The nature and distribution of flowing features in a weakly karstified porous limestone aquifer

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Abstract
The nature and distribution of flowing features in boreholes in an area of approximately 400 km^2 in a weakly karstic porous limestone aquifer (the Chalk) was investigated using Single Borehole Dilution Tests (SBDTs) and borehole imaging. 120 flowing features identified from SBDTs in 24 boreholes have densities which decrease from ~ 0.3 m^{-1} near the water table to ~ 0.07 m^{-1} at depths of more than 40 m below the water table; the average density is 0.20 m^{-1}. There is some evidence of regional lithological control and borehole imaging of 3 boreholes indicated that most flowing features are associated with marls, hardgrounds and flints that may be developed at a more local scale. Borehole imaging also demonstrated that many flowing features are solutionally enlarged fractures, suggesting that even in carbonate aquifers where surface karst is developed on only a small scale, groundwater flow is still strongly influenced by dissolution. Fully connected solutional pathways can occur over 100s, sometimes 1000s of metres. However, conduits, tubules and fissures may not always be individually persistent along a flowpath, instead being connected together and also connected to unmodified fractures to create a relatively dense network of voids with variable apertures (<0.1 cm to >15 cm). Groundwater therefore moves along flowpaths made up of voids with varying shape and character. Local solutional development of fractures at significant depths below the surface suggests that mixing corrosion and in situ sources of acidity may contribute to solutional enhancement of fractures. The study demonstrates that single borehole dilution testing is a useful method of obtaining a large dataset of flowing features at catchment-regional scales. The Chalk is a carbonate aquifer with small-scale surface karst development and this study raises the question of whether other carbonate aquifers with small-scale surface karst have similar characteristics, and what hydrological role small-scale dissolutional features play in highly karstic aquifers.

Keywords: Fracture identification; Single borehole dilution test; Carbonate aquifers; Chalk; Tracer; Small-scale karst.

1 Introduction

Understanding the distribution of flows in aquifers is important for sustainable use of groundwater resources, and to understand and manage contamination problems. In fractured aquifers flow distribution is often poorly understood because fracture distributions are spatially highly variable at a range of scales (Neuman, 2005). Carbonate aquifers may be even more problematic as karst processes result in even greater heterogeneity (Bakalowicz, 2005; Goldscheider and Drew, 2007). It is now recognised that karstic modification of aquifers can occur on a range of scales (Klimchouk and Ford, 2000; Worthington, 2009; Worthington and Ford, 2009), from highly channelled flows in conduit-dominated aquifers beneath classically karstic landscapes to carbonate aquifers where caves are rare but dissolution of both the surface and the subsurface occur on a small-scale. In highly karstic aquifers mapping of the larger conduits (caves) enables some flow patterns to be directly investigated (Quinlan and Ewers, 1989; Quinlan and Ray, 1989; Jeannin et al., 2007), although flows in the smaller voids can also be significant and are often less well understood. In carbonate aquifers where caves are rare or absent, small-scale sub-surface karst can only be inferred from the magnitude and character of springs, tracer testing, or from observation of flowing fractures within outcrops or boreholes.

In this study the single borehole dilution technique was applied to 24 boreholes in a catchment area of ~ 400 km^2 to investigate the distribution of groundwater flow. It is, to our knowledge, the first time that this technique has been applied systematically to investigate permeability structure at this scale. In three boreholes, imaging data were used to develop a conceptual model of the character and structure of the flowing voids that were identified. The results suggest that single borehole dilution tests (SBDTS) are a useful technique for catchment-regional scale investigations of horizontal flow distributions, although much less can be learned about vertical features because boreholes are inherently less likely to intercept these.

The catchments studied are within the English Chalk, which is a porous limestone aquifer that displays small-scale karstic characteristics (Harold, 1937; MacDonald et al., 1998; Banks et al., 1995; Maurice et al., 2006). The Chalk is widespread in northwest Europe providing important sources of water supply in many countries (Downing et al., 2005). Chalk aquifers have also been studied in other areas of the world, for example in Israel (Dahan et al., 1999) and Texas (Cooke et al., 2006). Although there are differences in the geological settings of chalk aquifers in different countries, small-scale karst development is likely to be common, and has been documented in chalks of several countries for example in Israel (Dahan et al., 2000), France (Rodet, 1991; Massei et al., 2006), and Belgium and the Netherlands (Willems et al., 2007)

Groundwater flow in chalk takes place through a hierarchy of different types of void defined collectively in this paper as ‘flowing features’. These flowing features have generally increasing permeability from unmodified fractures to fissures, tubules, conduits and caves. *Fissures* are defined for this paper as fractures that have been enlarged by solutional processes, but retain the broadly planar geometry of unmodified fractures, *e.g.* Fig.1 a,d,e. *Tubules* are small cylindrical voids of 1 to 50 mm diameter, as described by Lamont-Black and Mortimore (2000), *e.g.* Fig.1b. *Conduits* are larger solutional voids, often tubular, sometimes rectangular in cross section, *e.g.* Fig.1c, and *caves* are voids that are large enough to enter. Little is known about the structural organisation of these voids and their relationship to each other. It is not clear how frequently fissures, tubules, conduits or caves occur in chalk, or whether solution features are isolated or connected. The term *flowing feature* is used in the paper for situations where a localised flow has been detected which could be via any one of the types of void - fracture, fissure, tubule or conduit. Use of these more precise morphological terms is restricted to situations where imaging data have demonstrated which type of feature is present.

The objectives of this study were to improve our understanding of groundwater flow in chalk to enable better conceptualisation of the aquifer in groundwater pollution and management studies, and to investigate the nature of small-scale subsurface karst. Whilst there is evidence of occasional cave development in the English Chalk (Maurice et al., 2006) and more extensive cave development in the French Chalk (Rodet, 1991), it is likely that in general, groundwater flow in chalk is predominantly through smaller voids (fractures, fissures and conduits too small for humans to enter), and these form the subject of this paper. Although the details of our findings are of course specific to the English Chalk, our methods and general approach are appropriate for investigating the structure of permeability and consequent localisation of flow in the diffuse-flow parts of karstified carbonate aquifers generally (White, 1969; Atkinson, 1977, 1985; Ford and Williams, 2007).

2 Chalk groundwater flow and permeability

There have been many previous studies of flow and permeability in the Chalk which provide insight into the likely character of flow in carbonate aquifers with small-scale karstification and perhaps also the diffuse flow component (flow in fractures and fissures as opposed to larger conduits and caves) of more karstic aquifers (White, 1969; Atkinson, 1977; Atkinson, 1985). Several studies have demonstrated that beneath the near-surface weathered zone, unmodified fracture spacings in the Chalk are ~ 0.1 to 1 m (Price et al., 1976; Bevan and Hancock, 1986; Patsoules and Cripps, 1990; Younger and Elliot, 1995; Bloomfield, 1996; Zaidman et al., 1999). Price (1987) suggested that this fracture component of the Chalk aquifer typically has a hydraulic conductivity of ~ 0.1 $m.d^{-1}$ and a transmissivity of ~ 20 $m^2.d^{-1}$. In England, the median transmissivity of the Chalk is 540 $m^2.d^{-1}$ and the 25th and 75th percentiles are 190 $m^2.d^{-1}$ and 1500 $m^2.d^{-1}$ respectively (MacDonald and Allen, 2001). Price (1987) suggests that these high transmissivities cannot be accounted for by the unmodified fracture network. Packer testing, logging, and imaging have demonstrated that generally the transmissivity of individual boreholes comes from a small number of solutional fissures (e.g. Tate et al., 1970; Price et al., 1977, 1982; Schürch and Buckley, 2002).

There is a well-accepted conceptual model of the spatial distribution of fissures producing these high transmissivities. Fissures are believed to be most common beneath valleys, in the zone of water table fluctuation, and may be associated with specific lithological horizons (e.g. hardgrounds, flint layers and marls). They decrease in frequency with depth below ground level, and are more common in unconfined than confined chalk (Allen et al., 1997). This understanding has developed from spatial analysis of pumping test results (MacDonald and Allen, 2001), borehole logging techniques (Tate et al., 1970; Headworth, 1978; Schürch and Buckley, 2002; Robinson 1978, reported in Allen et al., 1997), and packer testing (Price et al., 1977; 1982, Williams et al., 2006).

Lithological factors are thought to determine anomalies in fissure distribution such as their sporadic occurrence at large depths below the water table, and instances of high transmissivity away from river valleys (Allen et al., 1997). The association between flint layers and marl seams and fissure development may be because they are laterally extensive and have low permeability impeding vertical flow and concentrating lateral flow. Lowe (1992) suggests that the geochemistry of chalk is altered near to flint layers and that this favours dissolution. Borehole logging studies have shown that some fissures are associated with hardgrounds (e.g. Schürch and Buckley, 2002). This may be because hardgrounds fracture cleanly (Allen et al., 1997) and are laterally extensive providing a well-connected flowpath. However, this may not be the case in all areas. An unpublished study of flowing horizons in the East Anglian Chalk using TV and geophysical logs found no significant relationship between fissures and hardgrounds (Wooton, 1994).

These studies provide considerable insight into the distribution of flow and permeability in the Chalk, and solutional fissures in other carbonate aquifers may have similar characteristics. However several questions remain which include: (1) What is the vertical spacing between flowing features? (2) Do flowing features occur more frequently in boreholes in river valleys and close to surface karst features? (3) To what extent are flowing features determined by stratigraphical controls ? (4) What is the physical nature of the voids which create the high transmissivity in the Chalk, and are flowing features laterally persistent creating a continuous connected network of solutional conduits and fissures, or does groundwater move into areas without conduits and fissures where it flows through fractures?

In this study Single Borehole Dilution Tests were undertaken to identify actively flowing features in boreholes, with the aim of addressing these questions and improving our understanding of the permeability structure in the Chalk aquifer.

3 Methods

3.1 Principles of identifying flows in boreholes

The identification of naturally flowing features in aquifers is inherently difficult because the presence of a borehole may disrupt the natural flow patterns in the aquifer. Other difficulties arise because the various methods available for identifying flowing features in boreholes may have different sensitivities and may reveal different sets of flowing features in the same borehole under ambient (i.e. non-pumped) conditions. In addition, different flowing features may be activated under pumped conditions (Mathias et al., 2007; Butler et al., 2009).

All voids intersected by a borehole can be identified using good quality imaging logs. However, there are often fractures and other voids visible on image logs that are not actively flowing (e.g. Price et al., 1977). Similarly, caliper logs indicate where there are enlargements in borehole walls but do not reveal flow. Fluid electrical conductance and temperature logs can be used to identify *in-flowing* features that cause a change in the electrical conductance or temperature of the water column (Price et al., 1977; Williams and Paillet, 2002; Schürch and Buckley, 2002). However, these methods are less effective for measuring *out-flowing* features. Flow logging using an impeller flowmeter or a heatpulse flowmeter (Molz et al., 1989; Paillet et al., 1987) provides good information on the location of in-flowing and out-flowing features which cause a change in the vertical flow rate within a borehole, but may leave cross-flowing features unidentified.

Single Borehole Dilution tests (SBDTs) provide a simple field method of investigating flow within and across boreholes (e.g. Doughty and Tsang, 2005; West and Odling, 2007; Butler et al., 2009; Maurice et al., 2011). The technique involves introducing a tracer into the open borehole and monitoring its subsequent movement within and away from the borehole. The flow that is seen results from a combination of the natural flow within the aquifer and vertical flows within the borehole caused by the existence of the borehole itself. Vertical flows occur because a borehole may connect regions of an aquifer which have different natural heads. Water will flow into the borehole where the head is greatest and out where the head is low, creating vertical flow within the borehole (e.g. Michelski and Klepp, 1990; Church and Granato 1996). Due to these vertical flows, as with any borehole flow logging technique, it is not possible to determine the location of all *natural* flows within the aquifer without the use of packers. However the SBDTs do provide information on the location of levels in the aquifer where flow occurs in the presence of the borehole, some of which may not be identified by other techniques (Maurice et. al., 2011). By definition, such flowing features represent concentrations of groundwater flow (whether induced by the presence of the borehole or not), and are therefore features in which the permeability is higher than for the rock surrounding them.

3.2 SBDT Field Methods

In this study SBDTs carried out under non-pumped conditions were used as the main method of identifying flowing features. Two types of SBDTs were carried out: uniform injection tests in which tracer was injected throughout the saturated length of the borehole, and point injections in which tracer was injected at a specific depth. The tracer used was sodium chloride, and multiple logs of fluid electrical conductance were obtained to monitor tracer dilution following injection. Full methods are described in Maurice (2009) and Maurice et al. (2011). Flowing features were identified from uniform injection SBDTs where there are persistent 'nick points' or steps at particular depths in multiple electrical conductance logs recorded at successive times, or where there is a sharp boundary between zones of faster and slower dilution, or at the top and bottom of sections with vertical flow inferred from the movement of a freshwater 'front' up or down the borehole (see Maurice et al., 2011 for a full discussion of this method of identifying flowing features in boreholes). Point injection tests clearly demonstrate vertical flow when the tracer is injected at a specific point creating a plume that moves up or down the borehole (Maurice et al., 2011). They therefore indicate flowing features at the top and bottom of vertical flow sections and at depths within sections of vertical flow at which there is tracer loss and/or a change in the rate of tracer movement. Background fluid electrical conductance and temperature logs were also used to indicate the location of flowing features at depths where there was a marked change in the electrical conductance or temperature of the borehole water.

There is uncertainty associated with using these techniques due to measurement errors and the subjective nature of interpreting fluid logs, so to avoid false identification of flowing features they were only inferred where the evidence from the logs was unambiguous. Therefore the numbers of flowing features identified in this study may tend to underestimate the true total number of flowing features.

4 Field Investigation

We carried out SBDTs in 24 boreholes with diameters of 0.2 to 0.3 m within an area of approximately 400 km^2 in two adjacent Chalk catchments in Southern England (Figure 2). The strata dip ~0.5-2^o to the south-south-east and in the lower reaches of the catchments the Chalk is overlain by younger Palaeogene sands and clays. The Chalk of the catchments has been geologically mapped according to the stratigraphical framework proposed by Bristow et al. (1997), and has been correlated across southern England using geophysical borehole logs (Woods, 2006). Most of the boreholes start in the flinty Seaford Chalk Formation. A further five Chalk formations underlie the Seaford Chalk, each of which is passed through by some of the boreholes tested (Figure 3).

The southern English Chalk contains a high density of small-scale surface karst features and the study catchments contain a dense network of tributary valleys which are predominantly dry. There is a clear spatial pattern in the distribution of surface karst features with three distinctive geomorphic zones (Maurice et al., 2006). These are characterised by the density of stream sinks and dolines and can be related to the distance from the Palaeogene-Chalk contact. Surface karst is most intensely developed in the lower reaches of the catchments (Zone 1) where the Chalk is overlain by Palaeogene deposits, which produce acidic soils (Figure 2). Dolines are common, but stream sinks are the diagnostic feature of Zone 1 and have developed on the edge of the Palaeogene cover. High densities of dolines also occur in the middle reaches of the catchments (Zone 2) where the Palaeogene deposits have recently been removed by erosion and much of the area is overlain by Clay-with-flints. In the upper reaches of the catchments (Zone 3), Chalk is exposed at the surface with no cover and little superficial material to concentrate drainage, dolines are rare, and recharge is diffuse. Tracer testing between stream sinks and springs in Zone 1 has demonstrated rapid groundwater flow (up to 6 km.d^{-1}), indicating that fully connected networks of conduits and large fissures occur there over distances of several kilometres (Banks et al., 1995; Maurice et al., 2011). SBDTs were carried out in boreholes in all three karst zones representing a range of topographic positions from valley floors to interfluves to enable relationships between surface karst and topography and subsurface flows to be investigated (Figure 2).

5 Results

5.1 Distribution of flowing features

120 actively flowing features were identified in 23 boreholes. One borehole (Brightwalton Common) lacked any identifiable flowing features. The number of flowing features identified in each borehole is listed in Table 1. The vertical distributions of flowing features in 22 boreholes are presented in Figure 3. The boreholes are aligned to the Chalk stratigraphy which was interpreted using a combination of geophysical logs (available for 14 of the boreholes), modelled geological surfaces (Aldiss et al., 2002) and published studies of Chalk stratigraphy (Aldiss et al., 2002; Woods and Aldiss, 2004; Mortimore et al., 2001). Briff Lane and Brightwalton Common are not included in Figure 3 because there were insufficient geological data.

5.1.1 Stratigraphical control on flowing features

Figure 3 shows that flowing features occur in all the different stratigraphical units. Some flowing features coincide with 'marker' horizons that are easily identified in geophysical logs, suggesting that they may be litho-stratigraphically controlled. Two such marker horizons, the Glynde Marl (GM) and the Chalk Rock (CR) occur below the water table in five boreholes each, and in all cases they are associated with a flowing feature.

Other lithostratigraphical horizons are more difficult to identify consistently, either because their expression is variable in geophysical logs, or they are not continuous, or because logging information is absent for some boreholes in Figure 3. This problem particularly affects the Seaford Chalk which is thick and outcrops widely in the study area. There is some indication that flowing features may be associated with the approximate positions of the Belle Tout Marls (BTMs) and the Seven Sisters Flint (7SF), but more data are needed to ascertain the precise location of these in every borehole. Elsewhere in the stratigraphic column the relationship between flowing features and stratigraphy is not always consistent. For example one might expect to observe flowing features at the base of the Holywell Nodular Chalk Formation where a hard chalk overlies a thick clay rich marly chalk, but this is only the case in one out of four boreholes.

In summary, some regional litho-stratigraphical marker horizons are good predictors of flowing features. For the Seven Sisters Flint flowing features were identified in six cases out of nine in which a borehole intersected this horizon in the saturated zone. For the Belle Tout Marls the figure is six out of eight; the Chalk Rock five out of five; and the Glynde Marl five out of five. However, most flowing features are not associated with regional marker horizons, although their position may be wholly or partially controlled by lithology or lithological contrasts.

5.1.2 Lithological control on flowing features

Borehole imaging data from three sites were used to investigate lithological controls on flowing features as well as whether dissolutional processes are important (section 5.3). At Gibbet Cottages data were obtained using an Electromind optical imager whilst at Trumpletts A and B data were obtained using a Makavision optical imager.

The results are presented in Table 2 and examples of some of the features observed are in Figure 1. Table 2 shows that of the 17 flowing features investigated using borehole imaging seven are associated with nodular flints, one with a sheet flint, four with hardgrounds, and three with marls. Only two flowing features have no obvious lithological control. The results suggest that lithology is an important control on flowing features, which may be associated with both regionally extensive marker horizons such as the Chalk Rock hardground (e.g. Figure 1b) and the Glynde Marl, as well as flint layers (e.g. Figure 1c and e), hardgrounds and marl layers that may be only locally developed. This high degree of lithological control on flow suggests that many flowing features may be orientated parallel to the bedding.

5.1.3 Depth control on flowing features

Figure 4 shows the density of the flowing features identified in this study against depth below the surface, depth below water table and with elevation. In each case the number of flowing features found in the boreholes over a particular interval (below ground, below water table or elevation above sea level) was divided by the sample size (the number of boreholes sampled in which the entire interval was present, uncased and saturated) to produce a normalised number of flow horizons per metre sampled. Boreholes that only sampled part of the interval were counted by the fraction of the interval they covered. The error bars represent 95% confidence limits. These histograms show some trend of decreasing numbers of flowing features with depth below ground level and depth below the water table but there is little apparent correlation between density and elevation. The increase in flowing fractures between 60 and 80 m below the water table (Figure 4b) and 0-10 m above sea level (Figure 4c) may be due to small sample size. It is also possible that flowing features are more likely to be identified near the bottom of boreholes using the SBDT technique because fractures with high hydraulic head near the bottom of boreholes generate upwards flow and are easily identified.

The results indicate that flowing features occur relatively frequently, but there is considerable variation in the number present in individual boreholes. In some boreholes there are very few flowing features (e.g. Brightwalton Common in which there are none in a total saturated depth of 20.3 m, and Greendown Farm in which there is one flowing feature in a saturated length of 47.2 m). In others there are much higher densities, with the highest density in Knighton Down borehole in which there are nine flowing features in a saturated length of 22.1 m.

Estimating the density of flowing features is useful for aquifer characterisation and conceptualising groundwater models. However, obtaining an accurate estimate of the density is difficult because of the small sample presented by each borehole individually. The density of flowing features was calculated for each borehole by dividing the number of flowing features by the length of borehole sampled (Table 1). The average of those individual densities for the entire dataset is 0.20 flowing features per metre (including Brightwalton Common where no features were intercepted). The reciprocal of that value gives an average spacing of flowing features of 5.11 m. Alternative estimates can be obtained from the ratio of the sum of all lengths and the sum of all numbers. The values are 0.15 m^{-1} and 6.48 m for density and spacing, respectively. The density of 0.15 m^{-1} can be regarded as a weighted average of the individual densities where the weighting is the borehole length. (The same weighting when applied to the spacings gives an infinite average spacing as zero features were encountered at Brightwalton Common.)

There is a 4-fold reduction in fracture frequency with increasing depth below the water table, from 0.3 flowing features per metre in the 0-10 m depth interval, to ~ 0.07 flowing features per metre between 40-70 m in depth below the water table

(Figure 4b). This implies average spacing that increases from ~ 3.3 metres to ~ 14 metres.

5.1.4. The role of topography and surface karst

Table 1 shows the topographical situation and karst zone of the boreholes. Boreholes within 250 m of a major river and where the ground surface elevation at the site of the borehole is at or only slightly above the river elevation were classed as river valley boreholes. Long dry valleys (> 2 km) which are directly connected to active river valleys were classed as major dry valleys, whilst short dry valleys connected to other dry valleys were classed as minor dry valleys. The average spacing of flowing features in boreholes in river valleys is always less than 6 m, but the average spacing of flowing features in boreholes in dry valleys and interfluves is variable.

Table 3 shows the density of flowing features in different topographical and karst situations. The overall density of flowing features taken across all boreholes in river valleys was 0.23 m^{-1} (Table 3). In major dry valleys it was 0.29 m^{-1}, whereas in interfluves and minor dry valleys was 0.15 m^{-1}. In all three karst zones there were boreholes with flowing features spaced more closely than these values. However, the average density in karst zone 1 (with active stream sinks and dolines) is 0.25 m^{-1}, that in karst zone 2 (with dolines) is 0.18 m^{-1}, and that in karst zone 3 (with almost no surface karst features) is 0.15 m^{-1}. The results suggest that flowing features occur more frequently in river valleys than interfluve areas, and more frequently in areas where surface karst features (stream sinks and dolines) are developed. However, the results also indicate that subsurface dissolutional enlargement of fractures to form dissolution tubules and conduits can occur in areas away from surface karst (e.g. Gibbett Cottages, Fig 1b and Table 2).

5.2 Lateral persistence of flowing features

At two sites SBDTs were undertaken in groups of several boreholes less than 50 m apart to investigate whether horizontal or sub-horizontal flowing features are laterally persistent. At Frilsham three boreholes are aligned in an approximately ENE-WSW direction with approximately 32 m between the outermost pair, B and C (Figure 5). Figure 5 shows the dilution logs and the interpreted flowing features in the overlapping sections of these boreholes (36 to 56 m above sea level). Six flowing features are only present in one borehole, but at four levels there are flowing features present at an almost identical elevation in two or three boreholes (e.g. at ~ 38 m above sea level in all three boreholes, and at ~ 44 m above sea level in Frilsham B and C). At Trumpletts, SBDTs were carried out in two boreholes 45 m apart. There are six flowing features that appear to be present in one borehole only but three that are at similar elevations in both boreholes (Figure 6). Imaging data show that three of the flowing features that were only present in Trumpletts B are inclined (Table 2) and therefore would not be expected to be present at the same level in Trumpletts A.

The data from Frilsham and Trumpletts suggest that some flowing features persist laterally for at least 32 and 45 m respectively. It is probable that these laterally persistent features are bedding controlled. At the catchment scale, strata dip approximately 0.5-2^{o} towards the SSE. Boreholes at Trumpletts and Frilsham are not orientated down dip, but even assuming the worst case that they were orientated down dip and that the dip were 2^{o}, the down dip displacement between the boreholes would only be 1.6 m at Trumpletts and 1.1 m at Frilsham, suggesting that dip controlled flowing features should be present at approximately the same depth in all these boreholes.

In total 19 flowing features intersecting 1,2, or 3 boreholes were identified. 12 (63%) were only present in one borehole so their length is uncertain. However, lower bounds can be put on the lateral persistence of flowing features intersecting 2-3 boreholes. The data suggest that ~ 30 % (6) of the 19 features identified definitely persist for more than 32 m. Of the 9 features identified in the Trumpletts boreholes 3 are present in both boreholes indicating that ~ 33 % of those identified at Trumpletts persist for more than 45 m. It is possible that more flowing features persist across the Trumpletts and Frilsham sites and are actually present in all boreholes but were not identified due to the difficulties of identifying all flowing features in the aquifer using single borehole dilution tests. It is also quite likely that some flowing features may be absent in boreholes because the openings are linear or anastomosing, and some features in the Frilsham boreholes may be vertical or inclined as observed at Trumpletts B using imaging data. The general conclusion is that sub-horizontal flowing features are laterally persistent at least over scales of 10s of metres.

5.3 The nature of flowing features

Borehole imaging data from Gibbet Cottages and Trumpletts A and B were used to investigate the types of features through which flow is occurring, and in particular whether dissolutional processes are important. For each flowing feature the morphology and aperture size were noted and used to determine whether dissolutional processes have modified the original fracture (Table 2). Features with low aspect ratios or a sinusoidal shape on the image (indicating that the feature was inclined e.g. Figure 1e) were classified as fractures. Features with higher aspect ratios were classified as conduits (e.g. Figure 1c). Conduits were assumed to be dissolutional. Fractures were also classified as dissolutional if there were multiple openings (e.g. Figure 1d) or the aperture was more than 1 cm (e.g. Figure 1a).

The results from these three boreholes suggest that small-scale dissolutional processes are important. Of 17 flowing features identified in these three boreholes from the SBDTs, conduits are present at 7 (41%), and solutionally enlarged fractures at 6 (35%). At 2 (12%), fractures are visible which may be solutionally enlarged and at 2 (12%), very thin fractures that appear not to have been enlarged by dissolution are present.

Some general observations can be made about the nature of solutional development at these sites. Individual fractures appear to have very variable apertures and are often characterised by multiple openings, suggesting that dissolutional processes have modified the fracture but that this dissolution is erratic and discontinuous (e.g. Figure 1a). At Gibbett Cottages, solutional features at 95.4 m above sea level (about 66 m below ground level) consist of multiple conduits up to 4 cm high on top of a hardground (Figure 1b), which resemble dissolution tubules described by Lamont-Black and Mortimore (2000). The largest conduits observed are ~ 15 cm in diameter (e.g. Figure 1c). At Gibbett Cottages there is a large conduit with a diameter of approximately 15 cm at about 72 m below ground level, demonstrating that conduits can form at considerable depths beneath the surface. Also at Gibbet Cottages there is sediment in the solutionally enlarged fracture 74 m below the surface (Figure 1d) suggesting that there is a connected system of fissures and conduits of sufficient size to transport sediment from the surface to this depth. Inclined fractures also occur (3 of the 17 flowing features) and these may connect areas of horizontally developed permeability and transport water down through the aquifer (e.g. Figure 1e).

6 Discussion

6.1 Small-scale subsurface dissolution

Carbonate aquifers are characterised by a hierarchy of void types from unmodified fractures to solutionally enlarged fractures (fissures, tubules and small conduits) to caves (conduits large enough to enter). Groundwater flow is generally slow in unmodified fractures but along connected networks of solutionally enlarged fractures it can theoretically be as fast as that in caves (Price, 1987). Yet flow in these small-scale dissolutional features is difficult to investigate.

Borehole imaging provides a good method of observing the character of small-scale dissolutional flowing features in carbonate aquifers. In this study borehole imaging data indicate that a large proportion of flowing features in the studied boreholes (15 out of 17 observed flowing features) are voids which have undergone dissolution. This supports the suggestion of Price (1987) that the most significant groundwater flows which give rise to the high transmissivities in the Chalk occur in fractures that have been enlarged by dissolution.

The imaging data from this study provide us with insights into the nature of small-scale dissolution. Fractures intersected by boreholes may be solutionally enlarged to form different types of voids: irregular widenings along all or parts of the fracture to produce fissures, more circular shaped tubules (multiple small circular voids of ~ 0.001 to 0.05 m in diameter), and single conduits up to ~ 0.15 m diameter. It is probable that these types of small-scale dissolutional features provide an important contribution to transmissivity in most carbonate aquifers.

6.2 Lithological controls on groundwater flow

It is well known that there can be lithological controls on dissolutional processes in carbonate aquifers. In karstic limestones, beds which are physically, lithologically or chemically different from the predominant carbonate facies have been found to favour dissolution, and have been termed “inception horizons (Lowe, 1992; Filliponi et al., 2008). Filliponi and Jeannin (2006) suggest that lithology and stratigraphy can be used as a predictor of the location of caves.

In this Chalk study, many flowing features identified are horizontal or near horizontal, suggesting they are bedding-plane controlled, as the strata have a shallow dip. Imaging data and geological data from this study suggests that there may be a strong lithological control on the location of flowing features. Flint layers, marls and hardgrounds all seem to be favourable for dissolution as most flowing features are found associated with these lithologies. These lithologies may be developed locally but there are also regional stratigraphically recognised flints, marls and hardgrounds which are likely to be associated with flow, as suggested by previous studies (e.g. Schürch and Buckley, 2002). These lithologies may act in a similar way to the inception horizons proposed by Lowe (1992). It appears that in the Chalk and perhaps other carbonate aquifers, lithology and stratigraphy can be used to predict some of the likely locations of flow through small-scale dissolutional features. However, not all occurrences of flints, marls and hardgrounds have associated flowing features.

6.3 Persistence and connectivity of small-scale solutional voids

The persistence and connectivity of small-scale solutional voids in carbonate aquifers has not been well studied. It is quite possible that these characteristics will vary between different types of carbonate aquifers. Conduits, dissolution tubules and fissures are likely to persist laterally some distance in the predominant direction of groundwater flow (the X direction on Figure 7). There may also be some lateral persistence of solutional voids perpendicular to this (the Y direction on Figure 7). However, estimating the distance that individual solutional voids persist is very difficult.

There is some evidence to suggest that solutional voids in the Chalk are sometimes laterally extensive. Rapid groundwater flow between stream sinks and springs indicates that solutional features may in places be locally extensive over several kilometres (Harold, 1937; Atkinson and Smith, 1974; Banks et al., 1995; Massei et al., 2006; Maurice et al., 2010). It is not clear from these tracer tests whether the flow is through larger conduits/caves or small-scale dissolutional features, although large-scale solutional development to form open caves is thought to be relatively rare in the English Chalk (Maurice et al., 2006). Forced gradient tracer tests between boreholes have also demonstrated rapid flow over distances of up to 270 m (Ward et al., 1998; Atkinson et al., 2000), suggesting that clusters or localised networks of solutionally enlarged voids may extend laterally over hundreds of metres.

The approach in this study has been to detect features that are intersected by boreholes which would be unlikely to intersect larger voids but enable investigation of small-scale disolutional features. The borehole siting is essentially random in relation to horizontal solutional features in the rock beneath. Truly linear features are unlikely to be intersected by randomly sited boreholes, so the fact that a high proportion of boreholes intersect several flowing features suggests that the features themselves are common and may be laterally persistent in both the X and Y directions. Certain stratigraphical horizons such as the Chalk Rock and the Glynde Marl are associated with flowing features in all five of the boreholes tested in this study in which these horizons are present beneath the water table. This suggests that flow associated with these horizons might be laterally persistent at the catchment scale, although data from more boreholes are needed to confirm this. This study also demonstrates that some flowing features occur at the same elevation in boreholes 45 m apart.

However, there is also evidence to suggest that solutional voids are not always well connected and laterally extensive. In this study flowing features do not always occur in all boreholes at the same site suggesting that they may be linear or there may be closed areas which extend for ~ 10 to 20 m within otherwise laterally extensive areas of flow. Borehole imaging data also suggest that the lateral extent of solutional enlargement of fractures may be quite limited because openings appear irregular and often do not persist across the entire circumference of the borehole (e.g. Figures 1a and 1d). The generally low incidence of pollution in the Chalk compared to more karstic aquifers suggests that it is unlikely that the larger solutional voids are widespread. This is also indicated by high attenuation along groundwater flowpaths during tracer tests (Maurice et al., 2010). Although in some areas Chalk conduits and fissures may be laterally extensive, in many areas the larger solutional voids are likely to be discontinuous.

6.4 Vertical development of permeability

Investigating vertical flows in aquifers is extremely difficult. In this study the density of flowing features is 0.20 m^{-1}, with a decrease in their density with depth from ~ 0.3 m^{-1} near the water table, to ~ 0.07 m^{-1} at depths of more than 40 m below the water table. The flowing features identified in this study are likely to be predominantly (although not exclusively) horizontal or near horizontal bedding controlled features. A further question arises as to whether bedding controlled areas of flow in the Chalk are connected by vertical or inclined flowing features.

There is some evidence that vertical flow occurs in the Chalk. The imaging data show that three out of seventeen flowing features are substantially inclined. The dominance of horizontally or near horizontally orientated flowing features might suggest that vertical development of permeability in the Chalk may be relatively limited. However, vertical boreholes are inherently much more likely to intercept horizontal flowing features than vertical ones, and therefore there are likely to be a higher proportion of vertical features present than those observed in boreholes. Flowing features are present up to 80 m below the water table and 110 m below ground level, and imaging data indicate that some of the deeper examples show evidence of dissolution. This might imply solutional development of vertical features to produce a fully connected system of larger voids enabling water undersaturated with respect to calcium carbonate to reach these depths. However, dissolution can occur far from the surface due to the extreme drop in dissolution rates as waters become more than 70-80 % saturated (Ford and Williams, 2007; Worthington and Ford, 2009). Additionally, solutional development at depth could be due to mixing corrosion (Bögli, 1964; see Gabrovsek and Dreybodt, 2010 and references therein for applications of mixing corrosion in modelling permeability development) or possibly in situ sources of acidity (e.g. from oxidation of pyrite). Imaging data also show sediment in deep flowing features. This implies that there must be a connected system of fissures and conduits of sufficient size to enable transport of sediment from the surface to these depths, and suggests that there is solutional development of vertical as well as horizontal fractures. The presence of large outflows from springs and boreholes in the Chalk suggests that there must be some vertical flows to sustain the discharges to the horizontal features supplying these springs and boreholes. There is one further piece of evidence for vertical flows in the aquifer. The Frilsham boreholes are adjacent to the river and yet there is rapid downward vertical flow within these boreholes to outflowing features of lower head up to 60 m below the surface and well below the levels of any springs and rivers in the area. This suggests that vertical pathways are developed in the aquifer, along which groundwater can eventually flow upwards to springs and riverbeds in the downstream parts of the catchment.

It appears that at the catchment scale there are some vertical linkages between the dominantly horizontal flowing features detected in our borehole based survey, and that there may be fairly frequent solutional development of vertical as well as horizontal fractures. However, there is also evidence that these vertical features may be restricted in vertical extent with clusters of connected solutional features spanning much greater distances horizontally than vertically. Cones of depression surrounding Chalk abstraction boreholes are particularly laterally extensive (much more so than for other aquifers such as sandstones), highlighting the importance of horizontal flows and suggesting that vertical flows may be limited. The low incidence of pollution in Chalk groundwaters compared to more karstic aquifers suggests that extensive fully integrated networks of solutional features are not commonly present. In addition, the existence of vertical flows in boreholes implies that there are head differences between flowing features at different levels in the aquifer. Such differences are most likely to occur if the vertical permeability of the rock between flowing features is restricted, i.e. the horizontal and vertical permeabilities of the fracture/fissure/conduit network are anisotropic. Of the 23 boreholes in which flowing features were detected, vertical flows occur in at least 19 suggesting that horizontally flowing features may be linked fairly infrequently by vertical flowing features.

Overall, it appears that the architecture of transmissive, solutionally enlarged voids in the Chalk may consist predominantly of horizontal flowing features, linked over relatively short distances by vertical or inclined flowing features. However, the distribution pattern, scale and frequency of these vertical features is not yet clear.

7 Conclusions

The single borehole dilution testing technique is a useful method of obtaining a large dataset of flowing features intersected by boreholes at catchment-regional scales. Investigating a large number of boreholes enables an improved understanding of the location of, and controls on, flows in aquifers. This is useful at the case study level for solving particular water management issues, and is also useful in terms of understanding the principles that govern the general characteristics of particular aquifer types. In highly karstified carbonate aquifers cave pattern development is relatively well understood through cave mapping (Klimchouk et al., 2000; Ford and Williams, 2007). However, flows through small-scale dissolutional features in weakly karstic aquifers, and the interaction of flows in small-scale dissolutional features with flows in caves in highly karstic aquifers are less well understood. This study demonstrates that combining the SBDT technique with borehole imaging is a good method of addressing these questions.

Returning to the questions posed in Section 2, the study has provided some new insights into the nature of groundwater flow in a weakly karstic aquifer, the Chalk:

- The average vertical density of flowing features is 0.20 m^{-1}, suggesting that they occur quite frequently. The density decreases from around 0.3 m^{-1} near the water table to ~ 0.07 m^{-1} at depths of more than 40 m below the water table.

- Flowing features are more common in river valleys than interfluves, and also occur more frequently in areas of surface karst (dolines and stream sinks) than in areas far from surface karst features. Conduits and dissolution tubules are also observed in some boreholes far from surface karst.

- Many flowing features have a local lithological control, and in some instances flows appear to be associated with particular regional stratigraphic horizons.

- Imaging data highlights the importance of dissolutional enlargement of fractures to form fissures, dissolution tubules, and conduits of ~ 0.001 – 0.15 m in diameter at the location of flowing features.

- Some flowing features have been shown to persist laterally for at least 45 m between boreholes, and there are indications from published tracer tests of lateral persistence over distances of hundreds of metres up to kilometres in some instances. However, the discontinuous nature of fissures and conduits in other instances suggests that mixing corrosion and in situ sources of acidity may be a factor enabling localised and isolated dissolution.

- Although many flowing features are horizontal or close to horizontal bedding-controlled features, there is also evidence that vertical or inclined solutional voids occur.

The study highlights the importance of small-scale dissolutional features in determining flow and transmissivity in chalk. Our conceptual model of subsurface karstic development in the Chalk is that many fractures are solutionally enlarged on a small scale. Although large-scale tracer testing has demonstrated that fully connected networks of larger conduits and fissures do occur over many kilometres, dissolutional features may not always be very extensive. It appears that the transmissive parts of the Chalk aquifer comprises a combination of conduits, fissures, tubules and unmodified fractures, and that groundwater flows between these different types of void which together form a relatively dense network of voids with variable apertures (<0.1 cm to > 15 cm).

The Chalk is a carbonate aquifer with small-scale surface karst development and this study raises the question of whether other carbonate aquifers with small-scale surface karst have similar characteristics, and also what role small-scale dissolutional features play in highly karstic aquifers. It would be useful to repeat this study in other areas of chalk and other carbonate aquifers to investigate how extensively our conceptual model of small-scale subsurface karst can be applied.

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Figure 1: Examples of images at the location of flowing features identified from the SBDTs (ticks indicate 10 cm intervals). Each image shows the whole circumference of the borehole wall, unwrapped from a cylindrical shape. The left and right edges of the image lie at the same vertical line on the borehole wall. (a) Solutionally enlarged fracture, up to 3 cm high at 10.6 m above sea level (99.4 m below ground level), associated with a marl layer, in Trumpletts B. (b) Conduits up to 4 cm high at 95 m above sea level (66 m below ground) on a hardground (the Chalk Rock) in Gibbett Cottages. (c) ~ 15 cm high conduit at 79.5 m above sea level (28 m below ground level) on a sheet flint in Trumpletts A. (d) Solutionally enlarged fracture containing sediment at 87 m above sea level (74 m below ground level) associated with nodular flints in Gibbett Cottages. (e) Inclined fracture, possibly solutionally enlarged at 47.2 m above sea level (62.8 m below ground level) associated with nodular flints in Trumpletts B.

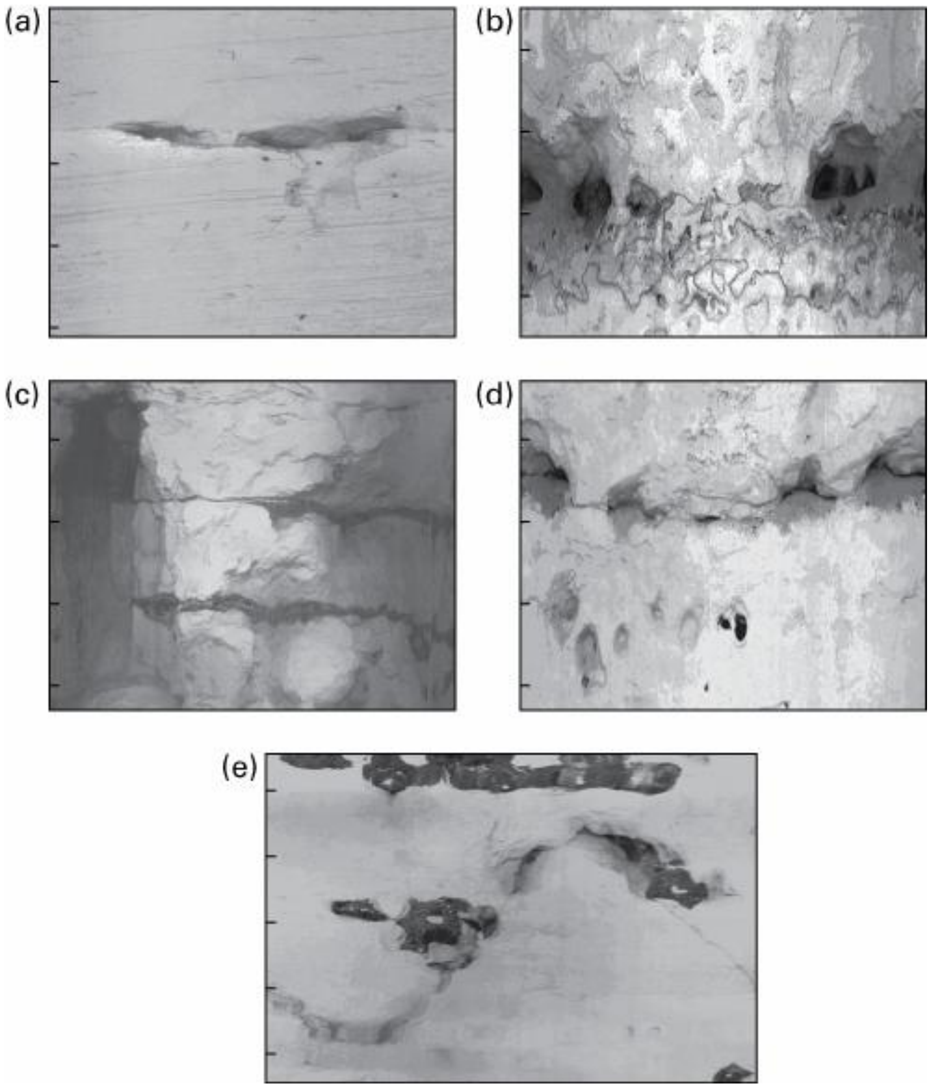


Figure 2 Study area geology (Cretaceous Chalk and Palaeogene sands and clays), karst zones and borehole locations.

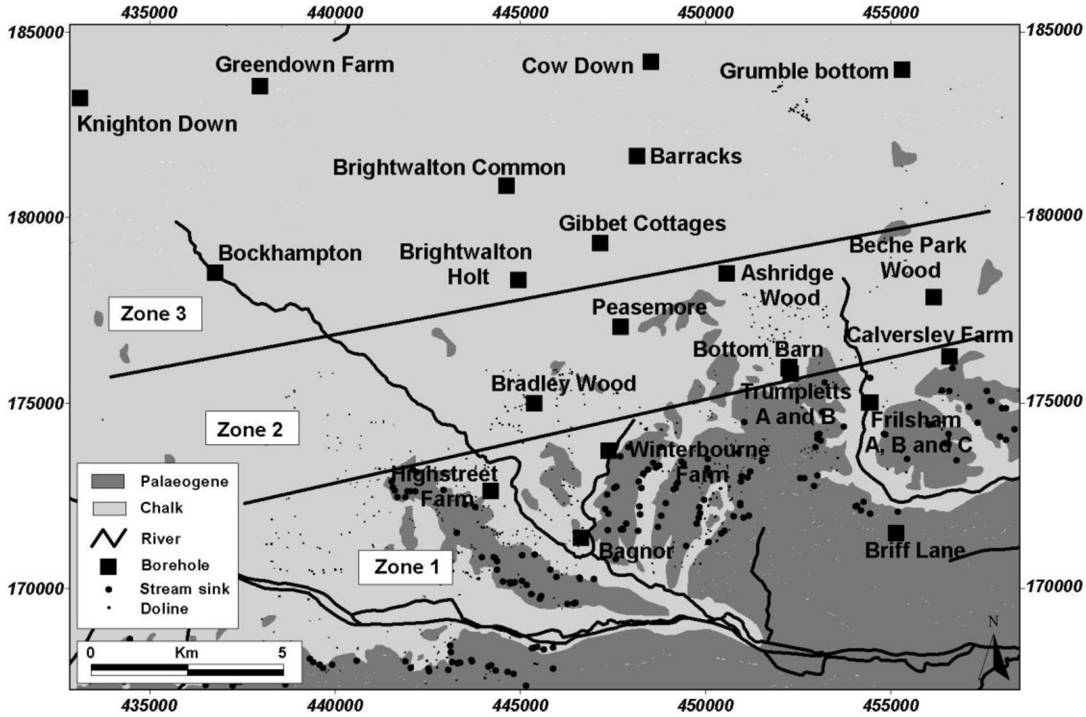


Figure 3 Flow horizons in 22 boreholes in the Pang-Lambourn catchments, Southern England related to Chalk litho-stratigraphy. Flow horizons that correlate with known litho-stratigraphic horizons the Chalk Rock (CR), the Glynde Marl (GM), the Belle Tout Marls (BTMs), and the Seven Sisters Flint (7SF) are indicated.

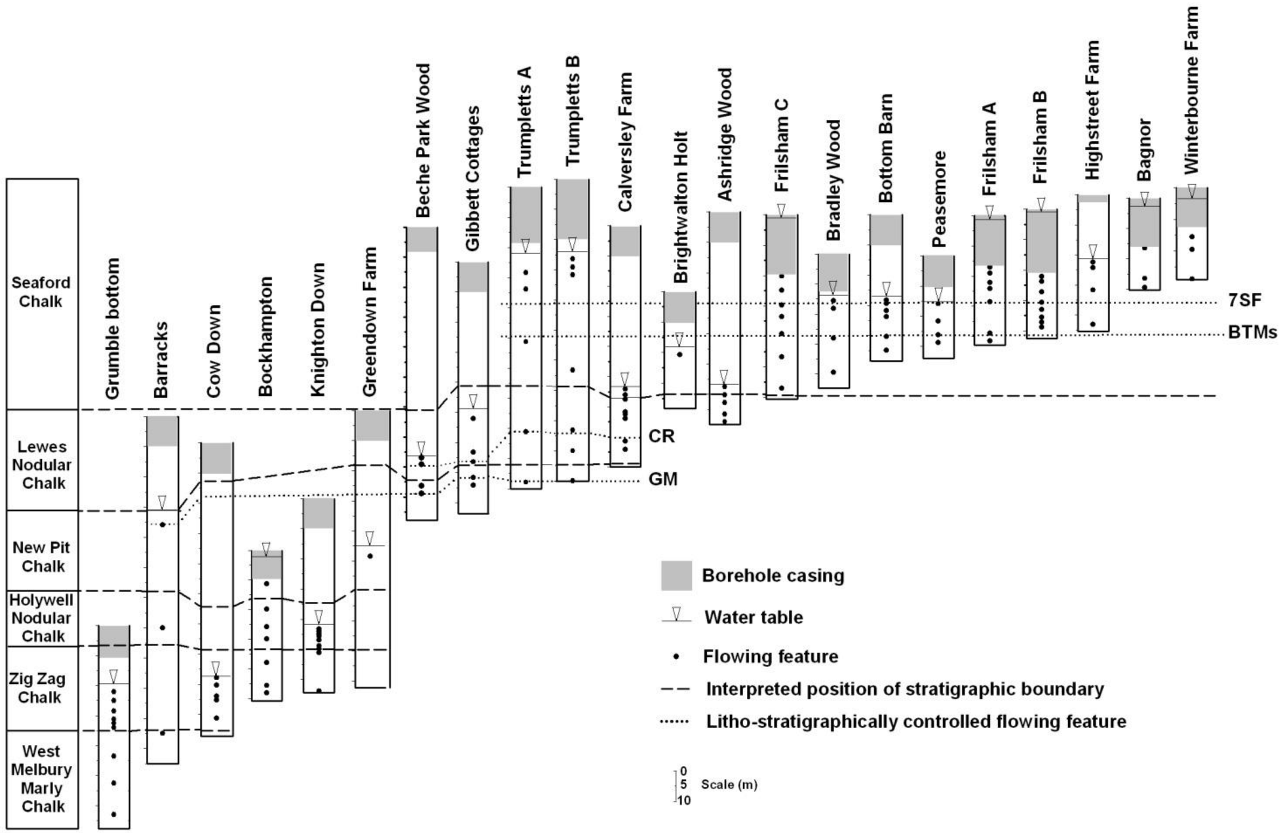


Figure 4: Distribution of flowing features in boreholes with: (a) depth below ground level, (b) below the water table, and (c) with elevation above sea level.

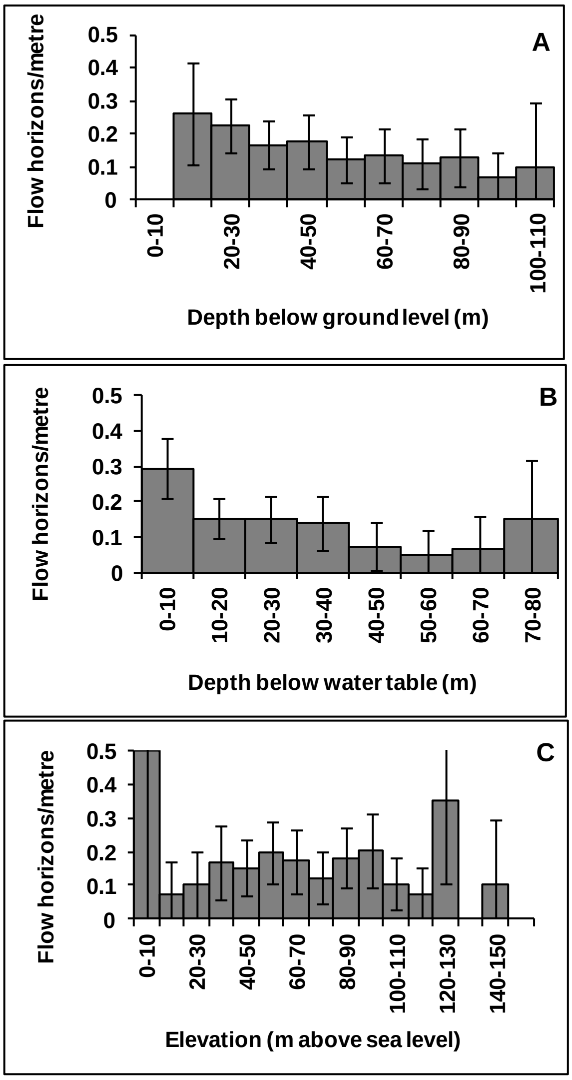
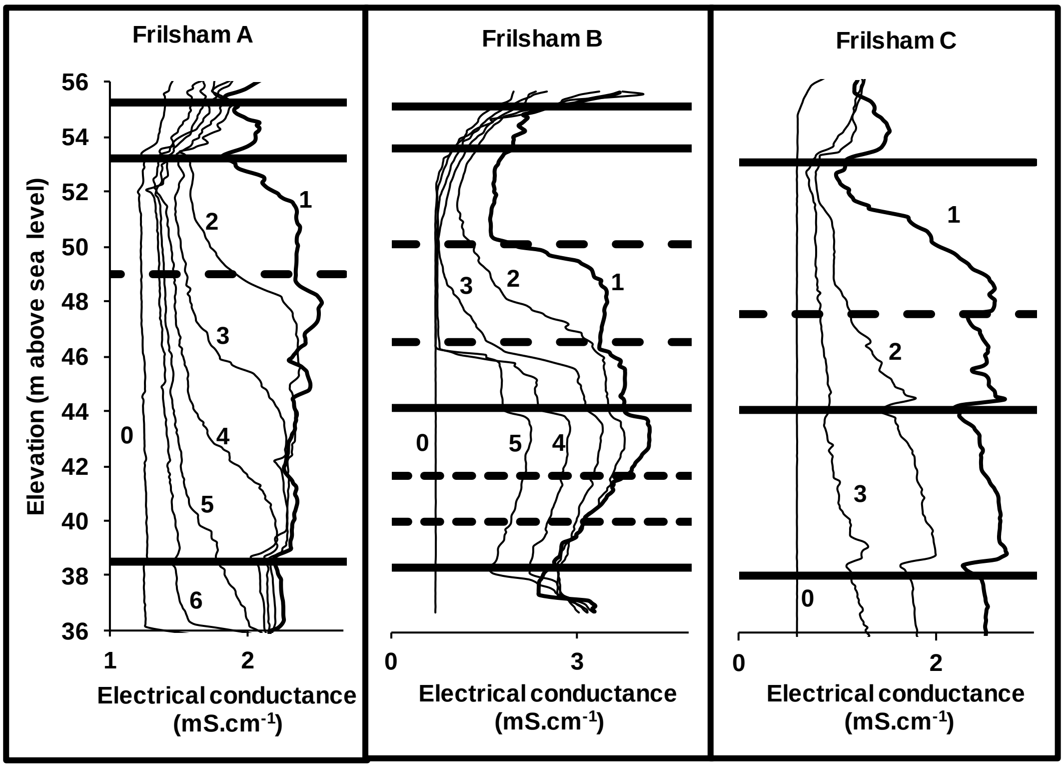


Figure 5: Flowing features in Frilsham boreholes between 26 and 56 m above sea level. Horizontal solid black lines depict flowing features present in two or three boreholes, dashed lines are features present in a single borehole. Sequentially numbered vertical profiles are background electrical conductance logs (marked 0) and electrical conductance logs following salt injections. Site layout illustrated below.



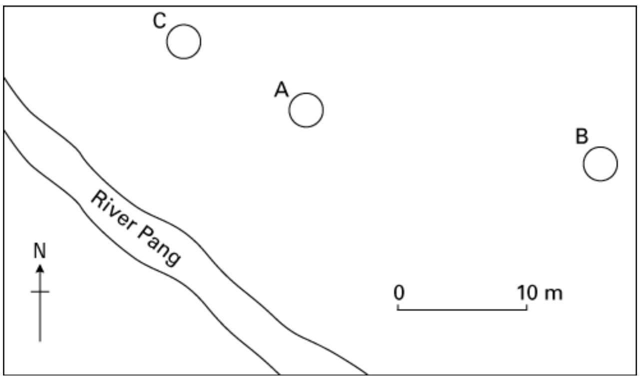


Figure 6: Flowing features in two boreholes 45 m apart at Trumpletts. Horizontal solid black lines depict flowing features present in two or three boreholes, dashed lines are features present in a single borehole. Sequentially numbered vertical profiles are background electrical conductance logs (marked 0) and electrical conductance logs following salt injections.

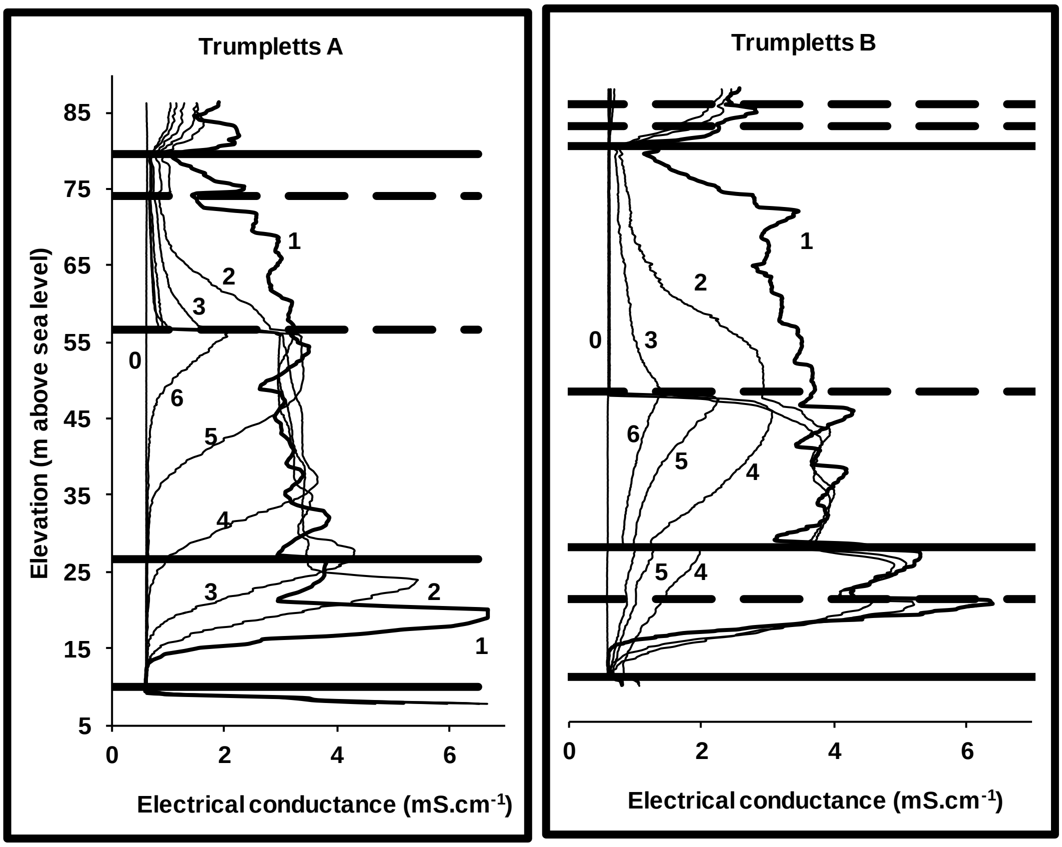


Figure 7: Schematic cross section of fracture enlarged to create fissures, tubules and a conduit.

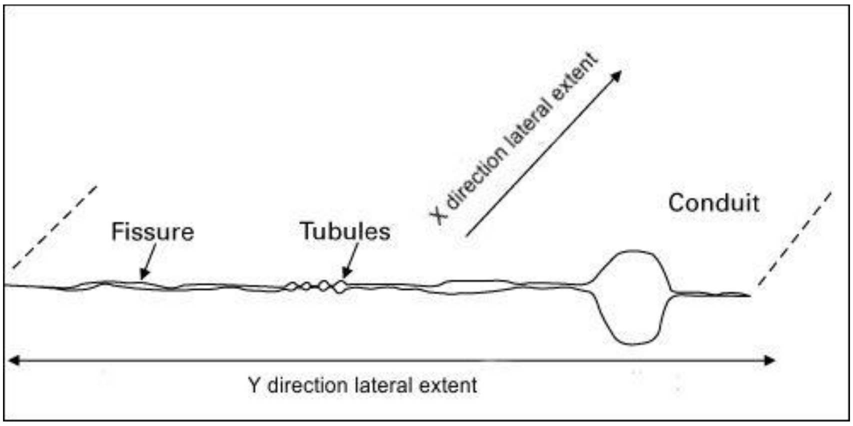


Table 1: The density and spacing of flowing features, with other factors for comparison.

Borehole	Total sample depth	No. flow horizons	Density (flow horizons per metre)	Spacing (1/density)	Topography	Karst Zone
Knighton Down	22.1	9	0.407	2.46	edge of major dry valley	3
Calversley Farm	20.75	8	0.386	2.59	interfluve	1
Ashridge Wood	13	5	0.385	2.60	edge of dry valley	2
Frilsham B	20	7	0.350	2.86	river valley	1
Frilsham A	26.9	8	0.297	3.36	river valley	1
Bottom Barn	20.4	6	0.294	3.40	interfluve	2
Cow Down	19.5	5	0.256	3.90	interfluve	3
Peasemore	15.7	4	0.255	3.93	in major dry valley	2
Briff Lane	18.2	4	0.220	4.55	interfluve	1
Bagnor	13.8	3	0.217	4.60	river valley	1
Winterbourne Farm	15.4	3	0.195	5.13	river valley	1
Grumble bottom	48.6	9	0.185	5.40	in minor dry valley	3
Beche Park Wood	21.9	4	0.183	5.48	interfluve	2
Bockhampton	40.5	7	0.173	5.79	river valley	3
Frilsham C	41.2	7	0.170	5.89	river valley	1
Highstreet Farm	23.8	4	0.168	5.95	interfluve	1
Gibbet Cottages	32	5	0.156	6.40	in minor dry valley	2
Bradley Wood	30.7	4	0.130	7.68	major dry valley	2
Trumpletts B	76.25	7	0.092	10.9	in minor dry valley	2
Trumpletts A	80.6	5	0.062	16.1	in minor dry valley	2
Brightwalton Holt	18.3	1	0.055	18.3	edge of minor dry valley	2
Barracks	83.8	3	0.036	27.9	in minor dry valley	3
Greendown Farm	47.2	1	0.021	47.2	in minor dry valley	3
Brightwalton Common	20.3	0	0.000	∞	interfluve	3

Table 2: Details of features on image logs at the location of flowing features in three boreholes

Flow horizon elevation (m AOD)	Morphology	Approximate maximum aperture (cm)	Solutional?	Situation
Trumplets A				
79.5	Single conduit	15	Yes	On top of a sheet flint layer
74.7	Single conduit	15	Yes	On top of a nodular flint layer
57	Fracture, multiple openings	5	Yes	Associated with a hardground
27	Single conduit	1	Yes	Associated with a hardground (the Chalk Rock)
10	Fracture, multiple openings	2	Yes	Associated with a marl layer (the Glynde Marl)
Trumplets B				
84	Multiple inclined fractures	0.5	No	Above a nodular flint layer
81.3	Fracture, multiple openings	3	Yes	Associated with nodular flints
78.6	Fracture, multiple openings	2	Yes	None?
47.2	Inclined fracture, multiple openings	1	?	Associated with a nodular flint layer
27.2	Multiple conduits	1	Yes	On top of a hardground (the Chalk Rock)
20.5	Inclined fracture, multiple openings	1	?	None?
10.6	Fracture, multiple openings	3	Yes	Associated with a marl layer (the Glynde Marl)
Gibbett Cottages				
109	Single conduit	10	Yes	On a nodular flint layer
97.8	Fracture, multiple openings	0.1	No	Associated with nodular flints
95	Multiple conduits	4	Yes	On top of a hardground (the Chalk Rock?)
89.5	Conduit	15	Yes	Associated with a marl layer (the Glynde Marl?)
87	Fracture, multiple openings	2	Yes	Associated with nodular flints

Table 3: The density of flowing features [m^{-1}], with 95% confidence limits, in different karst and topographical situations. Those with no confidence limits are for a single borehole

	River valley	Major dry valley	Interfluve and minor dry valley	All
Karst zone 1	0.25 ± 0.09	-	0.26 ± 0.28	0.25 ± 0.07
Karst zone 2	-	0.26 ± 0.32	0.14 ± 0.10	0.18 ± 0.09
Karst zone 3	0.17	0.41	0.10 ± 0.14	0.15 ± 0.14
All	0.23 ± 0.08	0.29 ± 0.20	0.15 ± 0.07	0.20 ± 0.05