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CHANGES OF STEADY-STATE INFILTRATION RATES IN RECURRENT PONDING INFILTRATION EXPERIMENTS

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ABSTRACT

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Ponding infiltration experiments on coarse acid brown soils (Cambisol) are described to show that the steady-state infiltration rate depends on the initial moisture content, which is in contrast with the theory. The effect is observed on three different scales: (1) in the field at randomly chosen places near grid points of a network for two recurrent days under various initial moisture content; (2) in the field, in cylinders installed at fixed places for several measurements under different initial moisture content; and (3) on undisturbed samples taken to the laboratory, where also the outflow of the sample was observed. The effect is most apparent in repetitive ponding infiltration experiments and is ascribed to trapped air which alters the volume available for the gravity dominated flow. Instead of piston-like flow, downward flow through macropores takes place. As a consequence, the ponding infiltration experiment does not supply theoretically assumed constants.

INTRODUCTION

Measurements of ponding infiltration were carried out for three years on a regular grid of a small experimental area to study the variability of infiltration and soil hydraulic characteristics in the Volynka River watershed. Repetitive measurements showed a strong dependence of the steady-state infiltration rates on the initial moisture content. The effect was observed on three different scales in the field and in the laboratory. It has been qualified as a flow irregularity.

Ponding infiltration experiments supply very useful information about the soil profile. Together with the initial pressure head or moisture content distribution over the soil profile, the course of infiltration from a flooded surface as a function of time represents its dynamic characteristic. Ultimately, a steady-state infiltration rate is reached which, according to theory, is independent of the initial moisture content. To report irregularities in steady-state infiltration rates, it should first be made clear what is exactly understood by this term.

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Ponding is an extreme boundary condition which is rare for well permeable soils under natural conditions. If it takes place at all it is for short time intervals only, during high-intensity showers. In routine ponding infiltration experiments in the field, the state of saturation is rarely monitored. The definition of the value of the steady-state infiltration rate from infiltration measurements is not standardized. Usually each author defines his own rules as to which quantity to consider as a steady-state infiltration rate. Thus, for instance, Sharma et al. (1985) and Wilcock and Essery (1984) take the value of the infiltration rate as the quantity after 60 min of infiltration, whereas Vieira et al. (1981) determine this value after four days of continuous ponding. The character of the soil under consideration and the available technical equipment play the main role in the decision making.

The steady-state infiltration rate resulting from ponding represents the integral influence of the saturated hydraulic conductivities of particular layers of the soil profile, including the influence of macrostructure, preferential pathways and anisotropy. Moreover, it depends on the technical details of the experiment, for example the number and size of the infiltration cylinders and the depth of insertion into the soil, etc. Apart from the assumed vertical downward flow some lateral flow also takes place.

Under field conditions all effects, such as structure and texture irregularities, hysteresis, layering, air–water interaction are always combined. Often these effects are hidden in the spatial variability parameters. They are the reason that the use of ordinary theoretical means to describe the water flow produces false results. To trace particular effects is very difficult. Up to now these problems have not been submitted to a systematic theoretical analysis and there is not much experimental evidence available.

LITERATURE REVIEW

For soils under field conditions, and also for materials of coarse texture in the laboratory, irregularities in flow behaviour are reported elsewhere which are in contradiction with the classical theory of flow in porous media.

The problem is presented in general in the work of Thomas and Philips (1979) who pointed out the importance of not ignoring the real conditions in nature, especially with respect to the rapid-flow-down macropores. The occurrence of mobile and immobile water is discussed in the sense introduced by Van Genuchten and Wierenga (1976). Based on field measurements of ponding infiltrations, Tricker (1981) and Wilcock and Essery (1984) reported the dependence of steady-state infiltration rate on the initial moisture content of the soil profile as observed at monthly intervals. Field et al. (1984) explain measured differences between field and laboratory saturated hydraulic conductivities. Kneale (1985) found values of unsaturated hydraulic conductivities, calculated from the drainage of large undisturbed soil cores, to vary with the size of the step in potential imposed at the start of each drainage experiment. Smettem (1987) studies the influence of macropores on the variability of infiltration parameters.

In the approach reviewed by Nielsen et al. (1986), the flow through structured soils is stated to be substantially different from that in homogeneous materials. The effect of macropores is described for example in papers of Bouma (1981), Beven and German (1982), and others. Hillel (1987) gives a review of unstable flow in layered soils characterized by instability of wetting fronts due to texture irregularities with effects described as "fingering" or "piping". The theoretical analyses for such cases were attempted by Dolezal (1971), Raats (1973), Philip (1975), Parlange and Hill (1976), Diment and Watson (1983), and others.

Finally, Poulovasilis (1970) described experiments on coarse material where changes of the values of saturated hydraulic conductivity and saturated moisture content for zero pressure head were found to be due to hysteresis.

This review is not exhaustive. According to our opinion, the listed irregularities could all be related to the problem we report in the present paper. It does not contribute to the theory but gives more experimental evidence about the subject as observed in the field.

DESCRIPTION OF THE EXPERIMENTAL AREA

The experimental area is located on a plane of very mild slope in the Volynka River watershed in the Sumava mountains which represent the main source area of the Moldau River. The total annual precipitation is about 800 mm. The soil profile described as sandy-loam acid brown soil (Cambisol or Umbrept) has a relatively high permeability due to its coarse texture. It consists of four layers: the surface plow horizon of 25–35 cm, followed by a less permeable horizon (0–40 cm) of bright reddish brown colour which is not present everywhere in the area. The third horizon is a gradual transition to the fourth horizon — an underlying decayed gneiss substratum beginning at about 85 cm depth. No significant structure is developed, especially in the lower layers. The mean content of clay particles is 8.8%, signs of swelling in any horizon are negligible. The mean values of saturated hydraulic conductivities K_s measured in the laboratory with a constant level apparatus for 100 cc core samples are shown in Table 1, together with the mean values of bulk and specific densities and mean values of saturated moisture content. The data were obtained in the ordinary soil survey of the experimental area. Signs of hysteresis and a relatively high variability of saturated moisture contents were noticed. During the measurements of K_s, the consistence of the core samples was always slightly disturbed due to unnatural saturation.

DESCRIPTION OF EXPERIMENTS AND DISCUSSION

For the ponding infiltration experiments in the field, cylinders (diameters see later) were carefully inserted into the soil to a depth of 15–20 cm. After an initial amount of water necessary to flood the surface of the inner cylinder up to the height of a fixed needle, regular doses of water were added at the time when the point of the needle cut the ponded water surface.

TABLE 1

The mean values of soil characteristics obtained in the soil survey of the experimental area

Horizon	Saturated moisture content		Densities				Hydraulic conductivity K_s	
			Bulk		Specific			
	Mean ($g\,cm^{-3}$)	*CV* (%)	Mean ($g\,cm^{-3}$)	*CV* (%)	Mean ($cm\,h^{-1}$)	*CV* (%)	Mean ($cm\,h^{-1}$)	Range ($cm\,h^{-1}$)
1	0.521	4.7	1.08	5.2	2.57	1.3	19.90	1.8 – 37.2
2	0.509	5.1	1.25	4.0	2.64	1.3	6.88	3.4 – 13.4
3	0.483	9.2	1.35	9.9	2.66	0.8	9.44	1.4 – 17.5
4	0.338	–	1.50	9.5	2.69	0.5	4.53	0.2 – 16.9

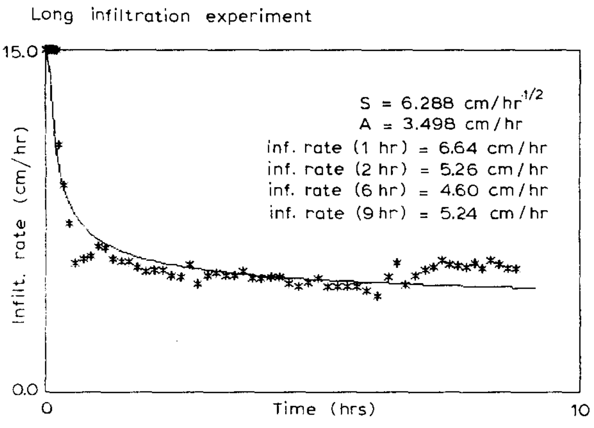

Fig. 1. The course of the long infiltration experiment measured in the field and compared with infiltration theory.

In advance of routine experiments, in the summer of 1984, a long-term ponding infiltration experiment was performed. A cylinder of diameter 60 cm was placed in the middle of a square area 2 × 2 m which was flooded in the same way as the inner part of the cylinder. In two access tubes, within the inner and the outer flooded area, the moisture content was measured every 10–15 minutes up to depth of 1.1 m by a neutron probe. Water was infiltrating for nine hours. The data about the infiltration rates can be seen in Fig. 1, together with the best fit of Philip's simplified two-term equation derived for homogeneous soil profiles. Parameters of the cumulative infiltration in time expressed as:

$$i = St^{1/2} + At \tag{1}$$

were fitted by the least squares method. The infiltration rate is calculated from the relation:

$$v = 1/2\,St^{-1/2} + A \tag{2}$$

S is the sorptivity $[\mathrm{L\,T^{-1/2}}]$, A is a constant $[\mathrm{L\,T^{-1}}]$.

The initial moisture content of the soil profile was about 80% of saturation in the surface and the bottom layers, 75–78% in the other horizons (Fig. 2). At 45 min from the start of the experiment the profile at the full depth showed a moisture content equal to the (field) saturation value. After that no further increase in moisture content was seen. In total 53 cm (4.5 m^3) of water infiltrated during the 9 h of experiment, assumingly leaving the location as lateral flow above the lowest, least permeable, horizon.

From the described long experiment it can be seen that the steady-state infiltration rate was reached soon after the start of ponding and that it changed only slightly afterwards. In view of this information it was decided to use in further infiltration experiments for the upper estimate of the steady-state infiltration rate the rates far behind the steep descent of the infiltration rate

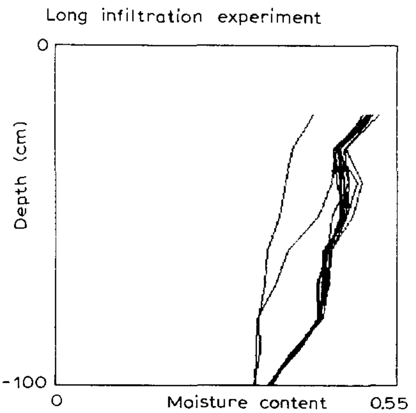

Fig. 2. Soil moisture profiles measured during the long infiltration experiment inside the inner cylinder by the Troxler neutron probe. The first curve is measured at the start, the other curves are measured at times (h. min) 0.10, 0.30, 0.45, 1.00, 1.15, 1.30, 2.30, 3.15, 4.30 and 9.00 after the start.

curve, particularly elected for each particular experiment. In the region under observation the time to reach such a value was within the range 1/2–3 h. As the lower limit of the steady-state infiltration estimate Philip's parameter A can be taken.

In contrast with the stable course of infiltration rates observed during the long ponding as reported above, the interruption of an infiltration experiment resulted in a sharp decrease of the infiltration rate found in the next run.

The changes in steady-state infiltration rates were observed on three different scales.

Scale 1

Routine type infiltration experiments were made in 18 points of a square grid (3×6 points in steps of 20 m) in a raygrass field. Single cylinders of diameter 36.7 cm were used. Measurements reported here were made in two independent runs during two succeeding days in September 1987. In between the runs a shower of 20 mm changed the initial condition. Instead of using the same sampling positions for both runs, the places for the cylinder installation were situated at different spots near the grid points. The results are represented by the mean values for each run (Table 2). The mean of the steady-state infiltration rate in the first run is twice as high as in the second run, while in the latter also the coefficient of variation is less. In this form the effect caused by differences in initial moisture content has appeared in our areal variability study. The difference in the infiltration rates is far beyond the possible influence of the initial moisture content as described by the theory (Philip, 1957).

The initial moisture contents of undisturbed 100 cc core samples taken from 5–10 cm depth at each grid point at the beginning of each infiltration show an

TABLE 2

Mean steady-state infiltration rates and coefficients of variations CV for the two sets of 18 infiltration measurements

Date (1987)	θ_i	CV (%)	θ_s	CV (%)	Inf. rate ($cm\,h^{-1}$)	CV (%)	Initial degree of saturation
18-9	0.263	10.3	0.528	3.4	45.7	102.0	49%
19-9	0.300	11.3	0.488	3.1	21.6	70.1	61%

Measurements were performed on a regular grid under the mean initial moisture contents θ_i of the surface layer as indicated and with corresponding mean saturated moisture contents θ_s measured on 100 cm^3 core samples.

increase of moisture between the two runs. The difference of the two mean values exceeds the range of variance over the experimental area. Interesting is the decrease of the saturated moisture contents obtained in the laboratory for both runs, which is also beyond the limits of variance.

Scale 2

In three cylinders of diameter 20 cm installed in one cluster in the grass covered area, repeated ponding infiltration measurements were performed during a whole summer season under various initial moisture conditions. They were always followed by a recurrent infiltration experiment to the saturated, partly redistributed soil profile. In cylinder I the grass layer was taken away and replaced by an artificial surface to prevent slaking. In cylinders II and III the surface remained natural. Cylinder III was inserted to its full depth into the soil and later dug out with its undisturbed content to continue the measurements in the laboratory. Selected results can be seen in Table 3. It is evident that the first steady-state infiltration rate in each sequence is much higher than the next one, in which the soil profile was more saturated at the beginning. This effect takes place already after a short time of redistribution (15–20 min) but also after a longer period (24 h). In Figs. 3 and 4 four infiltration runs, with pauses in between, are presented for cylinders I and II. They are compared with the least-squares approximation of eqn. (1).

Scale 3

Since the infiltration process in the field is difficult to control sufficiently, undisturbed samples were taken from each of the first three horizons with the same dimensions as in the previous case: a cylinder of 20 cm diameter and 20 cm long. On each sample the ponding infiltration experiments were performed in the laboratory, with the suction heads checked by three tensiometers installed at various heights in the sample body and with controlled outflow at the bottom

TABLE 3

Steady-state infiltration rates as measured on fixed places in the field under various initial conditions

Cylinder:			I	II	III
Cover:			Artificial	Grass	Grass
Inserted (cm):			12	12	20
Date (1987)	Time (h. min)	θ_i	Steady-state infiltration rate ($cm\,h^{-1}$)		
9-5		0.375	2.68		
10-5		0.466	0.87		
13-6		0.330	4.07	15.41	
14-6			1.62	7.83	
11-7		0.301	4.92	21.25	23.95
12-7	10.00	0.455	1.90	19.33	10.47
12-7	18.05		1.13	9.26	6.37
9.8		0.375	4.56	16.90	Dug out
18-9			3.65	13.80	
20-9	10.40		1.96	17.25	
20-9	12.45		1.87	12.60	
20-9	14.45		1.12	8.86	
20-9	18.10		0.82	7.97	

θ_i is the initial moisture content of surface layer; in recurrent infiltration experiments the initial moisture content corresponds to field saturation.

of each sample. The outflow volumes were collected in a fraction collector at measured time intervals.

In comparison with scales 1 and 2, both the boundary conditions and the stage of saturation are monitored. No lateral flow can take place and no

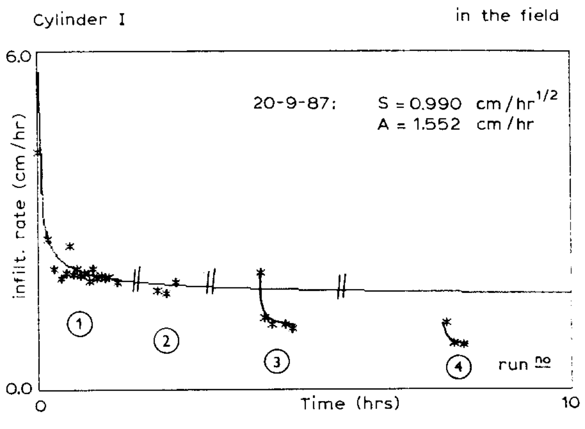

Fig. 3. Courses of the infiltration rate for four recurrent experiments measured 20-9-87 on cylinder I in the field (see Table 3).

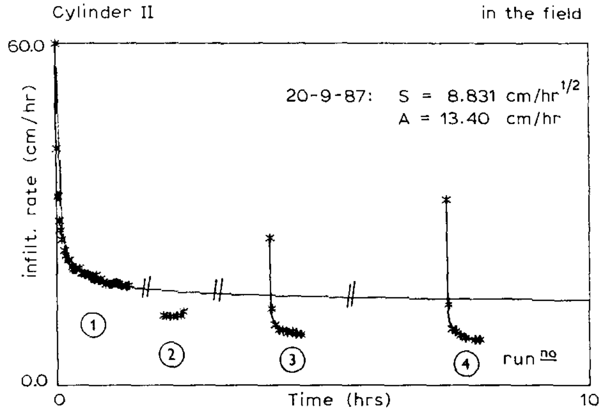

Fig. 4. Courses of the infiltration rate for four recurrent experiments measured 20-9-87 on cylinder II in the field (see Table 3).

gradients of potential to drier surroundings can influence the infiltration and redistribution. Also the air can freely escape through the bottom surface. Theoretically, in this case the steady-state infiltration rate equals the saturated hydraulic conductivity K_s of the sample.

Starting from various initial suction heads the same technique of ponding was used as in the field. Measurements were continued for a period safely exceeding the time at which inflow was equal to outflow and when all three tensiometer readings corresponded to a saturated state. An example of data measured on a cylinder taken from the second horizon is shown in Fig. 5 where infiltration rates and outflow rates of a series of three recurrent experiments are presented (values can be seen in Table 4 together with the corresponding pressure heads).

Even a short pause between the two recurrent experiments with low moisture at the beginning of the first one resulted in a sharp decrease of the steady-state infiltration rate in the next run. In cases where the sample was saturated from the beginning of the experiment, the steady-state infiltration rate reached a minimum value, almost equal in all recurrent saturated runs. The values of cumulative outflow from the soil sample after the end of infiltration has been compared. This post-infiltration part of cumulative outflow, calculated from the time at which the ponded water layer on the sample surface vanished, shows a significant decrease of the measured volume. This decrease in outflow volume is similar to the decrease of the steady-state infiltration rate (see Table 4).

An example of the course of subsequent infiltration rates is given in Figs. 6 and 7 for cylinder III. This cylinder which represents the surface horizon was originally measured in the field and later dug out to continue the measurements in the laboratory, where the infiltration rates were much higher, as expected (Table 3). In all runs the outflow started within a very short time after the start of experiment.

TABLE 4

Cylinder from the second horizon; values of pressure head, steady-state infiltration rate and outflow (see Fig. 5)

Date (1986)	Time (min. s)	Pressure head (cm) in tensiometers installed in depth (cm)			Steady-state infiltration rate (cm h^{-1})	Outflow started at (min. s)	Volume of outflow in % of porosity
		3.5	10	16.5			
17-12	0	−58.5	−52.4	−45.6	29.77	1.00	14.4
	2.59	−1.9	−20.9	−14.1			
	4.01		−19.7	−12.8			
	5.08		−14.6	−7.8			
	5.43		−12.6	−5.3			
	6.52	−0.6	−7.1				
	8.06		−5.8				
	9.51		−4.5	−4.0			
	11.39	0	−3.3				
	13.59		−2.0	−2.8			
	18.12			−1.5			
	23.45						
	25.00						
	51.55	0	0	0			
18-12	0	0	0	0	16.11	0.24	9.8
19-12	0	0	0	0	15.74	0.29	9.6

Total volume of the sample = 6063 cm^3; porosity = 0.5087; bulk density = 1.297 g cm^{-3}; saturated moisture content = 0.4071 (mean from three undisturbed 100 cm^3 core samples taken from this big sample at the end of measurements).

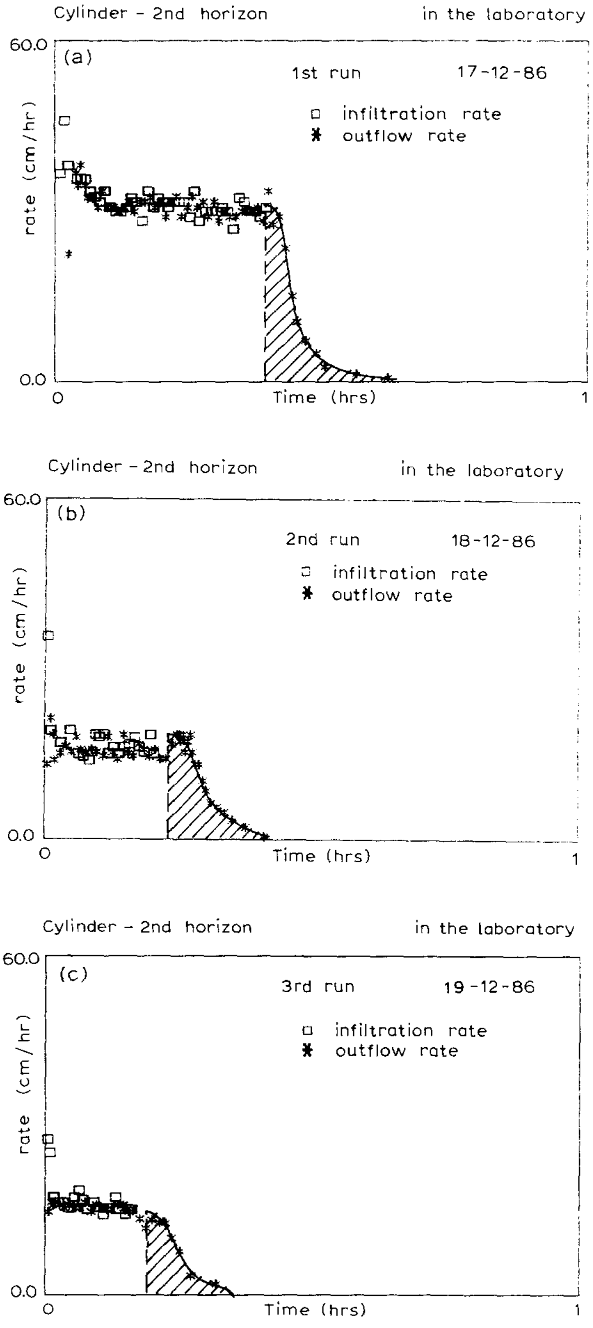

Fig. 5. Courses of the infiltration and outflow rates measured in consecutive days in the laboratory for the cylinder taken from the 2nd horizon. Values of tensiometer reading are shown in Table 4 together with values of steady-state infiltration rates and information about outflow. Note changes in post-infiltration outflow volume (hatched areas)

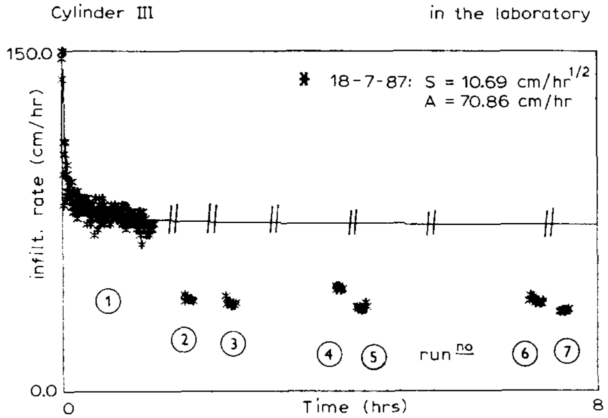

Fig. 6. Courses of the infiltration rate for seven recurrent measurements on cylinder III in the laboratory. Values of steady-state infiltration rates are 72.24, 40.06, 37.99, 44.96, 35.54, 39.70 and 34.70 cm h^{-1}, respectively.

At the end of experiments cylinder III was infiltrated by blue dye (in the saturated state) followed by a thin solution of plaster and then sliced to get a picture of the structure irregularities. No significant disturbances or continuous preferential pathways were found. From the dye distribution it was seen that water passed through about two thirds of the cross-sectional area and missed one third. The pattern stayed very similar along the whole vertical direction. There were no visible differences in the structure of both coloured and uncoloured parts. The root system of the grass layer was very regular, about 4 cm thick. The next few cm were fully coloured. The fast start of outflow together with the dye-distribution pattern gives evidence of an unstable wetting front during infiltration.

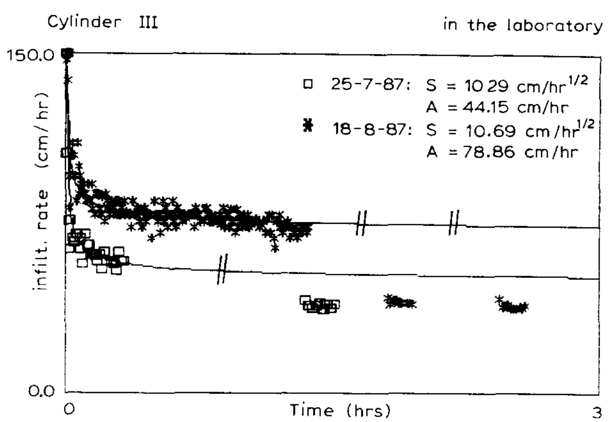

Fig. 7. Courses of the infiltration rate for two series of recurrent measurements taken on cylinder III in the laboratory at various days with different initial moisture contents. Values of steady-state infiltration rates of the first series (marked as □) are 57.98 and 37.73 cm h^{-1}. Values of steady-state infiltration rates of the second series (marked as ∗) are 72.24, 40.06 and 37.99 cm h^{-1}.

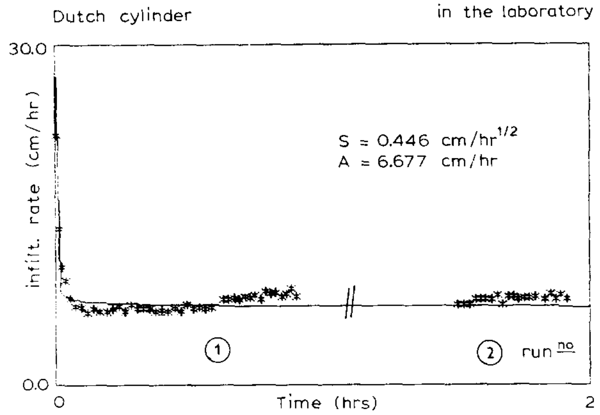

Fig. 8. Courses of the infiltration rate for two recurrent measurements on Dutch cylinder in the laboratory. Values of steady-state infiltration rates are 8.16 and 7.81 cm h^{-1}. This series had four recurrent measurements in total; the further two, which are not plotted, showed values of steady-state infiltration rates of 7.49 and 7.49 cm h^{-1}.

Two other samples were analysed at the end of the experiments to find possible changes in grain size distribution due to the long, and for the location unaturally heavy, load of water. No changes in texture were found.

For comparison we also did ponding infiltration experiments on a sample of Dutch fine sand from the BC-horizon of Haplaquepts, but the effects described above were not observed for this soil. All recurrent infiltration experiments produced equal values for the steady-state infiltration rates (Fig. 8). Also the cumulative outflow remained the same, with the post-infiltration outflow equal to zero. The same results were observed on a sample taken from the quite structured upper horizon of a loess profile. In both cases the material was of fine texture. No macrostructure was present in the Dutch sample. During the ponding of this sample there were slight signs of two-phase flow: an increasing infiltration rate after bubbling out of soil air. The time before the outflow started was much longer for the first run with the lowest initial moisture content (12 min). In this case the observed flow was in agreement with the theoretically assumed behaviour.

CONCLUSIONS

In ponding infiltration experiments on an acid brown soil of the Volynka watershed the values of steady-state infiltration rates decreased with the increase of the initial moisture content, reaching the minimum value for an initially saturated moisture content. The phenomenon is shown on all three scales described. The laboratory scale three indicates the change of the saturated hydraulic conductivity of particular layers. The changes took place already after a short redistribution. When seemingly steady-state infiltration which was started into a drier profile is interrupted, even for a short time, the recurrent infiltration continues at a decreased infiltration rate. The effect was accompanied by immediate outflow during the first infiltration and evident irregularities in the wetting front movement. On control samples of finer texture (Dutch fine sand, loess) no similar effects were seen.

Our results seem to support the theory of Parlange and Hill (1976) who stated that at higher initial moisture contents the air entrapment in large pores sealed off by water films will increase drastically and the saturated hydraulic conductivity will accordingly decrease. From changes in θ_s and changes in the post-infiltration outflow volume it is evident that the changes of the steady-state infiltration rate are caused by a change in the volume of the flow domain. The air entrapped by water films apparently influences the balance between the capillarity-dominated and gravity-dominated parts of total volume of water in the sample.

In all described cases only the gravity-dominated flow contributed to the post-infiltration outflow. It is not easy to distinguish which part of this flow was due to the effects of large pores — as reflected in the near-saturation part of the retention curve — and which part was provided by noncapillary macropores which do not appear in the retention curve. For lower horizons where no structure was visible it could be suggested that the first kind of flow is dominant. On the other hand, the zero tensiometer readings seem to exclude this type of flow. The nonuniform dye distribution pattern gives reason for doubts about the full saturation and supports the idea of flow in part of the sample only.

For brown soils irregularities have already been reported. The dependence of the infiltration rate on the initial moisture content was described for two types of coarse brown earth from the Derwent River watershed (Tricker, 1981). Wilcock and Essery (1984) found the same effect for the brown earth in a small lowland catchment in Northern Ireland. Beese and Van der Ploeg (1976) reported strong hysteresis found in all horizons of grey-brown podzolic soils. It seems that for brown soils, which are quite common on crystalline bed rock all over Europe, the adequacy of the classical soil physics theory should be carefully studied.

Since in the field also other deviations from ideal flow take place, there is a further variability of results, shown in the coefficients of variability of the infiltration rates and other characteristics measured in larger sets. Variations due to the type of the surface cover can be very high, in place as well as in time. Nevertheless, the changes of the steady-state infiltration rates as described in the present paper have appeared for the soil under study in any situation. For many practical hydrological or engineering purposes the consequences of the effect should be of concern. Often problems in connection with pollution appear in infiltration areas where, due to strong permeability of the soils and a usually high precipitation, quick recharge of groundwater takes place. In simulation studies of such movements, the described effect significantly complicates the situation, since it belongs to a type of problems in which the simple laws of flow in porous media do not hold any more.

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REFERENCES

Beese, F. and Van der Ploeg, R.R., 1976. Influence of hysteresis on moisture flow in an undisturbed soil monolith. Soil Sci. Soc. Am., J. 40: 480–484.

Beven, K. and German, P., 1982. Macropores and water flow in soils. Water Resour. Res., 18: 1311–1325.

Bouma, J., 1981. Soil morphology and preferential flow along macropores. Agric. Water Manage. 3: 235–250.

Diment, G.A. and Watson, K.K., 1983. Stability analysis of water movement in unsaturated porous materials: 2. Numerical studies. Water Resour. Res., 18: 1002–1010.

Dolezal, F., 1971. Transport of water in the volume-unstable porous media. Ph. D. Thesis, Res. Inst. Improv. Agric. Soils, Praha-Zbraslav (in Czech).

Field, J.A., Parker, J.C. and Powell, N.L., 1984. Comparison of field- and laboratory- measured and predicted hydraulic properties of a soil with macropores. Soil Sci., 138: 385–396.

Hillel, D., 1987. Unstable flow in layered soils: A review. Hydrol. Proc., 1: 143–147.

Hopmans, J.W., 1986. Scaling of soil hydraulic properties: I. A comparison of techniques. Res. Rep., Dep. Hydraul. Catchment Hydrol., Agric. Univ., Wageningen.

Kneale, W.R., 1985. Observations of the behaviour of large cores of soil during drainage, and the calculation of hydraulic conductivity. J. Soil Sci., 36: 163–171.

Nielsen, D.R., Van Genuchten, M. Th. and Biggar, J.W., 1986. Water flow and solute transport processes in the unsaturated zone. Water Resour. Res., 22: 89S–108S.

Parlange, J.-Y. and Hill, D.E., 1976. Theoretical analysis of wetting front instability in soils. Soil Sci., 122: 236–239.

Philip, J.R., 1957. Theory of infiltration: 5. The influence of the initial moisture content. Soil Sci., 84: 329–339.

Philip, J.R., 1975. Stability analysis of infiltration. Soil Sci. Soc. Am., Proc., 39: 1042–1049.

Poulovasilis, A., 1970. The hysteresis of pore water in granular porous body. Soil Sci., 100: 5 12.

Raats, P.A.C., 1973. Unstable wetting fronts in uniform and nonuniform soils. Soil Sci. Soc. Am., Proc., 37: 681–685.

Sharma, M.L., Gander, G.A. and Hunt, C.G., 1980. Spatial variability of infiltration in a watershed. J. Hydrol., 45: 101–122.

Smettem, K.R.J., 1987. Characterization of water entry into a soil with a contrasting textural class: Spatial variability of infiltration parameters and influence of macroporosity. Soil Sci., 144: 167 174.

Thomas, G.W. and Philips, R.E., 1979. Consequences of water movement in macropores. J. Environ. Qual., 8: 149–152.

Tricker, A.S., 1981. Spatial and temporal patterns of infiltration. J. Hydrol., 49: 261–277.

Van Genuchten, M.T. and Wierenga, P.J., 1976. Mass transfer studies in sorbing porous media. 1. Analytical solutions. Soil Sci. Soc. Am., J., 40: 473–480.

Vieira, S.R., Nielsen, D.R. and Biggar, J.W., 1981. Spatial variability of field-measured infiltration rate. Soil Sci. Soc. Am., J., 45: 1041–1048.

Wilcock, D.N. and Essery, C.I., 1984. Infiltration measurements in a small lowland catchment. J. Hydrol., 74: 191–204.