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Characterising the vertical variations in hydraulic conductivity within the Chalk aquifer

A. Williams [a,*], J. Bloomfield [a], K. Griffiths [a], A. Butler [b]

[a] *British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK*
[b] *Department of Civil and Environmental Engineering, Imperial College, London SW7 2BU, UK*

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Summary Various field methods have been used to examine and quantify the vertical variations in aquifer properties within the Chalk aquifer at a LOCAR site in Berkshire, UK. The site contains three 100 m open boreholes and three sets of two nested piezometers within an area of about 100 m^2. There is also an 86 m deep abstraction borehole about 40 m from the site. The techniques that have been used at the site include: geophysical logging, borehole imaging, packer testing, dilution testing and pumping tests. The packer test results show that the permeability of the aquifer varies by three orders of magnitude over the 70 m of tested material with a strongly non-linear decrease with depth below ground level. Comparison with the borehole images show that some of the highly permeable zones appear to be associated with obvious fractures. However, large fractures can be seen in zones which have much lower permeability while some highly permeable zones appear to be associated with poorly developed fractures. Single borehole dilution tests have shown that there are differences in flow velocity depth profiles over a few tens of meters across the site. These are inferred to be because the different boreholes, although of similar drilled depth and very close proximity, intersect slightly different parts of the fracture network and hence the groundwater flow system. In particular, a flowing feature at the base of one borehole is not intersected by the second, which is drilled from a slightly higher elevation. A dilution test carried out whilst the aquifer was being pumped shows that different fractures become active when the aquifer is stressed. This has implications for the interpretation of flow logs performed under pumping.
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Hydrogeological context

The Chalk is the most important aquifer in the UK (Downing et al., 1993) providing over half of all groundwater in the UK and locally in the south east of England up to ~70% of all water in public supply. The requirements of the Water

* Corresponding author. Tel.: +44 1491 692294.
E-mail address: atw@bgs.ac.uk (A. Williams).

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Framework Directive combined with a growing demand for water and other factors such as the increased frequency of hot dry summers in the last 10–15 years have led to pressure on Chalk groundwater resources. There is a need for more efficient groundwater source design and management, and one of the main challenges facing hydrogeologists working in this area is to optimise the use of groundwater given these changing environmental and social pressures. However, groundwater flow in the Chalk is highly heterogeneous and borehole yields may vary by orders of magnitude over distances of less than 100 m reflecting the complexity of flow in the aquifer. This paper reports on a field investigation aimed at increasing our understanding of controls on flow heterogeneity in the Chalk in the vicinity of groundwater sources.

A characteristic feature of the Chalk aquifer of England is that significant permeability is commonly developed in or near the zone of water table fluctuation (Lloyd, 1993; Allen et al., 1997) and that there is a non-linear decrease in permeability with depth (Owen and Robinson, 1978). The Chalk is a dual porosity aquifer (Price et al., 1993) consisting of a microporous matrix intersected by fractures. Due to the small pore-throat size of the matrix (typically about 0.1–1 μm, Price et al., 1976), it has a very low permeability (Allen et al., 1997) and does not contribute to regional groundwater flow. Therefore, it is features of the fracture porosity that principally control variations in permeability and it is variations in fracture characteristics with depth that influence the significant changes in vertical permeability. Price (1987) distinguished two types of fracture porosity in the Chalk; primary fracture porosity associated with unmodified fractures and secondary fracture porosity associated with fractures inferred to be enlarged by carbonate dissolution. Fracture apertures in secondary fractures are larger and hence more transmissive. Bloomfield (1996) has suggested that other factors may contribute to the development of secondary fracture porosity, but whatever their genesis, it is commonly assumed that it is the secondary fractures that have the most influence on rapid flow in the Chalk and that control the distribution of permeability within the aquifer (Downing et al., 1993).

A number of field investigations in the 1970s and 1980s used a combination of TV logs, flow logs, and packer test to investigate vertical variations in Chalk permeability (Tate et al., 1970; Headworth, 1972; Foster and Milton, 1974; Foster and Robertson, 1977; Price et al., 1977, 1992; Owen and Robinson, 1978; Connorton and Reed, 1978). Allen et al. (1997) summarized the main observations of these studies as follows:

- Permeability measured in boreholes using packer tests and other field scale methods is usually at least an order of magnitude higher than matrix permeability measured on core plug samples illustrating the contribution of flow in the primary fracture component of the fracture network.
- Most of the saturated thickness of the Chalk in a given borehole has low permeability with only a few intervals providing a significant contribution to the observed transmissivity. These may correspond to intervals with fractures.
- The major flow horizons are concentrated near the top of the saturated Chalk in the zone of water table fluctuation with little significant flow deeper than ∼50 m below the groundwater level. This is due to a decrease in fracture density and fracture aperture with depth because of the increasing overburden and a general reduction in groundwater circulation and hence potential for development of secondary fracture porosity.
- Geological heterogeneities, hardgrounds, flints and lithological boundaries can locally increase the permeability of the Chalk.

It is clear from the previous field studies that flow near individual boreholes is highly heterogeneous, but that there is great uncertainty in the relationship between the characteristics of a fracture observed in a borehole and the amount of flow which that fracture contributes to the borehole. In addition, few of the previous studies explicitly considered the influence that the borehole has on the observed flow. Using the LOCAR Programme field site at Trumpletts Farm, the aims of this study were to bring together a wide range of field investigation techniques to characterize vertical variations in the rock mass and hydraulic characteristics of the Chalk, to assess the relationships between fracture characteristics and the observed flow and head distributions, and to investigate the aquifer under natural and stressed conditions to see what this may reveal about the flowing features which dominate under these contrasting conditions. Following a description of the field site and the programme of work, the results of the packer testing and single borehole dilution tests are presented.

Description of site and field testing programme

The testing described in this paper was performed at LOCAR site PL10 in the Pang Lambourne catchment (Wheater et al., 2006). The site, known as Trumpletts Farm, consists of six boreholes drilled in the vicinity of an Environment Agency abstraction borehole (confusingly known as Bottom Barn). Three of the boreholes are completed with pairs of piezometers whilst the other three were left open, apart from surface casing. Completion details are given in Table 1.

The site is located on the side of a dry valley on the Chalk outcrop (Seaford Chalk formation at outcrop). It slopes gently from north to south, with an elevation difference of about 5 m between Borehole B and the abstraction borehole (Fig. 1). The water table at the site is about 20 m below ground level and has an annual fluctuation of about 7 m. The water table slopes gently in the same direction as the land surface but with a difference of only 0.5 m between Borehole B and the abstraction borehole. This gives a hydraulic gradient of about 0.001.

All of the boreholes were drilled in the Chalk, with some soil in the upper few metres. Geophysical logs for Borehole A are shown in Fig. 2. The Chalk Rock can be easily identified at a depth of 82 m below datum (25.8 m aOD). A comprehensive field testing programme was planned for this site. The techniques used were packer testing, pump testing and tracer testing. Each of these techniques is described in detail below.

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