

Diffusion and percolation in soils

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Soils are particularly complex porous media. Three mineral phases are present: **the solid grains** that make up the soil itself and which are generally of different natures and grain sizes (pebbles, sand, clay), the **water** that can completely fill the gaps between grains, especially at depth, **and the air** present in the upper layers, called unsaturated. Exchanges between these three mineral phases involve many physical and chemical phenomena, including the transport of chemical species essential for the growth of vegetation cover. In addition, there is intense biological activity in these soils, with various organisms living in, feeding on and transforming them: roots, animals, fungi, humus and a large number of microorganisms, such as bacteria and viruses.

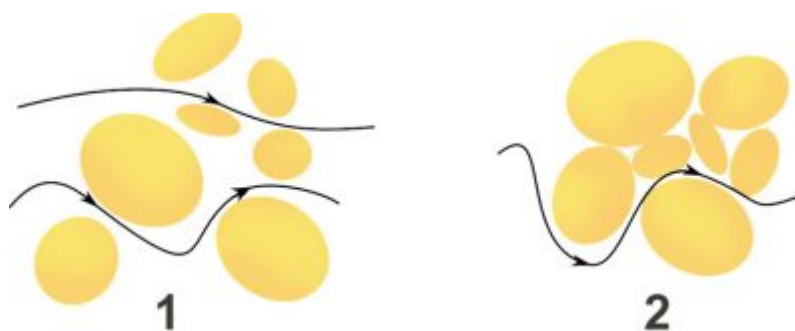


Figure 1. The porosity of a soil is determined by the size of the gaps between the grains. The water flow rate in situation 1 is higher than in situation 2, which is less porous. These interstices can be occupied by both a liquid phase and bubbles or gas pockets. [Source: By Lamiot[CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/>)], from Wikimedia Commons]]

In this focus, let us omit living organisms, assume the immobile solid phase, and designate by "water" the liquid phase treated as a homogeneous fluid, although this is not the case since it is generally a suspension of fine particles and a solution of dissolved physico-chemical substances like colloids. These materials carried away by water affect their properties, such as density and viscosity. Even in dry soil, there is usually a thin film of water left attached to each grain by the adsorption mechanisms [1]. The importance of the amount of immobile fluid contained in this film in relation to the volume of mobile fluid depends on the surface area in contact with the grains (this specific surface area varies from several hundred m² per gram of soil for some clays to a few cm² per gram for sands) and the ionic charge of these grains (very high for clays, zero for sands). **Diffusion** is the main exchange mechanism between this film and the surrounding liquid. It also has a significant influence within the mobile phase, for example when transporting chemicals by spreading a salinity front.

At the scale of the interstices shown in Figure 1, which is much larger than that of the bound film, capillarity requires the water to rise from the deep groundwater to the upper layers; here and there, bubbles or air pockets interrupt the liquid columns. This very slow upward movement feeds the surface evaporation. In addition, under the effect of pressure differences, a large scale, almost horizontal flow may be present. These pressure differences may arise from the relief, for example between two reservoirs at different altitudes, or may be imposed, for example when water is drawn from the water table (see Figure 2). It is this flow through the ground that is referred to as **percolation**. It combines with diffusion to generate the transport of the various species carried in this environment, both nutrients and pollutants.

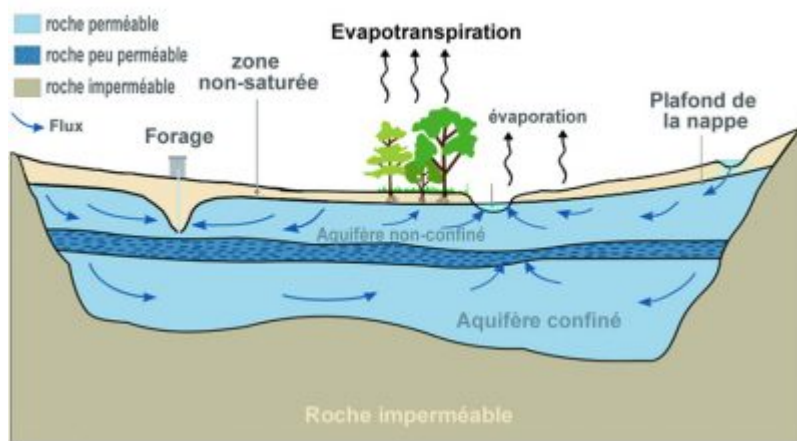


Figure 2. Illustration of large-scale water flows in a soil, with contributions from various media: groundwater, aquifer, unsaturated zone, reservoirs, drilling and vegetation cover. [Source: By Lamiot[CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/>)], from Wikimedia Commons]]

Let us limit ourselves here to recall the law that governs the flow of water in such soil, under the effect of pressure differences, in a situation such as that in Figure 2, and let us also limit ourselves to the largest scales, clearly greater than the thickness of the unsaturated layer. The main parameter is **the permeability K** of the porous medium constituted by this soil, introduced by Darcy

[2] and defined as follows. It is advisable to forget the complex geometry of the pores to imagine a fictitious flow through the entire section S of the medium, which includes both grains and pores. The velocity that is introduced is then fictitious, it is the ratio of the flow rate Q that actually flows through the pores to this large section S . Darcy proposed to express this flow rate Q as $Q = K S \Delta p / \mu L$, where μ denotes the dynamic viscosity of the water and $\Delta p / L$ the pressure gradient. This law is known as the Darcy's Law [3]. The K quantity, often referred to as intrinsic permeability, is mainly used in petroleum engineering. It is a very global representation of soil porosity. It has the size of a square of one length and is often expressed in $(\mu\text{m})^2$, a quantity still called the darcy.

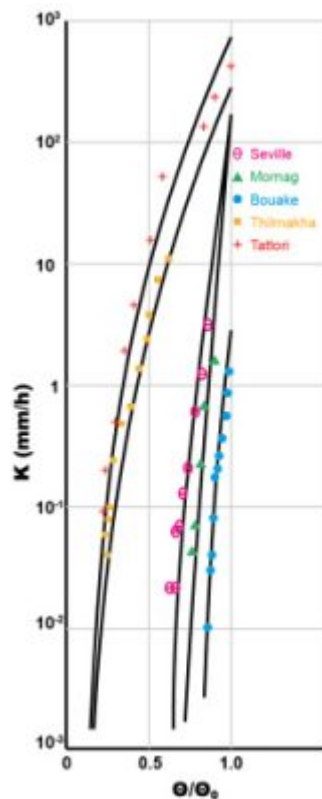


Figure 3. The hydraulic conductivity of a soil can vary from 10^{-2} to 10^3 mm/hour, depending on the type of soil. The curves shown correspond to 5 examples of sites ranging from very sandy soil (Tattori, Japan) to clayey soil (Bouaké, Cote d'Ivoire); the symbols correspond to values measured in situ, the lines to calculated variations) [Source: © EDP Sciences, Authorization to reproduce received by G Vachaud]

The common usage in hydrology is to write Darcy's law as $Q/S = k \text{ grad} H$, where **k is the hydraulic conductivity** in (m.s-1) and H (m) the hydraulic load. For example, in agricultural land the hydraulic conductivity k is between 0.1 and 1 $\mu\text{m.s}^{-1}$, and in sand with a more homogeneous grain size it reaches 10 to 100 $\mu\text{m.s}^{-1}$. Thus, the fictitious velocity Q/S generated by a pressure difference of 1 atmosphere (10^5 Pa or a height of 10 m of water) spread over 100 m, is of the order of 0.1 to 1 $\mu\text{m.s}^{-1}$ in agricultural land. It can reach values 100 times higher in sand.

Finally, it should be noted that in the unsaturated zone of Figure 2, which is the site of infiltration, capillary rise and evaporation processes, the value of this parameter depends very strongly on the saturation rate of the environment. Characteristic values of hydraulic conductivity obtained on different soil types [4] (from clayey agricultural soils to sandy soils) are given in Figure 3.

Finally, we will note the formal analogy between this expression of flow in soils, proportional to the pressure gradient, and the laws of Fick, Fourier and Newton, where the flow is proportional to the gradient of the transported quantity.

References and notes

Cover image. A section of soil that allows the analysis of its porosity, water content, evolution and biological activity. [Source: By HolgerK at English Wikipedia (Transferred from en.wikipedia to Commons.)[Public domain], via Wikimedia Commons]]

[1] Adsorption is a surface phenomenon based on dipolar atomic interactions or chemical bonds, which allows a solid surface to bind atoms, ions or molecules of the neighbouring fluid.

[2] Henry Philibert Gaspard Darcy (1803-1858), general engineer of the Ponts et Chaussées, designed and built the water supply system for the city of Dijon by draining former swamps, which enabled him to build a drinking water distribution network.

[3] H. Darcy, *Les fontaines publiques de la ville de Dijon : détermination des lois d'écoulement de l'eau à travers le sable*, V. Dalmont, Paris, 1856.

[4] M. Vauclin and G. Vachaud, *Hydrodynamic characterization of soils...*, Agronomy, EDP Sciences, 1987, 7 (9), 647-655, <hal-00885038>

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