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The significance of flow in the matrix of the Chalk unsaturated zone

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Abstract

The significance of flow in the matrix of the Chalk unsaturated zone, in comparison with flow in fractures, has been the subject of much debate. In this article, important elements of the literature are discussed in detail and several simple modelling analyses based on steady-state flow are presented. A study of the sensitivity of solute spreading to fracture spacing in models that ignore matrix flow shows that this latter assumption is generally incompatible with observed solute profiles, unless unrealistically small fracture spacings are assumed. The effect of air phase continuities (e.g. bedding planes) on matrix flow has also been examined. These discontinuities are frequently interrupted by points of connectivity between matrix blocks. An issue therefore is the relationship between connectivity and its effect on inter-block conductance. A simple analysis of the Laplace equation shows that just 1% connectivity represents an effective pathway equivalent to 18% of the local rock hydraulic conductivity. Obviously, when there is no fracture flow, solute spreading is significantly reduced. However, dual permeability model simulations show that matrix flow reduces solute spreading in the presence of persistent fracture flow. All of the above studies suggest that flow in the matrix of the Chalk unsaturated zone is significant and that ignoring it may result in a serious misunderstanding of the system.

Keywords: Chalk; Dual permeability models; Dual porosity models; Fractured rocks; Transport; Unsaturated zone

1. Introduction

Throughout the literature concerning flow and solute transport in the unsaturated zone of the Chalk there has been much debate as to whether the dominant element of flow occurs in the fractures or the matrix. Flow in the unsaturated zone of the Chalk was originally believed to be predominantly through fractures. Evidence to support this included the observed rapid response of the water table after high intensity rainfall events (Headworth, 1972) and the appearance of bacteria in boreholes (Maclean, 1969). This was largely unquestioned prior to a 1968 study of tritium content in pore-water from the unsaturated zone at a Berkshire site, which led Smith et al. (1970) to suggest that 85% of the total flow through the unsaturated zone was by intergranular seepage through the matrix at a mean rate of less than 0.9 m/yr. This rate of solute movement has been widely supported by many other similar studies (e.g. Oakes, 1977; Wellings, 1984b; Barraclough et al., 1994). The rapid observed response of water

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tables was then explained by a 'piston-displacement' mechanism whereby water arriving at the water table had been displaced from the bottom of the unsaturated zone instead of travelling quickly through it (Price et al., 1993).

Since the analysis of Smith et al. (1970), there have been parallel schools of thought with regard to whether flow in the matrix of the Chalk unsaturated zone is significant (e.g. Wellings, 1984a; Hodnett and Bell, 1990; Haria et al., 2003) or not (e.g. Oakes et al., 1981; Barker and Foster, 1981; Fretwell et al., 2000). Foster (1975) made an important contribution by highlighting the fact that solutes in fractures can be greatly retarded by lateral diffusion into adjacent matrix blocks. This provided an integrated theory of flow and transport, but one in which the role of matrix flow was not seen as significant. By studying the literature and performing some simple modelling analyses this article aims to resolve this issue to arrive at a well-founded conclusion regarding the significance of flow in the matrix of the Chalk unsaturated zone.

2. Pore water profiles

The findings of Smith et al. (1970) are based on the tritium profile presented in Fig. 1. A sharp peak can be seen at 4 m depth followed by a broader peak at between 7 and 9 m depth. These two peaks are thought to be associated with the very high tritium levels found in rainfall during the periods of 1963–1964 and 1958–1959. Smith et al. (1970) speculate that the existence of these peaks shows that downward movement of water is predominately by intergranular seepage through the matrix. From the position of these peaks the mean seepage velocity can be calculated at around 0.88 m/yr. On this basis it should be expected that any tritium observed below 13 m depth has travelled via faster pathways in the fractures. This portion represents around 15% of the total mass present in the profile. Furthermore, an implicit assumption was made that all tritium travelling through fractures was still present within the unsaturated zone. However, this ignores the possibility that very fast flowing tritiated water may have flowed through the unsaturated zone and into the saturated zone. This was probably overlooked because the estimate of tritium input mass (corrected for evaporation) appeared to be less than the total mass measured from the profile.

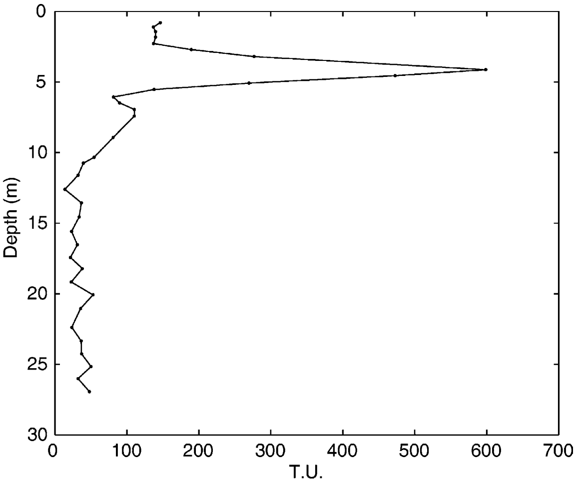

Fig. 1. Chalk unsaturated zone pore-water tritium profile from a Berkshire site in October 1968 after Smith et al. (1970).

The total amount of tritium in the profile was estimated to be 863 TU m. By contrast, the total amount of tritium which had fallen on the catchment in precipitation from 1954 to 1968 has been estimated at 2400 TU m (Smith et al., 1970). To equate the total mass in the profile with the input mass, Smith et al. (1970) applied a simple soil moisture accounting model to calculate an effective rainfall. Through the evaporation of tritiated water, an effective tritium input can be obtained using the ratio of effective to actual rainfall. Effective rainfall was calculated from the difference between monthly values of precipitation and evaporation with surface runoff assumed to be negligible. Actual evaporation was calculated as potential evaporation using Penman's formula (Penman, 1950), but with an upper limit of soil moisture deficit of 120 mm. Smith et al. (1970) found that a mass balance could only be achieved between the tritium profile and the input time-series by reducing the calculated evaporation by 25%. Furthermore, Smith et al. (1970) do not report any consideration of decay (tritium has a half-life of around 12.3 years) which would suggest that the evaporation estimate should be reduced even further before mass balance is obtained.

The required reduction in evaporation is probably due in part to inadequacies associated with their evaporation calculation and because the estimate of UK rainfall tritium content was derived from data