

Hydraulic conductivity

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Hydraulic conductivity, symbolically represented as *K*, is a property of vascular plants, soil or rock, that describes the ease with which water can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and on the degree of saturation. Saturated hydraulic conductivity, *K*_{sat}, describes water movement through saturated media. One application of it is the Starling equation, which calculates flow across walls of capillaries.

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Derivation through Darcy's law

Hydraulic conductivity is the proportionality constant in Darcy's law, which relates the amount of water which will flow through a unit cross-sectional area of aquifer under a unit gradient of hydraulic head. It is analogous to the thermal conductivity of materials in heat conduction, or 1/resistivity in electrical circuits. The hydraulic conductivity (*K* — the English letter "kay") is specific to the flow of a certain fluid (typically water, sometimes oil or air); intrinsic permeability (*κ* — the Greek letter "kappa") is a parameter of a porous media which is independent of the fluid. This means that, for example, *K* will go up if the water in a porous medium is heated (reducing the viscosity of the water), but *κ* will remain constant. The two are related through the following equation

$$K = \frac{\kappa \gamma}{\mu}$$

where

- K* is the hydraulic conductivity [LT^{-1} or m s^{-1}];
- κ* is the intrinsic permeability of the material [L^2 or m^2];
- γ* is the specific weight of water [$\text{ML}^{-2}\text{T}^{-2}$ or N m^{-3}], and;
- μ* is the dynamic viscosity of water [$\text{ML}^{-1}\text{T}^{-1}$ or $\text{kg m}^{-1} \text{s}^{-1}$].

Estimation of hydraulic conductivity

Direct estimation

Hydraulic conductivity can be measured by applying Darcy's law on the material. Such experiments can be conducted by creating a hydraulic gradient between two points, and measuring the flow rate (Oosterbaan and Nijland^[1]).

Empirical estimation

Shepherd^[2] derived an empirical formula for approximating hydraulic conductivity from grain size analyses:

$$K = a(D_{10})^b$$

where

a and *b* are empirically derived terms based on the soil type, and *D*₁₀ is the diameter of the 10 percentile grain size of the material

Note: Shepherd's Figure 3 clearly shows the use of *d*₅₀, not *d*₁₀, measured in mm. Therefore the equation should be *K* = *a*(*d*₅₀)^{*b*}. His figure shows different lines for materials of different types, based on analysis of data from others with *d*₅₀ up to 10 mm.

Pedotransfer function

A pedotransfer function (PTF) is a specialized empirical estimation method, used primarily in the soil sciences, however has increasing use in hydrogeology^[3]. There are many different PTF methods, however, they all attempt to determine soil properties, such as hydraulic conductivity, given several measured soil properties, such as soil particle size, and bulk density.

Experimental approach

There are relatively simple and inexpensive laboratory tests that may be run to determine the hydraulic conductivity of a soil: constant-head method and falling-head method.

Constant-head method

The constant-head method is typically used on granular soil. This procedure allows water to move through the soil under a steady state head condition while the quantity (volume) of water flowing through the soil specimen is measured over a period of time. By knowing the quantity *Q* of water measured, length *L* of specimen, cross-sectional area *A* of the specimen, time *t* required for the quantity of water *Q* to be discharged, and head *h*, the hydraulic conductivity can be calculated:

$$Q = Avt$$

Using Darcy's Law, *v* = *Ki*,

$$\text{yields } Q = \frac{AKht}{L}$$

Solving for *K* gives,

$$K = \frac{QL}{Ath}$$

Falling-head method

The falling-head method is very similar to the constant head methods in its initial setup; however, the advantage to the falling-head method is that can be used for both fine-grained and coarse-grained soils. The soil sample is first saturated under a specific head condition. The water is then allowed to flow through the soil without maintaining a constant pressure head^[4].

$$K = \frac{2.3aL}{At} \log \left(\frac{h_1}{h_2} \right)$$

Transmissivity

The **transmissivity**, *T*, of an aquifer is a measure of how much water can be transmitted horizontally, such as to a pumping well:

$$T = K_s b$$

Transmissivity is directly proportional to the aquifer thickness. For a confined aquifer, this remains constant, as the saturated thickness remains constant. The aquifer thickness of an unconfined aquifer is from the base of the aquifer (or the top of the aquitard) to the water table. The water table can fluctuate, which changes the transmissivity of the unconfined aquifer. This may provide positive feedback of a pumping well that is pumping more than can be provided by the aquifer, where the transmissivity drops as the well pumps, thus eventually reducing the aquifer to the height of the pumping well screen.

Transmissivity should not be confused with similar word transmittance (used in optics), which means fraction of incident light that passes through a sample.

Relative properties

Because of their high porosity and permeability, sand and gravel aquifers have higher hydraulic conductivity than clay or unfractured granite aquifer. Sand or gravel aquifers would thus be easier to extract water from (e.g., using a pumping well) because of their high transmissivity, compared to clay or unfractured bedrock aquifers.

Hydraulic conductivity has units with dimensions of length per time (e.g., m/s, ft/day and (gal/day)/ft²); transmissivity then has units with dimensions of length squared per time. The following table gives some typical ranges (illustrating the many orders of magnitude which are likely) for *K* values.

Hydraulic conductivity (*K*) is one of the most complex and important of the properties of aquifers in hydrogeology as the values found in nature:

- range over many orders of magnitude (the distribution is often considered to be lognormal),
- vary a large amount through space (sometimes considered to be randomly spatially distributed, or stochastic in nature),
- are directional (in general *K* is a symmetric second-rank tensor; e.g., vertical *K* values can be several orders of magnitude smaller than horizontal *K* values),
- are scale dependent (testing a m³ of aquifer will generally produce different results than a similar test on only a cm³ sample of the same aquifer),

- must be determined indirectly through field pumping tests, laboratory column flow tests or inverse computer simulation, (sometimes also from grain size analyses), and
- are very dependent (in a non-linear way) on the water content, which makes solving the unsaturated flow equation difficult. In fact, the variably saturated *K* for a single material varies over a wider range than the saturated *K* values for all types of materials (see chart below for an illustrative range of the latter).

Ranges of values for natural materials

Table of saturated hydraulic conductivity (*K*) values found in nature

Values are for typical fresh groundwater conditions — using standard values of viscosity and specific gravity for water at 20°C and 1 atm. See the similar table derived from the same source for intrinsic permeability values.^[5]

<i>K</i> (cm/s)	10 ²	10 ¹	10 ⁰ =1	10 ⁻¹	10 ⁻²	10 ⁻³	10 ⁻⁴	10 ⁻⁵	10 ⁻⁶	10 ⁻⁷	10 ⁻⁸	10 ⁻⁹	10 ⁻¹⁰
<i>K</i> (ft/day)	10 ⁵	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001	10 ⁻⁵	10 ⁻⁶	10 ⁻⁷
Relative Permeability	Pervious			Semi-Pervious				Impervious					
Aquifer	Good				Poor				None				
Unconsolidated Sand & Gravel	Well Sorted Gravel	Well Sorted Sand or Sand & Gravel			Very Fine Sand, Silt, Loess, Loam								
Unconsolidated Clay & Organic					Peat	Layered Clay			Fat / Unweathered Clay				
Consolidated Rocks	Highly Fractured Rocks				Oil Reservoir Rocks			Fresh Sandstone	Fresh Limestone, Dolomite		Fresh Granite		

Source: modified from Bear, 1972

See also

- Aquifer test
- Pedotransfer function—for estimating hydraulic conductivities given soil properties

References

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- [^] Wösten, J.H.M., Pachepsky, Y.A., and Rawls, W.J. (2001). "Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics" **251**: 123–150. doi:10.1016/S0022-1694(01)00464-4.
- [^] Liu, Cheng "Soils and Foundations." Upper Saddle River, New Jersey: Prentice Hall, 2001 ISBN 0-13-025517-3

5. ^ Bear, J. (1972). *Dynamics of Fluids in Porous Media*. Dover Publications. ISBN 0-486-65675-6.

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