Comparison of Laboratory and Field Methods for Determining the Quasi-Saturated Hydraulic Conductivity of Soils

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Abstract. Laboratory and field ponded infiltration tests in quasi-saturated soils (containing entrapped air) exhibit the same three-stage temporal variability for the flow rate and hydraulic conductivity. However, the values for the hydraulic conductivity may differ by as much as two orders of magnitude due to differences in the geometry and physics of flow when different laboratory and field methods are applied. The purpose of this paper is to investigate this variability using a comparison of results of ponded infiltration tests conducted under laboratory conditions using confined cores, with results of field tests conducted using partially isolated cores and double-ring infiltrometers. Under laboratory conditions in confined cores, during the first stage, the water flux decreases over time because entrapped air plugs the largest pores in the soils; during the second stage, the quasi-saturated hydraulic conductivity increases by one to two orders of magnitude, essentially reaching the saturated hydraulic conductivity, when entrapped air is discharged from the soils; during the third stage, the hydraulic conductivity decreases to minimum values due to sealing of the soil surface and the effect of biofilms sealing the pores within the wetted zone. Under field conditions, the second stage is only partially developed, and when the surface sealing process begins, the hydraulic pressure drops below the air entry value, thereby causing atmospheric air to enter the soils. As a result, the soils become unsaturated with a low hydraulic conductivity, and the infiltration rate consequently decreases. Contrary to the laboratory experiments in confined cores, the saturated hydraulic conductivity cannot be reached under field conditions. In computations of infiltration one has to take into account the variations in the quasi-saturated and unsaturated hydraulic conductivities, moisture and entrapped air content, and the hydraulic gradient in the quasi-saturated or unsaturated soils.

INTRODUCTION

The accuracy of numerical modeling of infiltration depends on how well the underlying mathematical model describes the physics of flow in variably saturated soils [*Hills et al.*, 1989]. The problem of infiltration into soils from flat circular shallow ponds was investigated in several papers [*Gupta and Staple*, 1964; *Wooding*, 1968; *Weir*, 1986; *Pullan*, 1992; *Philip*, 1993]. It was conventionally assumed that in the wetted region both the moisture content and the hydraulic conductivity are constant [*Milly*, 1985; *Philip*, 1993]. Using the *Green and Ampt* [1911] model, which is often called a delta function model, the wetting front is infinitely steep, and the pressure decreases linearly from a positive water pressure at the surface, to a negative capillary pressure at the wetting front [*Philip*, 1993]. A linear decrease in the moisture content from the surface toward the wetting front was considered by *Milly* [1985].

Because an apparent steady state flow regime is quickly reached in many field experiments, a quasi-linear approximation of the Richards equation was used in simulating infiltration [*Swartzendruber*, 1987; *Philip*, 1989; *Pullan*, 1992]. The total flux from a relatively small pond into soils was assumed to result from two main mechanisms: gravity and capillarity. The gravity term is proportional to the area of the pond, and the capillary term is proportional to the perimeter of the pond. Using Gardner's exponential function for the unsaturated hydraulic conductivity, *Youngs and Elrick* [1993] showed the relative importance of gravity to capillarity for fine and coarse soils. They also evaluated the shape factor, which takes into account the effect of the insertion depth of the infiltration ring into the soils. The formation of a surface crust and the reduction in the infiltration rate was investigated by *Hillel and Gardner* [1969] and *Mualem et al.* [1993]. However, the effect of the crust on the hydraulic head and hydraulic conductivity of underlying soils was not investigated.

The studies cited above have not considered a nonlinear character and superposition of factors affecting the flow regime in soils in the presence of entrapped air. Quasi-saturated soils are soils containing entrapped air below the water table within the zone of the fluctuation of the water table, in perched water zones, and below ponds [*Faybishenko*, 1986; 1995]. The water and entrapped air comprise a two-phase flow system. The modified Darcy law for quasi-saturated soils is given by [*Faybishenko*, 1995]

$$q = -K(\omega)\frac{\partial H}{\partial z} \tag{1}$$

where q is the water flux, $K(\omega)$ is the quasi-saturated hydraulic conductivity as a function of the volume of entrapped air ω, H is hydraulic head, $H= z + p/\rho g$, p is the water pressure, ρ is the water density, g is the gravitational acceleration, and z is the vertical coordinate.

Entrapped air may occupy up to 10 to 20% of the bulk volume of soils, and can reduce the hydraulic conductivity by 1 to 2 orders of magnitude [*Christiansen*, 1944; *Luthin*, 1964; *Dzekunov et al.*, 1987; *Faybishenko*, 1984; 1986; *Stephens et al.*, 1984; *Constantz et al.*, 1988]. Even though many investigators studied the effect of entrapped air in soils, they did not address the fundamental issues of the physics of flow under field and laboratory conditions in variably saturated soils in the presence of entrapped air.

The goal of this paper is to analyze the results of specially designed laboratory and field investigations, in order to understand the physics governing flow through quasi-saturated soils. First, we describe the laboratory and field methods; second, we analyze the main factors affecting flow in laboratory-confined cores [*Faybishenko*, 1995], and the data from field experiments using semiconfined cores and double-ring infiltrometers; and third, we discuss the physics of flow under laboratory and field conditions.

METHODS OF INVESTIGATION

Figure 1 schematically shows a vertical profile through a special three-level (0.5, 1, and 3 m) trench that was excavated in a loamy soil in the Saratov area in Russia [*Faybishenko*, 1986]. At each of three levels in the trench, conventional double-ring infiltrometer and semiconfined core tests were conducted. The semi-confined cores were cut off at the top and walls but not separated at the bottom from the soils beneath. (A semiconfined core, also called a carved pedestal [*Green et al.*, 1986], is an analog for an infiltration ring inserted into the soil.) Half-meter-long cores were taken from the same depths as the semi-confined cores, and then studied in the laboratory using the technique described in detail in *Faybishenko* [1995].

Laboratory Investigations

Laboratory experiments on the cores taken from the trench were conducted using carefully controlled boundary conditions. The flow rate, hydraulic head, and the volume of entrapped air were measured. The initially unsaturated cores were saturated from the top in order to duplicate field conditions during ponded infiltration. For this purpose, a top cover

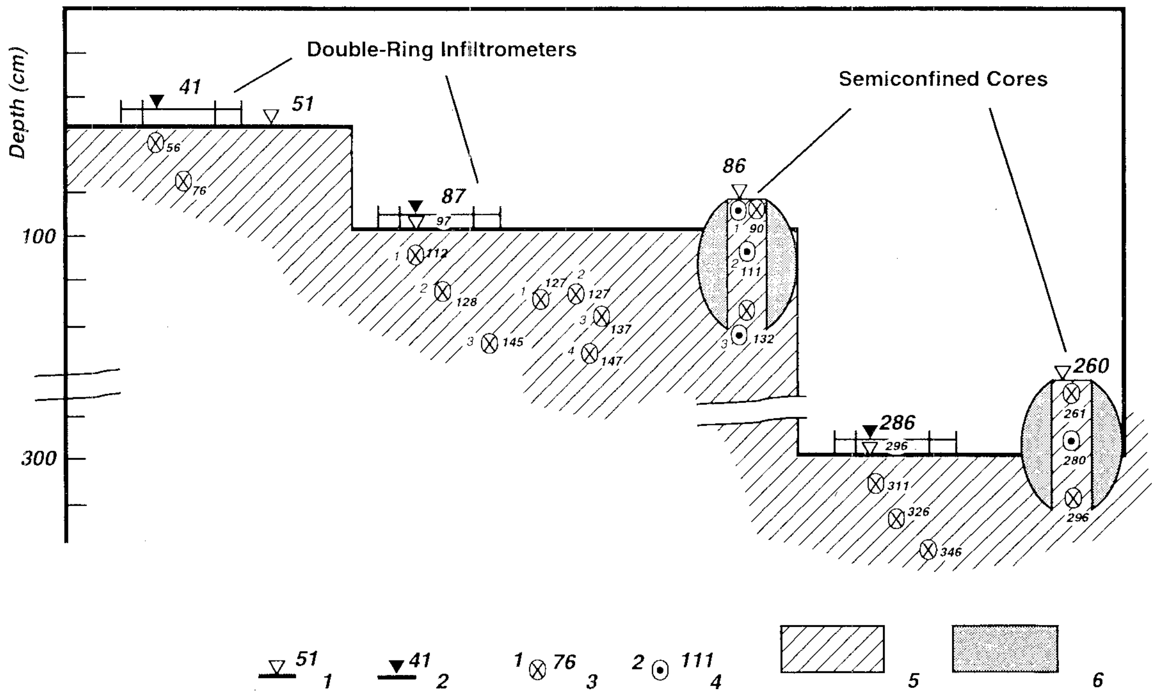

Fig. 1. Schematic of a three-level trench used to investigate water flow in field conditions, including double-ring infiltrometers, and semiconfined cores. (Note that cores for the laboratory experiments were collected from the same three levels.) 1 - Level of ponded surface, 2 - Water level, 3 - Tensiometer and its depth, 4 - Piezometer and its depth, 5 - Undisturbed soils, 6 - Packed soils.

plate was filled with water, and a fixed hydraulic head was applied to the core top in order to establish infiltration. During core saturation, as the wetting front advanced, the air phase ahead of the water front was connected to the atmosphere through the exit port, thus allowing mobile air to escape from the unsaturated soils. Once water appeared at the bottom port, fixed water heads were applied to the top and bottom boundaries, and water flow was controlled by regulating the difference in hydraulic heads at the entrance and exit ports. From this time on, variations in the flow rate and the hydraulic head along the length of the core (from piezometer measurements) reflected changes in the hydraulic properties of the quasi-saturated soils caused by the entrapped air.

Experiments were carried out using tap and deaerated water (used to dissolve entrapped air) with a total concentration from 0.1 to 0.2 g/l. The cores were installed on scales and weighed during the experiments in order to determine the change in mass and estimate the entrapped air content in the core. The following assumptions were made in calculating the quasi-saturated hydraulic conductivity: (1) the soil between two piezometers (or tensiometers) is homogeneous, and the hydraulic conductivity and the entrapped air saturation are uniform; and (2) water flow is one-dimensional along the core axis. The quasi-saturated hydraulic conductivity was calculated from the modified Darcy law given by Eq. (1).

Field Experiments

After a semiconfined core was finished using a special cylindrical knife, its walls were covered with a three-layer impermeable cover. The core surface was first sealed by spraying hot paraffin, then tightened with gauze strips while spraying hot paraffin, and subsequently compressed with rubber strips. This procedure ensured that no water flowed along the core perimeter. Water was supplied to the core through a top water chamber under a constant water level using the same design as in the laboratory [*Faybishenko*, 1995; Fig. 14]. Figure 1 shows the locations of the tensiometers and piezometers installed in and beneath the semiconfined cores, and the double-ring infiltrometers to measure the water pressure at different elevations. The piezometer consisted of a 3-mm ID glass tube inserted in the soil and connected to a conventional U-type water manometer. The piezometer registers the water pressure only when there is a hydraulic connection of soil water with the manometer water. The piezometer can measure positive pressures as well as small negative pressures, which are higher than the air-entry pressure of soils. When the soil water pressure drops below the air-entry pressure, atmospheric air breaks into the porous space and enters the piezometer, thus interrupting the hydraulic connection between the water in soil and in the manometer. At that moment the water in the open end of the manometer usually jumps. Using this procedure we determined the soil air-entry pressure and the time of entry of atmospheric air. Conventional moisture content measurements, such as neutron logging or TDR, can determine the moisture content of the variably saturated soils, but cannot distinguish between unsaturated (when air is connected to the atmosphere) and quasi-saturated (when air is entrapped) soils [*Faybishenko*, 1993]. Hence, the piezometer technique described here is the only method available for this purpose.

Water was supplied into initially unsaturated semiconfined cores from the top boundary under a small positive pressure head. The semiconfined cores were also saturated using CO_2 followed by water infiltration. Tap water and deaerated water were used in the field.

The double-ring infiltration experiments were conducted using two concentric rings (inner ring – 27.5 cm, and outer ring – 50 cm diameter) inserted about 0.5 cm in the soil at each level of the trench. Flow from the outer ring was expected to create a buffer zone around the inner ring in order to eliminate horizontal flow from the inner zone. The flow rate measured in the inner ring, and the pressure measured with tensiometers underneath the inner ring, were used to calculate the hydraulic conductivity using Eq. (1).

EXPERIMENTAL RESULTS

Laboratory Confined Cores

Based on the results of the investigations of water flow in large cores [*Faybishenko*, 1995], the volume of entrapped air in soils was determined to vary from 0.1-0.2% to about 10% of the bulk volume of soil depending on the direction and type of saturation – downward, upward, preliminary saturation with CO_2, and vacuum extraction, as shown schematically in Fig. 2. This figure also shows that during downward saturation, two types of entrapped air exist: (1) mobile air which can move together with flowing water, as well as under buoyancy, and (2) immobile air which can be removed only by dissolution into water.

Figure 3 summarizes the main factors that may affect the three-stage temporal variation in the quasi-saturated hydraulic conductivity. The first stage involving decreases in the flow rate and the quasi-saturated hydraulic conductivity is due to the redistribution of entrapped air and blocking of the largest pores. During the second stage an increase in the flow rate is due to removal of entrapped air from both the gas and dissolved phases. Entrapped air in the gas

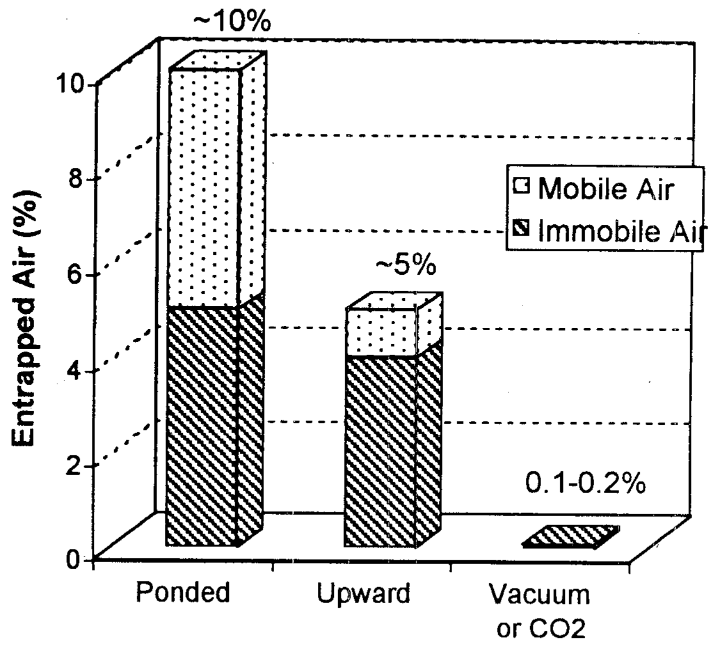

Fig. 2. Volume of entrapped air in soil cores after different methods of initial saturation: (1) downward saturation using ponding of water at the top, (2) upward saturation from the bottom, and (3) preliminary air removal using vacuum or CO_2 saturation of the porous space followed by water saturation.

phase may float up under buoyancy, and/or can be transmitted downward by moving water. Entrapped air is also dissolved in the liquid phase due to temperature and pressure fluctuations, with its dissolution rate depending on air saturation in the liquid phase. At the beginning of the second stage a moderate increase in the quasi-saturated hydraulic conductivity takes place. At this time the largest pores are still blocked by mobile entrapped air, which is progressively discharged from the soil. After release of mobile air from the largest pores, the remaining entrapped air can only be removed through dissolution. Aerobic soil bacteria and fungi consume low solubility oxygen and produce highly soluble CO_2 [*Stumm and Morgan*, 1996]. Due to quick dissolution of CO_2, the quasi-saturated hydraulic conductivity rapidly increases. When all entrapped air disappears at the end of the second stage, the quasi-saturated hydraulic conductivity of soils increases by about one to two orders of magnitude, up to a maximum value that is essentially the saturated hydraulic conductivity, K_s. This value represents the saturated hydraulic conductivity of soils beneath the zone of a fluctuating groundwater table where entrapped air is absent, whereas the quasi-saturated hydraulic conductivity characterizes the zone of fluctuations in the groundwater table within the aquifer. During the second stage, the relationship between the quasi-saturated hydraulic conductivity and the volume of entrapped air is described by a power law or an exponential function [*Faybishenko*, 1995].

During the third stage, the flow rate and saturated hydraulic conductivity decrease to the minimum values comparable to those determined at the end of the first stage. This process was observed on all cores regardless of the method used for saturation. For downward infiltration, this process originated at the top of the core, and then developed downward.

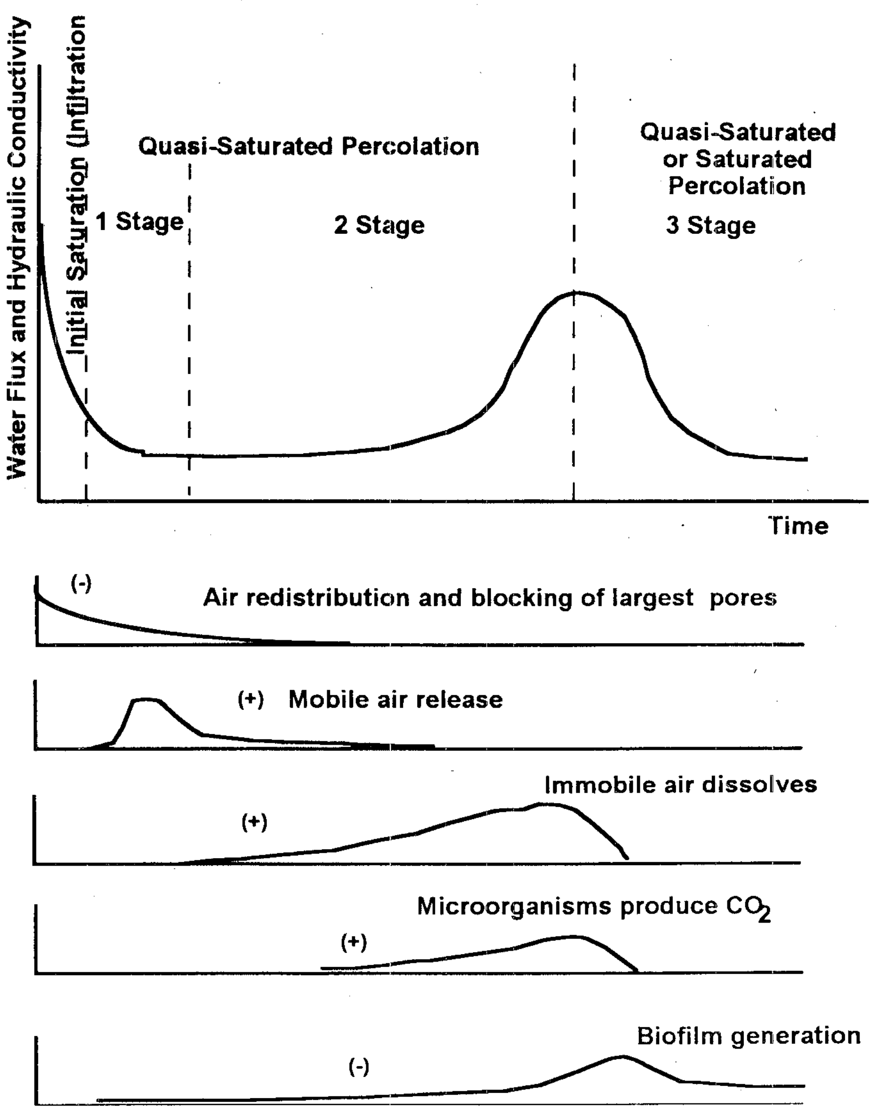

Fig. 3. Schematic of three-stage temporal variation in the quasi-saturated hydraulic conductivity of soils as affected by different factors. The + sign denotes factors that increase the hydraulic conductivity, and the - sign denotes factors that reduce the hydraulic conductivity.

Microbiological activity was assumed to be the major factor in this final decrease in hydraulic conductivity. During the third stage the flow rate and quasi-saturated hydraulic conductivity decrease until an equilibrium between the growing and removing biofilms is established, and the hydraulic conductivity reaches a constant value. Microbiological activity may cause a significant decrease in permeability, by as much as three orders of magnitude [*Cunningham*, 1993; *Jaffe and Taylor*, 1993; *Rittman*, 1993]. The reduction in permeability may be caused by plugging of pores, due to biological mechanisms such as biofilm accumulation (decreasing pore diameters and/or pore throats) and deposition of bacterial aggregates that makes the particle surface irregular and increases the friction factor [*Rittman*, 1993].

When the cores were air-dried after saturation, and then were resaturated with water and subjected to a new percolation, all three stages in the temporal variation of the soil hydraulic conductivity were again observed; however, the values of the quasi-saturated hydraulic conductivity were different. It is assumed that when free air entered the porous space, biofilms were eliminated [*Freeze and Cherry*, 1979].

Field Semiconfined Cores

Figure 4 shows the results of the experiment, conducted in four steps, on a semi-confined core at a depth of 0.86-1.3 m. During Step 1 the water flux initially decreased rapidly and then was practically constant for 3.5 days (Fig. 4a). In the upper half of the core, Piezometer 1p and Tensiometer 1t, as well as Piezometer 2p, showed a pressure of about zero (Fig. 4c), and the quasi-saturated hydraulic conductivity was practically constant at 0.07 m/day (Figure 4a). At the bottom of the core, Tensiometer 3t showed an increase in water pressure caused by infiltrating water, and then as water was absorbed by the surrounding unsaturated soils, the water pressure decreased to -60 cm of water (Fig. 4c). This pressure is below the air-entry pressure, and thus the soils were in an unsaturated state with the unsaturated hydraulic conductivity dropping to 0.014 m/day.

After 3.5 days of infiltration the water supply was turned off, and atmospheric air was allowed to enter the core for one day during drainage. This was followed by CO_2 injection. During Step 2, when the water supply restarted, the flow rate initially increased by about 5 times, and the quasi-saturated hydraulic conductivity increased along the whole core, followed by a decrease in K in the upper half of the core. The water pressure recorded by Piezometers 1p and 2p decreased to -18 and -20 cm at the time when atmospheric air entered into the piezometers (Figs. 4b and 4c). This pressure was identified as the air entry pressure. It is interesting to note that the bottom tensiometer (3t), located at the junction of the core with the surrounding soils, also registered the same pressure.

During Step 3, in order to reestablish saturation, the level of water supply into the core was elevated and deaerated water was supplied in order to accelerate the dissolution of entrapped air. This measure caused the flow rate, hydraulic heads, and the hydraulic conductivity first to increase, and then to decrease again. During Step 4 the water supply level was elevated one more time, resulting in an increase in the flow rate until the water pressure in the lower half of the core (below Piezometer 2p) dropped to the air entry pressure, which in turn caused atmospheric air to enter the soil column and decrease the flow rate. Note that in the upper half of the core the water pressure was positive, and thus the soils were quasi-saturated. The water pressure drop registered by Piezometers 1p and 2p was affected by sealing of the surface.

These data, in principle, confirm the existence of the three stages of temporal variability in the flow rate and the quasi-saturated hydraulic conductivity during both the laboratory and field studies. However, water flow under field conditions is affected by the air entry process, resulting in an unsaturated hydraulic conductivity and a quasi-saturated hydraulic conductivity, which are lower than those observed in the laboratory.

Field Double-Ring Infiltrometers

Figure 5 illustrates the results of measurements using the double-ring infiltrometer at a depth of 1 m. After the initial drop in the flow rate during the first day, the flow rate gradually increased, reaching a maximum value after 6 days (Fig. 5a). This increase could have been affected by the dissolution and removal of entrapped air. As the flow rate increased, the hydraulic head near the surface initially increased (Fig. 5b), followed by a decrease due to the soil sealing process. When the flow rate increased, the pressure in Tensiometers 1 and 2 (locations are shown in Fig. 1) was about -20 cm (Fig. 5c), i.e., the air entry pressure as observed in the semi-confined core. The lower tensiometer (#3) reached approximately the same pressure, -23 cm. The final decrease in the flow rate was caused by a decrease in the hydraulic conductivity, first of the upper segment (between the surface and Tensiometer 1), then the middle segment (between Tensiometers 1 and 2), and finally the lower segment (between Tensiometers 2 and 3). After 9 days the water pressure dropped below the air entry pressure, causing the soils to be unsaturated at all depths.

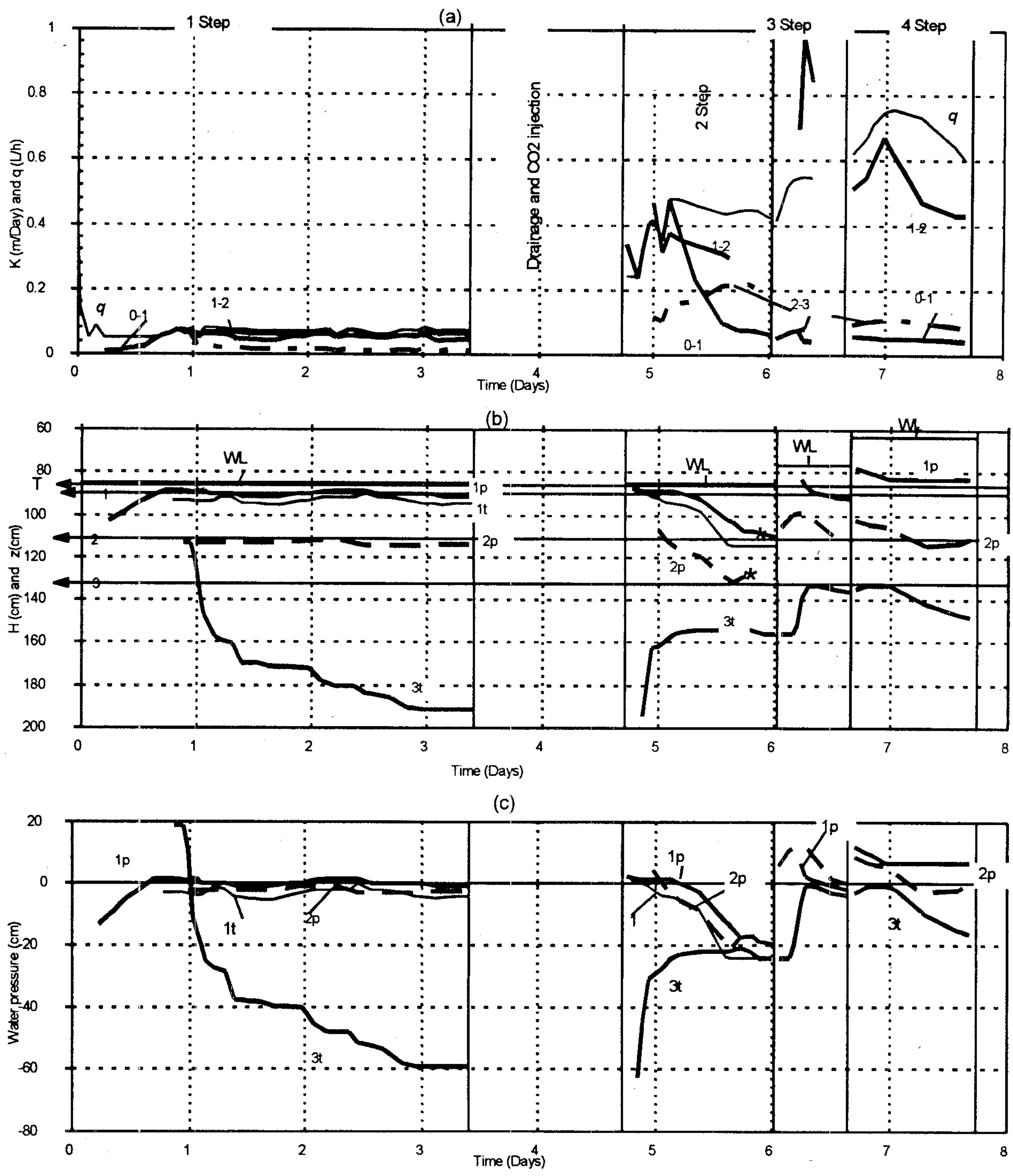

Fig. 4. Results of measurements and calculations obtained for ponded infiltration in a semiconfined core at a depth of 0.86 - 1.3 m: (a) Time trend of the water influx (q) and the quasi-saturated hydraulic conductivity as calculated from Eq. (1) for different intervals (0-1 is from 86-90 cm, 1-2 is from 90-111 cm, and 2-3 is from 111-132 cm; (b) Hydraulic heads at different elevations; and (c) Water pressure at different elevations. Time of atmospheric air entry, determined with piezometers, is indicated by asterisks. Horizontal lines with arrows indicate elevations of tensiometers and piezometers (Fig. 4b) while numbers are those of piezometers (p) and tensiometers (t) (Figs. 4b and 4c). T and WL denote the surface and water elevations, respectively.

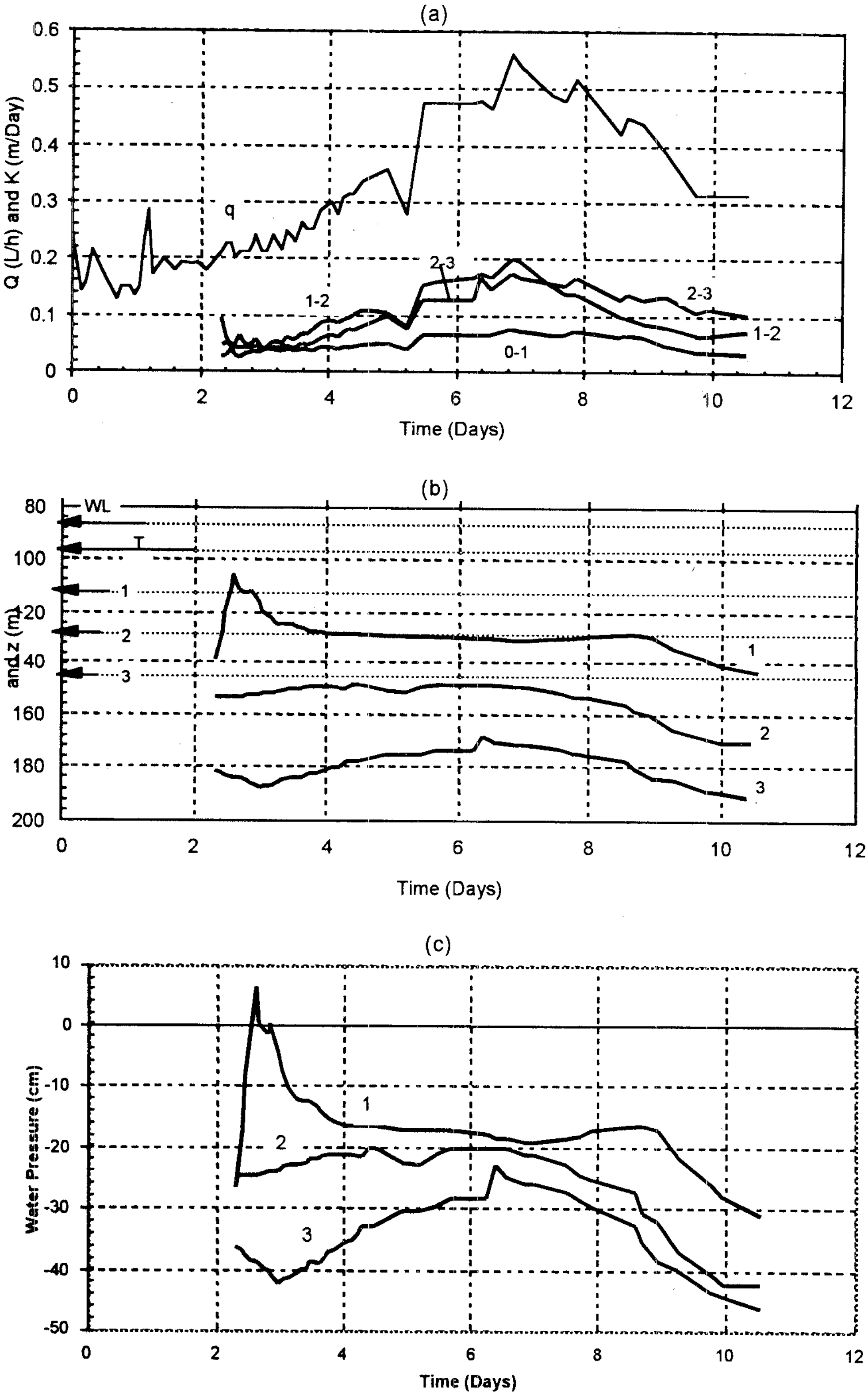

Fig. 5. Results of measurements using the double-ring infiltrometer at a depth of 0.97 m: (a) Flow rate (q) and quasi-saturated hydraulic conductivity calculated from Eq. (1) for different intervals (0-1 is from 97-112 cm, 1-2 is from 112 -128 cm, and 2-3 is from 128-145 cm), (b) Hydraulic heads at different elevations, and (c) Water pressure at different elevations. Horizontal lines with arrows indicate elevations of tensiometers and piezometers (Fig. 5b), numbers indicate piezometers and tensiometers (Figs. 5b and 5c), T and WL are the surface and water level elevations (Fig. 5b).

DISCUSSION

In field conditions, when a low-permeable sealing layer has developed at the surface, the water pressure below the sealing layer decreases and becomes negative (relative to atmospheric pressure). When the water pressure decreases to less than the air entry pressure, atmospheric air enters the soils, leading to the phenomenon of unsaturated flow below the ponding surface. It is interesting to note that field infiltration affected by a naturally forming sealing layer is analogous to infiltration through a crust, a feature used to determine the unsaturated hydraulic conductivity of soils [*Bouma et al.*, 1971; *Green et al.*, 1986].

Figure 6 illustrates that a laboratory core with fixed water level boundaries is a confined system with no access to atmospheric air. The soil sealing process decreases the hydraulic conductivity just beneath the water inlet surface, thereby causing the hydraulic gradient to increase in the near-surface zone. Consequently, the water pressure falls below atmospheric pressure, but atmospheric air does not enter the confined core. In the corresponding field situation, when pressure drops below the air-entry pressure, atmospheric air is drawn into the soil, which then becomes unsaturated. The unsaturated hydraulic conductivity is usually less than both the quasi-saturated and the saturated hydraulic conductivity. Therefore, the flow rate from the surface declines in both semi-confined cores and double-ring infiltrometers. Note that the same phenomenon of air entry beneath a ponded surface was observed under the larger ponds (6 by 6 m) in the field experiments described in *Faybishenko* [1993].

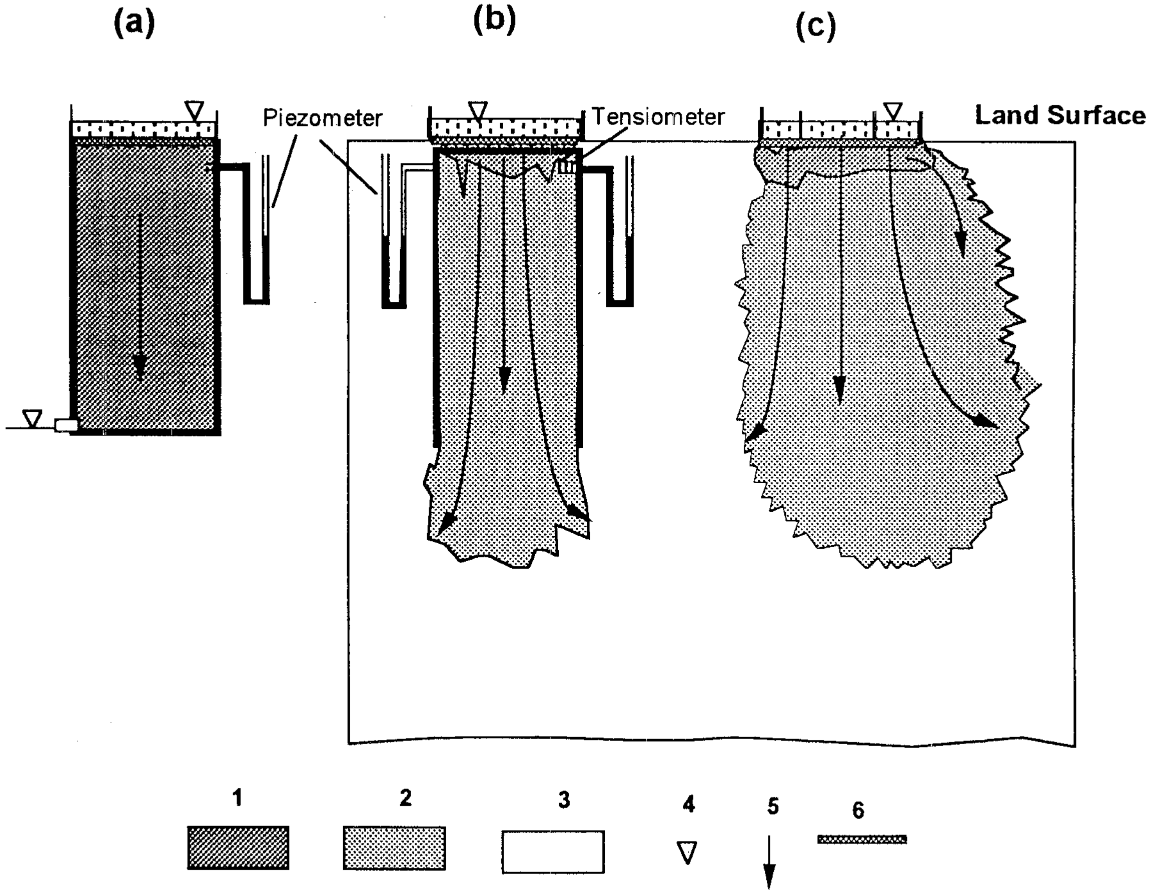

Fig. 6. Diagram showing the distribution of the quasi-saturated and unsaturated zones under ponded infiltration for (a) Laboratory confined cores, (b) Field semi-confined cores, and (c) Double-ring infiltrometers: 1 - quasi-saturated soils, 2 - unsaturated soils affected by infiltrating water, 3 - unsaturated soils with no effect from infiltrating water, 4 - water level, 5 - direction of flow, and 6 - surface sealing layer.

Figure 7 compares the results of the hydraulic conductivity measurements at the end of the first stage and the end of the second stage, using the double-ring infiltrometer, the semi-confined core (before and after the CO_2 saturation), and the confined core. Notice that the quasi-saturated hydraulic conductivity determined at the end of the first stage is confined to a small range, varying from 0.03-0.06 m/day regardless of the type of experiment (field or laboratory). The quasi-saturated hydraulic conductivity at the end of the second stage is 0.17-0.2 m/day when measured with the double-ring infiltrometers, and 0.7-1 m/day in the semi-confined core saturated with CO_2 and supplied with de-aerated water. The maximum saturated hydraulic conductivity, K_s=2.3 m/day, was observed in the confined laboratory core.

Note that capillary forces below the semi-confined core and the double-ring infiltrometer did not appear to affect the flow rate from the surface. We hypothesize that the decrease in the infiltration rate observed under field conditions is caused by a combination of several factors: (1) entrapped air blocking the porous space within the wetted zone, (2) the soil surface being sealed due to soil particle redistribution and biofilms, and (3) atmospheric air entering the soil profile when the water pressure drops below the air-entry pressure, and, consequently, allowing the soil to become unsaturated. This last statement is contrary to conventional theory, according to which the initial decrease in the flow rate is due to a decrease in the hydraulic gradient between the water surface and moisture front; for example, in the Green-Ampt model

$$q = K\,(h_o + L - h_f)/L$$

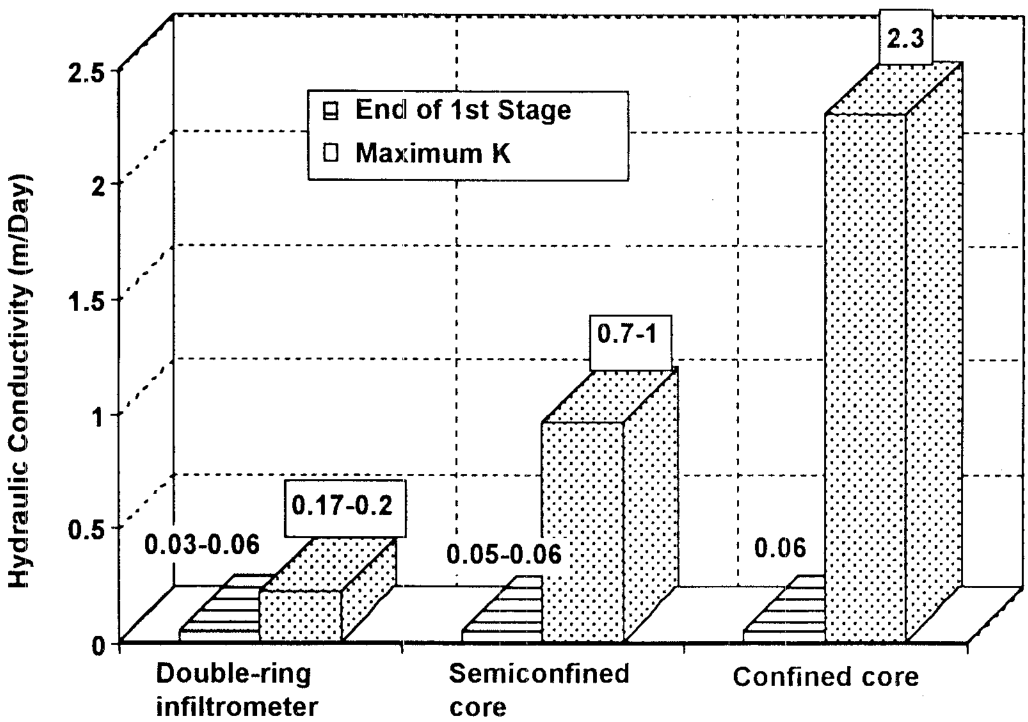

Fig. 7. Comparison of the quasi-saturated hydraulic conductivity determined from laboratory and field ponded infiltration tests.

where h_o is the ponding water level at the soil surface, L is the length of the saturated zone, h_f is the capillary pressure developed at the wetting front of the wetted zone (several techniques were proposed to determine h_f, [*Neuman*, 1976; *Rawls and Brakensiek*, 1989]), and K is a hydraulic conductivity value of the saturated soil if the soil water pressure is above the air-entry pressure [*Youngs and Elrick*, 1993]. *Youngs and Elrick* [1993], who investigated flow rates from ring infiltrometers in "Green and Ampt" and "Gardner" soils, stated that "...in the computations of steady state infiltration from surface sources the form of the hydraulic conductivity function is of little importance. The general nature of such relationships would indicate that some air entry value of the soil water pressure, above which the soil has a hydraulic conductivity value of the saturated soil, has to be included in the modeling of the flows." However, for the water pressure equal to or higher than the air-entry pressure, the hydraulic conductivity is much lower than the saturated hydraulic conductivity, and it is the quasi-saturated hydraulic conductivity that in general is a function of the volume of entrapped air, time, and depth, i.e., $K=K(\omega,z,t)$. Additionally, the hydraulic gradient within the quasi-saturated and unsaturated zones changes with time and depth, because of spatial and temporal changes in the hydraulic conductivity.

In an initially unsaturated soil within the near-surface zone, sufficient organic matter and nutrients are usually present, and moisture is the limiting substance. After water is added to initially dry soils, moisture and nutrients become available to microorganisms. Aerobic bacteria and other soil organisms such as fungi and protozoa awaken from a desiccated state and start consuming O_2 and producing highly soluble CO_2, which is dissolved during the second stage, thereby causing a decrease in the quasi-saturated hydraulic conductivity.

The important implication of the three-stage temporal behavior of the quasi-saturated hydraulic conductivity is that the same value of the hydraulic conductivity can be determined at three different times and for different saturations. The main cause for the nonperiodic time variation of K is the superposition of several internal (e.g., entrapped air, biofilms and macropores) and external factors (e.g., temperature, pressure and supply of bacteria) affecting flow in the soil. Each of these processes is indeed a deterministic process, which, however, cannot be easily investigated in detail and predicted precisely. The evolution of such a complex dynamic system is, as a result, not precisely predictable [*Haken*, 1983], and the possibility of having a deterministic-chaotic behavior cannot be ruled out; this will be a subject of a separate paper.

CONCLUSIONS

The water flux and the quasi-saturated hydraulic conductivity of soils during both field and laboratory conditions exhibit a three-stage temporal behavior determined by a superposition of several nonlinear processes. Values for the hydraulic conductivity may differ by as much as several hundred percent. The main difference between the laboratory cores and field infiltration tests is the entrance of atmospheric air into the soils under field conditions, which become then unsaturated. Therefore, the saturated hydraulic conductivity cannot be easily reached under field conditions. Even after replacing soil gas with CO_2 (which is highly soluble in water) and using de-aerated water, the hydraulic conductivity may significantly decrease thereafter. Soils under field conditions exhibit properties of the combined unsaturated and quasi-saturated soil system. Due to spatial and temporal instabilities in the moisture content, hydraulic conductivity, and the pressure distribution, the soil system is likely to preclude the development of steady flow, even under constant boundary conditions. Thus, because of a combination of several external and internal nonlinear processes, a quasi-saturated soil has limited predictive power identical to that of a deterministic-chaotic system.

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