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Catchment-scale modelling of flow and nutrient transport in the Chalk unsaturated zone

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ABSTRACT

The unsaturated zone exerts a major control on the delivery of nutrients to Chalk streams, yet flow and transport processes in this complex, dual-porosity medium have remained controversial. A major challenge arises in characterising these processes, both at the detailed mechanistic level and at an appropriate level for inclusion within catchment-scale models for nutrient management. The lowland catchment research (LOCAR) programme in the UK has provided a unique set of comprehensively instrumented groundwater-dominated catchments. Of these, the Pang and Lambourn, tributaries of the Thames near Reading, have been a particular focus for research into subsurface processes and surface water–groundwater interactions. Data from LOCAR and other sources, along with a new dual permeability numerical model of the Chalk, have been used to explore the relative roles of matrix and fracture flow within the unsaturated zone and resolve conflicting hypotheses of response. From the improved understanding gained through these explorations, a parsimonious conceptualisation of the general response of flow and transport within the Chalk unsaturated zone was formulated. This paper summarises the modelling and data findings of these explorations, and describes the integration of the new simplified unsaturated zone representation with a catchment-scale model of nutrients (INCA), resulting in a new model for catchment-scale flow and transport within Chalk systems: INCA-Chalk. This model is applied to the Lambourn, and results, including hindcast and forecast simulations, are presented. These clearly illustrate the decadal time-scales that need to be considered in the context of nutrient management and the EU Water Framework Directive.

1. Introduction

In the United Kingdom, abstractions from Cretaceous Chalk aquifers represent 20% of all national water supplies, and up to 60% of the groundwater supply (Downing, 1998). Typically, the recharge areas are overlain by intensively cultivated soils, which form a diffuse source of pollution. Nitrate loading is of particular concern, as elevated concentrations render water unsuitable for drinking and can have a detrimental impact on river ecology (Hayes and Greene, 1984). Many of the permeable catchments of south and east England have been subject to rising nitrate concentrations in both surface waters and groundwater over the past 25 years, and it is probable that this trend will continue (Limbrick, 2003; Wade et al., 2004).

These increases in nutrient loading are linked to intensification of agricultural practices. While such a link implies

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that, with appropriate farm management, a reversal of this trend is possible, there have been increasing concerns regarding the short- to medium-term prognosis of such a reversal in Chalk-fed systems, due to growing evidence that the Chalk unsaturated zone highly retards a variety of chemicals (Foster, 1993; Gooddy et al., 2006). Characterisation of this retardation is becoming increasingly important due to the implementation of European-wide legislation such as the Drinking Water Directive (COM 80/788/EC) and the Nitrates Directive. The former recommends guide and maximum admissible concentrations of 25 and 50 mg NO_3 l^{-1}, respectively, whilst the latter is designed to reduce water pollution by nitrate from agricultural sources and to prevent such pollution occurring in the future. In the UK, the Drinking Water Directive applies nationwide, while the Nitrates directive is implemented through action programme measures taken within designated Nitrate Vulnerable Zones (NVZs). The incoming Water Framework Directive aims to integrate the two directives and other guidelines to improve water quality and ecology. The UK has until 2015 to bring into force necessary provisions to comply with this new legislation, placing an immediate need for an improved understanding of nutrient behaviour in groundwater-dominated catchments to support informed management decisions, and improved modelling tools to capture the dominant controls on nutrient response. The latter can then be used to predict the likely water quality response to land management and climate change.

A multi-disciplinary research programme, lowland catchment research (LOCAR), was instituted by the National Environmental Research Council (NERC) in the UK to address such legislative requirements and gaps in understanding through undertaking integrated hydro-environmental research relating to the input–storage–discharge cycle, in-stream, riparian and wetland habitats within groundwater-dominated systems (see Wheater and Peach, 2004, for further details). A combined modelling and experimental programme, supported by additional resources from the Environment Agency of England and Wales, used the high quality field research facilities and collaboration opportunities established within LOCAR to develop a unified interpretation of the unsaturated zone behaviour with respect to groundwater recharge and solute transport. This interpretation supported the growing concerns that conventional surface water models fail to represent adequately the important unsaturated zone processes and the complexity of the groundwater response. Furthermore, both data findings and model simulations supported the concern that the unsaturated zone in lowland Chalk catchments highly retards nitrate, creating a store that may effectively prevent efforts to reduce nitrate concentrations in rivers or groundwater having any significant impact on the short- and medium-term timescales (see Neal et al., 2004a; Mathias et al., 2005; Gooddy et al., 2006; Jackson et al., 2006).

A catchment-scale model, the integrated catchments model of nitrogen (INCA-N; Wade et al., 2002) was enhanced to provide an appropriate representation of this retardation for the purpose of evaluating nutrient management options. The revised model (INCA-Chalk) is capable of representing the long memory of unsaturated zone solute residence time and the effect of this on the catchment-scale response of surface water and groundwater to nutrient inputs (both past and present). While it is formulated specifically to describe nitrate movement within Chalk lowland systems, the general principles have wider application to other aquifer types, catchment systems and chemical retardation scenarios.

This paper presents the development of this unsaturated zone representation and INCA-Chalk, and exercises the model to demonstrate its potential as a management tool. The following sections review the historical and current understanding of flow and transport processes within the unsaturated zone, and the hypotheses and model approaches that have been used to date. A simple conceptualisation, consistent with current understanding and capable of representing the varying residence times within the Chalk unsaturated zone, is then presented and integrated with INCA-N. Finally, both hindcast and forecast simulations are performed on a Chalk catchment in Southern England (the Lambourn) to examine the potential effect of the Chalk unsaturated zone storage on future groundwater and nitrate levels under different land-use management practices. Results are discussed in the context of the timescales of the Water Framework Directive.

2. Observations of flow and solute transport in the Chalk unsaturated zone

Chalk is a fractured porous medium composed of matrix blocks bounded by interconnected fractures. The Chalk matrix has a small pore throat size and hence retains large amounts of water under usual conditions (Price et al., 1976). It is also extensively fractured, and therefore, capable of rapid transmission of water when close to saturation. Chalk matrix porosity ranges between 0.3 and 0.4, whereas the fracture porosity is typically no more than 0.01 (Price et al., 1993), although fracture porosities as high as 0.2 have been observed in near surface weathered chalk layers (Ireson et al., 2006). This type of aquifer is often referred to as a dual-porosity aquifer whereby the aquifer possesses both matrix and fracture porosities. Matrix hydraulic conductivities from 0.1 to 0.6 cm day^{-1} have been observed at various Chalk sites (e.g. Wellings, 1984; Cooper et al., 1990; Hodnett and Bell, 1990) whereas the hydraulic conductivity of fractures can be up to 100 cm day^{-1} (Price et al., 1993). Hence the Chalk represents a system whereby, under saturated conditions, water is mostly stored in the matrix while flow mostly occurs in fractures (Price et al., 1993). There has been much debate as to whether flow in the Chalk unsaturated zone occurs predominately in the fractures or in the matrix. This debate is ongoing, but the balance of current evidence, from both modelling and data studies, lends most support towards the second hypothesis (Mathias et al., 2006; Ireson et al., 2006).

Reconciling the different facets of the observed response of Chalk systems has been problematic. Two phenomena are, at first appearances, particularly contradictory: water table responses to rainfall events are of the order of days-to-weeks (Headworth, 1972; Ireson et al., 2006) but solute migration within the unsaturated zone proceeds slowly, at rates of the order of 0.8 m $year^{-1}$ (Smith et al., 1970; Oakes et al., 1981; Barraclough et al., 1994). Other Chalk observations include strong preservation of unsaturated zone solute peaks, imply-