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Redistribution of contaminants by a fluctuating water table in a micro-porous, double-porosity aquifer: Field observations and model simulations

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Abstract

Large seasonal fluctuations of the water table are characteristic of aquifers with a low specific yield, including those fractured, double-porosity aquifers that have significant matrix porosity containing virtually immobile porewater, such as the Chalk of northern Europe. Where these aquifers are contaminated, a strong relationship between water table elevation and contaminant concentration in groundwater is commonly observed, of significance to the assessment, monitoring, and remediation of contaminated groundwater. To examine the processes governing contaminant redistribution by a fluctuating water table within the 'seasonally unsaturated zone', or SUZ, profiles of porewater solute concentrations have been established at a contaminated site in southern England. These profiles document the contaminant distribution in porewater of the Chalk matrix over the SUZ at a greater level of detail than recorded previously. A novel double-porosity solute transport code has been developed to simulate the evolution of the SUZ matrix porewater contaminant profiles, given a fluctuating water table, when the groundwater is initially contaminated and the SUZ is initially free of contamination. The model is simply characterised by: the matrix-fracture porosity ratio, the matrix block geometry, and a characteristic diffusion time. De-saturation and re-saturation of fractures is handled by a new approximation method. Contaminant accumulates in the upper levels of the SUZ, where it is less accessible to mobile groundwater, and acts as a persistent secondary source of contamination once the original source of contamination has been removed or has become depleted. The 'SUZ process' first attenuates the progress of contaminants in groundwater, and

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subsequently controls the slow release of contamination back to the mobile groundwater, thus prolonging the duration of groundwater contamination by many years. The SUZ process should operate in any fractured, micro-porous lithology e.g. fractured clays and mudstones, making this approach widely applicable.

Keywords: Unsaturated; Double-porosity; Diffusion; Contaminants; Chalk; Modelling

1. Introduction

Unconfined aquifers with a low specific yield characteristically show large seasonal changes in the level of the water table as a response to seasonal variations in recharge. Where such an aquifer is contaminated, variations in contaminant concentration in groundwater often show a direct correspondence to variations in the water table hydrograph, suggesting a causal relationship between contaminant mobility and water table fluctuation across the 'seasonally unsaturated zone' (SUZ). This is particularly so in double-porosity aquifers, in which the matrix porosity offers a large potential storage volume for dissolved contaminants. The relationship has important implications for groundwater quality monitoring, and the assessment and remediation of contaminated aquifers, yet the processes underlying the correspondence between water table elevation and groundwater quality have received sparse quantitative attention.

1.1. The seasonally unsaturated zone of the Chalk aquifer

The seasonally unsaturated zone, or SUZ, is that part of an unconfined aquifer that lies between the highest and lowest groundwater level stands in the long term, reflecting the effects of seasonal recharge and drainage of the aquifer. The term emphasises that processes operating under unsaturated conditions distinguish the SUZ from the permanently saturated part of an aquifer (Lawrence et al., 1992). Specifically, diffusive exchange between matrix porewater and mobile water in fractures can only occur under conditions of fracture saturation, and is therefore periodic (seasonal) in the SUZ of a double-porosity unconfined aquifer. Diffusion continues to operate in the residual porewater within matrix blocks under unsaturated conditions, i.e. when fractures surrounding the matrix blocks drain, leaving individual matrix blocks isolated.

The low specific yield of the Chalk aquifer of northern Europe leads to a seasonal water table fluctuation of up to 40 m in response to recharge in the unconfined aquifer (Price et al., 1993). The double-porosity nature of the Chalk is well established (Price, 1987; Price et al., 1993). The aquifer is comprised of blocks of low permeability, micro-porous matrix with pore throats typically in the range 0.1 to 1.0 μm in diameter, separated by an extensive fracture network with fracture apertures typically ranging from 50 μm to several millimetres in width (Price et al., 1993; Bloomfield, 1996). Fractures contribute a negligible proportion of the overall porosity, but dominate the bulk permeability of the Chalk (MacDonald and Allen, 2001). The narrow pore throats of the Chalk matrix can support a thick capillary fringe, in excess of 30 m, so the Chalk matrix is normally fully