Pak. J. Sci. Ind. Res. 2008 **51**(5) 235-241

Physical Sciences

The Role of Rainfall Intensity and Soil in Determining Rates of Flow Through Cryoturbated Chalk

M. Mahmood-ul-Hassan[ab]* and P. J. Gregory[ac]
[a]Department of Soil Science, The University of Reading, Whiteknights, PO Box 233, Reading, Berkshire, RG6 6DW, UK
[b]Institute of Natural Resources and Environmental Sciences, National Agricultural Research Centre, Islamabad-45500, Pakistan
[c]Scottish Crop Research Institute, Invergowrie, Dundee, DD2 1QJ, UK

(received May 26, 2008; revised August 9, 2008; accepted August 9, 2008)

Abstract. The effects of different water application rates (3, 10, 15 and 30 mm/h) and of topsoil removal on the rate of downward water movement through the cryoturbated chalk zone in southern England were investigated *in situ.* During and after each application of water, changes in water content and matric potential of the profile were monitored and percolate was collected in troughs. The measured water breakthrough time showed that water moved to 1.2 m depth quickly (in 8.2 h) even with application rate as low as 3 mm/h and that the time was only 3 h when water was applied at a rate of 15 mm/ h. These breakthrough times were about 150 and 422 fold shorter, respectively, than those expected if the water had been conducted by the matrix alone. Percolate was collected in troughs within 3.5 h at 1.2 m depth when water was applied at 30 mm/h and the quantity collected indicated that a significant amount of the surface applied water moved downward through inter-aggregate pores. The small increase in volumetric water content (about 3%) in excess of matrix water content resulted in a large increase in pore water velocities, from 0.20 to 5.3 m/d. The presence of soil layer had effect on the time taken for water to travel through the cryoturbated chalk layer and in the soil layer, water took about 1-2 h to pass thorough, depending on the intensity.

Keywords: breakthrough time, cryoturbated chalk; rainfall intensity; water flow

Introduction

Chalk has a dichotomous porous system consisting of intra- and inter-granular porosity. The intra-granular porosity is referred to as the matrix porosity and is usually 35 to 50% of the volume (Burnham, 1990). It has a large air entry suction and small, but relatively uniform pores, 0.1 to 1 μm in diameter (Price, 1987) that result in a low matrix conductivity that is typically 5 to 8 mm/d (Mahmood-ul-Hassan and Gregory, 2002; Cooper *et al*., 1990). The pores of the matrix are sufficiently small to store water against the force of gravity so that, even in the unsaturated zone, most of the pores remain virtually saturated during winter (Price *et al*., 1976).

The inter-granular porosity is referred to as the fissure porosity and constitutes about 4% (Reeves, 1979) to 14% (Mahmood-ul-Hassan, 1998) of the total porosity. The fissures range in diameter from 20 mm to 10 mm (Reeves, 1979) and provide the pathways for rapid flow. Water and solutes moving by this pathway do not move downward with the horizontally-uniform wetting front found in the matrix but, instead, travel rapidly through a small fraction of the total volume bypassing much of the matrix (Arnon *et al*., 2005; Nativ *et al.,* 2003; Geake and Foster, 1989).

In most of the chalklands of England, a shallow layer of well-drained and structured soil directly overlies cryoturbated, fractured chalk. This soil can affect the route and rate of water flow through the underlying chalk. In well-structured soils, preferential flow of water can occur at application rates lower than that required for saturated flow (Radulovich *et al*., 1992), so that there is the potential for the overlying soil to augment the preferential flow through the underlying chalk. In such soils, vertical transmission of water through preferred paths can occur during rainfall by either saturating the lower levels of the soil and then passing through the fissures between the chalk fragments, or directly entering into the fissures if they are, by chance, directly connected to the preferred path. However, there are also suggestions that the overlying soil may reduce the opportunity for preferential flow through the underlying chalk. For example, Gardner *et al*. (1990) reported that rainfall intensity rarely exceeds a few millimetres per hour in south-east England and that this can be stored temporarily in the overlying soil and weathered chalk materials near the surface; this buffering capacity allows water to be released to deeper layers at rates low enough to be conducted by the matrix alone.

The underlying fractured chalk has a very small water storage capacity at potentials > -100 kPa (Cooper *et al*., 1990), which means that steady state conditions are established quickly

---

*Author for correspondence; E-mail: mmh@comsats.net.pk
[b]Present address

during rain. Hence, if the hydraulic conductivity of the matrix exceeds the flux from the soil into the chalk, flow will be through the matrix. But, if the flux is larger than the matrix conductivity, the excess will be carried by the fissure system. The flux out of the overlying soil into the fractured chalk and the hydraulic conductivity of the chalk matrix are, then, key factors that determine the partitioning of flow between the chalk matrix and the fissures.

This paper reports the results of a series of field experiments in which known rates of water were applied to chalk with the soil present or not. The objectives of this study were first, to determine the effect of water application rate on preferential flow through the chalk zone and second, to investigate the role of the overlying shallow soil in controlling the pathways of water flow through the underlying chalk. Selected results are presented in this paper from a larger study (Mahmood-ul-Hassan, 1998).

Materials and Methods

Experimental site and instrumentation. The experiments were conducted in Ohio field at Bridgets Experimental Husbandry Farm, Winchester, Hampshire, UK (National Grid Reference SU 517337). The soil was mapped as an Andover series rendzina by Moffat (1985)-thin silty drift over chalk, comprising of about 26 cm calcareous silty clay loam (well structured moderate to fine subangular blocky overlying fractured upper chalk). The underlying fractured upper chalk material, down to about 1.5 m, was rubbly in nature and loose with many voids. Details of the soil and site are given in Mahmood-ul-Hassan and Gregory (2002). The experiments were conducted within a large (20 m x 60 m), long-term (> 5 years) grass plot. Two experimental plots, each 3 m long and 1.5 m wide were established on either side of a pit, approximately 1.4 m wide and 1.5 m deep dug for installation of instruments to observe rapid hydraulic changes at different depths (Fig. 1). Another smaller plot (1.5 m x 1.4 m) alongside the pit was also established and used to collect water draining from different depths.

Theta probe type ML1, moisture sensors (Delta-T Devices, Burwell, Cambridge, UK), were installed in duplicate on opposite sides of the pit on a diagonal line (Mahmood-ul-Hassan and Gregory, 2002), about 0.25 m apart laterally and at 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 m below the ground level to monitor changes in soil water content. The calibration graph for silty clay loam soil and upper chalk (Mahmood-ul-Hassan, 1998) was used to convert the output of the theta probe to volumetric water content. Changes in soil matric potential were monitored simultaneously using pressure transducer tensiometers (SWT3, Delta-T devices). In both the plots, pressure transducer tensiometers were installed 0.5 m away from the theta probe at 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 m depths and spaced at 0.25 m intervals. Data from the theta probes and pressure transducer tensiometers were logged using a Delta-T logger.

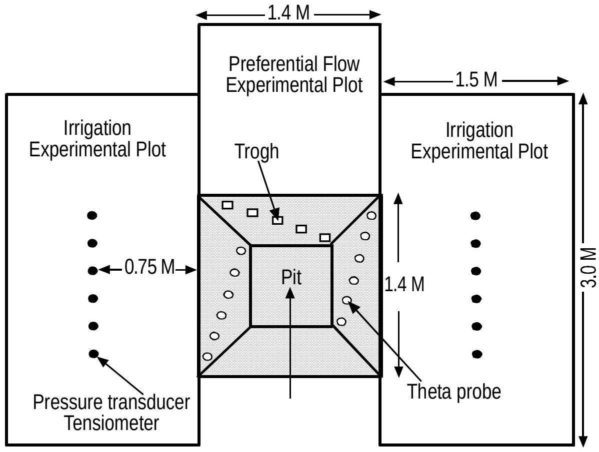

Fig. 1. Layout of experimental plots showing the position of pressure transducer tensiometers (PTT) and the installation of theta probes and troughs to collect percolate in the pit walls.

Rainfall simulator. Water was applied to the plots with a rainfall simulator consisting of a rectangular frame with six parallel aluminium pipes each spaced 30 cm apart. Water jets were mounted at 30 cm intervals along each aluminium pipe and the whole system was mounted on a 1.5 m x 3 m frame. The frame was moved across the plots on rails. Water from the jets came out as fine spray and for that reason the sides of the frame were covered with plastic sheets to prevent drift. Water was supplied to the simulator by a water pump at one end and pressure was maintained, for a constant rain intensity, with a gate valve fixed on the other end of the simulator. Surplus water was drained to a water tank. Uniformity of application was tested before and after the experiments for the three different water application rates (10, 15 and 30 mm/h) by computing uniformity coefficient (C_u) expressed as Christian's coefficient (James, 1988);

$$C_u = 100 \left[1 - \frac{D}{Mn}\right]$$

where:

> D is the deviation of the individual observation from the mean value, M is the mean values of the observations and n is the number of observations.

The coefficient ranged from 89 to 92% indicating an acceptable uniformity of application.

Irrigation treatments. Irrigation was applied either with intensities of 10, 15 and 30 mm/h in pulses using the simulator or with an intensity of 3 mm/h using a 1 m long dribble bar attached to a watering can. Irrigation was continued until steady state conditions had been achieved.

Irrigation with an intensity of 3 mm/h was achieved by delivering a total of about 24 mm water in 8.0 h. To achieve an intensity of 10 mm/h, a total of 60 mm water was applied in a period of 6 h. Similarly, 60 mm and 120 mm water was applied in a period of 4 h for the 15 and 30 mm/h treatments, respectively. After every irrigation, the plots were covered with plastic sheeting to prevent evaporation and the profile allowed to drain for one week. Soil water content and matric potential of the profile were monitored throughout.

The overlying soil (0.25 m layer) was then removed from both experimental plots. After removing the soil, a thin layer of fine sand was applied on the surface of the fractured chalk to even out the distribution of water as well as to avoid the direct entrance of water into the inter-granular pore spaces. Water was applied manually at a rate of 3 mm/h using a dribble bar and a total of about 24 mm of water was applied in 8.0 h. The profile was allowed to drain overnight and the next day the experiment was repeated to observe the effects of antecedent water content.

Collection of preferential flow. Preferential flow was collected at depths of 0.4, 0.6, 0.8, 1.0, and 1.2 m in 80 cm long steel channels (Fig. 2). The channels were 4.5 cm wide and 2 cm deep with a perforated steel sheet attached inside the channels about 0.5 cm above the bottom surface to facilitate water flow. A sharpened chisel was fixed on the fore-end of the channel to ease insertion into the chalk and a steel lid was fixed on the end of the channel to stop water dropping into the pit. Plastic tubing was used to run drainage from the steel channels to plastic collectors. The channels were very carefully inserted into the chalk using a jack acting against the opposite wall of the pit. The channels extended 65 cm into chalk and were inclined slightly towards the pit to aid collection.

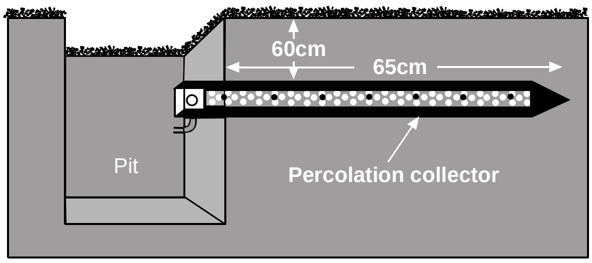

Fig. 2. Schematic diagram of a percolate collector at a depth of 60 cm, lateral view.

Calculation of drainage, unsaturated hydraulic conductivity and first breakthrough time. Drainage flux, D, from each depth was estimated using the water balance equation, assuming vertical flow only and no surface run-off;

$$D = R - E_p + \int_0^z \theta(t_1)dz - \int_0^z \theta(t_2)dz$$

where:

> R is the rainfall, E_p is the potential evaporation during the period from t_1 to t_2 and θ is the water content of the profile at time t_1 and t_2 at depth z. (during winter, the potential and actual evaporation are same: Cooper *et al.*, 1990).

The hydraulic conductivity was calculated from the drainage fluxes and the measured gradient of hydraulic potential using the instantaneous profile method (Hillel *et al.*, 1972). The mean water flow velocity was calculated by dividing drainage flux by the volumetric water content of respective depth. Saturated hydraulic conductivity of overlying soil and of underlying chalk (of different depths) was measured with a constant head using 10 cm long and 10 cm diameter undisturbed cores.

The measured first breakthrough time (MFBT) for a depth was determined as the time from start of the water application to the first appearance of water at the given depth, i.e., the time at which the theta probe at that depth started to show an increase in water content. The expected first breakthrough time (EFBT) for each depth was calculated by dividing interval of the distance by the mean water flow velocity of that depth.

Results and Discussion

Hydraulic properties. The relationship between matric potential and water content describes the hydraulic properties and pore size distribution of a porous medium. Fig. 3 shows that

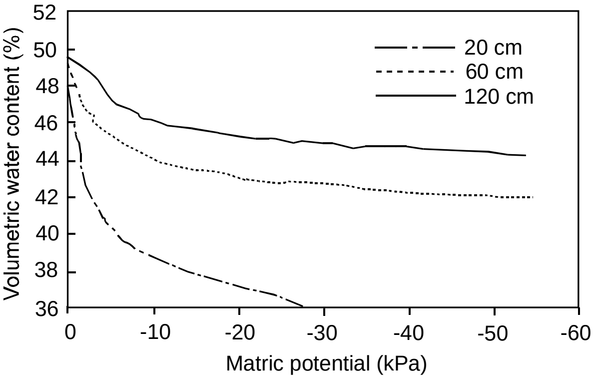

Fig. 3. Water release curves measured *in situ* using theta probes and pressure transducer tensiometers.

the soil overlying chalk released a large amount of water (≈0.10 m^3/m^3) as potential decreased from 0 to -10 kPa; this water represents the macroporosity. Less water was released from the greater depths (0.6 and 1.2 m). The saturated hydraulic conductivity of soil (5.2 ± 0.42 m/day) was greater than that of the underlying cryoturbated chalk (4.65 ± 0.24 and 3.35 ± 0.49 m/day at 0.4 and 0.6 m, respectively). Hydraulic conductivity as function of matric potential measured *in situ* decreased from ≈102 mm/d near saturation to ≈8 mm/d at -10 kPa.

Effect of rate of irrigation on water flow. The measured first breakthrough times at different rain intensities were shorter than the expected first breakthrough times calculated as if only the matrix were conducting (Table 1). This suggests that water flow through the overlying soil and underlying fractured chalk was not piston type flow with a uniform wetting front even at an application rate as low as 3 mm/h. The measured first breakthrough times for applications of 3mm/h were, as expected, longer than those for 10, 15, and 30 mm/h at all depths. The cumulative differences between breakthrough times at 3, 10 and 15 mm/h increased with depth and were greatest at 1.2 m depth but the difference between 15 and 30 mm/h rain was small. There was no difference in the breakthrough time at 0.2 and 0.4 m for applications of 10, 15, and 30 mm/h. At 0.8, 1.0 and 1.2 m depth, the differences in measured times between applications of 10 and 15 mm/h were about two fold, while at application of 15 and 30 mm/h there was no difference except at 0.8 m depth.

The measured breakthrough times at different depths were about 134 to 215 fold (at 3 mm/h intensity) and 430 to 872 times (at 30 mm intensity) smaller than the EFBTs. The decrease in breakthrough times as the rate of application increased was most likely due to the more rapid increase in volumetric water content resulting in a large increase in hydraulic conductivity (Fig. 4). At 1.2 m depth, for example, a 0.03 m^3/m^3 increase in volumetric water content (from 0.46 to 0.49 m^3/m^3) increased the conductivity from about 8 mm/d to 110 mm/d. Similar increases in conductivity for only small increases in water content were also observed at other depths (e.g., 0.6 m, Fig. 4).

Table 1. Measured first breakthrough time (MFBT) compared with the expected first breakthrough time (EFBT) if the matrix only were conducting water; times (h) for each 0.2 m depth are shown

Depth (m)	MFBT (h) Rain intensities (mm/h)				EFBT (h)
	3	10	15	30	
0 - 0.2	2.0	1.0	1.0	1.0	-
0.2 - 0.4	1.0	0.5	0.5	0.5	216
0.4 - 0.6	1.5	0.5	0.5	0.25	211
0.6 - 0.8	1.5	1.0	0.5	0.25	211
0.8 - 1.0	1.5	0.5	0.25	0.25	221
1.0 - 1.2	1.0	0.5	0.25	0.25	214

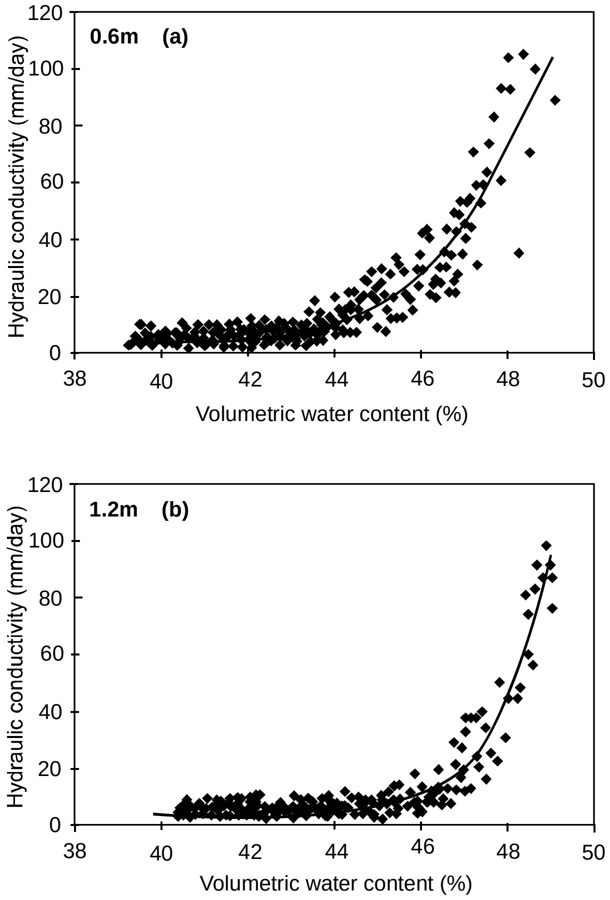

Fig. 4. Unsaturated hydraulic conductivity as a function of water content at (a) 0.6 m and (b) 1.2 m depth.

As additional pores between fragments of chalk become water filled, so the cross-sectional area available for flow increases as does hydraulic conductivity (Hodnett and Bell, 1990). For example, at 1.2 m depth, increasing the cross sectional conducting area by 0.02 and 0.03 m^3/m^3 (i.e., increasing water content from 0.46 to 0.48 to 0.49 m^3/m^3) would increase hydraulic conductivity from 8 mm/d to 57 and 110 mm/d thereby increasing water flow from 17.4 mm/d to 118.7 and 224.5 mm/d, respectively. This 7 and 13 fold increase is a direct consequence of water filling the pores between chalk fragments. The additional flux resulting from the additional wetted area as water content increased would raise the mean flow velocity to 2.45 m/d at water content of 0.48 and to 5.3 m/d at 0.49 m^3/m^3. A similar calculation for 0.6 m depth shows that the flow rate was also similar (5.0 m/d) as water content increased from 0.47 to 0.48 m^3/m^3. These calculated flow rates are in accordance with the very short measured breakthrough times observed and suggest that during rain storms, most of the flux could pass through this part of the chalk profile very rapidly.

Effect of overlying soil on water flow. The time taken for water to travel through fractured chalk (0.2 to 1.2 m depth) was almost the same with and without the overlying soil but the soil layer took about 2 h to pass through (Table 2). It was also found in other experiments (unpublished) that water took slightly more time to move through the top layer, 0-0.2 m, than through underlying layers of the same thickness. At low rain intensity, 3 mm/h, the initial breakthrough time for the soil layer was 2 h, whereas, the time for all succeeding layers was 1.5 h or less. At higher intensities, the time was 1 h for the top 0.2 m layer and 0.5 h or less for all deeper layers. The longer time taken to pass through the top 0.2 m may have been due to the surface conditions. In the case of overlying soil, there was a layer of moss of about 2 cm thickness on the soil surface under the grass. This may have reduced the infiltration rate into the soil and hence delayed the initial breakthrough time. Another possible factor that can reduce the flux is that at the start of rain, loose soil material may move down with water and plug the macropores, thereby increasing the breakthrough time. The longer breakthrough time through the top layer of the chalk even without the overlying soil might be due to the trampling of the surface during the removal of overlying soil in addition to the downward movement of soil particles. It is clear that once water had passed through the overlying soil, it moved quickly through the underlying chalk.

During winter, there were small changes in water content of the chalk profile (Mahmood-ul-Hassan and Gregory, 2002). Table 3 shows that the effect of water content at the start of irrigation on the measured first breakthrough time was small. In the upper 0.4 m, water content had a negligible effect on breakthrough time but below 0.6 m, the time was reduced by 1 to 1.5 h as water content increased.

Field measurement of preferential flow. Table 4 shows the rate of percolation at different depths as affected by the rate of irrigation. The rate was calculated by dividing the volume of water collected by the percolation collectors by the time in which it was collected. About 90% of the total percolate was collected within 7 h when water was applied at 15 mm/h and within 6 h when applied at 30 mm/h. Percolation started after about 1.5, 2.0. 2.5, 3.0 and 3.5 h at 0.4, 0.6, 0.8, 1.0 and 1.2 m depth when water was applied at 30 mm/h. The quantity of percolate collected suggests that at high rate of application, a significant amount of the surface applied water moved down through the inter-aggregate pores. At 30 mm/h rate, about half

Table 2. Effect of the overlying soil on the measured first breakthrough time at different depths with an irrigation applied at 3 mm/h

Depth (m)	First breakthrough time (h) with soil	without soil
0.2	2.0	-
0.4	3.0	1.5
0.6	4.5	2.5
0.8	6.0	4.0
1.0	7.5	5.5
1.2	8.5	6.0

Table 3. Effect of the initial water content on the measured first breakthrough time (MFBT) at different depths with 3 mm/h application

Depth (m)	Initial water (%)	MFBT (h)	Initial water (%)	MFBT (h)
0.2	37.70	2.0	41.31	1.5
0.4	44.20	3.0	46.19	3.0
0.6	41.28	4.5	43.62	4.0
0.8	43.40	6.0	45.16	5.0
1.0	44.62	7.5	46.75	6.0
1.2	43.10	8.5	46.10	7.0

Table 4. The rate of percolation into troughs at different depths at different rates of water application

Depth (cm)	Rain intensity (mm/h) 3: Percolation rate (mm/h)	3: Percolate (% of applied)	15: Percolation rate (mm/h)	15: Percolate (% of applied)	30: Percolation rate (mm/h)	30: Percolate (% of applied)
40	-	2.85	1.7	21.7	9.2	47.3
60	-	1.75	0.7	9.6	4.0	20.6
80	-	-	0.3	4.1	1.8	9.2
100	-	-	0.2	2.9	1.6	8.3
120	-	-	0.2	2.7	1.7	8.5

of the applied water moved down freely to 0.4 m depth, one fifth to 0.6 m and one tenth to 1.2 m depth at rates of 9.2, 4.0 and 1.6 mm/h, respectively. With 15 mm/h rain, the percentage of applied water that percolated to 0.8 m was about half of that at 30 mm/h and the rate was about 6 times lower. At 3 mm/h, only a small fraction, 1.7%, of the applied water drained into the trough at 0.6 m. The increase in the quantity of percolated water was not proportional to the increase in irrigation intensity from 3 to 15mm/h. However, a proportional increase (2 fold) in percolation to a depth of 0.8 m occurred as rain intensity increased from 15 to 30 mm/h.

Rainfall intensity or water application rate affects water movement through a profile having macropores (Radulovich *et al.*, 1992). Beven and Germann (1982) stated that when the same volume of water is applied at higher intensity, it may run deeper into the profile through the macropores. Results obtained from a column experiment by Edwards *et al.* (1992) support the above statement. In this irrigation experiment, no visible ponding on the soil surface was observed, even with an application rate of 30 mm/h. The water was applied in pulses, each of 5 min duration with 10 min between pulses so that for a mean application rate of 30 mm/h, the actual intensity during the period of application was three times greater. It is widely thought that the soil must be close to or fully saturated, with water ponded or nearly ponded on its surface, before preferential flow can occur (Seyfried and Rao, 1987; Watson and Luxmoore, 1986). Nevertheless, it is also well established that well-structured materials like the over-lying soil and the underlying fractured chalk at the experimental site have dual porosity. In a dual porosity medium, the intra-aggregate porosity has low infiltrability (in case of chalk it is usually 5-8 mm/d) while the inter-aggregate porosity has high infiltrability (14 m/d). In a well-structured soil, inter-aggregate pores are abundant and macropores, such as earthworm burrows and dead root channels may also be present. These pores and channels were especially abundant in the soil under study because it was under long-term grass that had not been tilled for a long period. The pulsed application of water used in these experiments exceeded, by a wide margin, the near saturated hydraulic conductivity of the soil and the chalk matrix. For example, the hydraulic conductivity of the overlying soil and fractured chalk measured *in situ* decreased from ≈110 mm/d near saturation to about <8 mm/d at a matric potential ≈-50 cm water (Mahmood-ul-Hassan and Gregory, 2002). Once the hydraulic conductivity of the soil aggregate/chalk fragments is exceeded, the surface of those aggregates/fragments becomes saturated and water flows around them and moves downward through the inter-aggregate pore network. Once the inter-aggregate pore network has started to conduct water, a very small increase in water content can then result in very large increase in hydraulic conductivity. Thus, the overlying soil and underlying fractured chalk need not be saturated for water to flow rapidly through the profile.

Freely draining water collected by the troughs at application rates of 15 and 30 mm/h confirms the preferential flow phenomenon in the fractured chalk profile. However, insertion of the trough may have disturbed the soil water pressure profile (boundary conditions) and therefore soil water movement. For water to drop into the trough, the boundary must be saturated and, therefore, matric potential may be different to that in undisturbed chalk. Physical disruption and compaction (due to insertion) may also affect flow in the preferential flow path. For example, local compaction may divert the preferential movement laterally rather than into the trough. Total avoidance of the disturbance of flow *in situ* is very difficult if not impossible. So the impact of the presence of the troughs and particularly the effect on boundary conditions requires further investigation.

Extensive inter-aggregate, non-capillary porosity is demonstrated by the large and rapid decrease in water content (from ≈0.48 to 0.38 m^3/m^3 at 0.2 m, ≈0.5 to 0.46 m^3/m^3 at 0.6 m and ≈0.50 to 0.46 m^3/m^3 at 1.2 m (Fig. 3) and in hydraulic conductivity as matric potential decreased from 0 to -10 kPa (Mahmood-ul-Hassan and Gregory, 2002). The application rates of water used in the experiments exceeded the matrix saturated hydraulic conductivity of the soil overlying the cryoturbated chalk. In another study on the same site, Mahmood-ul-Hassan and Gregory (2002) observed that most of the cryoturbated chalk matrix remained close to saturation during winter and hence had only a small additional ability to store water. A small increase in water content (1-3%, in excess of the usual matrix water content) results in an exponential increase in hydraulic conductivity (Mahmood-ul-Hassan and Gregory, 2002; Radulovich *et al.*, 1992; Hodnett and Bell, 1990). This implies that any application of water that exceeds the capacity of the matrix to conduct water would have to pass through the preferred pathways.

The measurements show that preferential flow in macro-pores occurred even at the lowest rate of 3 mm/h but that this was for an effective duration of 8 h and a total application of 24 mm. While events of this intensity and duration are not very common, they do occur in southern England especially in winter and summer storms. For example, in the two winters studied by Mahmood-ul-Hassan (1998), rainfall intensity exceeded 3 mm/h on several occasions and on at least two occasions in each season, the total rainfall was >24 mm/6 h. In winter the matrix remains close to saturation for prolonged periods so that whenever rain intensity exceeds the saturated hydraulic conductivity of the chalk matrix (0.4 mm/h) early breakthrough and preferential flow is likely.

Acknowledgement

We thank Mr. W. MacPhee for technical assistance, Mr. A. Chalmers and Mr. M. Froment for help with the fieldwork at Bridgets, and Mr. M. Hodnett for constructive criticism of an earlier draft of this paper.

References

Arnon, S., Ronen, Z, Adar, E., Yakirevich, A., Nativ, R. 2005. Two-dimensional distribution of microbial activity and flow patterns within naturally fractured chalk. *J. Contaminated Hyydrol.* **79:** 165-186.

Beven, K., Germann, P. 1982. Macropores and water flow in soils. *Water Resour. Res.* **18:** 1311-1325.

Burnham, C.P. 1990. Chalk and chalk debris as a medium for plant growth, with particular reference to Channel Tunnel spoil. *Soil Use Manag.* **6:** 131-136.

Cooper, J.D., Gardner, C.M.K., Mackenzie, N. 1990. Soil controls on recharge to aquifers. *Eur. J. Soil Sci.* **41:** 613-630.

Edwards, W.M., Shipitalo, W.A., Owens, L.B. 1992. Rainfall intensity affects transport of water and chemicals through macropores in no-till soil. *Soil Sci. Soc. Am. J.* **56:** 52-58.

Gardner, C.M.K., Cooper, J.D., Wellings, S.R., Bell, J.P., Hodnett, M.G., Boyle, S.A., Howard, M.J. 1990. Hydrology of the unsaturated zone of the chalk of southeast England. In: *Proc. Int. Chalk Symposium*, J. B. Burland, B. O. Corbett, D. C. Jones, R. N. Motimore and T. S. Roberts (eds.), pp. 611-618, Thomas Telford, London, UK.

Geake, A.K., Foster, S.D. 1989. Sequential isotope and solute profiling in the unsaturated zone of British Chalk. *Hydrol. Sci. J.* **34:** 79-95.

Hillel, D., Krentos, V.D., Stylliannou, Y. 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in situ. *Soil Sci.* **114:** 395-400.

Hodnett, M.G., Bell, J.P. 1990. Processes of water movement through a chalk coombe deposit in southeast England. *Hydrol. Process.* **4:** 361-372.

James, L.G. 1988. *Principles of Farm Irrigation System Design*, Washington State University, John Wiley and Sons Inc., USA.

Mahmood-ul-Hassan, M., Gregory, P.J. 2002. Dynamics of water movement on chalkland. *J. Hydrol.* **257:** 27-41.

Mahmood-ul-Hassan, M. 1998. Water Movement Through the Unsaturated Zone. *Ph.D. Thesis,* 156 p. The University of Reading, UK.

Moffat, A.J. 1985. *Soil of Bridget Experimental Husbandry Farm, Martyr Worthy, Winchester*, Soil Survey of England and Wales, Rothamsted Experimental Station, Harpenden, Herts, UK.

Nativ, R., Adar, E., Assaf, L., Nygaard, E. 2003. Characterization of the hydraulic properties of fractures in chalk. *Ground Water* **41:** 532-543.

Price, M., Bird, M.J., Foster, S.S.D. 1976. Chalk pore-size measurements and their significance. *Water Serv.* **80:** 596-600.

Price, M. 1987. Fluid flow in the Chalk of England. In: *Fluid Flow in Sedimentary Basins and Aquifers*, J. C. Goff and B. P. J. Williams (eds.), Geological Society Special Publication No. 34, pp. 141-156, Blackwell Sci. Publ., Oxford, UK.

Radulovich, R., Baveye, P., Sollin, P., Solorzano, E. 1992. Bypass water flow through unsaturated microaggregated tropical soils. *Soil Sci. Soc. Am. J.* **56:** 721-726.

Reeves, M.J. 1979. Recharge and pollution of the English Chalk: some possible mechanisms. *Eng. Geol.* **14:** 231-240.

Seyfried, M.S., Rao, P.S.C. 1987. Solute transport in undisturbed column of an aggregated tropical soil: preferential flow effects. *Soil Sci. Soc. Am. J.* **51:** 1434-1444.

Watson, K.W., Luxmoore, R.J. 1986. Estimating macroporosity in a forest watershed by use of a tension infiltrometer. *Soil Sci. Soc. Am. J.* **50:** 578-582.