry (1979), p. 29, 36-38; or Todd (1980, p. 25-31, 37-39.

*Look up and write the definitions of the following terms describing the flow medium in Fetter (1988), both in the glossary and in the index--isotropic, anisotropic, homogeneous, and heterogeneous.

In considering earth materials from the hydrogeologic viewpoint, the first level of differentiation generally is between consolidated and unconsolidated earth materials. In many ground-water studies, the thickness of the unconsolidated materials above bedrock defines the most permeable part of the ground-water system.

Relevant characteristics of earth materials from the hydrogeologic viewpoint include (a) mineralogy, (b) grain-size distribution of unconsolidated materials, (c) size and geometry of openings in consolidated rocks, (d) porosity, (e) permeability (hydraulic conductivity), and (f) specific yield.

Mineralogy is included in this list because it is one of the principal bases for the geologic classification of consolidated rocks, and it exerts a significant influence on the geochemical evolution of ground water, a topic which is not discussed in this course. Permeability and specific yield, included here to make the list of relevant characteristics more complete, will be defined and discussed later in the course.

Occurrence of Subsurface Water

Assignments

*Study Fetter (1988), p. 85-95, 99-101; Freeze and Cherry (1979), p. 38-41; or Todd (1980), p. 31-36.

Subsurface water generally is considered to occur in three zones--(a) the unsaturated zone, (b) the capillary or tension saturated zone, and (c) the saturated zone. The water table in coarse earth materials may be defined approximately as the upper bounding surface of the saturated zone. The main focus in this study guide is the saturated zone; however, hydrologic processes in the shallow saturated zone are controlled largely by physical processes in the overlying unsaturated zone. For example, most recharge to the water table must traverse some thickness of the unsaturated zone.

Pressure and Hydraulic Head

Assignments

*Work Exercise (1-3)--Hydrostatic pressure.

*Study Fetter (1988), p. 115-122; Freeze and Cherry (1979), p. 18-22; or Todd (1980), p. 65, 434-436.

*Study Note (1-1)--Piezometers and measurement of pressure and head.

*Work Exercise (1-4)--Hydraulic head.

Hydraulic head[1] is one of the key concepts in ground-water hydrology. However, it is a concept that remains confusing to many practitioners. Working with the concept will increase understanding.

The first assignment in this section is a review of hydrostatic pressure (Exercise (1-3)). This review provides background for the head concept which is developed in the reading from Fetter (1988). These concepts are developed further in Note (1-1) on the measurement of pressure and head in piezometers and wells. Practice in differentiating between the two components of hydraulic head--pressure head and elevation head, is provided in Exercise (1-4).

Exercise (1-3)--Hydrostatic Pressure

This exercise reviews the calculation of static fluid pressure, particularly the pressure exerted by a column of liquid whose upper surface is subject to atmospheric pressure. Further treatment of this topic may be found in any basic text on college physics or fluid mechanics.

The following definitions are provided for reference:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \quad [ML^{-1}T^{-2}]$$

$$\text{Hydrostatic pressure} = \frac{\text{Weight of fluid column}}{\text{Area}}$$

$$\text{By definition } \gamma = \rho g \quad \frac{\text{mass}}{\text{volume}} \bullet g = \frac{\text{weight}}{\text{volume}}$$

---

[1] Synonymous terms include "ground-water head," "total head," and "potentiometric head." We recommend and use in this course "hydraulic head," or simply "head."

where γ is weight density or specific weight $\left(\frac{\text{weight}}{\text{volume}}\right)$,

ρ is mass density $\left(\frac{\text{mass}}{\text{volume}}\right)$, and

g is acceleration due to gravity.

A reference prism of liquid that extends to a depth l in a larger body of static liquid bounded above by a free surface (a surface subject to atmospheric pressure) is shown in figure 1-3. The total force acting on the bottom face of the prism with area A is the sum of the forces exerted by atmospheric pressure on the top area of the prism plus the weight of the fluid column bounded by the prism (weight of fluid column = $\gamma l A$) or

$$P_t A = P_a A + \gamma_f l A \tag{1}$$

where P_t is the total pressure exerted at depth l in the liquid, P_a is atmospheric pressure, and γ_f is the weight density of the liquid. Dividing by A we have

$$P_t = P_a + \gamma_f l. \tag{2}$$

By convention, in hydraulics and fluid mechanics we generally do not work with total pressure, but with "gage" pressure--that is, the pressure exerted by the static liquid alone. Atmospheric pressure is regarded as an environmental constant that need not be taken into account explicitly. From (2) the pressure exerted by the static column of liquid P_f is

$$P_f = \gamma_f l. \tag{3}$$

From (3) the length of the fluid column l may be expressed as

$$l = \frac{P_f}{\gamma_f}. \tag{4}$$

In most developments of these relations the letter h is used instead of l to designate the vertical length of the fluid column under consideration. We use l because h generally is used to designate head in ground-water hydraulics (see later discussion on head).

Questions:

(1) Assuming that l is 12 feet and the liquid is fresh water (fig. 1-3), what is the water pressure acting at depth l in (a) lbs/ft^2 (pounds per square foot) and (b) lbs/in^2 (pounds per square inch)? (c) What is the "total" pressure acting at depth l?

(2) If the liquid is normal sea water, what is the fluid pressure acting at l = 12 ft, in lbs/in^2?

Constants for calculations:

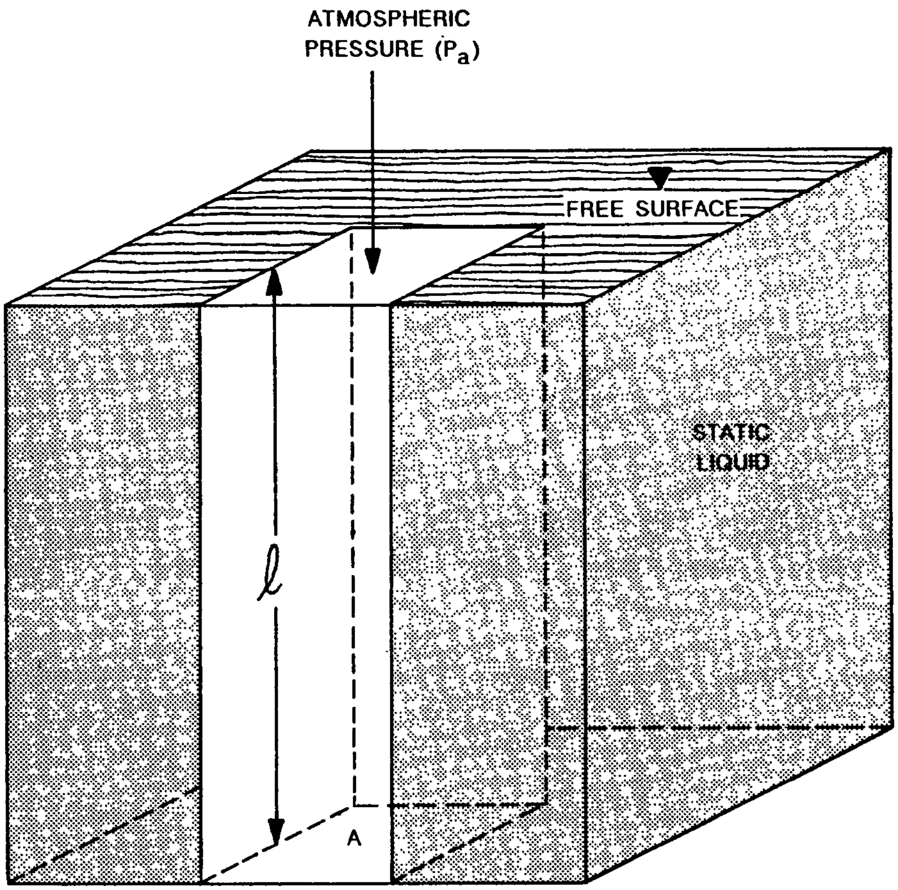

Figure 1-3.--Vertical reference prism of liquid that extends to a depth l in a larger body of static liquid bounded above by a free surface.

$\gamma_{\text{fresh water}} = 62.4 \text{ lbs/ft}^3 = 9.8 \times 10^3 \text{ N/m}^3$ (Newtons per cubic meter)

$\rho_{\text{fresh water}} = 1{,}000 \text{ kg/m}^3$ (kilograms per cubic meter)

$\rho_{\text{sea water}} = 1{,}025 \text{ kg/m}^3$

$P_{\text{atmospheric}} \approx 14.7 \text{ lbs/in}^2$

Note (1-1)--Piezometers and Measurement of Pressure and Head.

In hydraulics a piezometer is a pressure-measuring device consisting of a tube, one end of which taps the fluid system and the other end of which is open to the atmosphere (fig. 1-4). Pressure is measured at the point where the piezometer taps the fluid system (fig. 1-4)[1] and is proportional to the vertical height l of the fluid column in the piezometer above the measuring point. With reference to the preceeding discussion of hydrostatic pressure, the pressure at the point of measurement is calculated using the formula

$$P_{\text{point of pressure measurement}} = \gamma_{\text{fluid}}\, l. \tag{1}$$

In ground-water hydraulics a piezometer is a tightly cased well, usually of small diameter (4 in. or less), with a single, short (generally, 10 ft or less in length) well screen (fig. 1-5). For this discussion, we arbitrarily assume that the point of pressure measurement of the piezometer is at the midpoint of the screened interval. Usually, piezometers are installed for the specific purpose of measuring pressure and head at the piezometer's point of measurement.

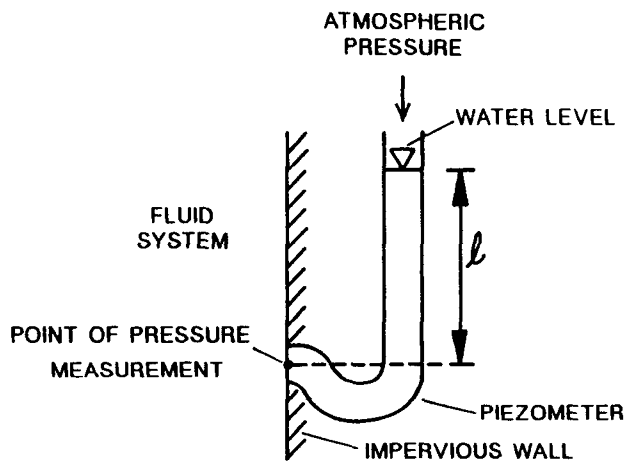

Figure 1-4.--A typical piezometer in a hydraulic system.

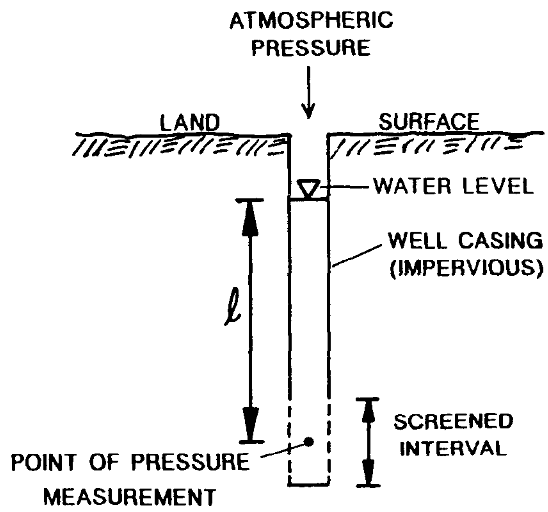

Figure 1-5.--A typical piezometer in a ground-water system.

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[1] In hydraulics other conventions sometimes are used for convenience; for example, a piezometer that taps a pipe flowing full generally is assumed to measure static pressure at the centerline of the pipe.

Wells installed for pumping ground water commonly have larger diameters and longer screened intervals than piezometers. Heads measured in wells with long screens effectively represent average heads in the aquifer opposite the screened interval. Generally, wells that are screened in more than one interval are not suitable for head measurements. The designation "observation well" is used widely. An observation well is used primarily to measure head and may be either a piezometer or a well as defined above.

Field measurements of head in a piezometer or well involve measurement of a depth to water (fig. 1-6 and following discussion) and thus require the identification and description of a fixed reference point or "depth-to-water measuring point" to which all field measurements are referred. This depth-to-water measuring point usually is a point at the top of the well casing, well cap, or access hole (fig. 1-6). As will become evident in the following discussion, an "accurate" determination of head requires that the altitude of the depth-to-water measuring point be accurately surveyed. Considerably less accurate determinations of the altitude of the depth-to-water "measuring point" (and also of head) are obtained by estimating

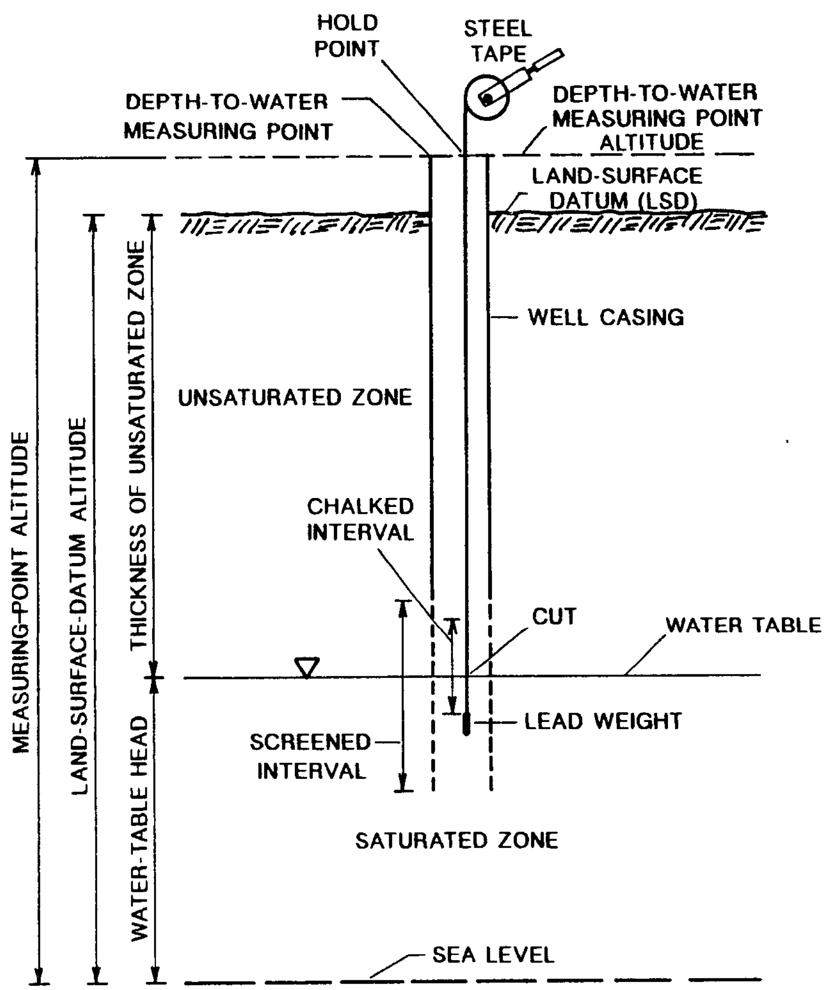

Figure 1-6.--Measurement of head in a well.

the land-surface altitude at the well from topographic maps and adding the measured vertical distance from the depth-to-water measuring point to the land-surface altitude (see following section).

Procedure for Making Accurate Head Measurements

The most used and generally most accurate method for making a head measurement utilizes a graduated steel tape with a weight attached to its end. The first step is to cover the bottom several feet of the tape with blue carpenter's chalk. Place the tape into the opening of the well and pull the first few feet of tape out by hand; then use the crank to lower the tape slowly down the well. When the desired level has been reached, hold the tape to the nearest whole number of feet at the depth-to-water measuring point (MP) of the well (fig. 1-6), making sure that the tape goes straight down from the MP and is not bent over the lip of the well. This number is the "hold" value.

While holding the tape firmly, slowly back away from the well 1 or 2 feet, and then slowly wind up the tape until the water mark or "cut" is visible. In standard practice, the "cut" value is read and recorded to the nearest hundredth of a foot (about 0.3 cm). If the wet mark cannot be read clearly, dry the tape and repeat the process. After recording both the "hold" and "cut" values, calculate the depth to water (DTW) (see sample calculations below). Repeat the process to insure accuracy, but this time extend the "hold" value an additional foot and determine whether the two DTW values are within an acceptable range of one another. The value of measured head is determined by subtracting the DTW from the MP elevation. The preceeding discussion indicates that field measurement of head is in essence a measurement of depth to water in a well from the depth-to-water measuring point.

In figure 1-6 the screened interval of the observation well intersects the water table and extends only a few feet below it. Thus, in this special case the head measurement in the observation well equals the adjacent altitude of the water table, and, therefore, represents the actual top of the saturated ground-water system.

Sample Head-Measurement Calculations:

Given well information: Depth-to-water measuring point

(MP) altitude = 100.00 ft

Land-surface datum (LSD) = 97.00 ft

To determine depth to water (DTW) inside well casing:

Hold value = 75.00 ft

Cut value = 3.25 ft

DTW = (75.00 ft) - (3.25 ft) = 71.75 ft

To determine head:

MP altitude = 100.00 ft above sea level

DTW = 71.75 ft

Head = (100.00 ft) - (71.75 ft) =

28.25 ft above sea level = altitude of water table

To determine unsaturated-zone thickness (depth to water table below land surface):

LSD = 97.00 ft

Water-table altitude = 28.25 ft

Unsaturated zone thickness = (97.00 ft) - (28.25 ft) =

68.75 ft

Variability of Head with Depth

Three pairs of observation wells are shown in figure 1-7. Each pair consists of one shallow observation well whose screened interval intersects the water table as shown in figure 1-6 and one deeper observation well whose screened interval is a considerable depth below the water table. In figures 1-7(A), (B), and (C) the heads in the deeper wells are less than, equal to, and greater than the heads in the immediately adjacent shallow observation wells, respectively. The water levels in the casings of the deeper observation wells do not represent the position of the top of the saturated deposits, but do represent hydraulic heads at the point of pressure measurement of these observation wells.

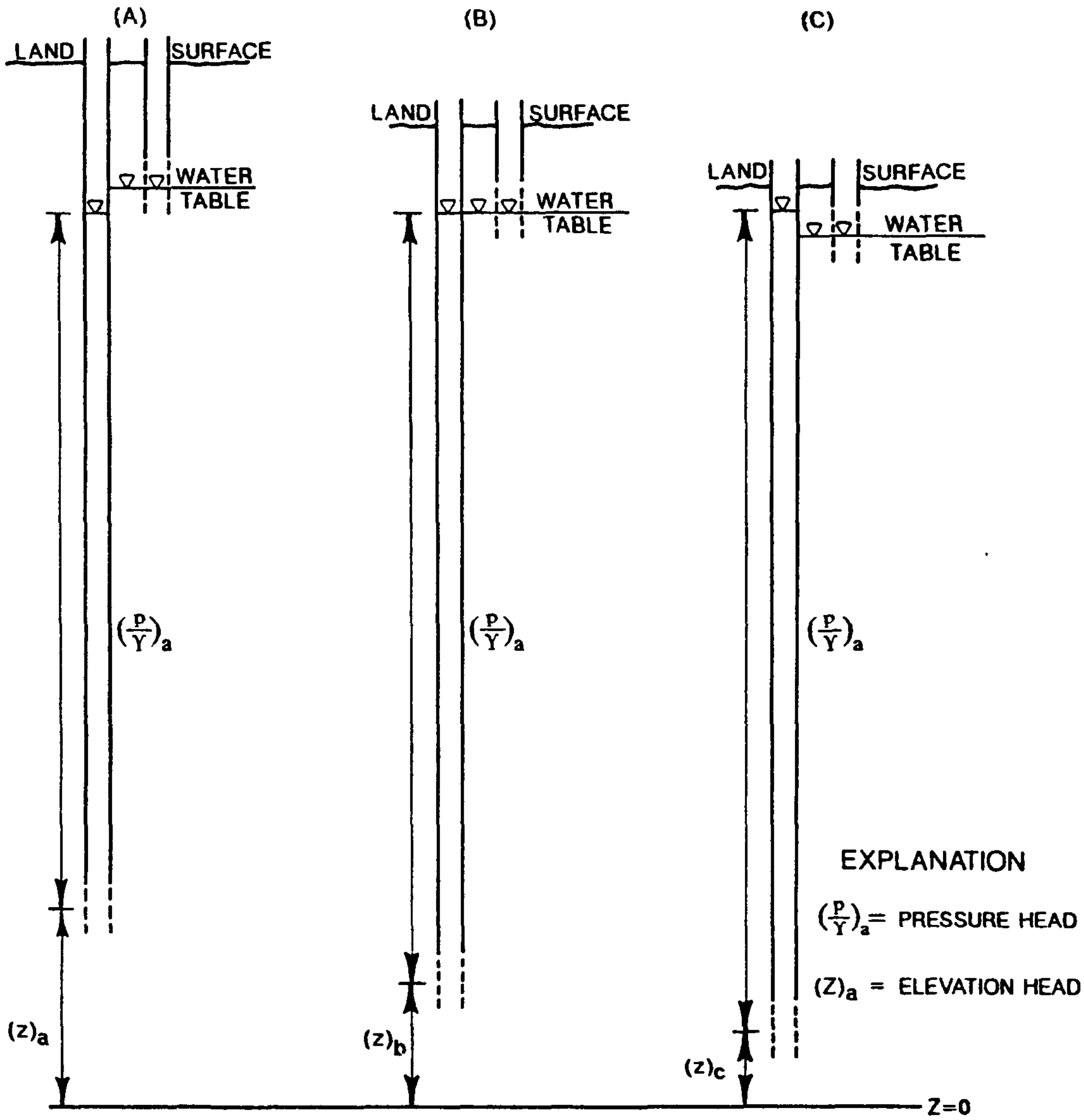

Figure 1-7.--Three pairs of observation wells in a hypothetical ground-water system; in each pair one observation well is screened at the water table and one is screened at some depth below the water table. In pair (A) head at the water table is greater than head in the deeper observation well; in pair (B) head at the water table equals head in the deeper observation well; in pair (C) head at the water table is less than head in the deeper observation well.

The relation between heads at the water table and heads in adjacent wells whose screened intervals lie at some depth below the water table depends on the position of the observation-well pair in the associated ground-water system. A general interpretation of the head relations depicted in figure 1-7 must wait for a more comprehensive discussion of ground-water systems in Section (3) of this course. The purpose of presenting figure 1-7 at this time is to emphasize that, in general, hydraulic head in ground-water systems varies not only with geographic location but also with depth.

Exercise (1-4)--Hydraulic Head

The purpose of this exercise is to provide practice in differentiating between the two components of head--pressure head and elevation head. The elevation head at a point in a ground-water system is arbitrary in that it depends on the altitude of an arbitrary datum. Sea level generally is used as head datum, the same datum used for land-surface topographic maps. However, the pressure head at a given point and a given time is not arbitrary, but is a physical quantity that can be measured directly. It is directly proportional to the height of the fluid column above the point of pressure measurement in a piezometer or observation well.

The data below are available for three closely spaced (in map view) observation wells with short well screens.

(1) Determine the missing entries in table 1-2.

(2) Make a careful sketch of each observation well on the accompanying worksheet (fig. 1-8). Plot and designate on each sketch the pressure head, elevation head, and total hydraulic head.

Table 1-2.--Head data for three closely spaced observation wells

Well	Land-surface altitude (feet above sea level)	Depth of top of screen below land surface (feet)	Depth to water (feet)	Altitude of water-level surface in well[1] (feet above sea level)	Pressure head (p/γ) (feet)	Elevation head (z) (feet)
1	50	25	15			
2	45	90	9			
3	51	350	13			

[1] Altitude of water-level surface in observation well equals hydraulic head at point of pressure measurement of observation well.

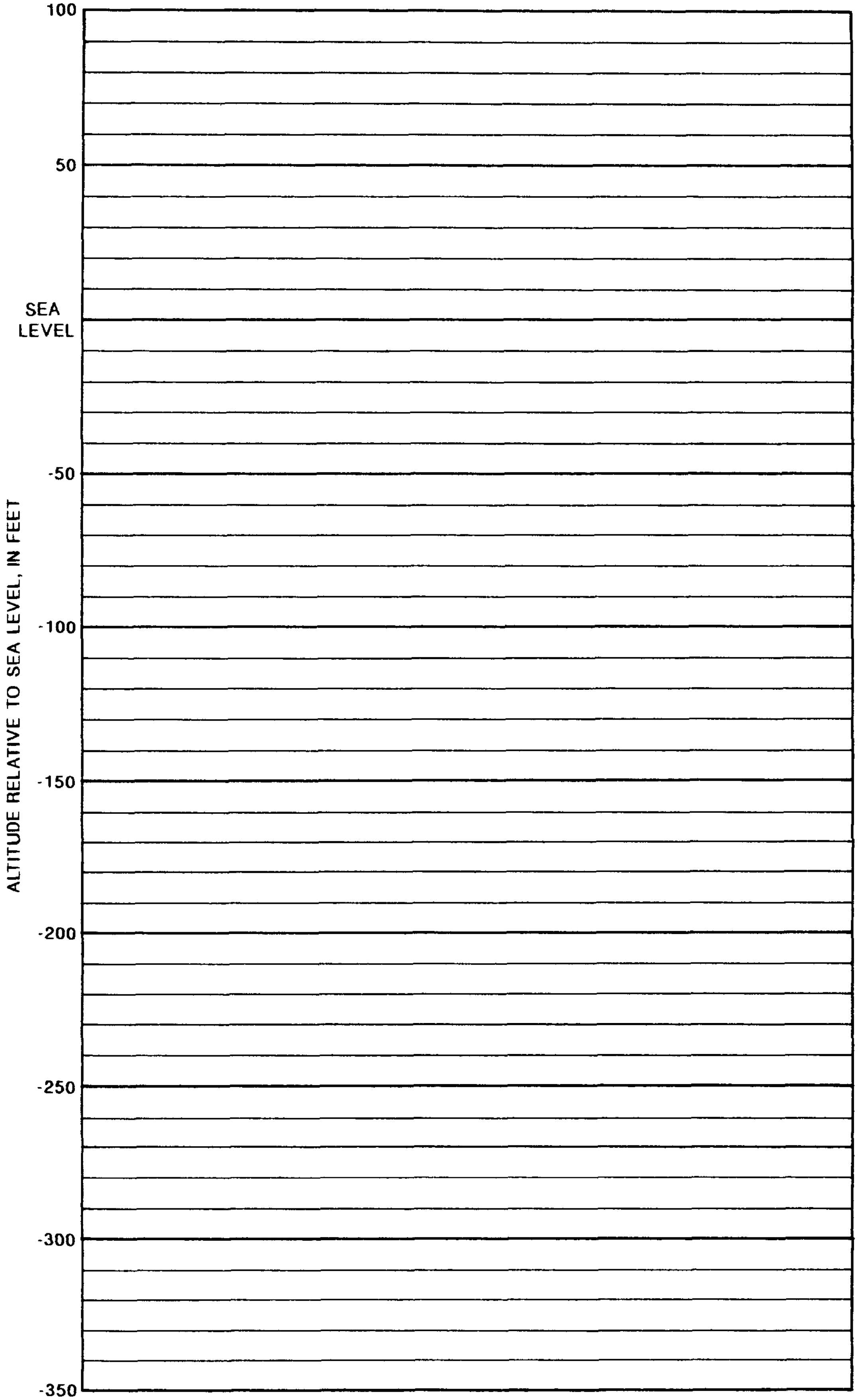

Figure 1-8.--Worksheet for head exercise.

An important rule concerning the value of hydraulic head in a stationary fluid body is that within such a body the *hydraulic head* is a constant at every point, including points along any boundary surface, regardless of the boundary-surface configuration. To visualize this concept, consider piezometers at various depths in a body of stationary fluid (fig. 1-9). At the surface of the fluid body (piezometer A), where the fluid is in contact with the atmosphere, $h = z$ because $p/\gamma = 0$. As one moves the piezometer downward from the fluid surface (piezometers B and C), the increase in pressure head (p/γ) is exactly balanced by a decrease in elevation head (z); thus, h remains constant. This relation will be useful when we consider physical boundaries between saturated ground water and surface-water bodies (for example, the streambed of a gaining stream); it indicates that the hydraulic head acting on such boundaries is equal to the water-level altitude of the surface-water body above the boundary, regardless of the surface configuration of this boundary.

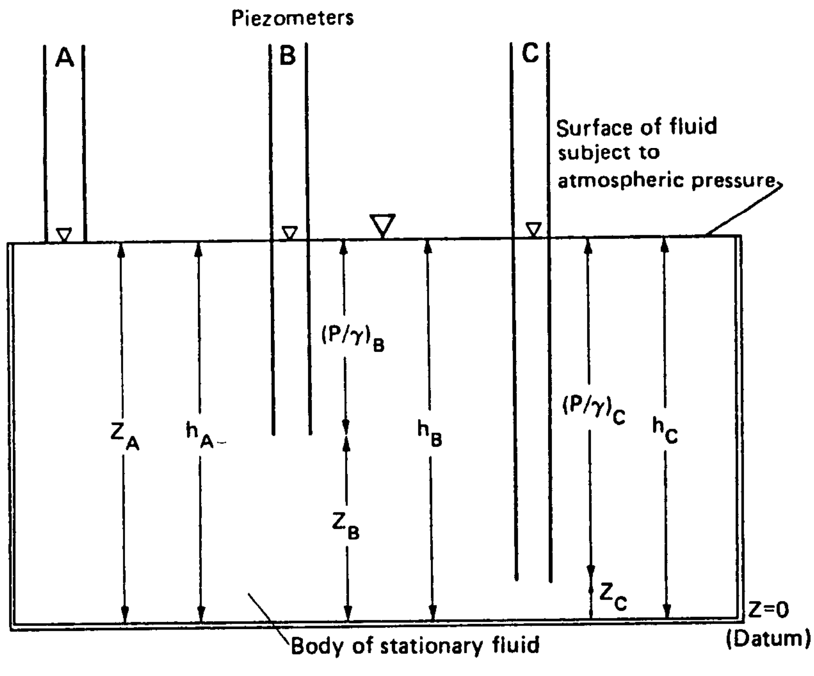

Figure 1-9.--Piezometers at three different depths, demonstrating that the total head at all depths in a continuous body of stationary fluid is constant. (From Franke and others, 1987, fig. 2.)

Preparation and Interpretation of Water-Table Maps

Assignments

*Study Fetter (1988), p. 136-137; Freeze and Cherry (1979), p. 45; or Todd (1980), p. 42-43, 85-88.

*Work Exercise (1-5)--Head gradients and the direction of ground-water flow.

The concept and procedure of contouring point data are familiar to geologists, meteorologists, and other scientists. At any given time the water table may be regarded as a topographic surface that lies for the most part below the land surface, the most familiar topographic surface. We measure water-table altitudes in shallow wells. The locations of the wells are plotted accurately on a map along with their associated water-table elevations. The objective is to develop the best possible representation of the water-table surface based on a few scattered water-table measurements at points. A water-table map is constructed by drawing contour lines of equal water-table elevation (equipotential lines or head contours)[1] at convenient intervals, using approximate linear interpolation between point measurements.

Head gradients commonly are estimated from water-table maps as demonstrated in Exercise (1-5). These gradient estimates necessarily are based on a two-dimensional representation of the equipotential surface. In nature, however, equipotential surfaces are inherently three-dimensional. Although "two-dimensional" gradients are adequate for many purposes, their use occasionally may lead to significant errors.

Exercise (1-5)--Head Gradients and the Direction of Ground-Water Flow

The purpose of this exercise is to gain familiarity with the concept of a head gradient and related direction of ground-water flow. We assume previous reading and (or) discussion of head-contour maps. Head-contour lines commonly are referred to as potential lines (lines of equal potential) or equipotential lines. We often forget that contour lines of equal head on a map are projections in map view of three-dimensional surfaces of equal head.

A gradient is the rate of change of a spatially continuous variable per unit distance in the direction of its maximum rate of change. We are concerned with head gradients. The spatially continuous variable is head measured in piezometers or observation wells.

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[1] In ground-water hydraulics the terms potential line, equipotential line, line of constant head, and head contour are used interchangeably. These terms also apply to surfaces of constant head or constant potential; for example, equipotential surface.

A formula for average head gradient (i) has the form $i = \frac{h_1 - h_2}{l}$ or $\frac{\Delta h}{l}$ [the symbol Δ (delta) means "change in"], where h_1 and h_2 are heads at a distance l apart, and the distance l is in the direction of the maximum rate of change of head. Because both the numerator and denominator of i have the dimensions of length, i is dimensionless.

In plan view, based on the assumption that ground-water flowlines or streamlines[1] are perpendicular to head contour lines[2], an average gradient can be calculated between any two points on the same streamline at which heads are known. Usually, however, average gradients are most useful when the length of streamline (l) between the points of known (or estimated) heads is small relative to the scale of the ground-water system under study.

Until now, we have discussed only average head gradients. In the following questions, bear in mind the difference between the average gradient between two points on a streamline and the gradient "at a point" on a streamline.

Three head-contour maps illustrating different contour patterns are shown in figure 1-10. With reference to this figure, answer the following questions.

(1) (a) With reference to figure 1-10(A), on the graph opposite figure 1-10(A) plot a topographic profile of the equipotential surface in the neighborhood of point A.

(b) Describe the pattern of head-contour lines in figure 1-10(A).

(c) Determine the gradient (maximum slope of the equipotential surface) at A. In this case the average head gradient in the neighborhood of A and the gradient at point A are ______________________________.

---

[1] In ground-water hydraulics the terms "flowline" and "streamline" are used interchangeably. They mean the smoothed or average path of water particles between two points in the ground-water flow field. A more formal definition of streamline is "a line drawn in the fluid so that its tangent at each point is in the direction of the fluid velocity at that point" (Milne-Thomson, 1955, p. 5).

[2] In this discussion, we assume the rule that ground-water streamlines are perpendicular to equipotential lines. This rule, which is strictly true only if the flow medium (earth material) is isotropic and homogeneous, often is utilized as a reasonable approximation when the aquifer material is fairly homogeneous, and the aquifer and ground-water streamlines within the aquifer are nearly horizontal.

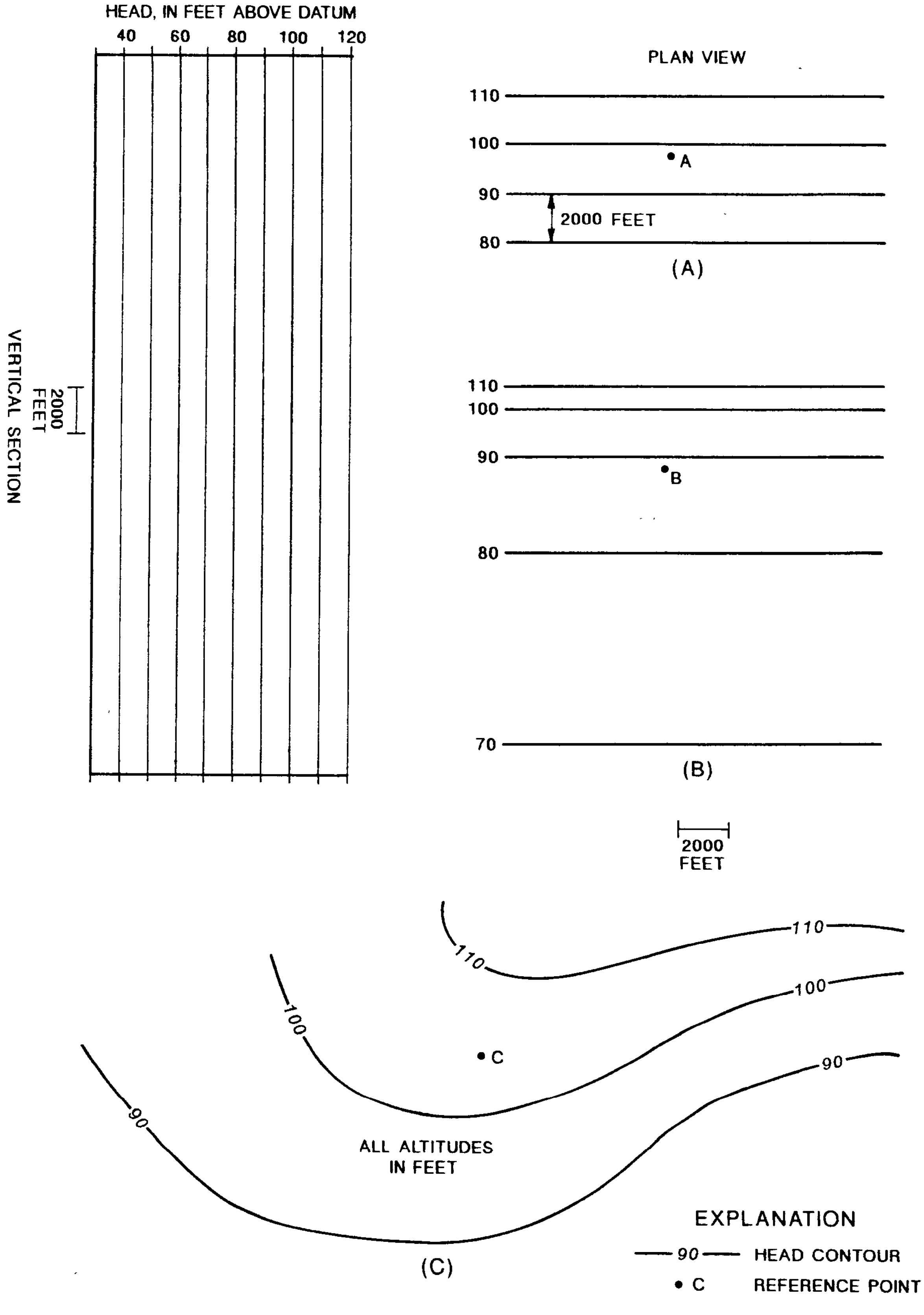


Figure 1-10.--Maps of ground-water head illustrating three different contour patterns.

(2) (a) With reference to figure 1-10(B), plot a topographic profile of the equipotential surface in the neighborhood of point B.

(b) Describe the pattern of head-contour lines in figure 1-10(B).

(c) Approximate an average gradient in the neighborhood of point B.

(3) Describe carefully a procedure for determining an average gradient in the neighborhood of point C in figure 1-10(C).

(4) Refer to the previous exercise, Exercise (1-4)--Hydraulic Head. Calculate the vertical component of the gradient between wells 1 and 2, which are located adjacent to one another. How is l in the gradient formula defined in this situation?

The following excerpt from Heath (1983, p. 10-11) provides additional discussion on head gradients and direction of ground-water flow.

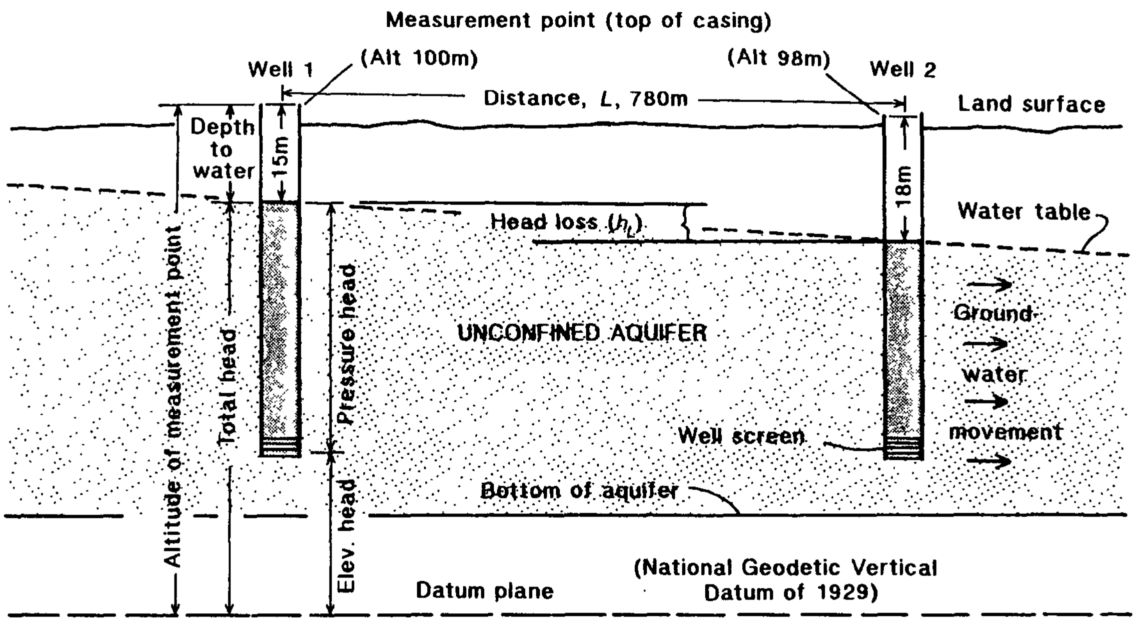
Following the directions provided in the foregoing discussion by Heath (1983), determine the approximate direction of ground-water flow and the head gradient using the data provided in question 5.

(5) Three piezometers are screened in the same horizontal aquifer. Piezometer A is 750 m (meters) due south of piezometer B and piezometer C is 1,000 m due east of piezometer A. The surface elevations of A, B, and C are 292 m, 284 m, and 288 m, respectively. The depth to water is 8 m in A, 4 m in B, and 6 m in C. Determine the direction of ground-water flow through the triangle ABC and estimate graphically the hydraulic gradient. The first step in solving this problem is to draw an accurate location map of the three points on the attached worksheet (fig. 1-11).

Comment 1: From geometry we know that the elevations of three points on a plane that are not in a straight line uniquely determine the position of the plane in space.

Comment 2: Course participants with a background in geology will recognize this problem as exactly the same as a "three-point problem" to determine the strike and dip of a plane. A line in the direction of the strike is a line of equal elevation (a contour line). The dip direction is perpendicular to the strike and parallel to the topographic gradient of the inclined plane.

Comment 3: In this problem we assume that the equipotential surface may be approximated locally by a sloping plane in space.



(1)

"The depth to the water table has an important effect on use of the land surface and on the development of water supplies from unconfined aquifers (1). Where the water table is at a shallow depth, the land may become "waterlogged" during wet weather and unsuitable for residential and many other uses. Where the water table is at great depth, the cost of constructing wells and pumping water for domestic needs may be prohibitively expensive.

The direction of the slope of the water table is also important because it indicates the direction of ground-water movement (1). The position and the slope of the water table (or of the potentiometric surface of a confined aquifer) is determined by measuring the position of the water level in wells from a fixed point (a measuring point) (1).To utilize these measurements to determine the slope of the water table, the position of the water table at each well must be determined relative to a *datum plane* that is common to all the wells. The datum plane most widely used is the National Geodetic Vertical Datum of 1929 (also commonly referred to as "sea level") (1).

If the depth to water in a nonflowing well is subtracted from the altitude of the measuring point, the result is the *total head* at the well. Total head, as defined in fluid mechanics, is composed of *elevation head*, *pressure head*, and *velocity head*. Because ground water moves relatively slowly, velocity head can be ignored. Therefore, the total head at an observation well involves only two components: elevation head and pressure head (1). Ground water moves in the direction of decreasing total head, which may or may not be in the direction of decreasing pressure head.

The equation for total head (h_t) is

$$h_t = z + h_p$$

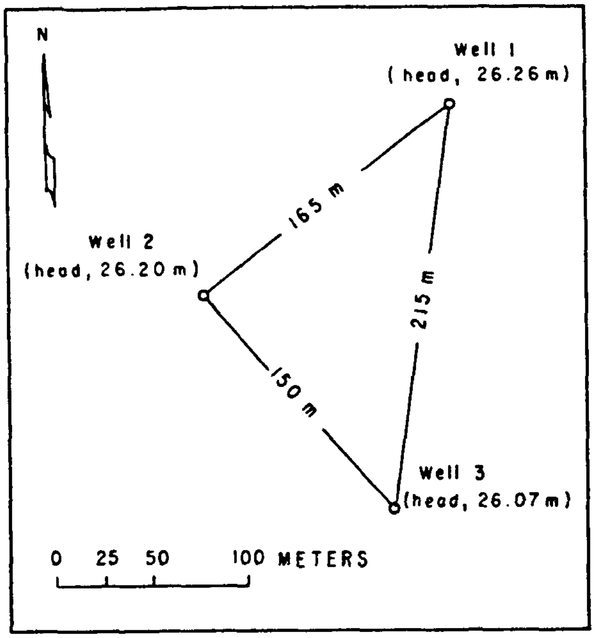
where z is elevation head and is the distance from the datum plane to the point where the pressure head h_p is determined.

All other factors being constant, the rate of ground-water movement depends on the *hydraulic gradient*. The hydraulic gradient is the change in head per unit of distance in a given direction. If the direction is not specified, it is understood to be in the direction in which the maximum rate of decrease in head occurs.

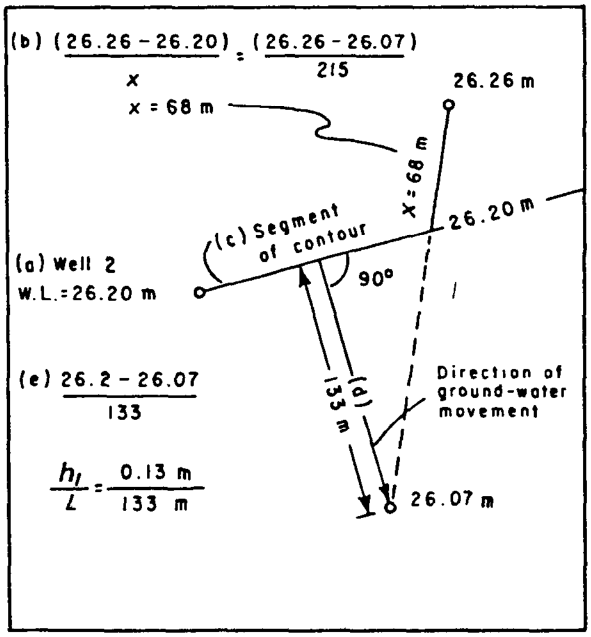
If the movement of ground water is assumed to be in the plane of sketch 1—in other words, if it moves from well 1 to well 2—the hydraulic gradient can be calculated from the information given on the drawing. The hydraulic gradient is h_L/L, where h_L is the head loss between wells 1 and 2 and L is the horizontal distance between them, or

$$\frac{h_L}{L} = \frac{(100\text{ m} - 15\text{ m}) - (98\text{ m} - 18\text{ m})}{780\text{ m}} = \frac{85\text{ m} - 80\text{ m}}{780\text{ m}} = \frac{5\text{ m}}{780\text{ m}}$$

When the hydraulic gradient is expressed in consistent units, as it is in the above example in which both the numerator and the denominator are in meters, any other consistent units of length can be substituted without changing the value of the gradient. Thus, a gradient of 5 ft/780 ft is the same as a gradient of 5 m/780 m. It is also relatively common to express hydraulic gradients in inconsistent units such as meters per



(2)



(3)

kilometer or feet per mile. A gradient of 5 m/780 m can be converted to meters per kilometer as follows:

$$\left(\frac{5\ \text{m}}{780\ \text{m}}\right) \times \left(\frac{1{,}000\ \text{m}}{\text{km}}\right) = 6.4\ \text{m km}^{-1}$$

Both the direction of ground-water movement and the hydraulic gradient can be determined if the following data are available for three wells located in any triangular arrangement such as that shown on sketch 2:

1. The relative geographic position of the wells.
2. The distance between the wells.
3. The total head at each well.

Steps in the solution are outlined below and illustrated in sketch 3:

a. Identify the well that has the intermediate water level (that is, neither the highest head nor the lowest head).
b. Calculate the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well.
c. Draw a straight line between the intermediate well and the point identified in step *b* as being between the well having the highest head and that having the lowest head. This line represents a segment of the water-level contour along which the total head is the same as that in the intermediate well.
d. Draw a line perpendicular to the water-level contour and through either the well with the highest head or the well with the lowest head. This line parallels the direction of ground-water movement.
e. Divide the difference between the head of the well and that of the contour by the distance between the well and the contour. The answer is the hydraulic gradient."

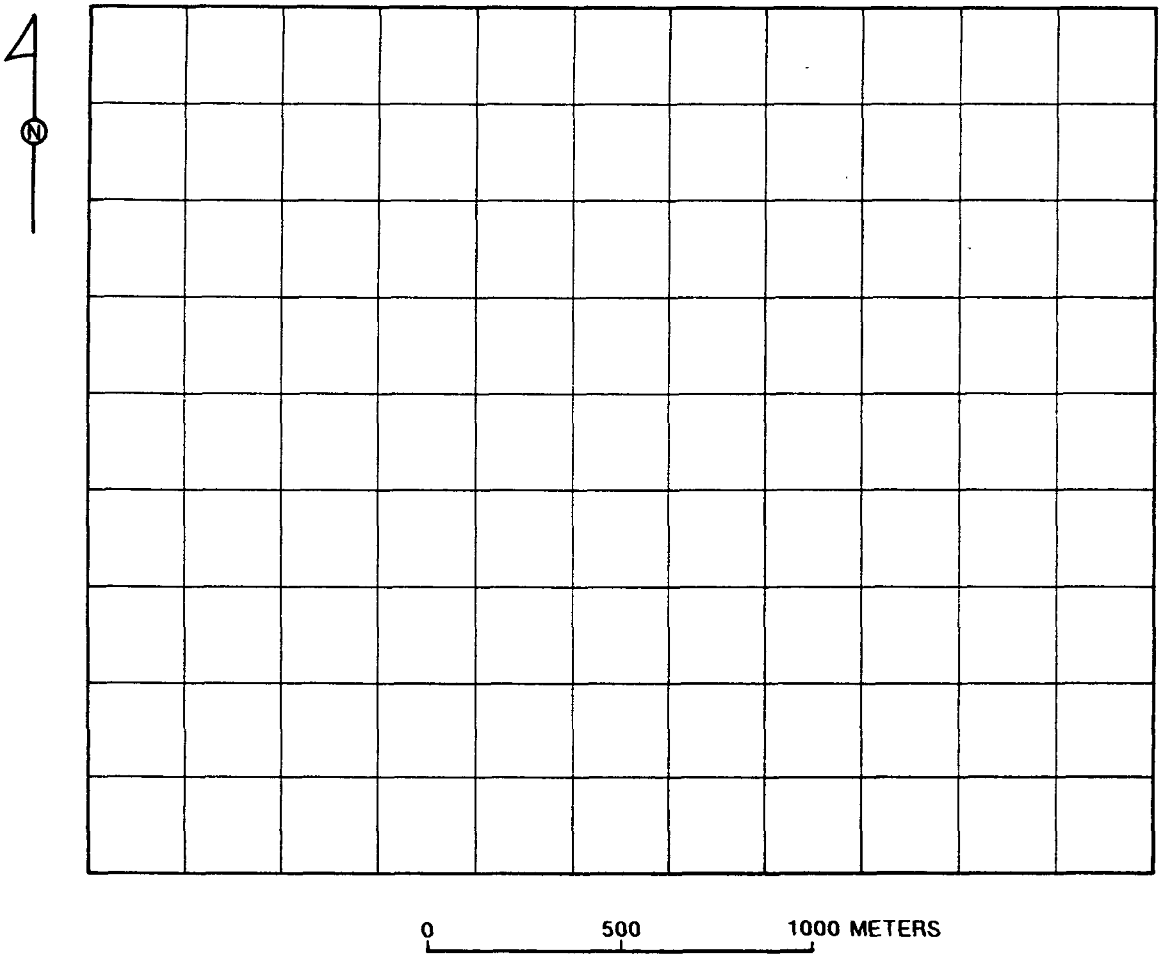


Figure 1-11.--Worksheet for the "three-point" head-gradient problem.

Ground-Water/Surface-Water Relations

Assignments

*Study Fetter (1988), p. 37-48; Freeze and Cherry (1979), p. 208-211, 217-221, 225-229; or Todd (1980), p. 222-230.

*Work Exercise (1-6)--Ground-water flow pattern near gaining streams.

*Sketch several water-table contour lines near a losing stream.

The relation between shallow aquifers and streams is of great importance in both ground-water and surface-water hydrology. The bed and banks of a gaining stream are an area of discharge for shallow ground water and this discharge is one of the principal outflow components from many ground-water systems. This water is usually a major part of the base flow of streams, which is the principal component of streamflow during dry periods. In many areas base flow is critical for water supply and maintenance of stream water quality.

In a gaining stream a "hydraulic connection" exists between the shallow aquifer and the stream--that is, the earth material beneath the streambed is continuously saturated, and saturated ground-water flow occurs between the aquifer and the stream. A losing reach of a stream may exhibit either (a) hydraulic connection between stream and aquifer or (b) no hydraulic connection. The absence of a hydraulic connection implies the presence of some thickness of unsaturated earth material below the streambed--that is, the stream is recharging the shallow aquifer through an unsaturated zone. Losing streams may be important sources of recharge to shallow ground-water systems.

Exercise (1-6)--Ground-Water Flow Pattern Near Gaining Streams

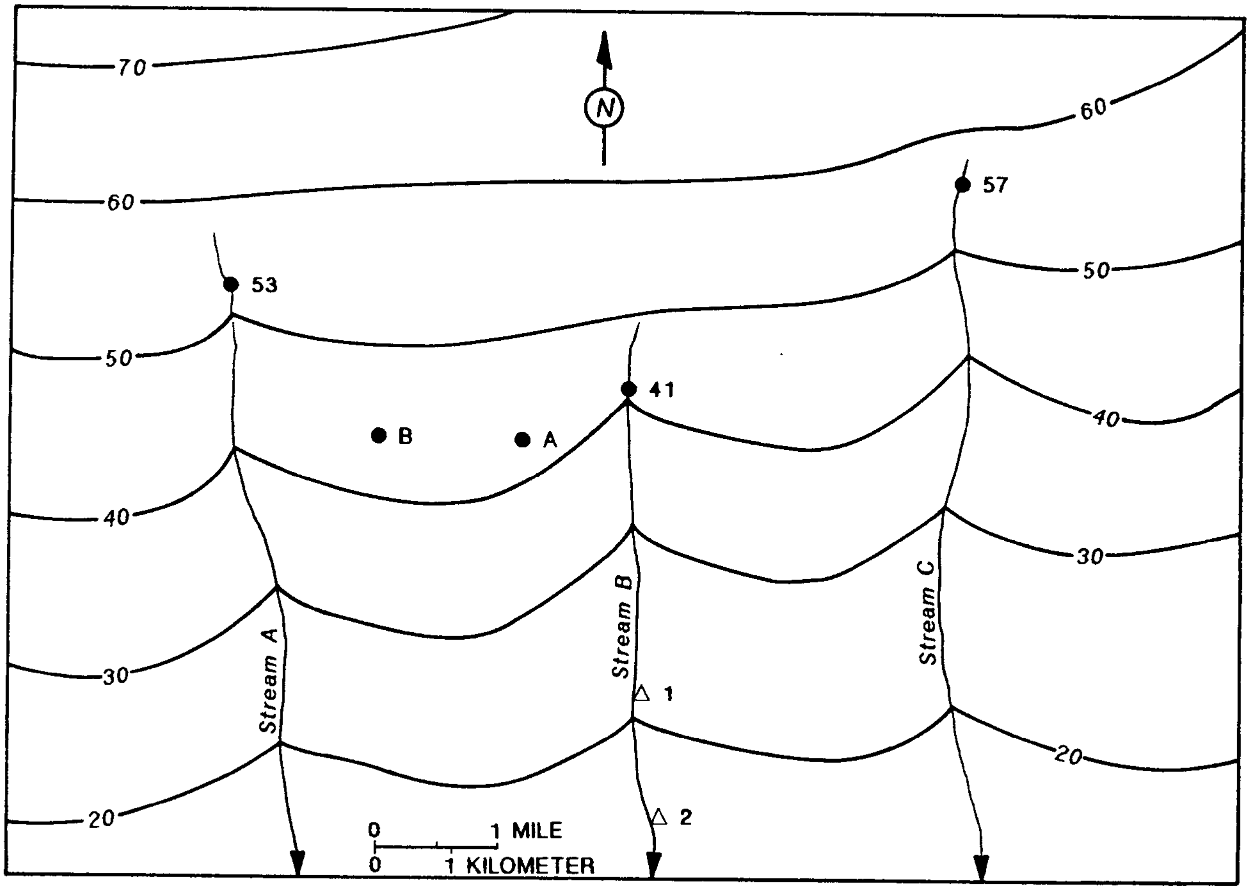
The following exercise assumes some previous discussion on the preparation of water-table maps. The basic assumption in this exercise is that ground-water flowlines, or streamlines, are perpendicular to water-table contour lines.

With reference to the attached hypothetical water-table map (fig. 1-12), answer the following questions. Assume the hydraulic conductivity of the water-table aquifer equals 125 ft/day and its porosity (n) equals 33 percent.

(1) Estimate the hydraulic gradient in the neighborhood of point B.

(2) Draw flowlines from points A and B to their points of discharge into a stream.

(3) Why do the lengths of the two flow paths differ significantly? Relate your explanation to the local configuration of the water-table contour lines, not to the observable fact that point B is further from the nearest stream than is point A.



EXPLANATION

—20— WATER-TABLE CONTOUR -- Shows altitude of water table. Contour interval 10 feet. Datum is sea level

● 41 LOCATION OF START OF FLOW OF STREAM -- Number is altitude of stream, in feet above sea level

△ 2 LOCATION AND NUMBER OF STREAM DISCHARGE MEASUREMENT POINT

Figure 1-12.--Hypothetical water-table map of an area underlain by permeable deposits in a humid climate.

(4) Considering that the particle of water at point A travels to stream B and the particle of water at point B travels to stream A, what hydrologic feature must exist between points A and B? Is the position of this feature fixed in space and time?

(5) Draw roughly north-south-trending ground-water divides between streams A and B and between streams B and C. Sketch streamlines from points 1 and 2 on stream B to the two lateral ground-water divides. Given that these are gaining streams, what does the area bounded by the four streamlines and the two lateral ground-water divides represent in relation to the stream reach between points 1 and 2 on stream B?

(6) Assume that the long-term average increase in discharge (stream "pick-up") between points 1 and 2 due to discharge of ground water into the stream is known. Using the information at your disposal and assuming the ground-water contributing area you have sketched is valid, what potentially useful hydrologic parameter can you now estimate?

(7) What are some of the problems and pitfalls involved in estimating the ground-water drainage area of an entire stream, particularly in its upper reaches?

Our interpretation of the water-table map in figure 1-12 assumes horizontal, or almost horizontal, flow in the water-table aquifer. Now, we will consider the field-measured head distribution in vertical section near a gaining stream on Long Island, New York (fig. 1-13). The field procedure for obtaining these head values is described in Prince and others (1988).

(8) Contour the head values in figure 1-13 at a contour interval of 0.20 feet. Draw contour lines for 26.20, 26.40 ... 27.20 ft.

(9) How does the ground-water flow pattern in figure 1-13 differ from the flow pattern in figure 1-12?

(10) At what distance from the streambank in figure 1-13 are the head contour lines almost vertical? What does this observation suggest about the direction of ground-water flow at this distance from the streambank?

(11) In figure 1-13, at the center of the stream, a head value of 26.70 ft was measured at about 3 ft below the streambed. Calculate an average vertical gradient beneath the streambed at the center of the stream. Find the ratio of this vertical gradient to the horizontal gradient calculated in question (1).

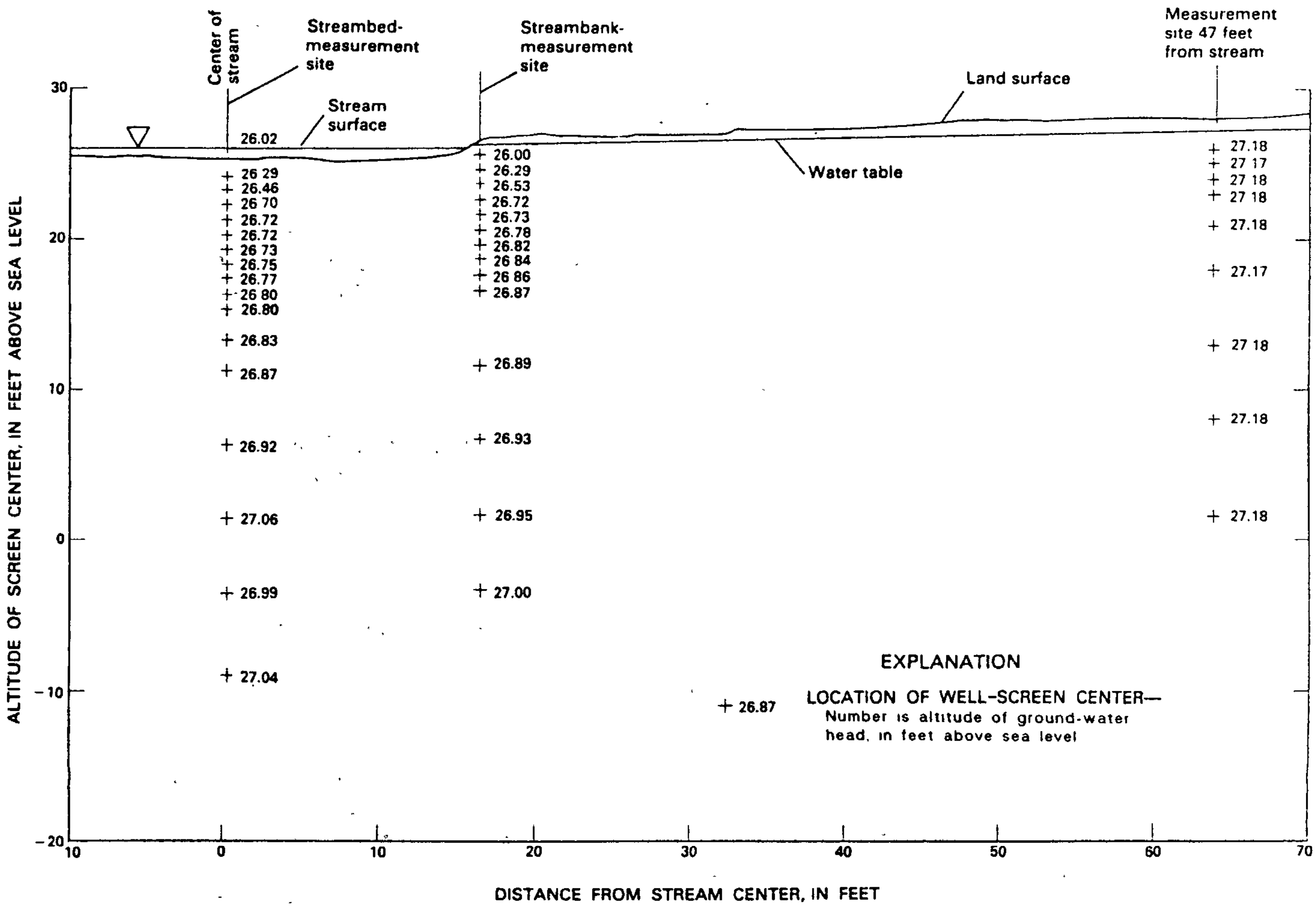


Figure 1-13.--Head measurements near Connetquot Brook, Long Island, New York, during a 3-day period in October 1978. (Modified from Prince and others, 1988, fig. 10.)