Definitions of Selected Ground-Water Terms—Revisions and Conceptual Refinements

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1988

Definitions of Selected Ground-Water Terms—Revisions and Conceptual Refinements

By S. W. LOHMAN *and others*

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1988

A report of the Committee on Redefinition of Ground-Water Terms—R. R. Bennett, R. H. Brown, H. H. Cooper, Jr., W. J. Drescher, J. G. Ferris, A. I. Johnson, S. W. Lohman (chairman beginning June 1968), C. L. McGuinness, A. M. Piper (chairman from 1965 until retirement in 1968), M. I. Rorabaugh, R. W. Stallman, and C. V. Theis

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

First printing 1960
Second printing 1961
Third printing 1966
Fourth printing 1973
Fifth printing 1983

For sale by the Distribution Branch, U.S. Geological Survey,
604 South Pickett Street, Alexandria, VA 22304

FOREWORD

This report by an ad hoc Committee on Redefinition of Ground-Water Terms contains recommendations for certain changes in terms and concepts and more importantly for the use of consistent units in ground-water flow equations. The report comes at an appropriate time as communication between hydrologists throughout the world is increasing greatly. The recommendations submitted by the committee will make future publications of the Water Resources Division, Geological Survey, more readily understood by all hydrologists and will promote more uniform usage of terms by Geological Survey personnel.

The terms defined and recommendations in the report shall be standard for reports of the Geological Survey. In accordance with prevailing Survey practice, however, it is permissible to use different terms, if local circumstances or conditions so require, once the standard usage has been made clear.

E. L. Hendricks

E. L. Hendricks,
Chief Hydrologist

CONTENTS

TABLES

SYMBOLS AND DIMENSIONS

Symbol	*Dimensions*	*Description*
A	L^2	Area.
b	L	Saturated thickness of aquifer.
cm	L	Centimeter.
ft	L	Foot.
g	LT^{-2}	Acceleration due to gravity.
H	L	Total head, $h_e+h_p+h_v$.
h	L	Static head, h_e+h_p.
h_e	L	Elevation head.
h_p	L	Pressure head.
h_v	L	Velocity head.
J	ML^2T^{-2}	Joule.
K	LT^{-1}	Hydraulic conductivity.
K_e	LT^{-1}	Effective hydraulic conductivity.
k	L^2	Intrinsic permeability.
kg	M	Kilogram.
l	L	Length.
m	L	Meter.
ml	L^3	Milliliter.

Symbol	*Dimensions*	*Description*
n	([1])	Porosity.
n_e	([1])	Effective porosity.
P	L^2	†Coefficient of permeability.
P_m	L^2	†Meinzer's coefficient of permeability.
P_f	LT^{-1}	†Field coefficient of permeability.
p	$ML^{-1}T^{-2}$	Pressure.
p_a	$ML^{-1}T^{-2}$	Atmospheric pressure.
Q	L^3T^{-1}	Total discharge, or total flux.
q	LT^{-1}	Specific discharge, or specific flux.
S	([1])	Storage coefficient.
S_r	([1])	Specific retention.
S_s	L^{-1}	Specific storage.
S_y	([1])	Specific yield.
s	L	Drawdown.
T	L^2T^{-1}	Transmissivity.
v	LT^{-1}	Velocity.
$\bar{v}_i$	LT^{-1}	Average interstitial velocity.
x, y	L	Coordinates in horizontal plane.
z	L	Vertical coordinate.
∇		Nabla: the gradient operator.
μ	$ML^{-1}\,T^{-1}$	Dynamic viscosity.
ν	L^2T^{-1}	Kinematic viscosity.
ρ	ML^{-3}	Density.
ϕ	L^2T^{-2}	Fluid potential.
†	----------------	Dagger preceding term indicates that use of term has been discontinued in reports of the U.S. Geological Survey.

[1] Dimensionless.

DEFINITIONS OF SELECTED GROUND-WATER TERMS—REVISIONS AND CONCEPTUAL REFINEMENTS

By S. W. Lohman and others

INTRODUCTION

For many years there has been a need for redefinition or more precise definition of certain ground-water terms used in publications by members of the U.S. Geological Survey. Another problem has been the expression of the coefficient of permeability (herein redefined as *hydraulic conductivity*) and the coefficient of transmissibility (herein redefined as *transmissivity*) in inconsistent units that included the U.S. gallon, the foot, and in some expressions, the mile. Such inconsistent units and the attendant confusing numerical conversion factors used in flow equations, such as 527.7, 264, and 114.6, makes it unnecessarily difficult for hydrologists, especially in foreign countries, to follow and use our published results. Because of this it is advisable that basic ground-water flow equations in publications by members of the Geological Survey contain only the pure dimensionless numbers that result from the derivation of the equations, such as 2, 2.30, e, π, and 4, and that numerical results having dimensions should be expressed in consistent units of measurement.

If in the solution of problems it is necessary or desirable to use inconsistent units, suitable conversion factors should be included so that the result is expressed in consistent units of length and time. For example, if a discharge rate is given in U.S. gallons per minute, conversion factors such as 7.48 gal ft^{-3} and 1,440 min day^{-1} should be included. Many hydrologists in English-speaking countries including the United States are already using consistent units in the fps, cgs, or mks systems of measurement.

To meet the growing need for consistency, J. T. Callahan, then acting chief, Ground Water Branch, in a memoradum of October 21, 1965, appointed the Committee on Redefinition of Ground-Water Terms. After two additions, the committee comprised:

R. R. Bennett	S. W. Lohman
R. H. Brown	C. L. McGuinness
H. H. Cooper, Jr.	A. M. Piper (chairman)
W. J. Drescher	M. I. Rorabaugh
J. G. Ferris	R. W. Stallman
A. I. Johnson	C. V. Theis.

A. M. Piper retired from the Geological Survey in 1968 and was succeeded as chairman on June 28, 1968, by S. W. Lohman.

The committee wishes to express its appreciation to A. M. Piper for his contribution as its first chairman and regrets that its work (the present report) was not completed prior to his retirement. The present chairman wishes to express his sincere thanks to all members of the committee for their excellent cooperation, and to several colleagues who contributed suggestions to various members of the committee. Finally, the committee wishes to express its deep appreciation to the late O. E. Meinzer for his pioneer work in the definition of ground-water terms (Meinzer, 1923) and to the late C. E. Jacob for his untiring promotion of the use of consistent units in all matters pertaining to ground-water movement. (See Jacob, 1946a, b.) Meinzer's classic statements relating "Facts, concepts, definitions, and terms" (1923, p. 1–2) were an inspiration to the committee. If not directly applicable in their established form, terms drawn from other physical sciences are defined with a parallel construction for use in ground-water hydrology.

TERMS

Aquifer

An *aquifer* is a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

The term aquifer was defined by O. E. Meinzer from a geological concept in which water bodies are classified in accordance with stratigraphy or rock types. Meinzer (1945, p. 159) clearly intended that an aquifer include the unsaturated part of the permeable unit.

Artesian

Artesian is synonymous with *confined. Artesian water* and *artesian water body* are equivalent respectively to *confined* ground water and *confined* water body.

An *artesian well* is a well deriving its water from an *artesian* or *confined* water body. The water level in an artesian well stands above the top of the artesian water body it taps.

If the water level in an artesian well stands above the land surface the well is a *flowing artesian well.* If the water level in the well stands above the water table, it indicates that the artesian water can and probably does discharge to the unconfined water body. Old definitions restricting *artesian* to one of these conditions, in particular Meinzer's definition (1923, p. 38) which specified a head higher than the water table, are abandoned. It should be noted also that in discharge areas wells having heads higher than the water table, or even flowing wells, may exist without confinement of the water body, owing to vertical components of gradient in the flow field.

Capillary fringe

The *capillary fringe* is the zone immediately above the water table in which all or some of the interstices are filled with water that is under less than atmospheric pressure and that is continuous with the water below the water table (Meinzer, 1923, p. 26). The water is held above the water table by interfacial forces (for example, surface tension). The capillary fringe is typically saturated to some distance above its base at the water table; upward from the saturated part only progressively smaller pores are filled and the upper limit is indistinct. In some quantitative studies it is convenient to define the upper limit more or less arbitrarily. For instance, this limit may be defined as the level at which 50 percent of the pore space is filled with water (R. W. Stallman, oral commun., May 15, 1969).

Some lateral flow generally occurs throughout the capillary fringe, but because the effective hydraulic conductivity decreases rapidly with moisture content, the lateral flow in the capillary fringe generally is negligible compared with that in the saturated zone, except where the capillary fringe and the saturated zone are of comparable thickness.

Capture

Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in the recharge, or a combination of these changes. (See Theis, 1940, p. 277.) The decrease in discharge plus the increase in recharge is termed *capture.* Capture may occur in the form of decreases in the ground-water discharge into streams, lakes, and the ocean, or from decreases in that component of evapotranspiration derived from the saturated zone. After a new artificial withdrawal from the aquifer has begun, the head in the aquifer will continue to decline until the new withdrawal is balanced by capture.

475-549 O - 72 - 2

Conductivity, effective hydraulic, K_e $[LT^{-1}]$

The *effective hydraulic conductivity* is the rate of flow of water through a porous medium that contains more than one fluid, such as water and air in the unsaturated zone, and should be specified in terms of both the fluid type and content and the existing pressure. For a precise definition of hydraulic conductivity for water, see "Conductivity, hydraulic." Effective hydraulic conductivity has been called capillary conductivity by many soil physicists and effective permeability by many petroleum engineers.

Conductivity, hydraulic, K $[LT^{-1}]$

Hydraulic conductivity, K, replaces the term †"field coefficient of permeability," P_f, introduced by Meinzer and Wenzel, 1942, p. 7), which embodies the inconsistent units gallon, foot, and mile. If a porous medium is isotropic and the fluid is homogeneous, the *hydraulic conductivity* of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Darcy's law can be expressed as

$$q=\frac{Q}{A}=-K\frac{dh}{dl}. \qquad (1)$$

K, the constant of proportionality in equation 1, is the hydraulic conductivity and may be expressed as

$$K=-\frac{q}{dh/dl}. \qquad (2)$$

Hydraulic conductivity can have any units of LT^{-1} suitable to the problem involved. In data tabulations of the Geological Survey, hydraulic conductivity may be expressed in feet per day and, so that the work of the Geological Survey may be readily interpreted in other countries, also in meters per day. Thus,

$$K=-\frac{\text{ft}^3}{\text{day ft}^2\ (-\text{ft ft}^{-1})}=\text{ft day}^{-1} \qquad (3)$$

$$K=-\frac{\text{m}^3}{\text{day m}^2\ (-\text{m m}^{-1})}=\text{m day}^{-1}. \qquad (4)$$

Hydraulic conductivity is dependent primarily on the nature of the pore space, the type of liquid occupying it, and the strength of the gravitational field. For comparing the hydraulic conductivities of aquifers at different localities that contain water of appreciably different kinematic viscosity, it is only necessary to relate them by the dimensionless ratio of the kinematic viscosities and values of the acceleration due to gravity; thus, for the same intrinsic permeability,

$$K_1 = \frac{\nu_2 g_1}{\nu_1 g_2} K_2 \tag{5}$$

Ordinarily, differences in the acceleration due to gravity are negligible; hence, equation 5 is closely approximated by

$$K_1 = \frac{\nu_2}{\nu_1} K_2 \tag{6}$$

In anisotropic media the direction of the specific discharge q is not generally parallel to that of the gradient (dh/dl) of the head. In such media the cartesian components of the specific discharge are related to those of the gradient by

$$-q_x = K_{xx}\frac{\partial h}{\partial x} + K_{xy}\frac{\partial h}{\partial y} + K_{xz}\frac{\partial h}{\partial z},$$

$$-q_y = K_{yx}\frac{\partial h}{\partial x} + K_{yy}\frac{\partial h}{\partial y} + K_{yz}\frac{\partial h}{\partial z},$$

$$-q_z = K_{zx}\frac{\partial h}{\partial x} + K_{zy}\frac{\partial h}{\partial y} + K_{zz}\frac{\partial h}{\partial z}$$

The quantities in the form K_{xx}, K_{xy}, K_{xz}, and so forth, called *conductivity coefficients*, are the components of a second-order tensor, generally symmetric. The physical meaning of the conductivity coefficients may be visualized from the following examples: K_{xx} is a conductivity coefficient that contributes a component of flux along the x-axis due to the component of head gradient along x $(=\partial h/\partial x)$. K_{zx} is a conductivity coefficient that contributes a component of flux along the z-axis due to the component of head gradient along $x(=\partial h/\partial x)$. K_{xz} is a conductivity coefficient that contributes a component of flux along the x-axis due to the component of head gradient along the z-axis $(=\partial h/\partial z)$.

Confining bed

Confining bed is a term which will now supplant the terms †"aquiclude," †"aquitard," and †"aquifuge" in reports of the Geological Survey and is defined as a body of "impermeable" material stratigraphically adjacent to one or more aquifers. In nature, however, its hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the aquifer. Its conductivity relative to that of the aquifer it confines should be specified or indicated by a suitable modifier such as slightly permeable or moderately permeable.

Flow, steady

Steady flow occurs when at any point the magnitude and direction of the specific discharge are constant in time. (See also "Flow, unsteady.")

Flow, uniform

A property is uniform if, at a given instant, it is the same at every point. Thus, *uniform flow* occurs if at every point the specific discharge has the same magnitude and direction.

Flow, unsteady

Unsteady, or *nonsteady, flow* occurs when at any point the magnitude or direction of the specific discharge changes with time. (See also "Flow, steady".)

The word *transient* is used in reference to the temporary features of unsteady flow. Thus, in unsteady flow, the specific discharge, the head, and perhaps other factors consist of a steady component plus a transient component.

Fluid potential, ϕ $[L^2T^{-2}]$

The *fluid potential* is the mechanical energy per unit mass of a fluid at any given point in space and time with respect to an arbitrary state and datum. Loss of fluid potential incurred as the fluid moves from a region of high potential to one of low potential represents loss of mechanical energy which is converted to heat by friction. The fluid potential may be expressed (Hubbert, 1940, p. 801) as

$$\phi = gz + \int_{p_a}^{p} \frac{dp}{\rho} + \frac{v^2}{2}. \qquad (7)$$

In ground-water movement the kinetic energy term $v^2/2$ ordinarily is negligible; therefore, for ground-water movement the fluid potential is closely approximated by

$$\phi = gz + \int_{p_a}^{p} \frac{dp}{\rho}. \qquad (8)$$

If the expansion and contraction of the fluid due to changes in pressure are unimportant to the problem being considered, the fluid can be assumed to be incompressible, and the equation for the potential is further approximated by

$$\phi = gz + \frac{p - p_a}{\rho}. \qquad (9)$$

At a given point in a body of liquid, the fluid potential is proportional to the head (see "Head, static"); that is,

$$\phi = gh. \tag{10}$$

Ground water, confined

Confined ground water is under pressure significantly greater than atmospheric, and its upper limit is the bottom of a bed of distinctly lower hydraulic conductivity than that of the material in which the confined water occurs.

Ground water, perched

Perched ground water is unconfined ground water separated from an underlying body of ground water by an unsaturated zone. Its water table is a *perched water table.* It is held up by a *perching bed* whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure.

Perched ground water may be either *permanent,* where recharge is frequent enough to maintain a saturated zone above the perching bed, or *temporary,* where intermittent recharge is not great or frequent enough to prevent the perched water from disappearing from time to time as a result of drainage over the edge of or through the perching bed.

Ground water, unconfined

Unconfined ground water is water in an aquifer that has a water table.

Head, static, h [L]

The *static head* is the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

The static head is the sum of the elevation head, h_e, and the pressure head, h_p; that is, $h = h_e + h_p$. (See "Head, total".) Under conditions to which Darcy's law may be applied, the velocity of ground water is so small that the velocity head, $h_v = v^2/2g$, is negligible. *Head,* when used alone, is understood to mean static head. Inspection of equation 10 shows that the head is proportional to the fluid potential; therefore, the head is a measure of the potential.

Head, total, H [L]

The *total head* of a liquid at a given point is the sum of three components: (1) *elevation head,* h_e, which is equal to the elevation of the point above a datum, (2) *pressure head,* h_p, which is the height of a column of static water that can be supported by the static pressure at the point, and (3) *velocity head,* h_v, which is the height the kinetic energy of the liquid is capable of lifting the liquid. Thus, the total head can be expressed as

$$H=h_e+h_p+h_v=z+\frac{1}{g}\int_{p_a}^{p}\frac{dp}{\rho}+\frac{v^2}{2g}, \tag{11}$$

where p_a is atmospheric pressure.

Homogeneity

Homogeneity is synonymous with uniformity. A material is homogeneous if its hydrologic properties are identical everywhere. Although no known aquifer is homogeneous in detail, models based upon the assumption of homogeneity have been shown empirically to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Hydraulic diffusivity, T/S or K/S_s $[L^2T^{-1}]$

The *hydraulic diffusivity* is the parameter T/S or K/S_s. It is the conductivity of the saturated medium when the unit volume of water moving is that involved in changing the head a unit amount in a unit volume of medium. By analogy with Maxwell's nomenclature in heat conduction theory (thermometric conductivity), it may be considered potentiometric conductivity. Similar diffusivities, having dimensions L^2T^{-1}, characterize the flow of heat and of electricity by conduction and the movement of a dissolved substance in a liquid by diffusion. The parameter arises from the fundamental differential equation for liquid flow in a porous medium.

In any isotropic homogeneous system the time involved for a given head change to occur at a particular point in response to a greater change in head at another point is inversely proportional to the diffusivity. As a common example the cone of depression affects moderately distant wells by measurable amounts in a short time in confined ground-water bodies for which the diffusivities are commonly large and only after a longer time in unconfined water bodies for which the diffusivities are commonly much smaller.

Hydraulic gradient [dimensionless]

The *hydraulic gradient* is the change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head. The *gradient of the head* is a mathematical term which refers to the vector denoted by ∇h or grad h, whose magnitude is equal to the maximum rate of change in head and whose direction is that in which the maximum rate of increase occurs. The hydraulic gradient and the gradient of the head are equal but of opposite sign. If the density of the water is not uniform, the hydraulic gradient can be written as (Hubbert, 1940, p. 815):

$$\frac{dh}{dl}=\frac{1}{g}\frac{d\phi}{dl}=\frac{1}{\rho g}\frac{dp}{dl}+\frac{dz}{dl}.$$

Isotropy

Isotropy is that condition in which all significant properties are independent of direction. Although no aquifers are isotropic in detail, models based upon the assumption of isotropy have been shown to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Permeability, intrinsic, k [L^2]

Intrinsic permeability is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement. It is a property of the medium that is dependent upon the shape and size of the pores.

Darcy's law may be expressed in several ways (Hubbert, 1940, p. 803, 819), such as:

$$q=-K\frac{dh}{dl}=-\frac{K}{g}\frac{d\phi}{dl}=-\frac{k}{\mu}\left(\frac{dp}{dl}+\rho g\frac{dz}{dl}\right)=-\frac{k\rho}{\mu}\frac{d\phi}{dl}=-\frac{k}{\nu}\frac{d\phi}{dl} \quad (12)$$

Then, solving the last version for k,

$$k=-\frac{q\nu}{d\phi/dl} \quad (13)$$

From equation 13 it may be deduced that if a porous medium is isotropic and the fluid is homogeneous, the *intrinsic permeability* of the medium is the volume of liquid of unit kinematic viscosity that will move in unit time under a unit potential gradient through a unit area, measured at right angles to the direction of flow.

If q is measured in m sec^{-1}, ν in m^2 sec^{-1}, ϕ in J kg^{-1}, and l in m, the unit for k is in m^2. In publications of the Geological Survey, k should be expressed in square micrometers, $1(\mu m)^2=10^{-12}$ m^2. Thus intrinsic permeabilities of water-bearing materials range from fractions to thousands of $(\mu m)^2$.

From equation 12, $k=K\,\nu/g$. If k is expressed in $(\mu m)^2[10^{-12}m^2]$ and K in m day^{-1}, ν/g would be expressed in m day; thus, for water at 60° F, the standard temperature used by Meinzer, for which $\nu=1.1296$ centistokes (table 3),

$$\frac{\nu}{g}=\frac{1.1296\times10^{-2}\ \text{cm}^2\ \text{sec}^{-1}}{(980.665\ \text{cm sec}^{-2})\ (10^2\ \text{cm m}^{-1})\ (86{,}400\ \text{sec day}^{-1})}$$

$$=1.333\times10^{-12}\text{m day}=\frac{4}{3}\times10^{-12}\ \text{m day}, \qquad (14)$$

whence

$$k[10^{-12}\,\text{m}^2]=\frac{4}{3}[10^{-12}\text{m day}]K[\text{m day}^{-1}]$$

in which, it will be noted, k is numerically equal to $\frac{4}{3}K$. For water at any other temperature, if ν is its kinematic viscosity in centistokes,

$$k[(\mu\text{m})^2]=\frac{4}{3}\,[10^{-12}\text{m day}]\left[\frac{\nu}{1.1296}\right]K\,[\text{m day}^{-1}]. \qquad (15)$$

It is apparent that k and K, in the designated units, differ numerically by only a small factor for most ground waters.

The darcy, the unit of permeability used in the petroleum industry was originally defined (Wyckoff and others, 1934, p. 166, 167) as the volume in cubic centimeters of water of 1 centipoise viscosity flowing in 1 sec through an area of 1 cm² under a pressure gradient of 1 atmosphere per cm² per cm. Although not stated in the definition, the direction of flow must be horizontal to negate gravitational effects. The volume was later changed to 1 ml; thus the darcy now contains the inconsistent units cm, ml, and atmosphere. The darcy has a value of 0.987 $(\mu\text{m})^2$, which corresponds closely with the unit proposed for Geological Survey usage.

Porosity, n [dimensionless]

The *porosity* of a rock or soil is its property of containing interstices or voids and may be expressed quantitatively as the ratio of the volume of its interstices to its total volume. (See Meinzer, 1923, p. 19.) It may be expressed as a decimal fraction or as a percentage. With respect to the movement of water only the system of interconnected interstices is significant. (See "Porosity, effective.")

Porosity, effective, n_e [dimensionless]

Effective porosity refers to the amount of interconnected pore space available for fluid transmission. It is expressed as a percentage of the total volume occupied by the interconnecting interstices. Although effective porosity has been used to mean about the same thing as specific yield, such use is discouraged. It may be noted that the present definition of effective porosity differs from that of Meinzer (1923, p. 28).

Potentiometric surface

The *potentiometric surface,* which replaces the term † "piezometric surface," is a surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells. Where the head varies appreciably with depth in the aquifer, a potentiometric surface is meaningful only if it describes the static head along a particular specified surface or stratum in that aquifer. More than one potentiometric surface is then required to describe the distribution of head. The water table is a particular potentiometric surface.

Pressure, static, p $[ML^{-1}T^{-2}]$

Static pressure is the pressure exerted by the fluid. It is the mean normal compressive stress on the surface of a small sphere around a given point.

The static pressure does not include the *dynamic pressure,* $\rho v^2/2$, and therefore is distinguished from the *total pressure.* The velocity of ground water ordinarily is so small that the dynamic pressure is negligible. Pressure, when used alone, is understood to mean static pressure.

Specific capacity $[L^2T^{-1}]$

The *specific capacity* of a well is the rate of discharge of water from the well divided by the drawdown of water level within the well. It varies slowly with duration of discharge which should be stated when known. If the specific capacity is constant except for the time variation, it is roughly proportional to the transmissivity of the aquifer.

The relation between discharge and drawdown is affected by the construction of the well, its development, the character of the screen or casing perforation, and the velocity and length of flow up the casing. If the well losses are significant, the ratio between discharge and drawdown decreases with increasing discharge; it is generally possible roughly to separate the effects of the aquifer from those of the well by step drawdown tests. In aquifers with large tubular openings the ratio between discharge and drawdown may also decrease with increasing discharge because of a departure from laminar flow near the well, or in other words, a departure from Darcy's law.

Specific discharge, or specific flux, q $[LT^{-1}]$

The *specific discharge,* or *specific flux,* for ground water is the rate of discharge of ground water per unit area of the porous medium measured at right angles to the direction of flow. Specific discharge has the dimensions of velocity, as follows:

$$q=Q/A \qquad (16)$$

where Q equals *total discharge*, or *total flux*, through area A.

Specific discharge has sometimes been called the bulk velocity or the Darcian velocity. Specific discharge is a precise term (Hubbert, 1940, p. 790) and is preferred to terms involving "velocity" because of possible confusion with actual velocity through the pores if a qualifying term is not constantly repeated.

Specific retention, S_r [dimensionless]

The *specific retention* of a rock or soil is the ratio of (1) the volume of water which the rock or soil, after being saturated, will retain against the pull of gravity to (2) the volume of the rock or soil. (See Meinzer, 1923, p. 28–29.)

Ideally, the definition implies that gravity drainage is complete. However, the amount of water held in pores above the water table during gravity drainage is dependent upon particle size, distance above the water table, time of drainage, and other variables. Lowering of the water table and infiltration occur over such short periods of time that gravity drainage is rarely or never complete. Thus the concepts embodied in specific retention do not recognize adequately the highly complex set of interacting conditions that regulate moisture retention. Nevertheless, specific retention is a useful though approximate measure of the moisture holding capacity of the unsaturated zone in that region above the capillary fringe. (See also "Specific yield.")

Specific yield, S_y [dimensionless]

The *specific yield* of a rock or soil is the ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil. (See Meinzer, 1923, p. 28.) The definition implies that gravity drainage is complete.

In the natural environment, specific yield is generally observed as the change that occurs in the amount of water in storage per unit area of unconfined aquifer as the result of a unit change in head. Such a change in storage is produced by the draining or filling of pore space and is therefore dependent upon particle size, rate of change of the water table, time, and other variables. Hence, specific yield is only an approximate measure of the relation between storage and head in unconfined aquifers. It is equal to porosity minus specific retention.

Storage, bank $[L^3]$

The change in storage in an aquifer resulting from a change in stage of an adjacent surface-water body is referred to as *bank storage*.

Storage, specific, S_s $[L^{-1}]$

In problems of three-dimensional transient flow in a compressible ground-water body, it is necessary to consider the amount of water released from or taken into storage per unit volume of the porous medium. The *specific storage*, S_s, is the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

Storage coefficient, S [dimensionless]

The *storage coefficient* is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

In a confined water body the water derived from storage with decline in head comes from expansion of the water and compression of the aquifer; similarly, water added to storage with a rise in head is accommodated partly by compression of the water and partly by expansion of the aquifer. In an unconfined water body, the amount of water derived from or added to the aquifer by these processes generally is negligible compared to that involved in gravity drainage or filling of pores; hence, in an unconfined water body the storage coefficient is virtually equal to the *specific yield.*

Stream, gaining

A *gaining stream*, which replaces the term † "effluent stream," is a stream or reach of a stream whose flow is being increased by inflow of ground water.

Stream, losing

A *losing stream*, which replaces the term † "influent stream," is a stream or reach of a stream that is losing water to the ground.

Transmissivity, T $[L^2 T^{-1}]$

Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It replaces the term † "coefficient of transmissibility" because by convention it is considered a property of the aquifer, which is transmissive, whereas the contained liquid is transmissible. However, though spoken of as a property of the aquifer, it embodies also the saturated thickness of the aquifer (b) and the properties of the contained liquid. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths.

Velocity, average interstitial, $\bar{v}_i$ $[LT^{-1}]$

Although the *specific discharge*, q, has the dimensions of a velocity, it expresses the average volume rate of flow rather than the particle velocity. In order to determine the average interstitial velocity, $\bar{v}_i$, it is necessary to know also the effective porosity, n_e. (See "Porosity, effective.") The *average interstitial velocity*,

$$\bar{v}_i = q/n_e = -\frac{K dh/dl.}{n_e} \tag{17}$$

As the hydraulic gradient and effective porosity are dimensionless ratios, $\bar{v}_i$ has the same dimensions as q and K. Even within a homogeneous medium there is a wide range of velocities within the pores and from one pore to another, and in a nonhomogeneous medium the velocities may range over several orders of magnitude.

Water table

The *water table* is that surface in a ground-water body at which the water pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists. (See also "Ground water, perched.")

Zone, saturated

The *saturated zone* is that part of the earth's crust beneath the deepest water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric. The saturated zone may depart from the ideal in some respects. A rising water table may cause entrapment of air in the upper part of the zone of saturation, and the lower part may include accumulations of other natural fluids. The saturated zone has been called the † phreatic zone by some. (See Meinzer, 1923, p. 5, 22; Daubrée, 1887, p. 19; Hantush, 1964, p. 283.)

The foregoing definition is virtually that given by Meinzer (1923, p. 21). Later, other authors, emphasizing that ordinary interstices somewhat above the water table in porous media are filled with capillary water, extended the term "saturated zone" to include this water. However, this capillary water cannot be distinguished in the field without special instrumentation. Hence, the definition accepting the water table as the top of the saturated zone is standard for reports of the Geological Survey.

Zone, unsaturated

The *unsaturated zone*, which replaces the terms † "zone of aeration" and † "vadose zone," is the zone between the land surface and the deepest water table. It includes the *capillary fringe*. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies the water pressure locally may be greater than atmospheric.

SELECTED REFERENCES

Daubrée, A. G., 1887, Les eaux souterraines à l'époque actuelle et aux époques anciennes: v. 1, Paris.

Hantush, M. S., 1964, Hydraulics of wells, *in* Chow, Ven Te, ed., Advances in hydroscience, v. 1: New York, Academic Press, Inc., p. 281–442.

Hubbert, M. K., 1940, The theory of ground-water motion: Jour. Geology, v. 48, no. 8, pt. 1, p. 785–944.

Jacob, C. E., 1946a, Report of the Subcommittee on Permeability: Am. Geophys. Union Trans., v. 27, no. 2, p. 245–256.

———, 1946b, Notes on the permeability coefficient and its units: Am. Geophys. Union Trans., v. 27, no. 2, p. 265–273.

Meinzer, O. E., 1923, Outline of ground-water hydrology, with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

———1945, Problems of the perennial yield of artesian aquifers: Econ. Geology, v. 40, no. 3, p. 159–163.

———1949, Occurrence, origin, and discharge of ground-water, chap. 10b *in* Meinzer, O. E., ed., Hydrology: New York, McGraw-Hill Book Co., Inc., p. 385–443; Natl. Research Council, Physics of the earth, v. 9.

Meinzer, O. E., and Wenzel, L. K., 1942, Movement of ground water and its relation to head, permeability, and storage, *in* Meinzer, O. E., ed., Hydrology: New York, McGraw-Hill Book Co., Inc., p. 444–477; Natl. Research Council, Physics of the earth, v. 9.

Theis, C. V., 1940, The source of water derived from wells: Civil Eng., v. 10, no. 5, p. 277–280.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods, *with a section on* Direct laboratory methods *and* Bibliography on permeability and laminar flow, by V. C. Fishel: U.S. Geol. Survey Water-Supply Paper 887, 192 p.

Wyckoff, R. D., Botset, H. G., Muskat, Morris, and Reed, D. W., 1934, Measurement of permeability of porous media: Am. Assoc. Petroleum Geologists Bull., v. 18, no. 2, p. 161–190.

TABLES 1-4

TABLE 1.—*Relation of units*

[Equivalent values shown in same horizontal lines. † indicates abandoned term]

A. Hydraulic conductivity

Hydraulic conductivity (K)		†Field coefficient of permeability (P_f)
Feet per day (ft day $^{-1}$)	Meters per day (m day^{-1})	† Gallons per day per square foot (gal day $^{-1}$ ft^{-2})
One	0. 305	7. 48
3. 28	**One**	24. 5
. 134	. 041	**One**

B. Transmissivity (T)

Square feet per day (ft^2 day^{-1})	Square meters per day (m^2 day^{-1})	† Gallons per day per foot (gal day^{-1} ft^{-1})
One	0. 0929	7. 48
10. 76	**One**	80. 5
. 134	. 0124	**One**

C. Permeability

Intrinsic permeability $k=-\frac{q\nu}{d\varphi/dl}$ [$(\mu m)^2=10^{-8}cm^2$]	Darcy $=-\frac{q\mu}{dp/dl+\rho g\,dz/dl}$ [$0.987\times10^{-8}cm^2$]	† Coefficient of permeability P or $P_m=-\frac{q(\text{at }60^\circ F.)}{dh/dl}$ †[gal day^{-1}ft^{-2} at 60° F.]
One	1. 01	18. 4
0. 987	**One**	18. 2
. 054	. 055	**One**

TABLE 2.—*Conversion factors for hydraulic units of measure*

[Equivalent values shown in same horizontal lines]

Cubic feet per second ($ft^3\ sec^{-1}$)	Acre-feet per day (acre-ft day^{-1})	Acre-feet per year (acre-ft yr^{-1})	Gallons per minute (gal min^{-1})	Gallons per day (gal day^{-1})	Cubic feet per day ($ft^3\ day^{-1}$)	Cubic meters per day ($m^3\ day^{-1}$)	Square mile-inch per year (mi^2-in yr^{-1})
One	1. 9835	7.2397×10^{2}	4.4883×10^{2}	6.4632×10^{5}	8.6400×10^{4}	2.4466×10^{3}	1.3574×10^{1}
5.0417×10^{-1}	**One**	3.6500×10^{2}	2.2629×10^{2}	3.2585×10^{5}	4.3560×10^{4}	1.2335×10^{3}	6. 8438
1.3813×10^{-3}	2.7397×10^{-3}	**One**	6.1996×10^{-1}	8.9274×10^{2}	1.1934×10^{2}	3. 3794	1.8750×10^{-2}
2.2280×10^{-3}	4.4192×10^{-3}	1. 6130	**One**	1.4400×10^{3}	1.9250×10^{2}	5. 4510	3.0244×10^{-2}
1.5472×10^{-6}	3.0689×10^{-6}	1.1201×10^{-3}	6.9444×10^{-4}	**One**	1.3368×10^{-1}	3.7854×10^{-3}	2.1003×10^{-5}
1.1574×10^{-5}	2.2957×10^{-5}	8.3793×10^{-3}	5.1948×10^{-3}	7. 4805	**One**	2.8317×10^{-2}	1.5711×10^{-4}
4.0873×10^{-4}	8.1071×10^{-4}	2.9591×10^{-1}	1.8345×10^{-1}	2.6417×10^{2}	3.5314×10^{1}	**One**	5.5483×10^{-3}
7.3668×10^{-2}	1.4612×10^{-1}	5.3333×10^{1}	3.3065×10^{1}	4.7613×10^{4}	6.3649×10^{3}	1.8024×10^{2}	**One**

TABLE 3.—*Variation of properties of pure water with temperature*

[*, interpolated]

Temperature °C	Temperature °F	Density at 1 atmosphere [1] (gm cm^{-3})	Dynamic viscosity, in centipoises [2] (10^{-2} dyne-sec cm^{-2})	Kinematic viscosity, in centistokes [3] (10^{-2} cm^{2} sec^{-1})	Surface tension against air [4] (dyne cm^{-1})	Vapor pressure [5] (mm Hg)
0	32.0	0.999841	1.7938	1.7941	75.64	4.579
1	33.8	.999900	1.7320	1.7322	75.50	4.926
2	35.6	.999941	1.6740	1.6741	75.35	5.294
3	37.4	.999965	1.6193	1.6194	75.21	5.685
4	39.2	.999973	1.5676	1.5676	75.06	6.101
5	41.0	.999965	1.5188	1.5189	74.92	6.543
6	42.8	.999941	1.4726	1.4727	74.78	7.013
7	44.6	.999902	1.4288	1.4289	74.64	7.513
8	46.4	.999849	1.3872	1.3874	74.50	8.045
9	48.2	.999781	1.3476	1.3479	74.36	8.609
10	50.0	.999700	1.3097	1.3101	74.22	9.209
11	51.8	.999605	1.2735	1.2740	74.07	9.844
12	53.6	.999498	1.2390	1.2396	73.93	10.518
13	55.4	.999377	1.2061	1.2069	73.78	11.231
14	57.2	.999244	1.1748	1.1757	73.64	11.987
15	59.0	.999099	1.1447	1.1457	73.49	12.788
16	60.8	.998943	1.1156	1.1168	73.34	13.634
17	62.6	.998774	1.0875	1.0889	73.19	14.530
18	64.4	.998595	1.0603	1.0618	73.05	15.477
19	66.2	.998405	1.0340	1.0357	72.90	16.477
20	68.0	.998203	1.0087	1.0105	72.75	17.535
21	69.8	.997992	.9843	.9863	72.59	18.650
22	71.6	.997770	.9608	.9629	72.44	19.827
23	73.4	.997538	.9380	.9403	72.28	21.068
24	75.2	.997296	.9161	.9186	72.13	22.377
25	77.0	.997044	.8949	.8976	71.97	23.756
26	78.8	.996783	.8746	.8774	71.82	25.209
27	80.6	.996512	.8551	.8581	71.66	26.739
28	82.4	.996232	.8363	.8395	71.50	28.349
29	84.2	.995944	.8181	.8214	71.35	30.043
30	86.0	.995646	.8004	.8039	71.18	31.824
31	87.8	.995340	.7834	.7871	*71.02	33.695
32	89.6	.995025	.7630	.7668	*70.86	35.663
33	91.4	.994702	.7511	.7551	*70.70	37.729
34	93.2	.994371	.7357	.7399	*70.53	39.898
35	95.0	.99403	.7208	.7251	70.38	42.175
36	96.8	.99368	.7064	.7109	*70.21	44.563
37	98.6	.99333	.6925	.6971	*70.05	47.067
38	100.4	.99296	.6791	.6839	*69.88	49.692
39	102.2	.99259	.6661	.6711	*69.72	52.442
40	104.0	.99221	.6536	.6587	69.56	55.324
41	105.8	.99183	.6415	.6468	*69.40	58.34
42	107.6	.99144	.6298	.6352	*69.23	61.50
43	109.4	.99104	.6184	.6240	*69.07	64.80
44	111.2	.99063	.6075	.6132	*68.90	68.26
45	113.0	.99021	.5970	.6029	68.74	71.88
46	114.8	.98979	.5868	.5929	*68.57	75.65
47	116.6	.98937	.5770	.5832	*68.41	79.60
48	118.4	.98893	.5675	.5739	*68.24	83.71
49	120.2	.98849	.5582	.5647	*68.07	88.02
50	122.0	.98804	.5492	.5558	67.91	92.51
51	123.8	.98759	.5405	.5473	*67.74	97.20
52	125.6	.98712	.5320	.5389	*67.56	102.09
53	127.4	.98666	.5236	.5307	*67.39	107.20
54	129.2	.98618	.5153	.5225	*67.22	112.51
55	131.0	.98570	.5072	.5146	67.05	118.04
56	132.8	*.98522	.4994	.5069	*66.87	123.80
57	134.6	*.98472	.4918	.4994	*66.70	129.82
58	136.4	*.98422	.4843	.4921	*66.53	136.08
59	138.2	*.98372	.4770	.4849	*66.35	142.60
60	140.0	.98321	.4699	.4779	66.18	149.38
61	141.8	*.98269	.4629	.4711	*66.0	156.43
62	143.6	*.98217	.4561	.4644	*65.8	163.77

See footnotes at end of table.

TABLE 3.—*Variation of properties of pure water with temperature*—Continued

Temperature °C	Temperature °F	Density at 1 atmosphere [1] (gm cm^{-3})	Dynamic viscosity, in centipoises [2] (10^{-2} dyne-sec cm^{-2})	Kinematic viscosity, in centistokes [3] (10^{-2} cm^2 sec^{-1})	Surface tension against air [4] (dyne cm^{-1})	Vapor pressure [5] (mm Hg)
63	145.4	*.98164	.4495	.4579	*65.7	171.38
64	147.2	*.98110	.4431	.4516	*65.5	179.31
65	149.0	.98056	.4368	.4455	*65.3	187.54
66	150.8	*.98002	.4306	.4394	*65.1	196.09
67	152.6	*.97947	.4245	.4334	*64.9	204.96
68	154.4	*.97891	.4186	.4276	*64.8	214.17
69	156.2	*.97835	.4128	.4219	*64.6	223.73
70	158.0	.97778	.4071	.4164	64.42	233.7
71	159.8	*.97720	.4016	.4110	*64.2	243.9
72	161.6	*.97663	.3962	.4057	*64.0	254.6
73	163.4	*.97604	.3909	.4005	*63.9	265.7
74	165.2	*.97545	.3857	.3954	*63.7	277.2
75	167.0	.97486	.3806	.3904	*63.5	289.1
76	168.8	*.97426	.3756	.3855	*63.3	301.4
77	170.6	*.97365	.3708	.3808	*63.1	314.1
78	172.4	*.97304	.3661	.3762	*63.0	327.3
79	174.2	*.97242	.3615	.3718	*62.8	341.0
80	176.0	.97180	.3570	.3674	62.61	355.1
81	177.8	*.97118	.3526	.3631	*62.4	369.7
82	179.6	*.97054	.3483	.3589	*62.2	384.9
83	181.4	*.96991	.3440	.3547	*62.0	400.6
84	183.2	*.96927	.3396	.3504	*61.9	416.8
85	185.0	.96862	.3357	.3466	*61.7	433.6
86	186.8	*.96797	.3317	.3427	*61.5	450.9
87	188.6	*.96731	.3278	.3389	*61.3	468.7
88	190.4	*.96665	.3240	.3352	*61.1	487.1
89	192.2	*.96598	.3203	.3316	*60.9	506.1
90	194.0	.96531	.3166	.3280	60.75	525.76
91	195.8	*.96464	.3130	.3245	*60.6	546.05
92	197.6	*.96396	.3095	.3211	*60.4	566.99
93	199.4	*.96327	.3061	.3178	*60.2	588.60
94	201.2	*.96258	.3027	.3145	*60.0	610.90
95	203.0	*.96189	.2994	.3113	*59.8	633.90
96	240.8	*.96119	.2962	.3082	*59.6	657.62
97	206.6	*.96048	.2930	.3051	*59.5	682.07
98	208.4	*.95978	.2899	.3020	*59.3	707.27
99	210.2	*.95906	.2869	.2991	*59.1	733.24
100	212	.95835	.2839	.2962	58.85	760.00

[1] Computed from the relative values in the "Absolute Density of Water" table of Weast, R. C., ed., 1965, Handbook of chemistry and physics [46th ed.]: Cleveland, Chem. Rubber Co., p. F-4.
[2] National Academy of Sciences, 1929, International critical tables of numerical data, physics, chemistry, and technology: Natl. Acad. Sci., v. 5, p. 10.
[3] Dynamic viscosity divided by density.
[4] National Academy of Sciences, 1929, International critical tables of numerical data, physics, chemistry, and technology: Natl. Acad. Sci., v. 5, p. 447.
[5] Weast, R. C., ed. 1965, Handbook of chemistry and physics [46th ed.]: Cleveland, Chem. Rubber Co., "Vapor Pressure of Water Below 100° C." table, D-94.

TABLE 4.—*Relation between head of water and units of pressure* [1]

[Equivalent values shown in same horizontal lines]

Ft of water at 4°C	Lb in^{-2}	Atmospheres (standard)	Bars	Dyne cm^{-2}
One	4.3352×10^{-1}	2.9499×10^{-2}	2.9890×10^{-2}	2.9890×10^{4}
2.3066	One	6.8046×10^{-2}	6.8947×10^{-2}	6.8947×10^{4}
3.3899×10^{1}	1.4696×10^{1}	One	1.01325	1.01325×10^{6}
3.3456×10^{1}	1.4504×10^{1}	9.8692×10^{-1}	One	1.0000×10^{6}
3.3456×10^{-5}	1.4504×10^{-5}	9.8692×10^{-7}	1.0000×10^{-6}	One

[1] Hodgman, C. D., ed., 1955, Handbook of chemistry and physics [37th ed.]: Cleveland, Chem. Rubber Publishing Co., p. 2873–2874.

☆U.S. GOVERNMENT PRINTING OFFICE:1983-381-614/565