HYDROLOGICAL INFLUENCE OF SOIL AIR

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ABSTRACT

Air in soil increases pressure under the percolating water. Early ideas of the importance of air influence consideration are referred. Own measurements are presented, which show that percolated water and soil air considerably influence each others.

INTRODUCTION

Above groundwater infiltrated water and soil air influence each others (Morel-Seytoux, 1973; Touma and Vauclin, 1986; Bear and Bachmat, 1991).

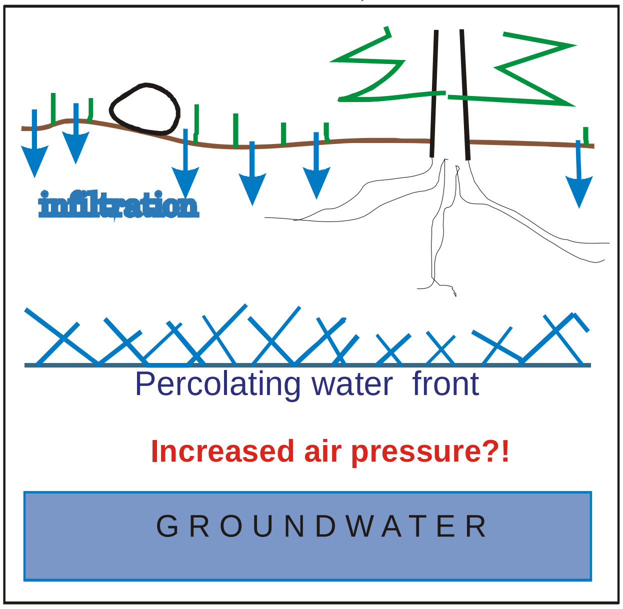
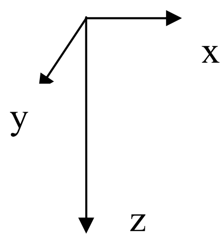


Figure 1. Piston flow, fingering processes, or the both together?

Already in 1855-56 Henry P. G. Darcy conducted column measurements where he found generally a very good relation between the water head h [m] (or piezometric head) and the water flow $\mathbf{q}$ [$m^3s^{-1}m^{-2}$] in saturated conditions, mentioned Darcy law (Brown, 2005; Hubbert, 1940) valid for groundwater flow. When the x and y coordinates are horizontal and the z coordinate down, Darcy law has (Morel-Seytoux, 1973) the differential form

$$\mathbf{q} = -K\,\nabla h = -\frac{K}{\rho\, g}\nabla p + K\,\mathbf{e}_z, \qquad (1)$$



where K (the hydraulic conductivity) is the proportionality coefficient between the flow $\mathbf{q}$ and the head gradient. ρ is density and p pressure of water (or another fluid), g is the acceleration of gravity, and $\mathbf{e}_z$ is the unite vector of the vertical (down) direction.

In groundwater the air bubbles can only occur close to the groundwater surface in about 1 m and even there influence water movement (Ronen et al., 1989). In the larger depths the gas bubbles are dissolved by hydraulic pressure, Henry law (10).

GREEN-AMPT AND RICHARDS RESEARCH

Green and Ampt (1911) considered that air and water movements in soil are as important. They measured air and water penetration in soil columns as Darcy did for water. Darcy equation became soon significant for groundwater and Richards (1931) applied it for percolating water in unsaturated conditions. However, Richards made his infiltration experiments in special circumstances: the air pressure in the soil samples was constant, atmospheric. This condition can not be applied for water transfer in the natural circumstances of water percolation.

After snow melt and rain events, maybe, water infiltrates like a piston into soil. The air in soil under the water front has pressures above the atmospheric. The signal of the pressure is transferred rapidly into the surface of groundwater (Grip and Rodhe, 1988). This also often causes a rise of the groundwater surface. The air conductivity of soil is much higher than its conductivity for water. Air molecules are livid; at 277.2 K the mean velocities of N_2, O_2 and Ar molecules are 458, 428 and 384 ms^{-1}, respectively.

Green and Ampt (1911) measured air and water conductivities, the values of K, in three different soil types, for air only when substances were dry. Using these values and the values of air and water dynamic viscosities $\nu = \mu / \rho$ (μ is viscosity), they calculated the values of the quantity $k = K\nu/g = K\mu/\rho g$. Viscosity is a quantity of fluid. The k is seen to be a quantity of porous matter. It is permeability, i.e., how easily fluid penetrates matter. Their results of the ratios of air and water permeabilities are presented in Table 1. They expected the value $k_a/k_w = 1$. This should mean, that it exists the intrinsic permeability $k = k_w = k_a$ (see next page).

Table 1. Relative permeabilities of 3 soils for air and water (Green and Ampt, 1911).

Soil	Sand	loam	clay
k_a/k_w	2	3-6	14

These values show that the permeabilities are not entirely independent on fluid type. In clay the relative transmissivity of air is greater. Water wettability has greater importance in the clay case than in the penetration through more rough matters. When pores are larger the adhesive contacts influence less.

The pore channels are tortuous. The channel types in porous matter can vary in different directions. Soils are not always isotropic.

The infiltration model of Green and Ampt (1911) assumes that the hydraulic conductivity K has two values K_0 of saturated soil and 0 for the dry soil. Youngs (1988) shows that the Green-Ampt model and the assumption, that K is an exponential function of water pressure, the both give the results in satisfactory agreements with infiltration experiment.

MORE OF BASIC EQUATIONS

Observations and air flow measurements have shown that it is necessary to use the infiltration and percolation calculation methods for both the water and air of unsaturated soils (Morel-Seytoux, 1973; Touma and Vauclin, 1986). Mostly and here also it is assumed that solid skeleton matter is stable. Let n be porosity, and S_i is the volume portion of substance i in the pore space; i = *a* for air, i.e., soil gas, and i = *w* for water.

$$S_w + S_a = 1 . \qquad (2)$$

The continuity demands (assume: soil properties vary only in z-direction)

$$-\nabla \cdot (\rho_i \mathbf{q}_i) = -\frac{\partial(\rho_i q_i)}{\partial z} = \frac{\partial(\rho_i S_i n)}{\partial t} , \qquad (3)$$

where $\mathbf{q}_i$ is from (1). For water as incompressible we have

$$-\nabla \cdot \mathbf{q}_w = -\frac{\partial q_w}{\partial z} = n\frac{\partial(S_w)}{\partial t} , \qquad (4)$$

but for air the mass equation

$$-\nabla \cdot (\rho_a \mathbf{q}_a) = -\frac{\partial(\rho_a q_a)}{\partial z} = n\frac{\partial(\rho_a S_a)}{\partial t} \qquad (5)$$

must be written. For the ideal gas

$$\rho = \rho_0 \frac{p}{p_0}\frac{T_0}{T} , \qquad (6)$$

where the zero-circumstances are selected as Relevant, e.g. T_0= 273.15 K and $p_0 = 1$ atm for air. Morel-Seytoux (1973) showed that (1), in the onedimensional case

$$q_i = -K_i \frac{\partial h_i}{\partial z} = -\frac{K_i}{\rho_i g}\frac{\partial p_i}{\partial z} + K_i , \ i = \text{w or a}, \qquad (1')$$

is relevant when Hubbert's (1940) presentation

$$h_a = \int_{p_0}^{p} \frac{dp}{\rho_a g} - z \qquad (7)$$

is used for air.

For K_w and K_a the presentations $K_i = kk_{ri} g/\nu_i$ have mostly been used (Phuc and Morel-Seytoux, 1972, Morel-Seytoux, 1973, Touma and Vauclin, 1986), where *k* is the intrinsic permeability and k_{rw} and k_{ra} are relative permeabilities.

Touma and Vauclin (1986) did not find that the presentation above agreed well with their column measurements. In percolation the water and air counter-currents, and maybe the cross Darcy effects with the double equations

$$\mathbf{q} = -K_{ii}\nabla h_i - K_{ij}\nabla h_j , \text{ where } i, j = 1, 2 \text{ and } i \neq j \qquad (8)$$

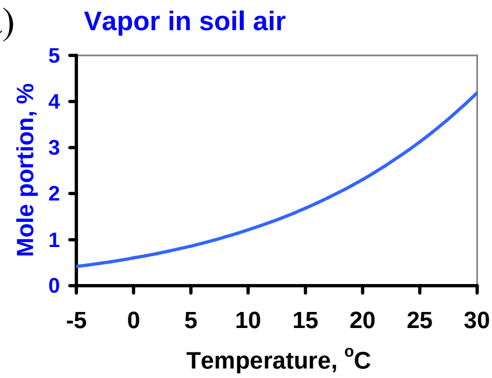
are useful (e.g. Kalaydjin, 1990, Kasi, 2000). Li et al. (2005, 2006) carried out some relevant experiments and their simulations. Kalaydjin (1990) showed that for all the four *K* in (8) the relative permeability values can be found when water and oil are the fluids.

EFFECTS INFLUENCING IN SOIL

Soil air temperature. Ground water in Finland generally is in liquid form, but about the third of year the ambient temperature is mostly below zero. Some atmospheric air flows into soil and some comes out from soil. When gas mass m_0 is closed in the volume V_0 part of pore system, because density (6) is then constant, we can write

$$p = p_0 \frac{T}{T_0}. \qquad (9)$$

a)



b)

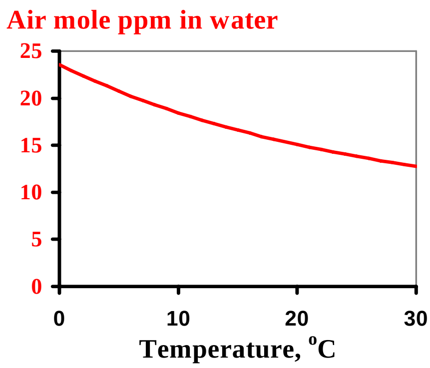


Figure 2. a) Temperature dependence of soil air saturating water vapour portion. b) Temperature dependence of in water dissolved saturating air portion, x, when p = 1 atm.

Vapour in air. Soil air certainly is saturated by water vapour. Vapour is transferred within the air transfers.

Dissolved air in water. Though the air dissolves in water in relatively small amounts, then, when dissolved, the air pressure is diminishing. This is a slow process, for solubility x is proportional to pressure:

$$x = \mathrm{H}\, p, \qquad (10)$$

Henry law, the coefficient H mentioned Henry constant.

When water percolates, it continuously occupies a new volume, and the preceding volume fills with air. In winter the soil is warmer than the ambient air, and the cold ambient air finds certain ways to penetrate (Okko, 1957) into soil. It then warms up, and because of (9) increases in pressure. In summer then certain groundwater depositions can be in frozen state, see references of (Kasi, 2005).

OBSERVATIONS

Morel-Seytoux (1973) refers to a couple of measurements in soil columns and to the numerical results of his group (e.g. Phuc and Morel-Seytoux, 1972). A later experiment is that of Touma and Vauclin (1986).

In the last years the author has made observations and measurements of soil air movements in glaciofluvial formations (Kasi, 2003, 2004). Outflows of soil air have been observed in low parts of the esker hills and also in winter in upper parts of esker, where soil is porous because of it contains a lot of relatively big stones. Snow melting, caused by these air flows, has been observed.

On the tops of hills where the outflows in winter are observed, in summer the air flow is into the soil. Resembling types of air movements Tanaka et al. (2000) have measured in Japan and Korea. They have also modelled the air movements.

Kasi (2003) first measured air temperature and humidity, and later the velocities of the inflow and outflow by using a hot wire anemometer (Kasi, 2004).

Air flows after the rain event July-August 2004

In the last days of July 2004 there was a big rain event (Fig. 3) between 27.7. and 3.8. in southern Finland. The rain values of 8 precipitation stations around Leiriharju

(Fig. 4) in Lammi gave the total precipitation of the event 130 mm at Leiriharju (when calculating from a weighing procedure using the squares of the distance inverses of stations the numerical result was 129 mm).

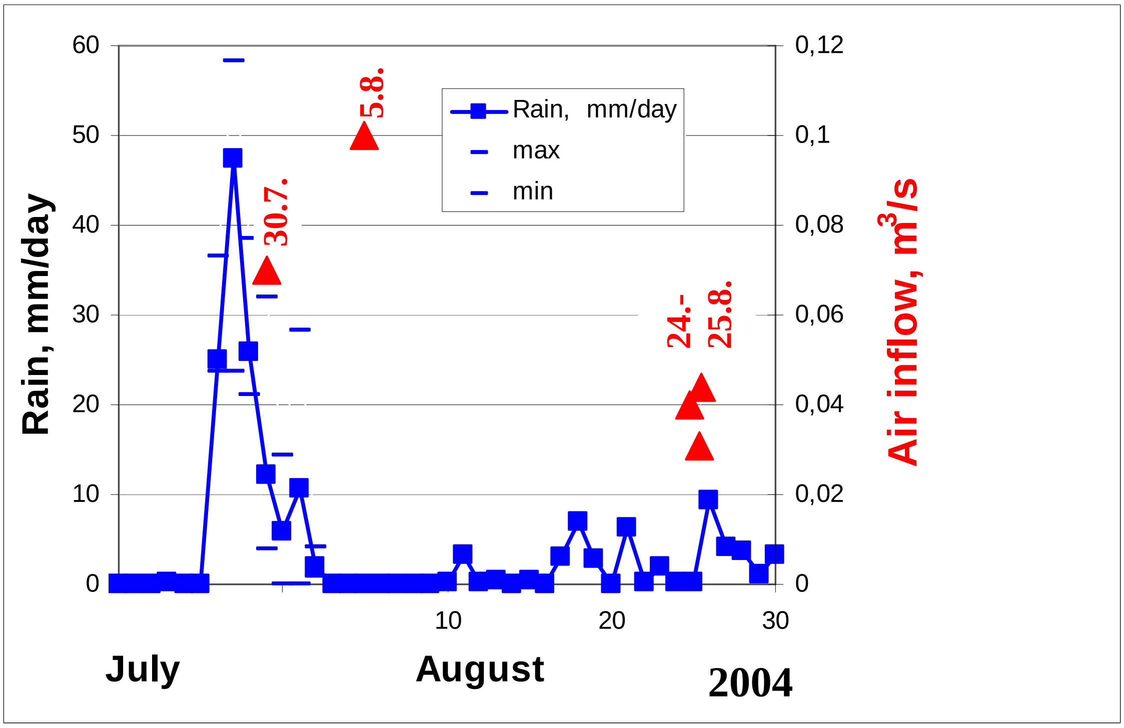


Figure 3. Daily rains at Leiriharju (max and min among 8 close stations) and the inflows, measured in 4 dates, below the Leiriharju stone, cf. Fig. 4.

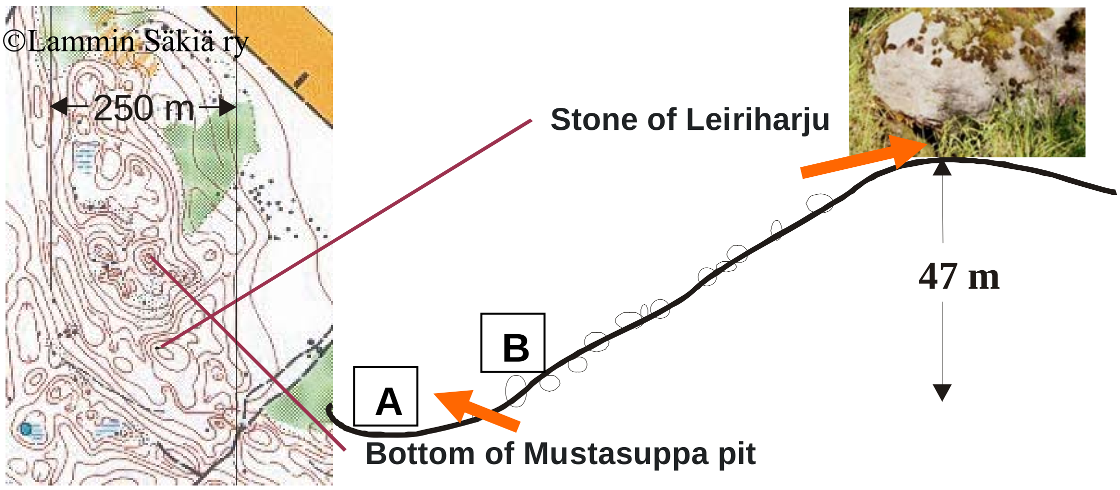


Figure 4. Research site in Lammi. Stone 61º8'11.7"N 24º57'27.9"E. Arrows give the positions of air inflow and outflow after the rain event in July-August 2004. **A** and **B**, see Table 2 and text.

At the end and after this big event Kasi (2004) examined the air movements in Lammi. At the top of Leiriharju (or Mustasuppa esker), Fig. 4, into the hole below the stone there is air inflow in summer (and the warm air outflow in winter). The slope and bottom of the Mustasuppa pit is mainly of loose boulders. In such soils there are also very big pores which are connected to each others. The upper part of Leiriharju is of moraine, with boulders.

The hole mouth has the cross area 0.10 m^2. In 2004 the air inflow was measured 30.7., 5.8. and 24-25.8, Fig. 3, and also the outflows in the Mustasuppa pit, Fig. 3 and Table 2. The values of air velocity at the same position vary considerably; 5.8. the largest value (in a point at the mouth of the hole) varied in the range 0.8 - 1.3 m/s.

Table 2. Outflows of air in Mustasuppa pit. Hole positions, see Fig. 4.

Date 2004	30.7.			5.8.			24-25.8.		
	m/s	^oC	RH%	m/s	^oC	RH%	m/s	^oC	RH%
Holes **A**	0.15	4.2	62	0.07-0.22	3.6	48	0.2-0.4	3.9	55
Holes **B**	No flow			0.1-0.55	8.8	89	0.2-0.5	5.3	

At 19.11.2004 in holes **A** there were outflows about 0.2 m/s. At the same time the inflow below the stone at the top of hill was turned into outflow too (cf. Tanaka et al., 2000). 31.1.2005 all these outflows were almost similar. 16.3.2005 in Mustasuppa pit in the holes **A** the outflows were very weak.

What to see in the results

During the big rain event 30.7.04. the air inflow was maybe normal, but 5.8. it was increased considerably. After water infiltration the down-flowing waterbed presses the air below it. In 29.6.2004 in Mustasuppa pit in **A** (Fig. 4) was also then the outflow. In Table 2 is to see that 30.7.04. the outflow was only in **A**. However, 5.8.04. the outflows have increased considerably, and in the holes more up, in **B**, the temperature was 8.8 ^oC. The inflow (i.e.ambient) temperature at Leiriharju stone in 30.7.04. was 18.2 ^oC.

If in soil the porosity $n = ⅓$ and the percolating bed has 100 mm water, then its height is 0.3 m. The hydrostatic pressure in the water front is about 3 kPa. Then below the percolating water bed there occurs relatively rapidly growing 3 % increase of soil air pressure (above the atmospheric) in a certain soil air volume.

CONCLUSION

The observations and air movement measurements of this paper have been made in hilly forests. After the big rain event in summer 2004 in the month break July-August the infiltrated water clearly caused the increased air outflow from the esker root and also the increase of the air inflow into the esker on its top.

However, in flat terrains the air movement below waterbeds is more difficult, and air influences maybe stronger. Air escape below gravitational water descent can be more difficult. In soils the counter-flows of air and water occur. Then the hysteresis of drainage and imbibition phases (Li et al. 2006) can be important. Already Green and Ampt (1911) found that permeability depends on fluid. Consideration of water as a wetting and air as non-wetting fluid does not seem to be the sufficient starting point of theory. The relative permeabilities for the co- and counter-flows, as Kalaydjin (1990) determined for water and oil, maybe can be found for water and air and applied in the equation (8). Pore size distribution and structure influence too.

It seems that both the piston flow and fingering processes should be applied in modelling. For all kind of soil circumstances the hydrological phenomena prosperously simulating models are to be found.

Research on the hydrological influence of air in grounds, soils and rocks should go on.

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