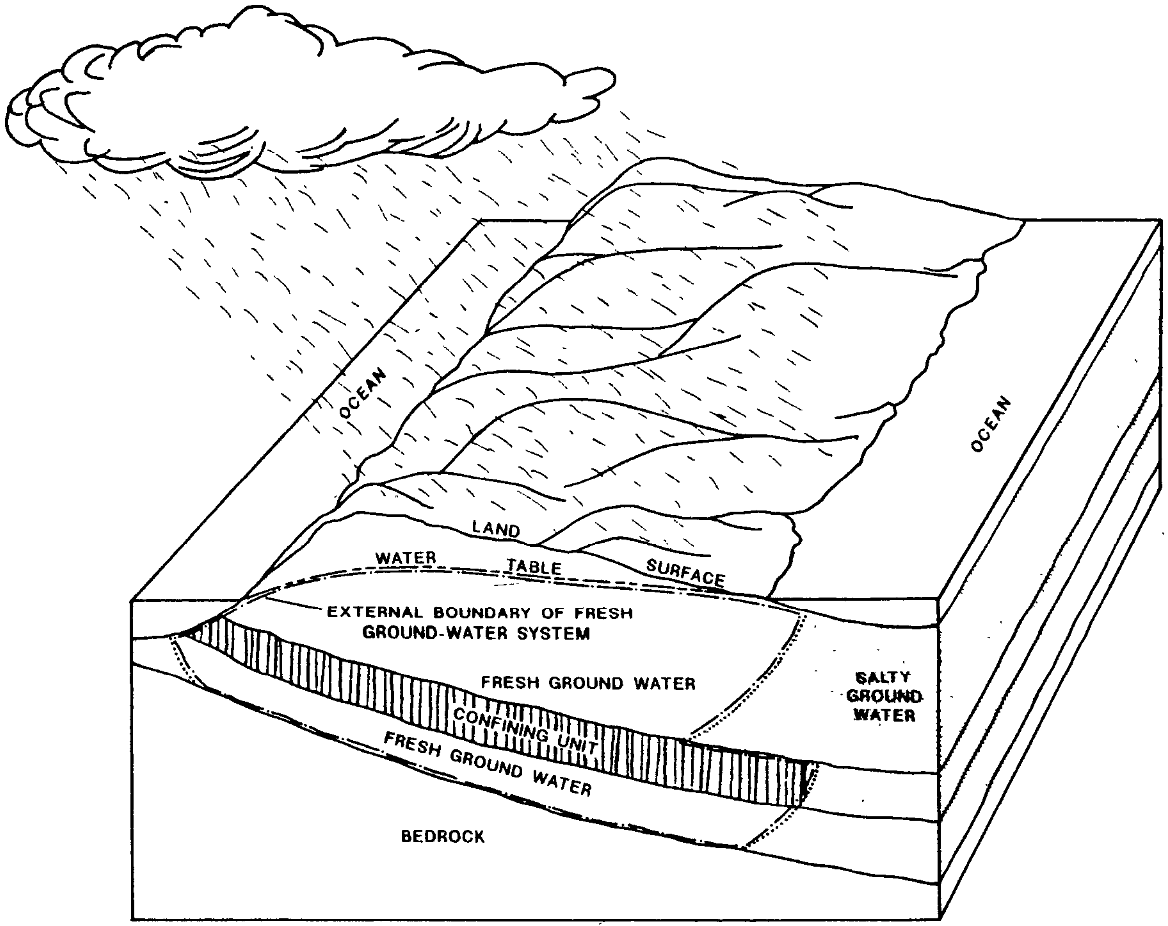
STUDY GUIDE FOR A BEGINNING COURSE IN GROUND-WATER HYDROLOGY: PART II -- INSTRUCTOR'S GUIDE



U.S. GEOLOGICAL SURVEY
Open-File Report 92–637

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STUDY GUIDE FOR A BEGINNING COURSE IN GROUND-WATER HYDROLOGY: PART II -- INSTRUCTOR'S GUIDE

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U.S. GEOLOGICAL SURVEY
Open-File Report 92–637

Reston, Virginia
1993

U.S. DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS[1]

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[1] Numbers of illustrations are the same as those in Part I of the Study Guide (Franke and others, 1990). Because the Instructor's Guide does not include all the illustrations found in Part I of the Study Guide, figure numbers in this publication are not consecutive. Two of the illustrations in this publication are new and are not found in Part I of the Study Guide.

ILLUSTRATIONS (continued)

TABLES[1]

[1] Numbers of tables are the same as those in Part I of the Study Guide (Franke and others, 1990). Because the Instructor's Guide does not include all the tables found in Part I of the Study Guide, table numbers in this publication are not consecutive.

LIST OF NOTES IN PART I OF STUDY GUIDE[1]

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[1] This listing is for reference only. The page numbers refer to those in Part I of the Study Guide (Franke and others, 1990).

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	*by*	*To obtain*
inch (in.)	25.4	millimeter (mm)
inch (in.)	2.54	centimeter (cm)
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 [$(m/yr)/km^2$]

Additional abbreviations used in this report:

cm^2 - square centimeter
cm^3 - cubic centimeter
cm/s - centimeter per second
cm/d - centimeter per day
cm^2/s - square centimeter per second
cm^3/s - cubic centimeter per second
d - day
ft^2 - square foot
ft^3 - cubic foot
ft/d - foot per day
ft/yr - foot per year
ft^3/d - cubic feet per day
ft^3/yr - cubic feet per year
gal/d•ft - gallon per day per foot
gal/d•ft^2 - gallon per day per square foot
gal/d•mi^2 - gallon per day per square mile
in^2 - square inch
in/hr - inch per hour
lbs - pounds
lbs/in. - pounds per inch
lbs/ft^2 - pounds per square foot
lbs/ft^3 - pounds per cubic foot
m^3/d - cubic meters per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

INTRODUCTION

This publication is a companion to "Study Guide for a Beginning Course in Ground-Water Hydrology: Part I--Course Participants" (Franke and others, 1990) and is not designed to stand alone. The companion study guide, hereafter referred to as Part I of the Study Guide, includes suggested readings in a selection of appropriate ground-water texts, comments on outline topics, and specially prepared notes and exercises.

Purpose and Scope of Instructor's Guide

The purpose of this publication is to provide (1) suggestions to instructors on teaching the course outlined in Part I of the Study Guide, (2) additional references and comments on the topics in Part I of the Study Guide, and (3) answers to the exercises in Part I of the Study Guide.

This instructor's guide consists of five sections. Within each section, we proceed sequentially through each subsection in Part I of the Study Guide and provide the following information: (1) a repetition of the assignments and comments from each subsection in Part I of the Study Guide; (2) additional references for certain subsections; (3) further comments on the subsection topic--either technical comments or suggestions on teaching; and (4) detailed answers to exercises in the Study Guide.

Suggestions to Instructors on Teaching the Course

In this section, we make brief suggestions and comments on course mechanics, pace of teaching, additional references to supplement the keyed course texts, and sources of additional problems.

Instructors have considerable latitude in how a course is organized and presented. In class sessions that meet for no longer than 2 to 3 hours, intensive lecturing with reading and problem assignments between classes can be an effective teaching approach. In workshops that are scheduled for 8 hours or more a day, however, continuous lecturing is virtually fruitless, particularly in workshops lasting several days. In this latter situation, we recommend that formal lecturing be limited to less than one-half of the scheduled time. The remaining time can be spent profitably in reading notes, in class discussion, and in working well-designed exercises. We believe the latter to be particularly important for developing an understanding of new concepts.

We suggest making overhead transparencies of all figures in the notes and exercises so that these figures can be discussed readily with the entire class when appropriate. If an instructor prepares additional figures, these need be nothing more than neat pencil sketches, as simplicity of design aids understanding by the viewer. As a rule, course participants benefit from having a paper copy in their notes of any overhead transparency that is discussed. This same principle applies to equation derivations--if course participants have complete derivations in their hands, they will be able to make additional marginal notes as the derivation proceeds.

The ideal pace for presenting material in a course is difficult to fix rigidly, as it depends to a large degree on the technical background and motivation of the participants. The technical background of participants in in-house training courses often varies widely. In this situation the best approach is to aim the presentations for the "middle-level" participants, and to encourage those less-prepared with individual help and the more advanced with additional, more challenging assignments. In this setting, instructors are not under pressure to complete a prescribed curriculum in a fixed time frame, as is often the case in an academic setting. In general, we recommend covering less material more thoroughly, rather than covering more material in a manner in which only the best-prepared participants achieve understanding. One pitfall to avoid is the assumption that, because a topic is covered clearly in a lecture from the instructor's standpoint, this topic is assimilated and understood in perpetuity by the participants. Understanding by course participants is enhanced by judicious repetition of key concepts, particularly as they apply to practical examples.

The level of detail and related time alloted to some course topics should be determined in part on the basis of the technical background of the course participants. For example, if most of the participants have a geologic background, the discussion of geologic framework maps can be shortened in comparison with the discussion of this topic if the participants have other technical backgrounds. Circulation of a brief questionnaire that surveys the technical background of each participant at the beginning of the course will assist the instructor in evaluating this variable.

Course instructors should have appropriate source material readily available for quick reference. For the beginning course in ground-water hydrology that we have outlined, the combination of the keyed course texts (Fetter, 1988; Freeze and Cherry, 1979; and Todd, 1980) and the annotated list of references provided at the beginning of Part I of the Study Guide generally is sufficient. Additional pertinent references are listed in this publication and in Part I of the Study Guide, and all three textbooks listed above contain carefully selected and widely ranging bibliographies.

Well-designed and relevant exercises, particularly those with answers, are less readily available than are reference materials. As noted previously in the Study Guide, we believe that a selection of such exercises is one of our principal contributions to this course. Additional illustrative problems can be found in both Fetter (1988) and Freeze and Cherry (1979). An answer book is available for the problems in Fetter's text. In addition, worthwhile exercises, several of which stress the geologic aspects of hydrogeology, are available in Heath and Trainer (1968).

SECTION (1)--FUNDAMENTAL CONCEPTS AND DEFINITIONS

This initial section of the course provides a background in earth materials, selected hydrologic concepts and features, and physical principles that is 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), in both the inside cover and several appendixes; Freeze and Cherry (1979), p. 22-23, 29, 526-530, and front inside cover; and Todd (1980), p. 521-526, and back inside cover.

Comments

Experience indicates the need to continually emphasize the units of all variables when teaching beginning hydrologists, even for variables as familiar as hydraulic conductivity and transmissivity. In all exercises, stress the necessity for using the appropriate units with the numerical answers. Upon completion of Section (2) in Part I of the Study Guide, instructors can review units by associating common hydrologic variables with the unit combinations in Exercise (1-1).

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

Below is a list of several conversions to be calculated. Before performing the calculations, test whether the two sets of units are dimensionally compatible. (In one or more examples, they 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 to (a) in/hr, (b) cm/s

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

(3) 500 $gal/d \bullet ft^2$ to (a) ft^2/d, (b) m^2/d

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

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

Answers:

(1) [L/T], (a) $$\frac{15\ \text{ft}}{\text{d}} \bullet \frac{12\ \text{in.}}{\text{ft}} \bullet \frac{\text{d}}{24\ \text{hr}} = 7.5\ \frac{\text{in.}}{\text{hr}}$$

(b) $$\frac{7.5\ \text{in.}}{\text{hr}} \bullet \frac{2.54\ \text{cm}}{\text{in.}} \bullet \frac{\text{hr}}{3{,}600\ \text{s}} = 5.29 \times 10^{-3}\ \text{cm/s}$$

(2) [L^3/T], (a) $$\frac{200\ \text{gal}}{\text{min}} \bullet \frac{1{,}440\ \text{min}}{\text{d}} \bullet \frac{\text{ft}^3}{7.48\ \text{gal}} = 38{,}503\ \frac{\text{ft}^3}{\text{d}}$$

(b) $$\frac{38{,}503\ \text{ft}^3}{\text{d}} \bullet \frac{\text{d}}{86{,}400\ \text{s}} \bullet \frac{(2.54\ \text{cm})^3}{\text{in.}^3} \bullet \frac{(12\ \text{in.})^3}{\text{ft}^3} = 12{,}619\ \frac{\text{cm}^3}{\text{s}}$$

(3) [L/T] - [L^2/T], not compatible units

(4) [L^2/T], (a) $$\frac{250\ \text{ft}^2}{\text{d}} \bullet \frac{7.48\ \text{gal}}{\text{ft}^3} = 1{,}870\ \text{gal/d}\bullet\text{ft}$$

(b) $$\frac{250\ \text{ft}^2}{\text{d}} \bullet \frac{\text{d}}{86{,}400\ \text{s}} \bullet \frac{(2.54\ \text{cm})^2}{\text{in.}^2} \bullet \frac{(12\ \text{in.})^2}{\text{ft}^2} = 2.69\ \frac{\text{cm}^2}{\text{s}}$$

(5) [L/T], (a) $$500{,}000\ \frac{\text{gal}}{\text{d} \bullet \text{mi}^2} \bullet \frac{365\ \text{d}}{\text{yr}} \bullet \frac{\text{ft}^3}{7.48\ \text{gal}} \bullet \frac{\text{mi}^2}{(5{,}280)^2\ \text{ft}^2} \bullet \frac{12\ \text{in.}}{\text{ft}} = 10.50\ \frac{\text{in.}}{\text{yr}}$$

(b) $$\frac{10.50\ \text{in.}}{\text{yr}} \bullet \frac{2.54\ \text{cm}}{\text{in.}} \bullet \frac{\text{yr}}{365\ \text{d}} = 0.073\ \frac{\text{cm}}{\text{d}}$$

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: (1) the differentiation between inflows and outflows from a basin as a whole and flows within the basin, (2) the possible specific inflow and outflow components of the saturated ground-water part of the hydrologic system, and (3) the necessity of clearly defining a reference volume when determining a water budget for the saturated ground-water part of the system. This reference volume will be used again later in the development of concepts specifically related to ground-water systems.

Reference

Heath and Trainer (1968), p. 230-244.

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

Participants who have not had a previous course in hydrology may have difficulty getting started with this exercise, particularly in matching given "budget numbers" with flow lines in figure 1-1. In this case, the beginning of this exercise may be completed as part of a class discussion.

	Inflow	Outflow
(1) System budget (See fig. 1-1)	Precipitation 45 in.	Total evapotranspiration 25 in. Stream discharge 12 in. Subsurface outflow 8 in.
(2) Stream budget (bodies of surface water)	Direct runoff 1 in. Ground-water seepage to streams 11 in.	Total stream discharge 12 in. Neglected--evaporation from stream surface
(3) Ground-water-reservoir budget (zone of saturation)	Recharge 20 in. Neglected--recharge of ground water by streams	Seepage to streams 11 in. Subsurface discharge 8 in. Neglected--ground-water evapotranspiration

(4) $$250\ \text{mi}^2 \bullet \frac{(5{,}280\ \text{ft})^2}{\text{mi}^2} \bullet 45\ \frac{\text{in.}}{\text{yr}} \bullet \frac{\text{ft}}{12\ \text{in.}} = 2.614 \times 10^{10}\ \frac{\text{ft}^3}{\text{yr}}$$

(5) (a) $$2.614 \times 10^{10}\ \frac{\text{ft}^3}{\text{yr}} \bullet \frac{\text{yr}}{365\ \text{d}} \bullet \frac{\text{d}}{86{,}400\ \text{s}} = 828.9\ \frac{\text{ft}^3}{\text{s}}$$

(b) $$\frac{(5{,}280\ \text{ft})^2}{\text{mi}^2} \bullet \frac{45\ \text{in.}}{\text{yr}} \bullet \frac{\text{ft}}{12\ \text{in.}} \bullet \frac{7.48\ \text{gal}}{\text{ft}^3} \bullet 10^{-6} \bullet \frac{\text{yr}}{365\ \text{d}} =$$

$$2.14\ \frac{\text{Mgal}}{\text{d} \bullet \text{mi}^2}$$

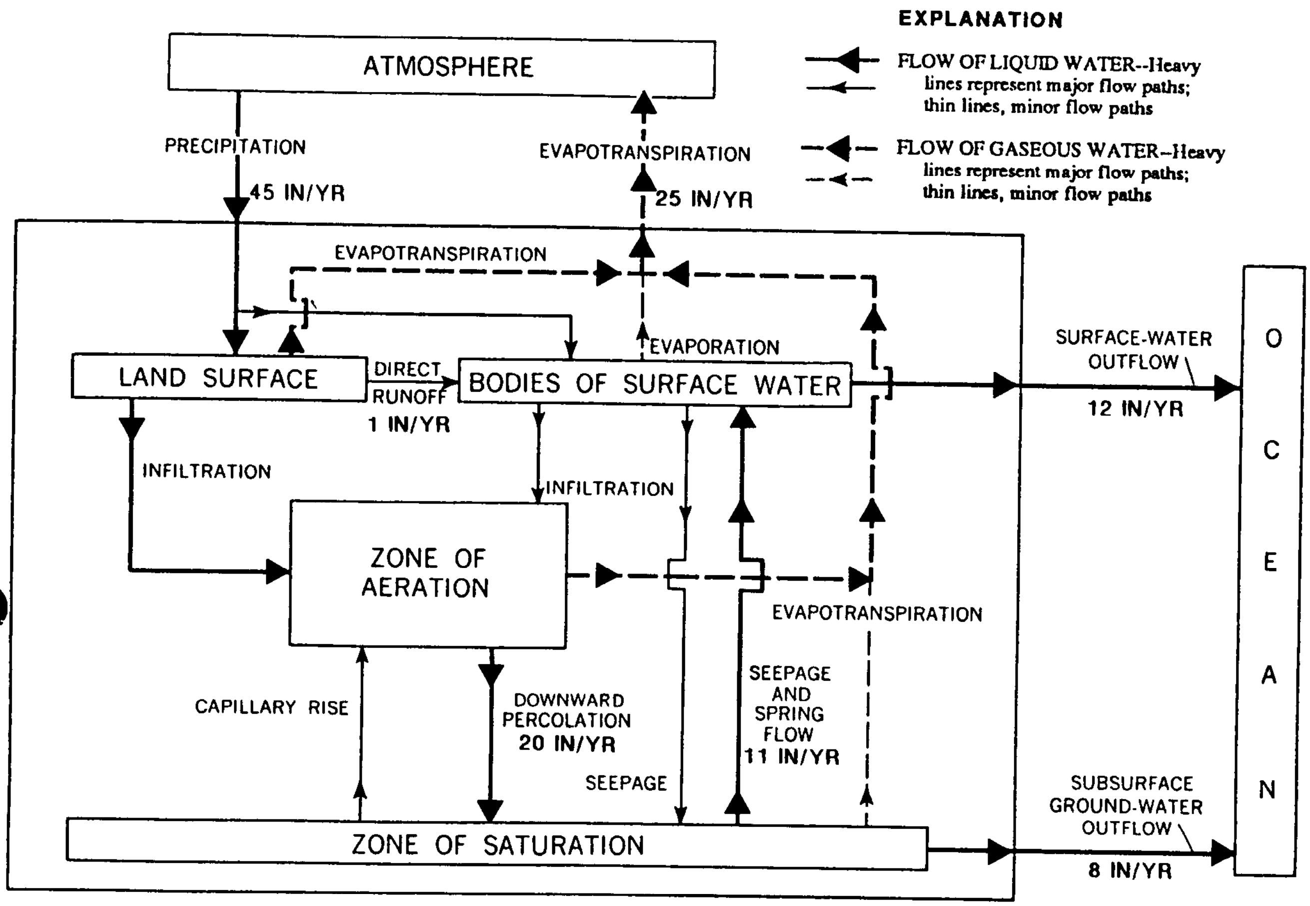

Figure 1-1.--Flow diagram of a hypothetical hydrologic system under predevelopment conditions showing assumed budget values associated with selected flow paths. (Modified from Franke and McClymonds, 1972, fig. 13.)

(6) Inflow - Outflow = $\pm \Delta$ Storage

Precipitation - (Total Evapotranspiration + Surface Water Outflow + Subsurface Ground-Water Outflow) = $\pm \Delta$ Storage

35 in. - (20 in. + 10 in. + 7 in.) = 35 in. - 37 in. = -2 in.

$\Delta S = -2"$

```
Inflow                  Outflow
----------> System  ---------->


35 in.                         37 in.
---------->       -2 in.      ---------->
           (From storage)
```

If the (Δ Storage) term is on the right-hand side of the water-budget equation, a ($-\Delta S$) means that water has been removed from storage in the hydrologic system and appears as outflow from the system.

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 in both the glossary and the index in Fetter (1988) and write the definitions of the following terms describing the flow medium: 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 (1) mineralogy, (2) grain-size distribution of unconsolidated materials, (3) size and geometry of openings in consolidated rocks, (4) porosity, (5) permeability (hydraulic conductivity), and (6) 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 an important influence on the geochemical evolution of ground water (a topic that is not discussed in this course). Permeability and specific yield, included here to make the list of relevant characteristics more complete, are defined and discussed later in the course.

References

Davis (1969), p. 53-89.
Heath (1983), p. 2-3, 7-9.
Heath and Trainer (1968), p. 7-29.
Meinzer (1923), p. 2-18.

Comments

The references above and these comments discuss the most relevant hydrogeologic characteristics of earth materials, including permeability and specific yield, which have not yet been introduced in the course. Thus, some of the following topics are more appropriately discussed later.

Some hydrogeologic features of earth materials that merit discussion include (1) the fundamental difference between the geometry and spatial distribution of void space in unconsolidated materials composed of grains and that in fractured bedrock; (2) the fact that the porosity of fractured bedrock commonly is lower than that of granular materials; (3) the large spatial variations in porosity (and permeability) exhibited by certain types of consolidated rock, such as limestone and basalt; (4) the importance of grain sorting on porosity and permeability--well-sorted materials tend to have higher porosities than less well-sorted materials; (5) the absence of a general, direct relation between porosity and permeability--that is, a high porosity does not <u>necessarily</u> imply a high permeability; for example, clays generally have higher porosities but lower permeabilities than sands and gravels; (6) the concept of primary and secondary permeability; and (7) the importance of solution openings as well as fractures in consolidated rocks.

Davis' (1969) overview of porosity and permeability of earth materials provides much more information than would normally be presented in a beginning ground-water course. Heath and Trainer (1968) provide exercises on openings in rocks and the relation between sorting and porosity of granular materials. Most textbook discussions on openings in rocks refer to a figure in and discussion of this topic by Meinzer (1923, fig. 1, p. 3).

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--(1) the unsaturated zone, (2) the capillary or tension saturated zone, and (3) the saturated zone. The water table in coarse earth materials can be defined approximately as the upper bounding surface of the saturated zone. The focus of this course 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.

References

Davis and DeWiest (1966), p. 38-43, 54-55.
Heath (1983), p. 4-6, 16-18, 72-73.
Meinzer (1923), p. 29-39.

Comments

The principal purpose of this subsection is to differentiate between and characterize the unsaturated and saturated zones and to define the water table. The level of detail of the treatment of the unsaturated zone will depend on the time available and the inclination of the instructor.

As pointed out by Fetter (1988, p. 86) and Lohman (1972b, p. 14), we use two definitions of the water table--(1) the surface below the land surface at which pore-water pressure is atmospheric, and (2) the altitudes of water levels in wells that penetrate the saturated water body just far enough to hold standing water. The second definition is an <u>operational</u> definition because it reflects the way we determine the position of the water table in the field. For this reason, this definition should be emphasized at this point in the course. The first definition is necessary for a comprehensive discussion of head and pressure in the unsaturated and saturated zones, which is premature at this time. A description of digging a shallow well until standing water is encountered in the bottom of the excavation is a useful technique for introducing the concepts of the unsaturated zone, the water table, and the saturated 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 difficult 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).

References

Lohman (1972b), p. 6-8 (refer to fluid potential; head, static; head, total).

Comments

Although the readings and exercises in this subsection are designed to be self-contained, the head concept commonly is a difficult one for beginning hydrologists to understand. Therefore, we recommend its detailed discussion in class at this juncture and a review of this concept at every opportunity during the remainder of the course.

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

Answers to Exercise (1-3)--Hydrostatic Pressure

(1) $p = \gamma l$ where p is fluid pressure, γ is weight density of fluid, and l is length of fluid column.

(a) (b)

$$p = 62.4\ \text{lbs/ft}^3 \times 12\ \text{ft} = 748.8\ \frac{\text{lbs}}{\text{ft}^2} \bullet \frac{\text{ft}^2}{144\ \text{in}^2} = 5.2\ \frac{\text{lbs}}{\text{in}^2}$$

(c) Atmospheric pressure $\approx 14.7\ \frac{\text{lbs}}{\text{in}^2}$

Total pressure $\approx 14.7 + 5.2 \approx 19.9\ \frac{\text{lbs}}{\text{in}^2}$

(2) $\left(\frac{1.025}{1.000}\right) \bullet 5.2\ \frac{\text{lbs}}{\text{in}^2} = 5.33\ \frac{\text{lbs}}{\text{in}^2}$

The first term in (2) in parentheses is the ratio of the density of seawater to the density of freshwater (dimensionless).

Answers to Exercise (1-4)--Hydraulic Head

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

Well	Land-surface elevation (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	35	10	25
2	45	90	9	36	81	-45
3	51	350	13	38	337	-299

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

Comment: The instructor may wish to differentiate between pressure head and elevation head in an additional example in which total head is below datum and, therefore, is designated with a minus (-) sign.

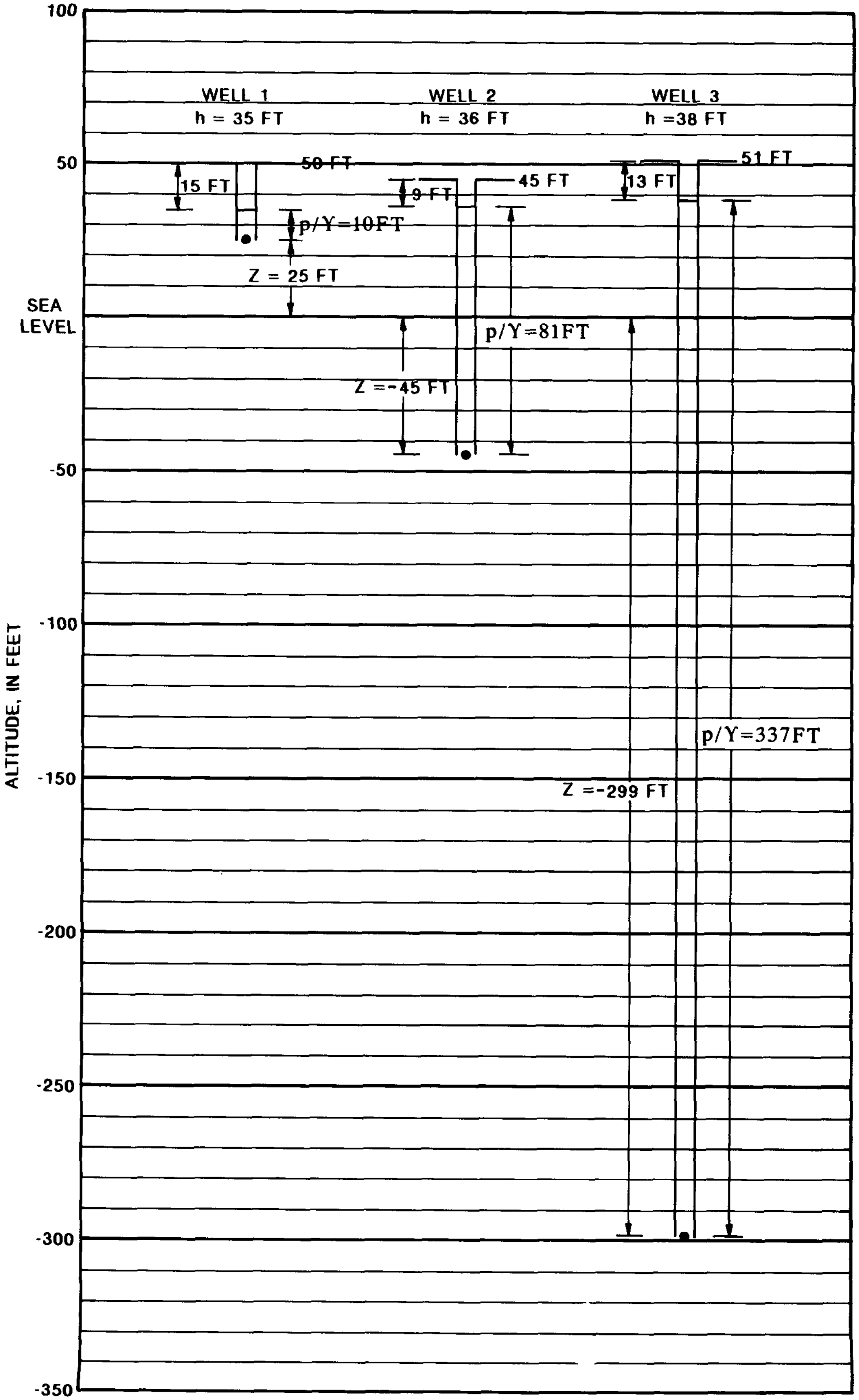


Figure 1-8.--Sketches showing pressure head (p/γ) and elevation head (z) in three closely spaced observation wells.

Preparation and Interpretation of Water-Table Maps

Assignments

*Study Fetter (1988), p. 136-137; Freeze and Cherry (1979), p. 45; or 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 can 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 altitudes. The objective is to develop the best possible representation of the water-table (topographic) surface on the basis of a few scattered water-table measurements at points. A water-table map is constructed by drawing contour lines of equal water-table altitude (equipotential lines or head contours)[1] at convenient intervals, through use of approximate linear interpolation between point measurements.

Head gradients commonly are estimated from water-table maps, as shown 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.

References

Davis and DeWiest (1966), p. 48-53.
Heath (1983), p. 10-11, 20.
Heath and Trainer (1968), p. 188-195.

Comments

The goals of this subsection are to convey (1) what a water-table map represents and (2) the concept of a head gradient and associated direction of ground-water flow. Although extensive practice in head contouring, both in map view and in vertical section, is provided in a later exercise (Exercise 3-1), the instructor may wish to introduce an additional simple contouring exercise at this juncture. Heath and Trainer (1968, p. 183-195) provide the necessary data for such a contouring exercise. Davis and DeWiest (1966, p. 48-53) offer a useful discussion of head maps.

---

[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 <u>surfaces</u> of constant head or constant potential--for example, equipotential surface.

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

(1) (a) See figure 1-10.

(b) The head contours are parallel and equally spaced. Thus, the head surface is a sloping plane.

(c)
$$i = \frac{\Delta h}{l} = \text{constant}$$

$$i = \frac{10 \text{ ft}}{2{,}000 \text{ ft}} = 0.005$$

In this case the average head gradient in the neighborhood of point A and the gradient at point A are <u>equal</u>.

(2) (a) See figure 1-10.

(b) The head contours are parallel but not equally spaced. The head surface is a curved surface whose slope varies with altitude but is a constant at any specified altitude on the surface.

(c) $$i = \frac{\Delta h}{l} \approx \frac{100 - 70}{10{,}800} \approx 0.0028$$

Graphical determination of the gradient or slope of a curve at a point is difficult to execute accurately "by eye;" expect considerable variation in the answers from participants. The answer provided above is not "exact," but only a rough approximation. The point of this exercise is to differentiate between an "average gradient or slope in the neighborhood of a point" and the "slope at a point." We usually use the "average slope in the neighborhood of a point" when obtaining slope estimates from head maps.

(3) The streamline through point C is not straight, but curved. Starting at point C, draw a smooth curve through point C that intersects the 110- and 100-ft contours at right angles. An approximation of the average slope of the head contours in the vicinity of point C is $i = \frac{110 - 100}{l}$ where l is the length of the streamline between the 110- and 100-ft contours through point C (fig. 1-10).

(4) Vertical distance between measuring points

25 ft + 45 ft = 70 ft

$$i_{vertical} = \frac{\Delta h}{l} = \frac{1 \text{ ft}}{70 \text{ ft}} = 0.0143$$

This question confuses some participants because they are accustomed to determining horizontal gradients from head maps, but not vertical gradients. <u>The vertical distance between measuring points of adjacent wells</u>, the distance l in the gradient formula, is the key to this question. Ground-water flow may not be strictly vertical at this location in the ground-water system. A horizontal component of flow that we are not measuring may be present. Thus, on the basis of the available data, we calculated only one component of the actual gradient.

(5) "Three-point problem" answer is presented on figure 1-11.

Answers to Exercise (1-5) (continued)--(1), (2), (3)

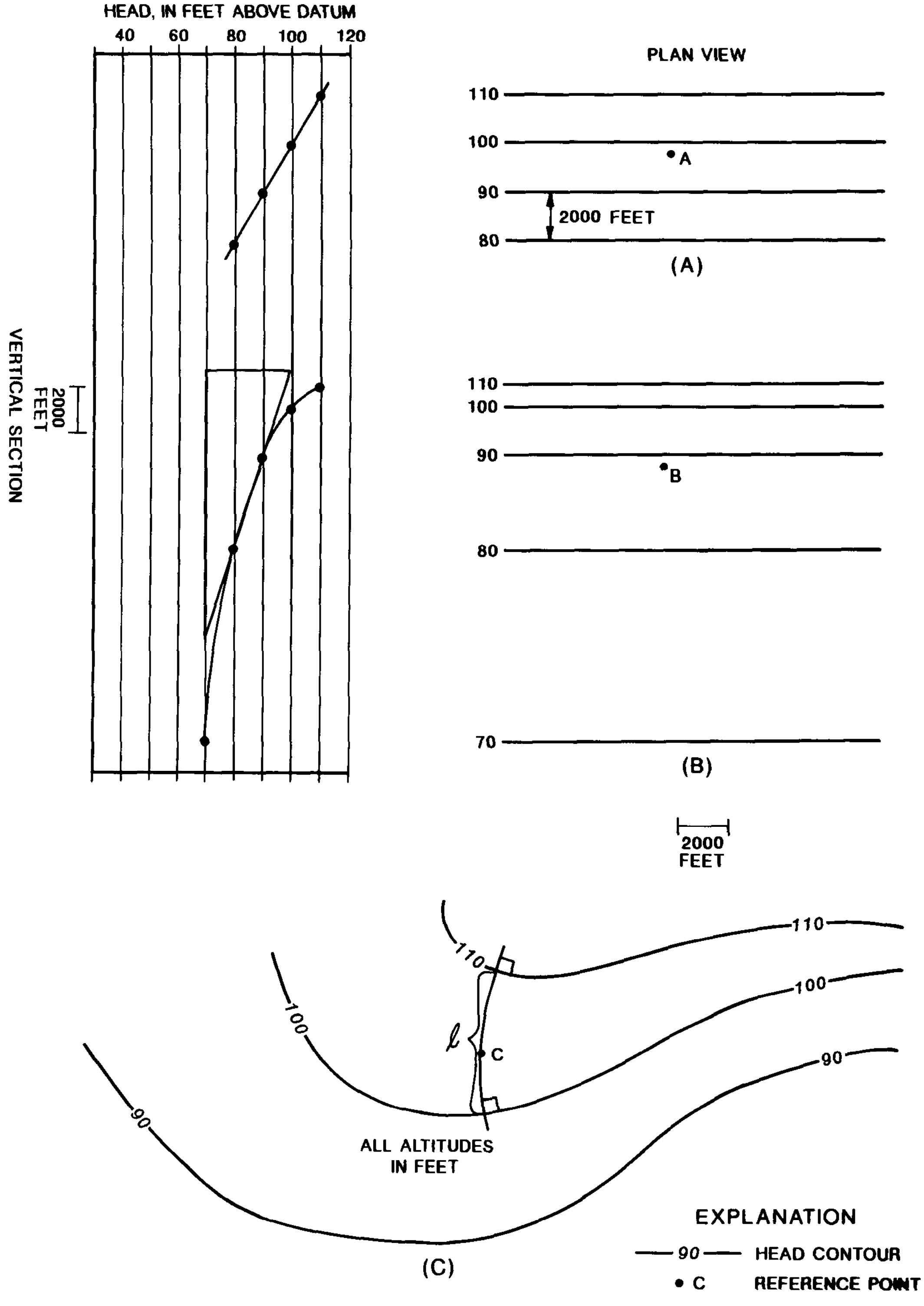
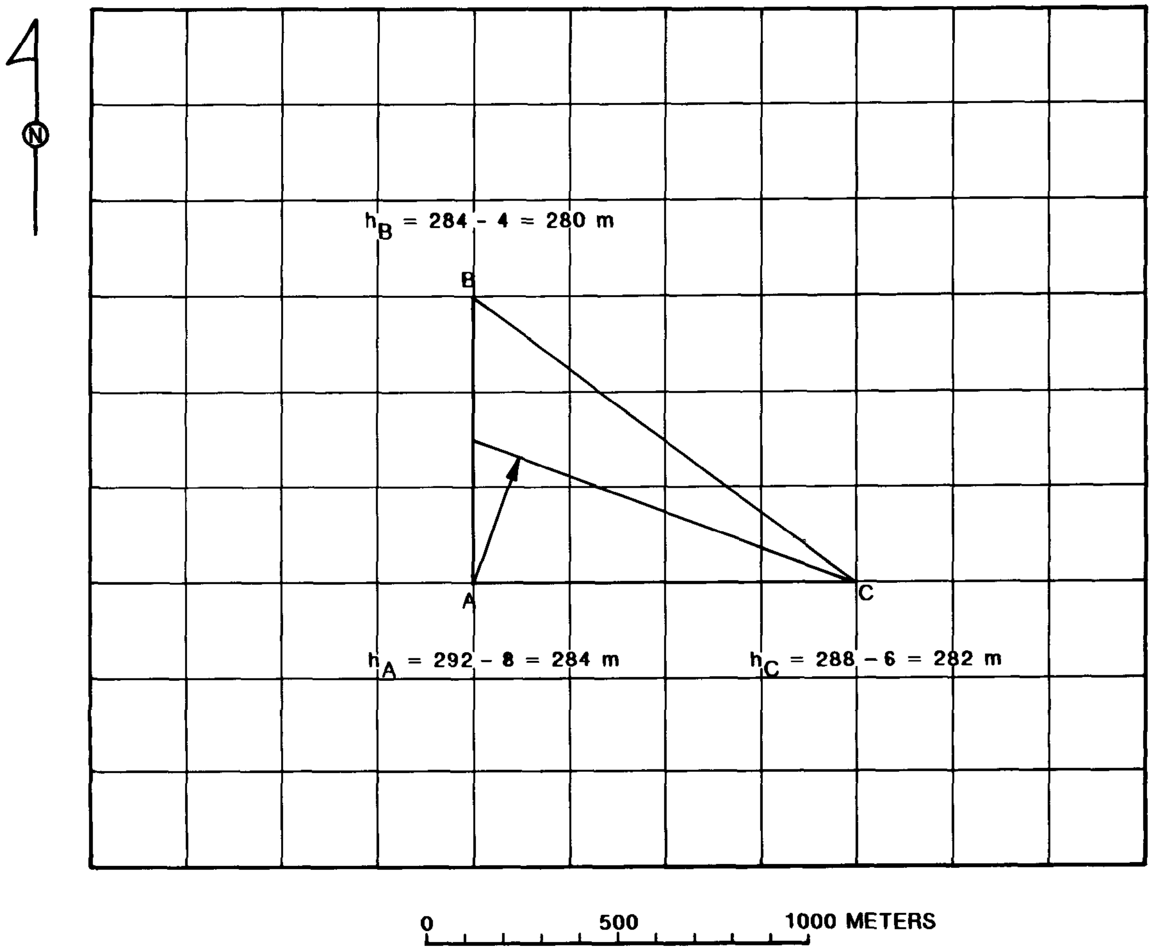


Figure 1-10.--Maps of hydraulic head illustrating three different contour patterns and plots of head that assist in estimating head gradients.

Answers to Exercise (1-5) (continued)--(5)



(a) Direction of flow is toward northeast

(b) Hydraulic gradient $i = \frac{h1 - h2}{\ell} \approx \frac{284 - 282}{350} \approx 0.0057$

Figure 1-11.--Plot 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 usually is a major part of the base flow of streams and is the principal component of streamflow during dry periods. In many areas base flow is critical for water supply and maintenance of streamwater 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 can exhibit either (1) hydraulic connection between stream and aquifer or (2) 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 can be important sources of recharge to shallow ground-water systems.

References

Heath (1983), p. 22-23.
Heath and Trainer (1968), p. 215-219.

Answers to Exercise (1-6)--Ground-Water Flow Pattern near Gaining Streams

Depending on their background in hydrology, many course participants may be unable to answer some of the questions in this exercise without assistance. In this situation the instructor may choose to work through the exercise as an interactive discussion with the class.

(1) See figure 1-12.

$$l \approx 1.2 \text{ mi} \approx 6{,}340 \text{ ft}$$

$$i \approx \frac{50 \text{ ft} - 40 \text{ ft}}{6{,}340 \text{ ft}} \approx 0.00158$$

(2) See figure 1-12.

(3) An important factor determining the length of a streamline from a point on the water table to its point of intersection with a nearby stream is the local curvature of the water-table contours.

(4) A "lateral" ground-water divide exists between adjacent gaining streams. The position of the lateral ground-water divide can change as the curvature of the local water-table contours changes for any reason (fig. 1-12).

(5) We have outlined an approximate ground-water contributing area for reach 1-2 of stream B (fig. 1-12).

(6) We can estimate the long-term average annual ground-water recharge of the contributing area, assuming that (1) the contributing area is correct, (2) there is no artificial disturbance of the local ground-water system, and (3) discharge of ground water by ground-water evapotranspiration within the contributing area is negligible. Our general assumption about the flow system is that all ground-water recharge from precipitation over the contributing area discharges to the stream between the two measuring points on the stream, 1 and 2. To estimate recharge, we use the relation

$$\text{Average annual areal recharge } W = \frac{\text{Average annual stream pick-up}}{\text{Area of contributing area}}$$

Common units for areal recharge are feet per year or inches per year and units for stream pickup are cubic feet per second.

(7) (a) We are already aware that small changes in the curvature of water-table contours can influence greatly the position of streamlines. We never have available a sufficiently dense network of observation wells to determine accurately the local contributing areas of streams. Furthermore, even if a dense observation well network were available, the combination of the effect of system noise on heads and the achievable precision of head measurements in the field may well frustrate the precise determination of contributing areas.

(b) Upstream or uphill from the point of start-of-flow of the stream, some fraction of the ground-water recharge may flow to deeper parts of the ground-water system and may not discharge into the stream at all, at least not locally. It is virtually impossible to draw a divide line on a map between areas contributing recharge to the shallow system discharging into the local stream and areas contributing recharge to the deeper flow system on the basis of field-measured head data.

(8) See figure 1-13.

(9) In our analysis of figure 1-12, we assumed almost horizontal flow, which implies equipotential head surfaces that are almost vertical. Looking at heads in the third (vertical) dimension, we see evidence of significant components of vertical flow in the immediate vicinity of the stream. In fact, ground-water flow beneath the middle of the stream probably is vertical, or nearly so.

(10) At about 47 ft from the streambank, heads are virtually constant with depth within measurement error. This observation implies that at this "short" distance from the stream ("short" relative to the areal dimensions of the shallow flow system), ground-water flow is horizontal, or nearly so.

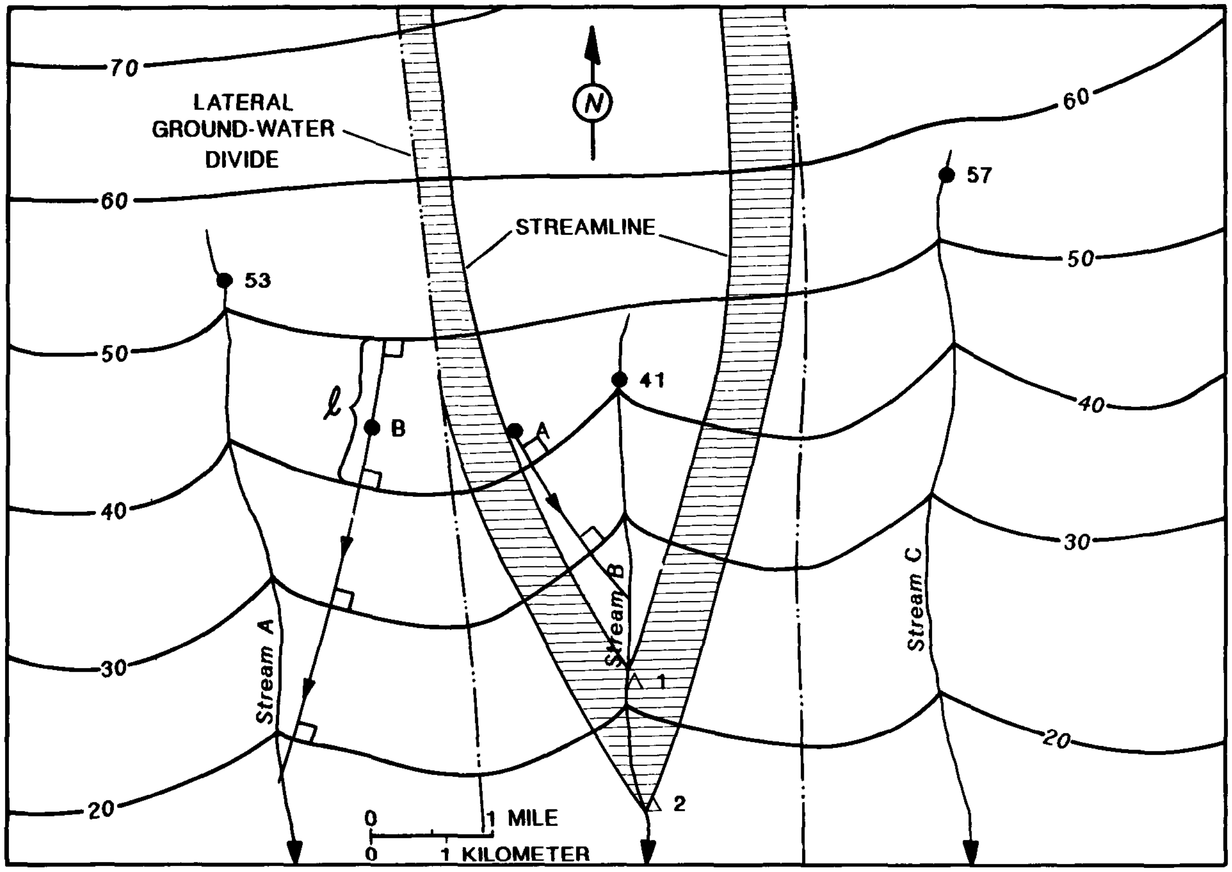
(11)

$$i \text{ (beneath center of stream)} = \frac{h_1 - h_2}{l} = \frac{26.70 - 26.02}{3.0} = \frac{.68 \text{ ft}}{3.0 \text{ ft}} = 0.227$$

$$\frac{\text{Vertical gradient beneath streambed}}{\text{Horizontal water-table gradient}} = \frac{.227}{.00158} = 144$$

The horizontal water-table gradients in figure 1-12 are approximately the same as horizontal water-table gradients near the south shore of Long Island, New York. We see that vertical gradients acting over a very small area of streambed are on the order of 100 times greater than typical horizontal water-table gradients in this ground-water system.

In this ground-water system, nearly horizontal ground-water flow through relatively large cross-sectional areas converges to the relatively small discharge area of the streambed and banks.



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
- —··— ESTIMATED POSITION OF LATERAL GROUND WATER-DIVIDE
- INFERRED GROUND-WATER CONTRIBUTING AREA FOR THE STREAM REACH BETWEEN POINTS 1 AND 2 ON STREAM B

Figure 1-12.--Hypothetical water-table map of an area underlain by permeable deposits in a humid climate showing selected streamlines, lateral ground-water divides, and the inferred ground-water contributing area for a stream reach.

Answers to Exercise (1-6) (continued)--(8), (9), (10), (11)

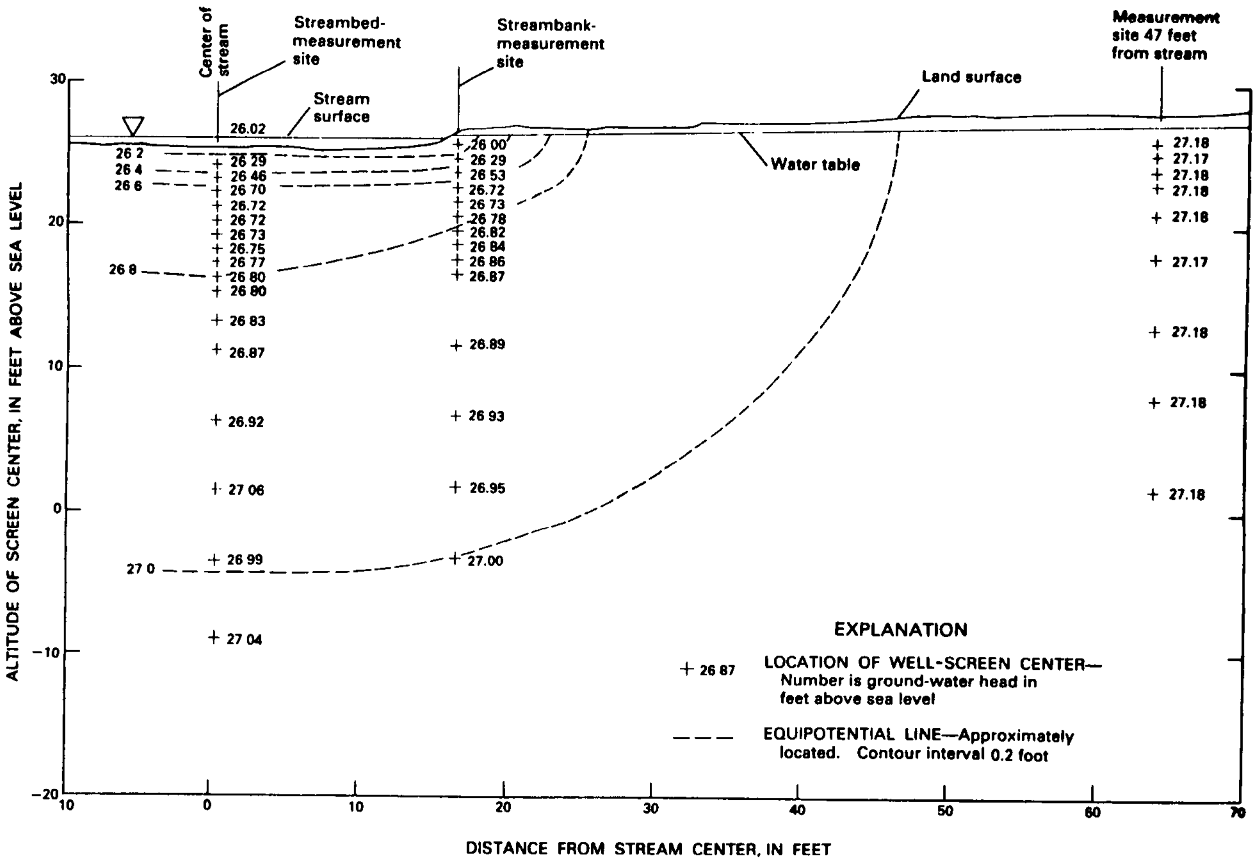


Figure 1-19.--Head measurements near Connetquot Brook, Long Island, New York, during a 3-day period in October 1978. (Modified from Prince and others, 1988, fig. 10.)

Supplemental Problem on Ground-Water/Surface-Water Relations, with Answers

This supplemental problem (not in Part I of the Study Guide), which builds on the assignment in which course participants are asked to sketch water-table contour lines near a losing stream, can be the basis for a worthwhile classroom discussion. After a review of the pattern of water-table contours near gaining streams, and after the class has sketched several water-table contour lines that intersect a losing stream, ask participants to (1) plot an arbitrary reference point near the losing stream, and (2) trace a ground-water streamline both upgradient and downgradient from the reference point and designate the direction of ground-water flow along the streamline.

Question: Where does the streamline originate?

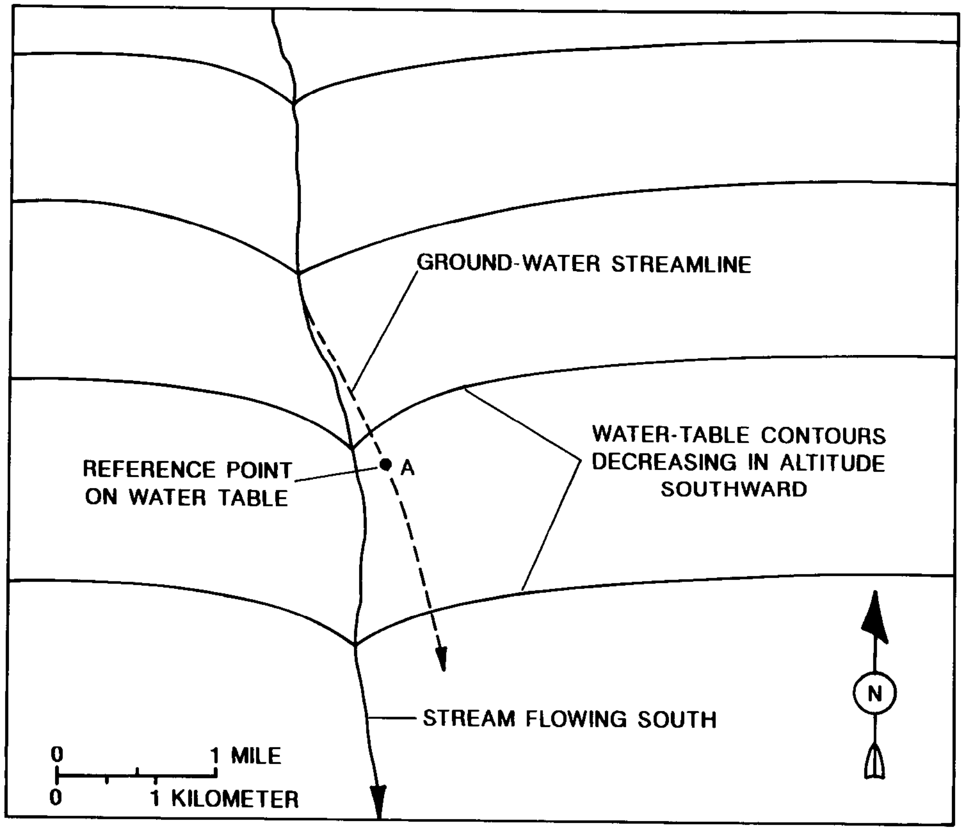
Answer: At the stream.

Question: What is the source of the moving ground water?

Answer: Water flowing in the stream that moves through the streambed into the shallow ground-water system.

Review question: What is the source of ground water discharging to a gaining stream?

Answer: Areal recharge to the water table.



Comment: Note that the ground-water streamline through reference point A starts at the flowing stream and moves downgradient away from stream.

Comment: Note that the ground-water streamline through reference point A starts at the flowing stream and moves downgradient away from the stream.

Figure 1-14.--Sketch of water-table contours near a losing stream.