Evidence for the onset and persistence with depth of preferential flow in unsaturated fractured porous media

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ABSTRACT

Two distinct types of fracture flow can occur in unsaturated fractured porous media: non-preferential flow, whereby the fractures and matrix wet up in equilibrium, and preferential flow, whereby water in the fractures bypasses the matrix. This has important implications for how infiltration, recharge, groundwater flooding and contaminant transport are modelled. Taking the UK Chalk as a case study, we explore evidence for the occurrence of unsaturated preferential fracture flow, considering separately its initiation in the near surface, and persistence at 20–30 m depth. We postulate a link between the apparent hysteretic response of the Chalk soil moisture characteristic, which was observed and simulated, and the initiation of preferential recharge. Focusing on observed water table responses to an extreme rainfall event on 20th July 2007, we show by inverse modelling of recharge that preferential flow persisted to a depth of 20 m below ground level, but not to 30 m, resulting in markedly different water table responses at two boreholes. These findings both lend support to our conceptualisation. However, since the observations from which preferential flow can be inferred are few and are indirect, quantification of the controls on the onset and depth persistence of preferential flow remains a significant challenge.

Key words | chalk, fractured porous media, preferential flow, unsaturated zone

INTRODUCTION

In fractured-porous unconfined aquifer systems flow processes in the unsaturated zone are complex functions of the properties of the matrix domain, the nature of the fractures and the climatic environment. Processes may be highly non-linear functions of the moisture state in each domain, or, as is typically the case in the saturated zone, dominated by a single domain. The Chalk aquifers that occur in much of northwestern Europe are an example of this type of aquifer. In the UK and France, in particular, understanding of these processes is essential in order to quantify recharge (Rushton 2005; Lee *et al.* 2006; Ireson *et al.* 2009a, 2010), understand the risks from groundwater flooding (Pinault *et al.* 2005; Habets *et al.* 2010; Hughes *et al.* 2011; Upton & Jackson 2011) and manage the migration of contaminants, in particular agricultural nutrients, to the aquifers (Zaidman *et al.* 1999; Brouyère 2006; Gooddy *et al.* 2007; Jackson *et al.*

2007). We have previously suggested (Ireson *et al.* 2009a) that three modes of recharge are operative in the Chalk: under low rainfall intensities recharge transmission to the water table is slow (lags >100 d) and through the matrix; under moderate intensities recharge is via the matrix and partially saturated fractures (lags ~20–30 d) and, if sustained can cause flooding (as occurred over parts of southern England and northern France in 2000/1); under high intensity rainfall fractures transmit rainfall preferentially, leading to a large, rapid (<1 d) water table response. It is thus possible to activate the fractures without activating a preferential flow response, which can be explained by the storage and flow in partially saturated fractures, with possible mechanisms described by Price *et al.* (2000) and Haria *et al.* (2003). We consider preferential fracture flow to be enhanced flow through fractures which bypasses the matrix, either partially

or completely. Conversely, non-preferential fracture flow occurs when the fractures and matrix remain in local pressure equilibrium. Our conceptual model for preferential fracture flow is that it is initiated at the ground surface or beneath the soil layer, as a function of rainfall characteristics (intensity and duration) and antecedent soil moisture. It is then propagated with depth through the fracture network, and will either reach the water table, or be completely imbibed into the matrix before reaching the water table. This is also consistent with the conceptualisation of Slater *et al.* (1997) and Zaidman *et al.* (1999), which was based on interpretations from cross borehole electrical resistivity imaging of a saline tracer applied to the Chalk unsaturated zone in Yorkshire. In this paper we provide support for this conceptualisation based on field evidence and models, by looking separately at: (i) the initiation of preferential flow at the top of the unsaturated zone; and (ii) the persistence of preferential flow at the base of the unsaturated zone. We then discuss the implications of this for modelling recharge, especially in the context of groundwater flooding and contaminant transport.

THE INITIATION OF PREFERENTIAL FLOW

Preferential flow can either be initiated by the infiltration of rainfall within the soil layer at ground surface, or due to flow focussing either at the ground surface or below ground, in both cases due to relatively impermeable layers. We focus here on the former.

Soil moisture characteristic data measured at field sites in weathered Chalk appear to exhibit significant hysteresis. As Chalk wets up, the pore water in the matrix and fractures may remain in pressure equilibrium, if wetting is slow compared with the time for exchange between the domains. Alternatively, the fractures may wet preferentially, with water bypassing the matrix, and this we can consider as the initiation of preferential flow in the unsaturated profile. Considering the sampling volumes of various field instrumentation, we use field observations and numerical models to postulate a link between the apparent hysteretic response of the Chalk unsaturated zone and the occurrence of preferential wetting, which might lead to preferential recharge.

Soil moisture characteristics of the Chalk

A record of water content, θ, and matric potential, ψ, data measured at Warren Farm (SU36558092, Berkshire, UK) previously published by Ireson *et al.* (2006, 2009b) has been extended and was available in this study. At 1 m depth, measurements from a neutron probe (a reliable measure of water content, but only read once every two weeks), a profile probe (Delta T, PR1, a dielectric instrument which logs water content every 15 minutes), a pressure transducer tensiometer (Delta T, SWT4R, which measures matric potential down to -8.5 m, logged every 15 minutes) and an equitensiometer (Delta T, EQ2, a porous block sensor that measures matric potential below -5 m, logged every 15 minutes) are available from May 2003 until March 2007 (see Ireson *et al.* 2005, for a more detailed discussion of the instruments). With the addition of new data it was apparent that an improved profile probe calibration could be achieved by assuming a linear drift in the calibration with time. Hence, water content, θ_p, was obtained using an equation of the form

$$\theta_p = a \cdot \varepsilon_p + b \cdot t + c \tag{1}$$

where ε_p is the apparent dielectric constant of the soil using the standard manufacturer's calibration (see PR2 Profile Probe product manual, available from the website http://www.delta-t.co.uk/), t is time in days since installation, and a, b and c are regression coefficients, identified by regression against water content measured using the neutron probe. The performance of the calibration is shown in Figure 1. The matric potential measured by the tensiometer and the porous block sensor were consistent over the range -8 m$<\psi<-5$ m, and therefore a good continuous record was achieved by taking data from the tensiometer when $\psi>-5$ m and from the porous block sensor when $\psi<-5$ m, shown in Figure 1.

To investigate the consistency of these two datasets, quantile mapping (Hashino *et al.* 2007) was used to estimate the water content from the matric potential data. The result is also shown in Figure 1. On the whole, the two series of data appear consistent with one another, with errors no larger than those between the two different measurements of water content. However, in the summer
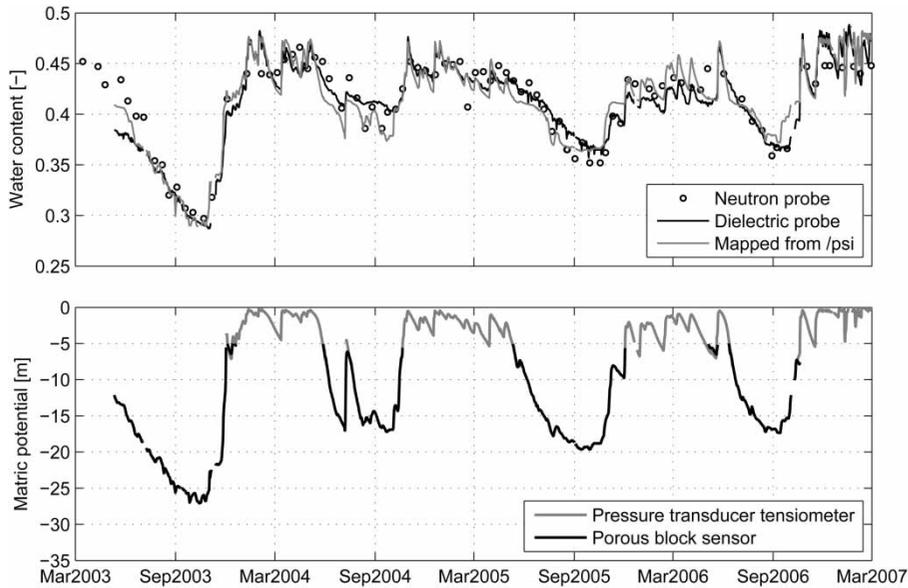
Figure 1 | Observed soil moisture data at 1 m depth at Warren Farm.

of 2004 and the winter of 2005/6 there are differences which merit further investigation. The same data are plotted in Figure 2 as soil moisture characteristic curves. These clearly show the dual porosity nature of the Chalk, with the fractures starting to fill as the matric potential increases above −5 m, and the matrix starting to drain as the matric potential falls below about −15 m. The porosity of the fracture domain is of the order of 5%, which is due to the fact that at 1 m depth the Chalk is expected to be quite weathered (see Ireson et al.

Figure 2 | Observed soil moisture characteristic curves.

2009b). Data from the logged instruments exhibit what appears to be classic hysteresis, and closer examination reveals that the wetting data, which generally occurs in the autumn/winter, tends to have a higher water content that the drying data in the spring/summer months (highlighted in Figure 4(a)). Note also that the neutron probe data, though heavily scattered, are consistent with the more numerous dielectric probe data, suggesting that this apparent hysteresis is not an artefact associated with the dielectric probe.

For the English Chalk, despite the fact that there have been numerous studies which have looked at field observations of water content and matric potential (including Wellings & Bell 1980; Wellings 1984; Cooper et al. 1990; Hodnett & Bell 1990; Haria et al. 2003), evidence of soil moisture hysteresis has only been reported by Mahmood-ul-Hassan & Gregory (2002) and Ireson et al. (2006). This is probably due mainly to the challenges faced in the past in obtaining frequent, simultaneous measurements of water content and matric potential, but perhaps also because it is extremely challenging to model hysteretic responses. A review of hysteresis models was presented by Pham et al. (2005). They found that the best model at reproducing scanning curves (i.e. the transient responses to wetting and drying on the soil moisture characteristic
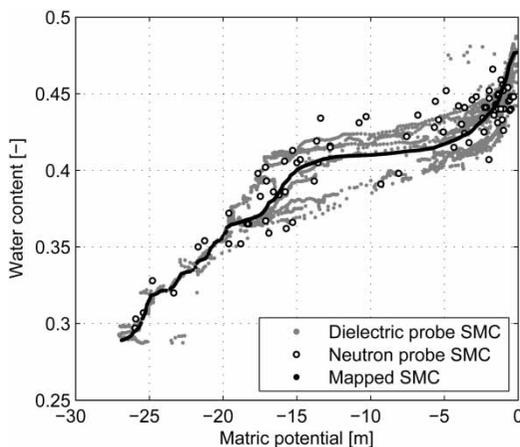
curve) observed by Topp (1971) was the Mualem (1974) model, which is physically based. We note, however, that this model is very similar to the empirical model of Kool & Parker (1987), which was not included in the review by Pham et al. (2005). Such models are extremely difficult to parameterise even for controlled laboratory experiments (in particular the $K(\psi)$ relationship), and to the authors' knowledge, have never been successfully applied to simulate transient field conditions. However, Chalk is not a single porous medium, and we suggest that rather than the classic ink-bottle effect (Pham et al. 2005), the apparent hysteresis is caused by a discrepancy between the sampling volumes of the instruments for measuring water content and those for measuring matric potential. Both the neutron probe and dielectric probe take an integrated reading of water content over some volume of rock, with a minimum radius of about 0.1 m. It is therefore likely that these readings are representative of the bulk fracture-matrix water content, especially in the weathered zone where the typical spacing between 'fractures' (i.e. voids formed between gravel and cobble sized pieces of chalk matrix) is relatively small. Tensiometers and porous block sensors, on the other hand, sample over the contact area between the instrument tip and the rock. The instrument tip will necessarily be located in a fracture (either natural or caused by the installation), but will also have contact with the matrix surface. Therefore, we intuitively expect the tensiometers to respond to increases in pressure in the fracture domain, but not to dry out below the pressure in the matrix. This was discussed by Ireson et al. (2006), but it was suggested that the fracture and matrix domains would be in pressure equilibrium (on the basis of the analysis given below), and hence the fracture matric potential would be representative of the system as a whole. By the same logic, the apparent hysteresis observed in the data might suggest that this assumption is invalid, that is, the fractures and matrix are not in pressure equilibrium. This possibility is explored further in the following sections.

The fracture-matrix equilibrium assumption

Many previous physically based models for flow in the Chalk unsaturated zone (Chapter 4 of Mathias 2005;

Brouyère 2006; Ireson et al. 2009b) have assumed that matrix and fractures can be treated as if they are in pressure equilibrium (exceptions are the model of Ireson & Butler 2011, and some models which combined flow with transport of solutes, e.g. Mathias et al. 2006; Van den Daele et al. 2007) with hysteresis effects ignored. The equilibrium assumption was justified by Ireson (2008) on the basis that the time for imbibition to the matrix block, t_i, would be small compared with the time taken for fracture flow to occur across the matrix block face, t_f. Time for matrix imbibition was estimated using an analytical solution to Richards' equation for one-dimensional flow into a semi-infinite block (Zimmerman et al. 1995, in Appendix C of their report), given by

$$t_i = \frac{4n\alpha\theta_s^m[m(S_{es} - S_{er})]^{1/n}(V_m/A_m)^2(S_{es} - S_{ei})^m}{(n+1)K_s^m} \quad (2)$$

where α [m^{-1}], n [–] and m [–] are van Genuchten (1980) parameters, θ_s^m [–] is the saturated water content of the matrix, V_m and A_m are the volume and surface area of the matrix blocks, S_{es}, S_{er} and S_{ei} [–] are the saturated (100%), residual (0%) and initial saturation, respectively, and K_s^m [m d^{-1}] is the matrix saturated hydraulic conductivity. The time for fracture flow across a matrix block is given by

$$t_f = \frac{L \cdot w_f}{i} \quad (3)$$

where L [m] is the matrix block width, w_f [–] is the fracture porosity and i [m d^{-1}] is the infiltration rate. Properties for the Chalk were taken from Mathias (2005; α=0.033 m^{-1}, n=3, m=2/3, θ_s^m=0.35, K_s^m=0.001 m d^{-1}, w_f=0.01), a conservative (i.e. large) value of L of 0.51 m was taken based on the survey of Bloomfield (1996), and the matrix blocks were assumed to be cubic.

Equations (2) and (3) demonstrate that for a given set of properties and matrix block geometry, the validity of the fracture-matrix pressure equilibrium assumption depends on the infiltration rate, i, and the initial matrix saturation, S_{ei}. Considering a range of S_{ei} from 0 to 99%, Figure 3(a) shows the maximum infiltration rate that can be accommodated before non-equilibrium, or preferential flow, is initiated, on the basis of Equations (2) and (3). As reported in Ireson (2008), for an infiltration rate of 50 mm d^{-1} bypass flow will only be initiated if the initial matrix saturation is less
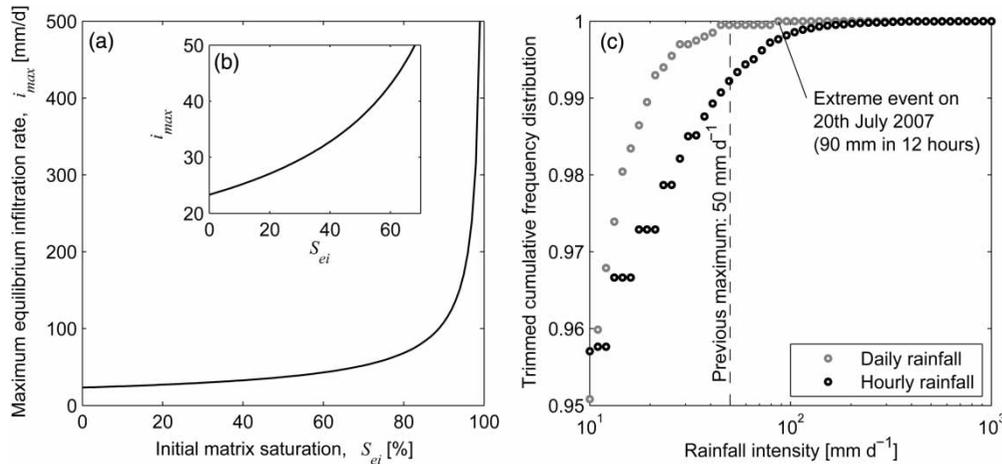
Figure 3 | The maximum infiltration rate that can be transmitted through the Chalk unsaturated zone before bypass flow occurs, depending on the initial saturation of the matrix (a, b), and distribution of high intensity rainfall at Warren Farm between 2004 and 2007 using daily and hourly rainfall data (c).

than 68% (Figure 3(b)). Water content data in Figures 1 and 2, assuming θ_s^m is around 0.42 suggest that the matrix saturation may once have fallen this low in late 2003. However, 50 mm d^{-1} was an upper bound based on daily rainfall intensities observed at the site between January 2004 and January 2006. Subsequently, an extreme rainfall event that occurred on 20th July 2007 was almost double this value (90 mm d^{-1}). Furthermore, even under non-extreme conditions if sub-daily intensities are considered, then much higher intensities occurred, as shown in Figure 3(c). This analysis suggests that the assumption of pressure equilibrium between the matrix and the fractures may not always be appropriate, especially if we are interested in sub-daily recharge responses which are important in certain contexts (e.g. groundwater flooding; Ireson *et al.* 2009b).

Modelling preferential flow in the near surface

Ireson & Butler (2011) attempted to model the recharge processes at East Ilsley, in the Pang catchment (see section *Persistence of preferential flow with depth*), including the extreme recharge event on 20th July 2007, using a 1D dual permeability Richards' equation model of the Chalk unsaturated zone. This modelling exercise showed that in order to obtain the very rapid recharge responses observed by deep jacking tensiometers and piezometers, it was necessary to allow for preferential flow in the fractures – that is to say, an equivalent continuum representation of

the matrix and fractures, assuming local equilibrium between the domains, was inappropriate. A dual continua representation (Doughty 1999) appeared to be appropriate, however, two problems with this were: (i) the model parameter space could not be adequately explored, due to computational restrictions, and (ii) it was possible to simulate indicative recharge fluxes with the 1D model, but it was not possible to simulate the water table response. In this paper we have adapted this model to look at the conditions under which preferential (i.e. non-equilibrium) flow is initiated in the near surface, using a series of numerical experiments. Details of the model are provided in the Appendix (available online at http://www.iwaponline.com/nh/043/030.pdf).

We consider a series of infiltration pulses into a hypothetical Chalk block, initially at hydrostatic conditions. Figure 4 shows the simulated soil moisture characteristic relationships, based on bulk water content, and matric potential in the fractures (consistent with our interpretation of the field measurements). In each figure the equilibrium soil moisture characteristic relationship is shown. For reference, the observed data are shown in Figure 4(a), but it should be noted that this represents the response to a continuous pattern of rainfall and evapotranspiration, whereas the simulated responses are to individual hypothetical rainfall events. In particular, whilst we have simulated the response to large rainfall events from an initial matrix saturation of 60%, there was no such large rainfall event in the
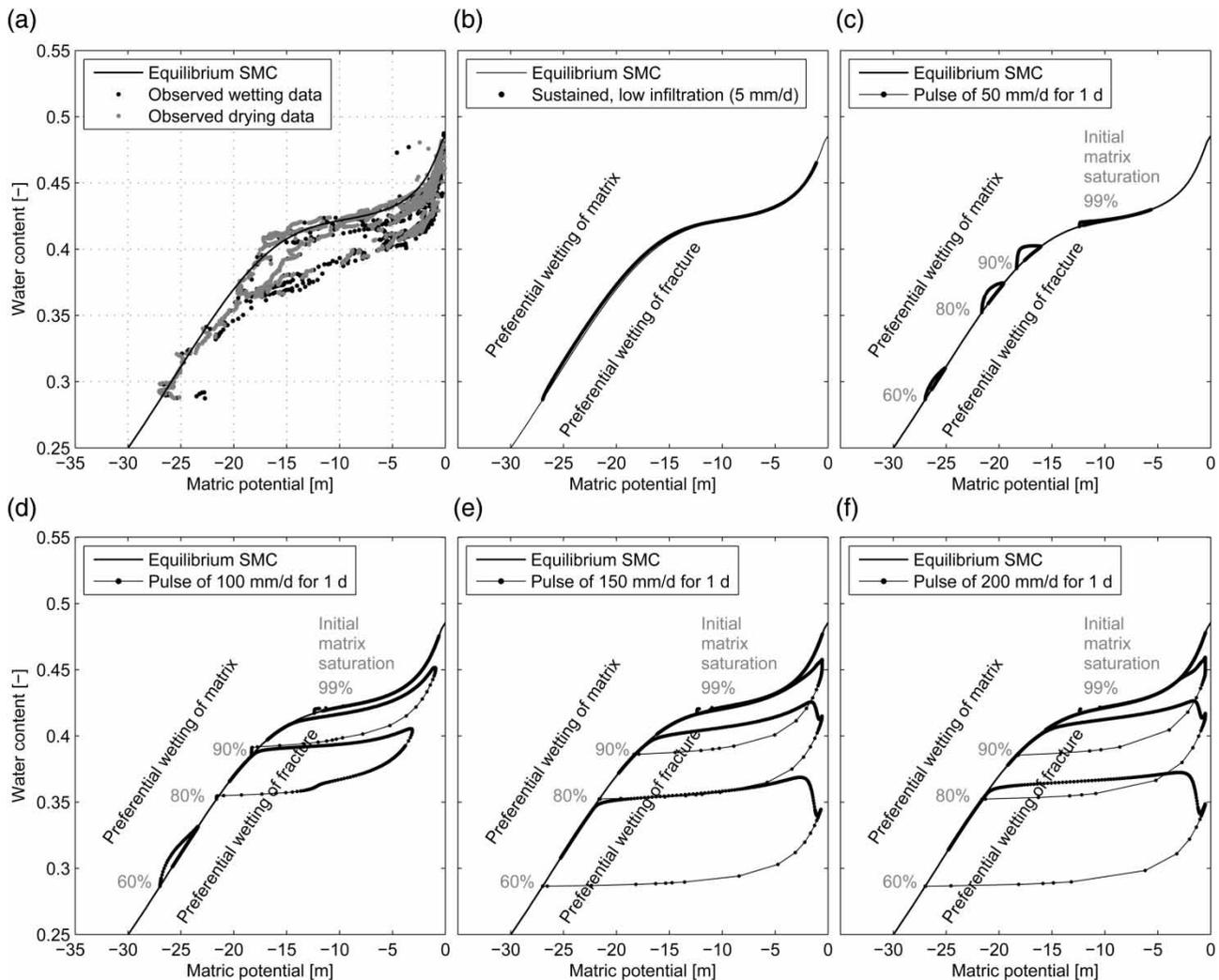
Figure 4 | Soil moisture characteristic curve observed at Warren Farm compared with responses from a series of hypothetical infiltration experiments.

observed record when the soil dried out to similarly low matric potentials (which happened in 2003, Figure 1). If the simulated water content is higher than the equilibrium water content, this suggests that preferential wetting of the matrix has occurred. This is an artefact caused by the upper boundary condition of the model, in which infiltration is applied preferentially to the matrix until the matrix at the surface is saturated (Equations (A7–A9), online Appendix). These responses should therefore be ignored, and further investigation into how the infiltration boundary flux should be partitioned between the matrix and the fractures is warranted. When the simulated water content is lower than the equilibrium water content this indicates

preferential wetting of the fractures, causing a large change in matric potential (potentially up to and beyond saturation), but only a moderate change in the water content, as only the relatively small fracture porosity can be filled preferentially. For sustained low infiltration (Figure 4(b)), or daily pulses of infiltration less than or equal to 50 mm d^{-1} (Figure 4(c)), there is no preferential fracture flow, irrespective of the initial matrix saturation. This is consistent with the analytical results presented above. For larger daily pulses (Figure 4(d), 4(e) and 4(f)), preferential wetting of the fractures starts to occur, with a strong dependency on the initial matrix saturation. For an initial matrix saturation of 99%, since the matrix is already close to saturation, the

wetting and drying curves follow the path of the equilibrium soil moisture characteristic. As the initial matrix saturation reduces, so the extent of apparent hysteresis changes. For a daily pulse of 100 mm d^{-1} with a low initial matrix saturation (60%) the effect is small, because the pulse is absorbed by the change in storage in the matrix, again caused by preferential wetting of the matrix at the surface imposed by the boundary condition. For 150 and 200 mm d^{-1}, hysteresis is highly significant for initial matrix saturations of 60, 80 and 90%.

Simulating hysteretic soil moisture characteristics

To further investigate the link between the observed apparent hysteresis and preferential flow, the model of Ireson & Butler (2011), which incorporates a representation of vertical heterogeneity in the soil and weathered Chalk layers, was applied to transient field observations at Warren Farm. The results, in terms of the simulated soil moisture characteristic at 1 m depth, are reproduced in Figure 5(a). The artefact of preferential wetting of the matrix caused by the boundary condition is fairly significant. We would not expect the model to reproduce individual scanning curves, since it was not possible to rigorously calibrate the model. It was found that the form of the simulated scanning curves was highly sensitive to changes in parameters. Nonetheless, the general form of the responses is reasonably consistent with observations.

The model was originally driven using hourly rainfall and evapotranspiration data, but when we re-ran the model using daily driving data, preferential wetting of the fractures was substantially reduced (Figure 5(b)). This again demonstrates that if preferential fracture flow processes are important, it is necessary to consider sub-daily driving data to adequately capture the system response.

PERSISTENCE OF PREFERENTIAL FLOW WITH DEPTH

Evidence of rapid (<1 d), deep (>20 m BGL) water table responses to high intensity rainfall events in Chalk has previously been reported by Lee et al. (2006), Ireson et al. (2009a) and Ireson & Butler (2011). Ireson et al. (2009a) suggested that such responses are dependent on rainfall characteristics, in terms of intensity and duration, and antecedent soil moisture. The responses observed by Lee et al. (2006) occurred during the onset of the major groundwater floods in the winter of 2000/2001. During this period, short time scale (daily-weekly) rainfall intensities were unexceptional, but due to sustained moderate intensity rainfall, groundwater flooding occurred (Pinault et al. 2005; Hughes et al. 2011). However, the antecedent soil and unsaturated zone moisture would have been very high, which is probably why preferential responses occurred, consistent
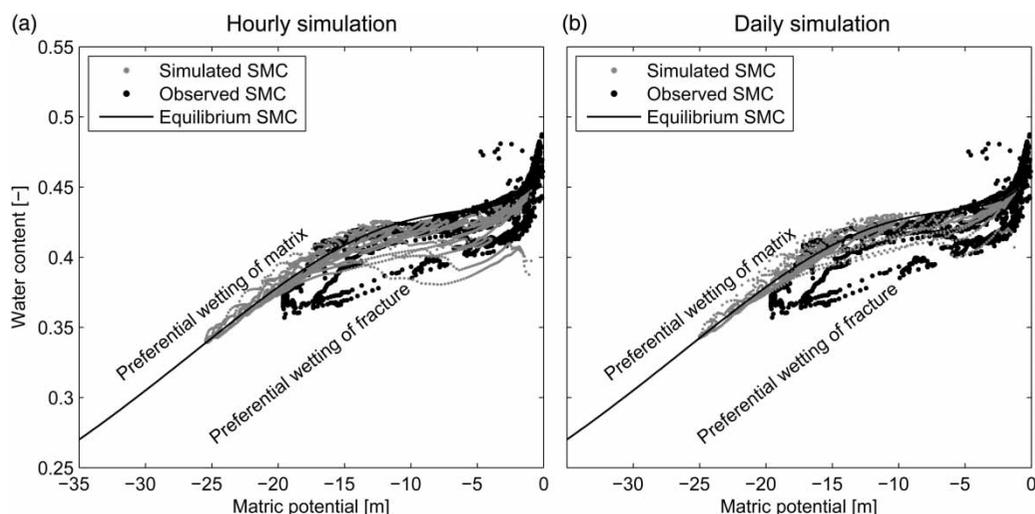

Figure 5 | Transient simulations, reproduced with the model of Ireson and Butler (2011).

with the findings of Ireson *et al.* (2009a). By contrast, the events reported by Ireson *et al.* (2009a) and Ireson & Butler (2011) occurred during a period of groundwater recession in the summer of 2007, in response to extreme high intensity rainfall.

In this paper, we again focus on the water table response in the Pang catchment, Berkshire, UK, to the extreme high intensity rainfall event on 20th July 2007. Two boreholes, East Ilsley, EI, and Hodcott, HC, are both located in the intermittently dry valley of the River Pang, about 1.3 km apart, shown in Figure 6(a). Both boreholes are located a similar distance from the base of the dry valley (EI~250 m and

HC~210 m). HC is higher up in the catchment, and as such the water table elevation is higher, by approximately 10 m, but in general, the water table responds consistently at the two boreholes (Figure 6(b)). HC is also located on a localised topographic high (Figure 6(a)), meaning that the unsaturated depth is greater than at EI, by about 10 m (the unsaturated zone thickness on 19th July 2007 at EI is 19.5 m and at HC is 30.1 m). The most notable difference in the water table response at each of these boreholes occurs following the 20th July 2007 extreme event, shown in detail in Figure 6(c). Radar data (UK Meteorological Office, rain radar product NIMROD, NCAS British Atmospheric Data Centre, accessed October 2009, available from http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_nimrod) show that this rainfall event moved across the area from southeast to northwest, and spatially covered the entire Pang catchment. These sites are within a single grid cell of the 2 km gridded radar dataset, so it is not expected that significantly different rainfall amounts would have fallen at each borehole. At HC, the response does begin at the same time as EI, but the early response is far more gradual. The response at EI has been interpreted as evidence of preferential flow by Ireson *et al.* (2009a), who showed that the water table response preceded the response in tensiometers located approximately 1 and 2 m above the water table, and by Ireson & Butler (2011), who found it necessary to allow for non-equilibrium fracture flow to simulate the recharge processes (as discussed above).

In order to simulate the water table response, it is necessary to simulate the incoming recharge flux as well as lateral exchange in the saturated zone, the net balance of which results in a movement in the water table. This can be achieved with a 2D saturated-unsaturated zone model applied to a hillslope slice, but this remains an outstanding challenge. In this paper, we attempt to infer the recharge signal that would be required to produce the observed responses at EI and HC. This avoids the complex problem of simulating how effective rainfall in transmitted through the unsaturated zone to generate recharge. In general this can be performed for ideal aquifer systems using the 'water table fluctuation' method for recharge estimation (Cuthbert 2010). The essential requirement of this method is that lateral exchange in the saturated zone can be quantified, and in reality there will always be a large amount of
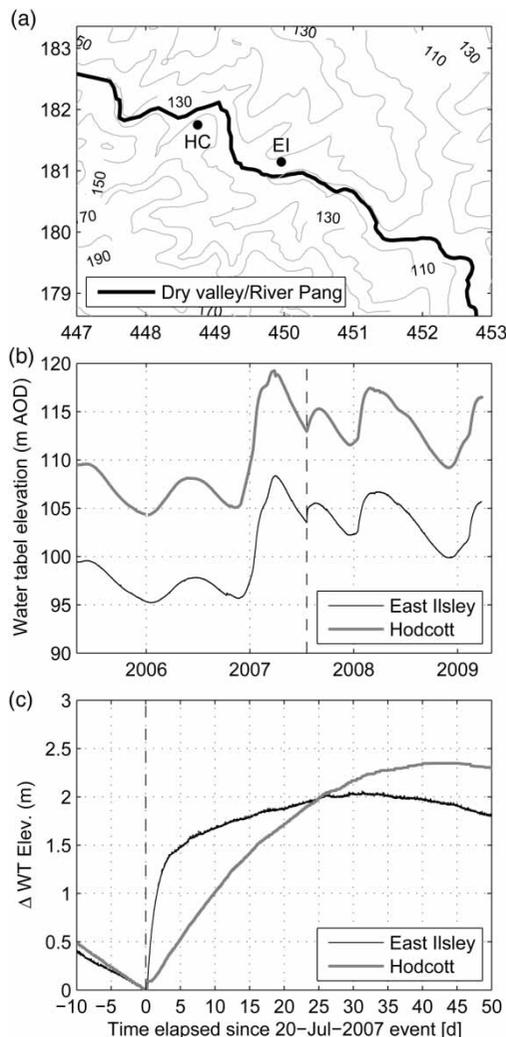

Figure 6 | (a) The location of boreholes at East Ilsley and Hodcott, in the dry valley of the River Pang, (b) water table responses at each borehole, and (c) the detailed water table response to an extreme rainfall event on 20th July 2007.

uncertainty associated with this, as well as the problems of heterogeneity and delayed drainage from the rock above the water table. In our case, however, we shall only apply this method to the response to an individual event, and our aim is not to obtain a reliable quantitative estimate of recharge, but to explore the pattern of recharge required to obtain the observed responses. To do this, the Boussinesq equation is used to simulated the water table response on a hillslope scale

$$S_\text{y} \frac{\partial h}{\partial t} = -\frac{\partial}{\partial x}\left(K(h - z_\text{b})\frac{\partial h}{\partial x}\right) + R \qquad (4)$$

subject to boundary conditions

$$
\begin{array}{ll}
h = h_R & (x = 0; \qquad 0 \geq t \geq t_\text{N}) \\
\left(K(h - z_\text{b})\dfrac{\partial h}{\partial x}\right) = 0 & (x = L; \qquad 0 \geq t \geq t_\text{N}) \\
h = h_\text{i} & (0 \geq x \geq L \quad t = 0)
\end{array}
\qquad (5)
$$

where h is hydraulic head [m], x is distance up the hillslope in the horizontal direction, with $x=0$ at the base of the hillslope where a fixed head boundary, h_R [m], is applied, L is the hillslope length [m], t is time [d], S_y is specific yield [–], K is hydraulic conductivity [m d^{-1}], z_b is the elevation of the base of the aquifer [m] and R is the unknown recharge time series [m d^{-1}]. The initial hydraulic head, h_i [m], is based on an arbitrary steady-state solution to Equation (4), with a fixed recharge rate of $R=0.1$ mm d^{-1}. Equation (4) is solved numerically in MATLAB using standard finite difference approximations for the right hand side, and an ODE solver (ODE15s) for the temporal integration, using the method of lines.

EI and HC are located around 3–4 km from the perennial head of the River Pang (the model lower boundary), approximately along a groundwater flow line. The groundwater divide is around 10 km from the lower boundary, but is highly dynamic in this catchment (see Figure 4 in Wheater *et al.* 2006). Therefore, $L=10{,}000$ m, and the domain is discretised uniformly into 60 nodes. A spatially uniform, transient recharge flux, R, is applied to the hillslope and the water table response, h, at $x=4{,}000$ m is taken as an approximation to the water table responses at both EI and HC. The objective, again, is not to obtain accurate quantitative recharge estimates, but is to find temporal

distributions of R that provide a reasonable simulated water table response, and this is done separately for each borehole. In each case, an initial 10 day recession is adopted (i.e. period of zero recharge), since the observed water table was initially dropping. The subsequent recharge pulse from the rainfall event is represented as the sum of one or more normally, or log-normally distributed pulses, described by three parameters: the magnitude, R_p, and first and second moments (μ and σ). These parameter values were optimised by minimising the squared residuals between the observed and simulated change in water table elevation, using the MATLAB optimisation algorithm fminsearch. In each case, we started with a single normal or log-normal pulse, and if this was unable to reproduce the response a second pulse was added, and in principle any number of additional pulses could also be included.

The results of this exercise are shown in Figure 7. For reference, daily rainfalls recorded at Warren Farm tipping bucket rain gauge are also shown in this figure, but note that these data were not used in the model. It can be seen that the water table response at HC was very well reproduced by a single, log-normally distributed pulse of recharge, with a peak intensity of 1.7 mm d^{-1} (with moments $\mu=5.5739$ d and $\sigma=2.1088$ d). For EI, no single pulse was found which was able to reproduce the observed response well. Instead, a similar log-normally distributed pulse was used, with a peak intensity of 1.2 mm d^{-1} (with moments $\mu=7.1931$ d and $\sigma=2.5580$ d) with an additional normally distributed pulse superimposed, with a peak intensity of 13.5 mm d^{-1} (with moments $\mu=0.4033$ d and $\sigma=0.3571$ d). As shown in Figure 7, this results in a simulated water table response which was reasonably consistent with observations.

The recharge signals at these boreholes very clearly suggest that at HC the response was caused by a single, relatively slow, attenuated recharge pulse, whilst at EI there are two clear pulses, one rapid, and one relatively slow. This suggests preferential flow occurred at EI, which is consistent with previous suggestions (Ireson *et al.* 2009a; Ireson & Butler 2011), but, crucially, not at HC. Hence, preferential flow which was initiated at the surface following the intense rainfall event persisted to a depth of 19.5 m BGL at EI, but not to 30.1 m at HC. Note also that the total volume of recharge over this 50 day period
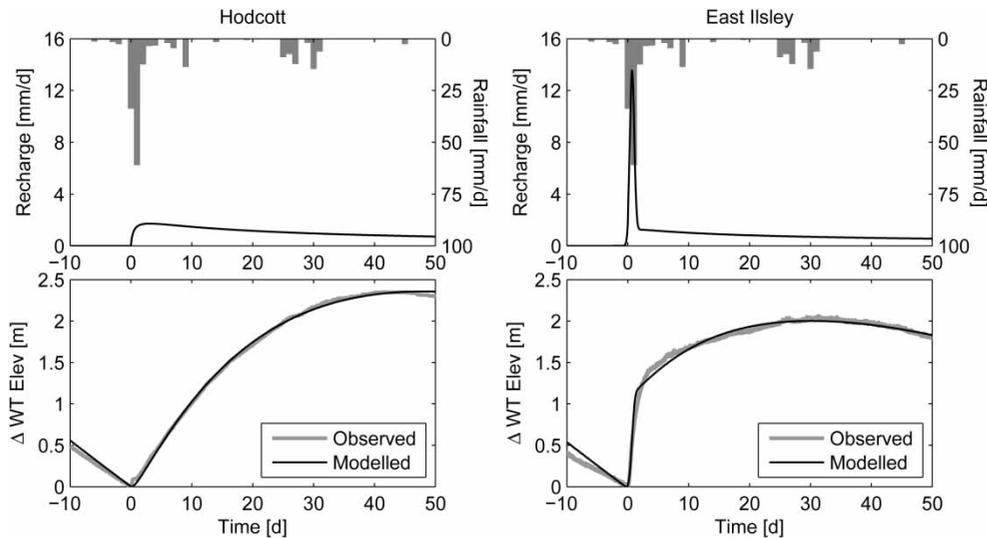
Figure 7 | Recharge pulses used to simulate the water table response at East Ilsley and Warren Farm.

was roughly the same (around 50 mm) for the two bore-holes. This lends convincing support to our conceptual model for the Chalk unsaturated zone, which says that once preferential flow is initiated at the ground surface, it will propagate down the fracture network, being continually attenuated with depth as it is imbibed into storage in the matrix. The preferential flow will only reach the water table if the unsaturated thickness is sufficiently thin. However, other factors, such as soil thickness, localised fracture features and other heterogeneities in the Chalk properties, could play a role.

CONCLUSIONS

A conceptual model for preferential flow processes in the Chalk unsaturated zone – a particular case of a fractured porous material – was tested using interpretations from field data and models. We look separately at the initiation and depth persistence of preferential fracture flow.

Initiation

We suggest that the clearly apparent hysteresis in field observed soil moisture characteristic data from the Chalk may be caused by: (i) differences in the sampling volume of the instruments for measuring water content and matric potential, and (ii) the fact that the matric potential in the matrix and fractures can be significantly different, especially following intense infiltration events. We sought to demonstrate this using a series of numerical experiments with a dual-continua model. Results were consistent with an analytical solution for the maximum infiltration rate that could be accommodated under fracture-matrix equilibrium conditions, and suggest that preferential wetting of the fractures – associated with the initiation of preferential fracture flow – may be a plausible explanation for the apparently hysteretic observed soil moisture characteristic curves. There were problems with the model associated with how infiltration is partitioned between the fractures and the matrix which need to be addressed. Further research is needed to explore whether a dual-continua model can be calibrated to reproduce hysteretic scanning curves from field data sets.

Depth persistence

An extreme high intensity rainfall event on 20th July 2007 led to very rapid (<1 d) water table responses at two boreholes in the Pang catchment. However, the form of these responses was markedly different. Inverse modelling of these water table responses was used to establish recharge patterns that could have caused the responses. At East Ilsley, where the unsaturated zone is thinner (~20 m

thick), a fast, high intensity recharge pulse is required for the initial, rapid water table rise, with a sustained, relatively slow, low intensity recharge pulse for the continued water table rise. However, at Hodcott, where the unsaturated zone is thicker (∼30 m thick), the response can be reproduced by a single, relatively slow pulse, similar to that at East Ilsley. This could be because preferential fracture flow reached the water table at 20 m depth, but was completely attenuated by 30 m depth. The results help corroborate previous suggestions (Ireson *et al.* 2009a; Ireson & Butler 2011) that the water table response at East Ilsley was caused by preferential recharge, and is consistent with the conceptualisation above.

The proposed conceptual model of three forms of recharge in the Chalk – matrix flow, non-preferential fracture flow and preferential fracture flow – has significant implications for the way that recharge processes are modelled. Rushton (2005) provides a good, authoritative summary of how recharge to Chalk aquifers is conventionally modelled. For the fracture flow component, some fixed amount of rainfall, and/or rainfall over some threshold (Rushton & Ward 1979) becomes bypass flow which passes directly to the aquifer. Typically, 15% of rainfall is considered as bypass recharge, uniformly throughout the year, which originates from interpretations of Tritium profiles by Smith *et al.* (1970). Based on the analysis in this and other recent papers (Lee *et al.* 2006; Ireson *et al.* 2009a, 2010) we can be confident that this is an oversimplification. However, given that the groundwater models driven by these recharge models are typically used for the long term estimation of water resources, and short time scale responses are less important, these models may be fit for purpose. To explore more complex processes, such as groundwater flooding and solute transport processes it is necessary to use physically based models for flow in the Chalk unsaturated zone. Most physically based models adopt a continuum representation of the fractures and matrix, in one of two ways: either as an equivalent continuum (ECM), assuming instantaneous pressure equilibrium between fractures and matrix, or as dual continua (DCM), with first order transfer of water between them. ECM approaches to model the Chalk unsaturated zone include Chapter 4 of Mathias (2005), Brouyère (2006) and Ireson *et al.* (2009b). DCM approaches, which include Mathias *et al.* (2006), Van den Daele *et al.* (2007)

and Ireson & Butler (2011), are better suited to simulate problems where preferential flow is significant. The appropriate representation depends to a large extent on the temporal and spatial scale of interest, with preferential flow becoming more significant on smaller temporal and spatial scales. However, results presented here suggest that preferential flow can persist throughout the entire unsaturated depth (tens of metres) and play a significant role in recharge, depending on the depth of the water table.

It is important to note limitations in this study. Firstly, there are other plausible interpretations of these data. The conventional model of hysteresis (the 'ink bottle effect'; Pham *et al.* 2005), operating on the matrix domain, cannot be ruled out to explain the observed soil moisture characteristic curves. In addition, it is possible that differences in soil properties at Warren Farm, Hodcott and East Ilsley are a more significant control on the onset and persistence of preferential flow than the unsaturated depth. It is also possible that flow focussing, caused either by impermeable layers in the Chalk unsaturated zone, or large apertures (either natural fractures, or boreholes) may act as a strong control on preferential flow. There is no evidence of significant differences in the stratigraphy at East Ilsley and Hodcott (located just over 1 km apart), but that does not mean that differences do not exist, and might explain the different responses. Finally, the qualitative conceptualisation here may provide useful direction, but quantifying the controls on initiation and persistence of preferential flow is a significant and outstanding challenge, requiring more data both at these sites for a wider range of conditions, and at other field sites both in this catchment and in other catchments.

ACKNOWLEDGEMENTS

Finch from the Centre for Ecology and Hydrology. Data were provided by CEH from the NERC LOCAR, and we are grateful in particular to Ned Hewitt for his hard work collecting the data over many years.

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