Also by R. J. M. DeWiest

GEOHYDROLOGY

HYDROGEOLOGY

Stanley N. Davis

Professor of Geology
Stanford University

Roger J. M. DeWiest

Professor of Hydraulics and Hydrology
Princeton University

U.S. NUCLEAR REGULATORY COMMISSION

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This Book Is Dedicated to

Charles V. Theis

Hydrogeologist and Founder
of Modern Well Hydraulics

per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 at a temperature of 60°F.

A second coefficient, the field coefficient of hydraulic conductivity, is also used by the Water Resources Division of the U.S. Geological Survey. This unit is defined as the flow of water in gallons per day through a cross section of aquifer 1 foot thick and 1 mile wide under a hydraulic gradient of 1 foot per mile at field temperature [38].

In Equation 6.7 it is assumed that both porous material and water are chemically and mechanically stable. This may never be true. Ion exchange on clay and colloid surfaces will cause changes of mineral volume which in turn will change the pore size and shape. Extreme changes in pressure will cause dilatation or compaction of aquifers. Moderate to high ground-water velocities will move colloids and small clay particles. Also, all water movement will facilitate solution or deposition of dissolved constituents. Relatively small changes in pressure or temperature may cause gases to come out of solution and clog pore space, thus reducing the hydraulic conductivity.

Table 6.1 Average Values of K and k

Soil Class	K, cm/sec	k, darcys	K, gpd/ft²
Gravel	1–10^2	10^3–10^5	10^4–10^6
Clean sands (good aquifers)	10^{-3}–1	1–10^3	10–10^4
Clayey sands, fine sands (poor aquifers)	10^{-6}–10^{-3}	10^{-3}–1	10^{-2}–10

Table 6.2 Representative Values for k and K

Geologic Classification		Darcys, k	Meinzers, K
Argillaceous limestone	2% porosity	1.0×10^{-4}	1.80×10^{-3}
Limestone	16% porosity	1.4×10^{-1}	2.50
Sandstone, silty	12% porosity	2.6×10^{-3}	4.74×10^{-2}
Sandstone, coarse	12% porosity	1.1	19.90
Sandstone	29% porosity	2.4	43.60
Very fine sand	well sorted	9.9	18.00×10
Medium sand	very well sorted	2.6×10^2	4.60×10^3
Coarse sand	very well sorted	3.1×10^3	5.80×10^4
Gravel	very well sorted	4.3×10^4	7.88×10^5
Montmorillonite clay[a]		10^{-5}	10^{-4}
Kaolinite clay[a]		10^{-3}	10^{-2}

[a] For the clays only the order of magnitude is indicated.

Table 6.3 Equivalence between K and k Values

1 darcy	$= 9.87 \times 10^{-9}$ cm² $= 1.062 \times 10^{-11}$ ft²
10^{-10} cm²	$= 1.012 \times 10^{-2}$ darcys
0.1 cm/day	$= 1.15 \times 10^{-6}$ cm/sec $\approx 1.18 \times 10^{-11}$ cm² for water at 20°C
1.0 cm/sec	$\approx 1.02 \times 10^{-5}$ cm² for water at 20°C
1 darcy	≈ 18.2 meinzer units for water at 60°F
1 meinzer	$= 0.134$ ft/day $= 4.72 \times 10^{-5}$ cm/sec $\approx 5.5 \times 10^{-2}$ darcys for water at 60°F

Tables 6.1, 6.2, and 6.3 contain useful data about K and k. In Table 6.3, $\approx$ means "equivalent to."

K may be determined by laboratory methods as well as by field measurements. In the laboratory, the hydraulic conductivity may be determined by means of so-called permeameters [34] in which small samples taken at different points of the aquifer are submitted to flow under constant head or variable head. These samples are generally disturbed, and, moreover, even if they were undisturbed they might not be representative of the average K of the aquifer. More significant for the hydrogeologist is the determination of K through a well-pumping test in the field.

Many researchers have tried to investigate the various factors which influence the intrinsic permeability and hence the hydraulic conductivity, both in experimental and analytical work. Among others, the influence of porosity was studied by Kozeny [22], that of grain size by Hazen [16], and that of void ratio by Zunker [39]. Other important contributions were made by Slichter [31,32,14], Fair and Hatch [11], Rose [27,28], and Bakhmeteff and Feodoroff [1].

The influence of the fluid properties on the value of the hydraulic conductivity is evident from Equation 6.7. Hence, hydraulic conductivity may be measured by using different fluids. It is possible, at least in principle, to measure the hydraulic conductivity using a gas, say air, and to compute the intrinsic permeability k. Once k is known, it suffices to multiply k by g/ν to find the hydraulic conductivity for any fluid. Klinkenberg [21], however, has shown that the permeability of a porous medium to a liquid and to a gas is not the same. Owing to the slip phenomenon, whereby the velocity of a gas layer in the immediate vicinity of the surface of the grains has a finite (instead of zero) velocity, the permeability to a gas is higher than to a liquid. Klinkenberg derived the equation

$$k_a = k\left(1 + \frac{b}{p}\right) \qquad (6.11)$$