Flow heterogeneity in the fractured Chalk aquifer of southern England

John P BLOOMFIELD[1)], Adrian P BUTLER[2)], Jude E COBBING[1)], Alex GALLAGHER[1)], Kate GRIFFITHS[1)], Magali MOREAU[1)], Ann T WILLIAMS[1)], Denis W PEACH[1)] and Andrew BINLEY[3)]

[1)] British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK.
[2)] Department of Civil and Environmental Engineering, Imperial College of Science, Technology and Medicine, Exhibition Road, London SW7 2BU, UK.
[3)] Department of Environmental Science, Lancaster University, Lancaster, LA1 4YQ, UK.

Abstract: The aim of the current work is to investigate the heterogeneity of flow in the Chalk aquifer of southern England. The rock mass properties and hydraulic characteristics of the aquifer have been characterised using a suite of geological and geophysical surveys and hydraulic tests. Fracture logs have been produced based on core logging and using optical images of boreholes. Flow has been characterised using borehole flow logs and dilution tests and hydraulic conductivity measured using packer tests. Fractures have been recorded with apertures in the range <1mm to about 30cm (sub-karstic enlargement) in diameter, however, hydrogeologically significant flow is not restricted to the enlarged fractures and is affected by the local groundwater head distribution. The work is being undertaken as part of the LOCAR Programme. LOCAR is a multi-project programme with the aim of measuring and modelling processes controlling water and material fluxes within lowland permeable catchments in the UK.

BACKGROUND TO THE STUDY

The Chalk aquifer is important because it sustains most of the surface waters, and consequently, freshwater habitats, throughout large parts of southern England and the Paris Basin, and understanding the distribution of flow in the aquifer is therefore central to the sustainable management of Chalk lowland catchments. Flow in the Chalk aquifer is known to be highly heterogeneous over a range of scales and uncertainties arising from heterogeneous flow in the aquifer have significant implications for water resource management at borehole to catchment scales (Allen et al., 1997). In addition, an understanding of flow heterogeneity in the aquifer is of great importance for groundwater source protection (van Leeuwen et al., 1998), and for our ability to predict the movement and fate of contaminants in the Chalk.

The heterogeneity of flow is a function of the fracture distribution, particularly the preferentially enlarged component of the fracture network (Bloomfield, 1996), and of groundwater head distributions in the aquifer (Price 1987). Hydraulic tests, including pumping, borehole packer, and tracer tests can be used to obtain effective values for hydraulic conductivity and storage at a borehole or site scale, however it is not trivial to extrapolate these observations to larger scales given the nature of flow heterogeneity in the Chalk.

Modelling studies of flow in UK Chalk aquifers usually use a continuum approximation, where the fractured rock mass is replaced by an equivalent porous medium. Parameter values for such models (e.g. hydraulic conductivity) are generally obtained through analyses of aquifer pumping tests. Such an approach carries the implicit assumptions that the aquifer not only behaves as a continuum at the scale of the test, but that it also behaves as the same continuum on the catchment scale. In fact, as the flow in the Chalk occurs almost entirely through discrete fractures and these fractures are highly heterogeneous over a range of scales, it is unlikely that these assumptions are valid. Consequently, there is a need to better understand flow heterogeneity in the Chalk aquifer and to be able to predict the nature of flow heterogeneity on the basis of often relatively sparse data, up to the catchment scale. More specifically, there is a need to link an understanding and interpretation of flow in the Chalk using the discrete fracture approach on a local scale with catchment scale continuum methodologies.

This paper describes field investigations into the relationship between fracture distributions and groundwater flow distributions in the Chalk aquifer at two sites in the Pang-Lambourn catchment in southern England. The work is part of the LOCAR Programme, a programme aimed at

- developing an improved understanding of hydrological, hydrogeological, geomorphological and ecological interactions within permeable catchment systems, and their associated aquatic habitats, at different spatial and temporal scales and for different land uses
- developing improved modelling, database and GIS tools to inform and support the integrated management of lowland catchment systems

Details of the LOCAR Programme can be found at the following web site (http://www.nerc.ac.uk/funding/thematics/locar).

SITES AND FIELD STUDIES

Field data has been collected using an integrated suite of geological and geophysical surveys and field hydraulic tests at two sites, Frilsham Meadow and Trumpletts Farm. Both these sites are located in the Pang catchment on the Chalk aquifer about 80 km west of London. The site at Trumpletts Farm is located on an interfluve while the Frilsham Meadow site is located next to the River Pang, a small tributary of the River Thames. Eight boreholes were drilled (rotary with air flush) at Frilsham Meadow and seven were drilled at Trumpletts Farm. Of these boreholes one was cored at each site. Typical drilled depths were in the range 40 to 100 metres below ground level (mbGL). It was necessary to case most of the boreholes down to about 18 mbGL to prevent collapse of the borehole in the upper interval.

Lithological and fracture logs were prepared using the core. In addition, digital optical imager logs were run on each borehole and fractures in the boreholes were picked from these logs to obtain orientation information. A suite of geophysical logs was obtained for each borehole including gamma, resistivity, temperature and electrical conductivity. In addition impeller flow logs were produced under static and pumped conditions. Following geophysical logging three boreholes at Frilsham Meadow and one borehole at Trumpletts Farm were left open for hydraulic testing, the remaining boreholes were completed as piesometers. Borehole dilution tests were undertaken on the open borehole at Trumpletts Farm. These were performed by filling the borehole with a weak brine solution and monitoring the dilution of the salt column within the borehole due to flow under both natural groundwater gradient conditions and while a neighbouring public supply borehole was pumped. Following the borehole dilution test eleven packer tests were performed on the same borehole, over intervals of 2 to 3 metres. These tests were

used to characterise the hydraulic conductivity profile in the borehole.

RESULTS

Fracturing at the sites is typical of bedded Chalk. There are three predominant fracture sets present, one joint set parallel to the sub-horizontal bedding and two fracture sets at high angles to bedding. Fracture density reduces in a non-linear manner with increasing depth, with the top 10 metres of the Chalk typically consisting of a Chalk gravel. The optical imager logs show the most enlarged fractures to be associated with sub-karstic development at the intersections of faults, particularly near the base of the weathered Chalk at about 20 to 30 mbGL, and to a lesser extent along isolated fractures parallel to bedding planes in the deeper, intact Chalk.

The graph on the right hand side of Figure 1 shows the location of joints and faults in a typical borehole at Frilsham Meadow. A cluster of intersecting conjugate faults at about 26 mbGL is associated with a large sub-karstic void as recorded in the calliper log and a similar slightly smaller feature is seen at about 32 mbGL. The feature on the calliper log at 41 mbGL is associated with an enlarged bedding parallel fracture.

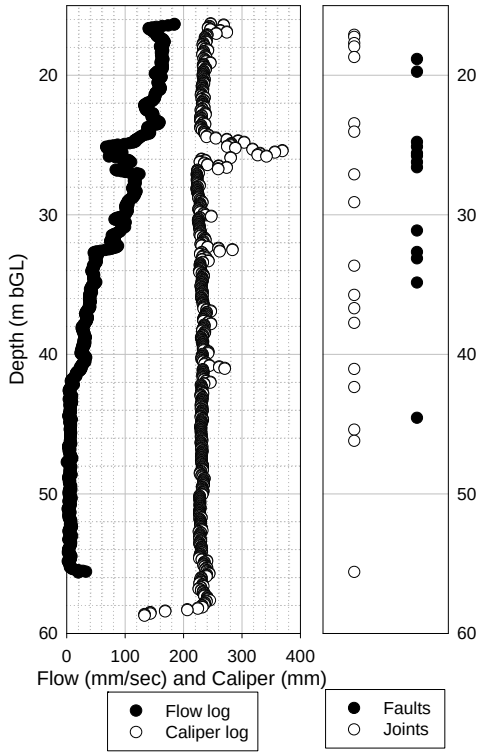

Fig. 1 Typical flow and calliper logs and fracture logs derived from optical imager logs for a borehole at Frilsham Meadow.

The flow log in Figure 1 shows the deepest significant inflow into the borehole is associated with the bedding parallel fracture at about 41 mbGL. There is then a continuous gradual accumulation of flow into the borehole above this depth. This trend is only disrupted by a small discrete inflow associated with the faults at about 32 mbGL and an apparent outflow associated with the sub-karstic void on the fault planes at 26 mbGL.

Borehole dilution tests at Trumpletts Farm are summarised graphically in Figure 2. Above about 50 mbGL inflow into the borehole causes a rapid dilution of the tracer over 200 minutes. There is only limited dilution in the depth interval 50 to 75 mbGL, although below about 85 mbGL there appears to be some flow into the borehole. The identification of a relatively active upper flow horizon down to 50 mbGL is consistent with the temperature profile at the site.

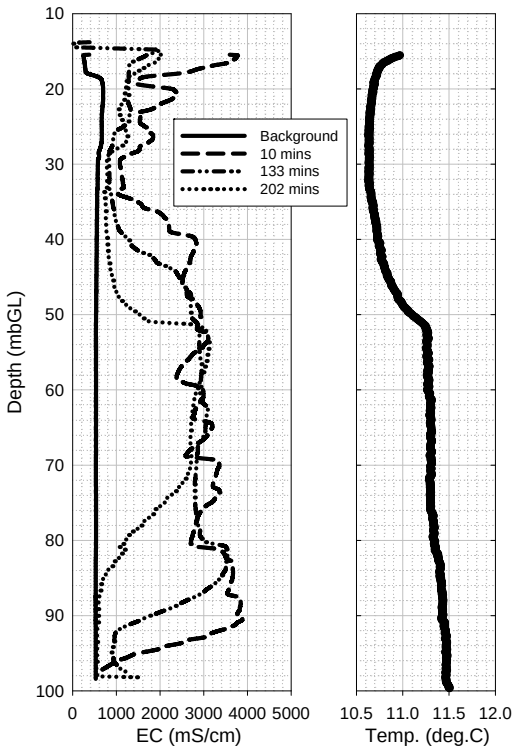

Fig. 2 Graphical summary of the natural gradient borehole dilution test for the borehole at Trumpletts Farm.

DISCUSSION

Even though the two sites are in contrasting locations, on an interfluve and in an area of groundwater discharge, the following common features can be identified: i) an active flow system in the upper part of the aquifer down to about 50 mbGL, and ii) an interval below about 50 mbGL where there is more limited flow into the boreholes. It is inferred that although large sub-karstic voids are present at both sites, much of the inflow into the boreholes is associated with flow along more minor, relatively undeveloped, joints sub-parallel to bedding. The results of packer tests at the Trumpletts Farm site suggest that there is a non-linear decrease in hydraulic conductivity with depth in the interval 40 to 80 mbGL, consistent with a reduction in fracture frequency with depth. Based on this observation and given the heterogeneity of flow into the borehole in this interval, as indicated by the borehole dilution test (Figure 2), it is inferred that flow into the borehole at Trumpletts Farm is affected by vertical variations in the head gradient in the immediate vicinity of the borehole.

REFERENCES

Allen DJ, Brewerton LJ, Coleby LM, Gibbs BR, Lewis MA, MacDonald AM, Wagstaff SJ and Williams AT (1997) The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report WD/97/34.

Bloomfield JP (1996) Characterisation of hydrogeologically significant fracture distributions in the Chalk: an example from the Upper Chalk of southern England. Journal of Hydrology 186: 355-379.

Price M (1987) Fluid flow in the Chalk of England. In: Goff JC, Williams BPJ (eds) Fluid flow in sedimentary basins and aquifers, Special Publication of the Geological Society of London 34: 141-156.

van Leeuwen M, de Stroet CBM, Butler AP and Tompkins JA (1998) Stochastic determination of well capture zones. Water Resources Research 34: 2215-2223.