Evidence for Rapid Groundwater Flow and 'Karst' Type Behaviour in the Chalk of Southern England

MacDonald, A. M., Brewerton, L. J. and Allen, D. J.

Hydrogeology Group, British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford, OXON, OX10 8BB, amm@bgs.ac.uk.

Abstract

With the growing importance of groundwater protection, there is increasing concern about the possibility of rapid groundwater flow in the Chalk of southern England and therefore in the frequency and distribution of 'karstic' features. Pumping test data, although useful in quantifying groundwater resources and regional flow, give little information on groundwater flow at a local scale. Evidence for rapid groundwater flow is gathered from other, less quantifiable, methods. Nine different strands of evidence are drawn together: tracer tests; observations from chalk caves; Chalk boreholes that pump sand; descriptions of adits; the nature of water level fluctuations; the Chichester flood; the nature of the surface drainage; geomorphological features; and the presence of indicator bacteria in Chalk boreholes. Although the evidence does not prove the widespread existence of karstic features, it does suggest that rapid groundwater flow should be considered seriously throughout the Chalk. Rapid groundwater flow is generally more frequent close to Palaeogene cover and also may be associated with other forms of cover and valley bottoms.

Running head: Rapid groundwater flow in the Chalk.

Introduction

Recently, emphasis has been placed on protecting both groundwater sources and resources from contamination (NRA 1992). As a consequence it has become important to identify flow routes from the ground surface, through the unsaturated zone and the aquifer, to water supply boreholes or wells. As the most important of British aquifers, the Chalk has come under particular scrutiny. Chalk groundwater accounts for more than half of the groundwater used in the country (55% in 1988, Downing 1993) and 18% of the total water used in England and Wales (Water Authorities Association 1986). The large outcrop area of the Chalk, over 21 500 km^2, combined with the high population density of southern England make protection of both the resource and individual sources a large and expensive task.

The hydraulic properties of the Chalk result from a combination of matrix and fracture properties (Price 1987, Price *et al* 1993). Groundwater flow in the saturated zone is primarily through fractures; usable groundwater storage comprises storage within macro and micro fractures and a little from within the matrix. Although complex, these general hydraulic properties still allow the aquifer to be approximated at a regional scale as having intergranular flow - this permits groundwater head distributions to be modelled relatively simply. However, at a local scale, extremely rapid groundwater flow also occurs within the Chalk. Groundwater sources can be linked to the ground surface via rapid transport routes in which groundwater can flow through the unsaturated zone and the aquifer in a matter of days. The frequency and distribution of these rapid groundwater flow features in the Chalk is largely unknown.

Various strands of evidence suggesting the existence of rapid groundwater flow and karst type behaviour are presented here for the Chalk of southern England. Taken on their own, each piece of evidence is not sufficiently convincing to draw any conclusions; however, together, they suggest that rapid groundwater flow may be widespread throughout the Chalk of southern England. Before presenting the evidence, the limitations of pumping test data must first be examined.

Pumping test data

As part of a joint-funded project between the British Geological Survey (BGS) and the Environment Agency, pumping test data were collected for the major aquifers in England and Wales (Allen *et al* in press). Data on aquifer properties for the Chalk are available from 2000 pumping tests at approximately 1300 locations throughout England. These data are of varying quality, having been calculated from pumping tests of different lengths analysed using both observation and production borehole measurements.

Figure 1 shows the distribution of all the available data. The data are not evenly spread over the Chalk outcrop: most are clustered within East Anglia, with a much lower density over the Hampshire and Thames Basins and to the north in Yorkshire and Lincolnshire. At a larger scale, the data are even less randomly distributed. Data are calculated from pumping tests undertaken in boreholes that have generally been drilled for production and are therefore in areas known to be high-yielding. Throughout the Chalk outcrop therefore, data are clustered within valleys, where the transmissivity and storage tend to be high. This bias towards high value data points creates a significantly unbalanced data set. For example, the geometric mean of the transmissivity values calculated for the 2000 tests in the Chalk is approximately 330 m^2/d; which is unreasonably high for large areas of Chalk. Therefore, the data should not be treated as indicative of the aquifer properties of the entire Chalk, but only of the *measured* sites, which are by their nature highly biased.

Pumping tests integrate the hydraulic properties of the aquifer throughout the depth of the borehole. Similar aquifer properties might be estimated from two boreholes with radically different flow regimes; eg a borehole that intersects one highly permeable fracture can give the same transmissivity and storage coefficient estimates as a network of small fractures with moderate permeability (eg Foster and Milton 1974). Consequently, groundwater models that use transmissivity and storage, derived from pumping tests, to characterise the aquifer, although adequately describing regional groundwater flow and *resources,* give little indication of groundwater transport (and in particular, groundwater flow velocities) around a *source*. The potential for rapid groundwater flow is not easily identified from pumping tests, evidence must be gathered from other, less quantifiable sources.

Evidence for rapid groundwater flow and karst

The term 'karst' is a geomorphological term associated with terrain having distinctive landforms and hydrology. In hydrogeological terms, the importance of karst is that groundwater is concentrated in, and flows rapidly through, a network of fractures, conduits (significantly enlarged fractures) and caves (conduits that are large enough to be explored physically by man). Karst characteristics are more developed in some terrains (e.g. Carboniferous Limestone) than others (e.g. Jurassic limestone, Chalk). This prompted Atkinson and Smart (1981) to suggest that carbonate aquifers should be considered as possessing varying degrees of karst, rather than being wholly karstic or wholly non-karstic. Characterising the Chalk as having 'karstic' properties can lead to emotive discussion, and secondary debates on the precise definition of terms. However for understanding and managing the Chalk aquifer, it is not the precise terminology that is of primary concern; rather, it is the velocity with which groundwater can flow from the ground surface to the aquifer, and within the aquifer to a borehole. In this discussion 'karst' is used to describe features of any diameter that allow rapid groundwater flow and also, where appropriate, geomorphological dissolution features.

Evidence of hydrogeologically significant karstic features in the Chalk can be gained in a variety of ways.

Tracer tests

Tracer tests in the Chalk may be divided into two broad categories; those associated with observed karstic features and those carried out without reference to such features. Tests in the first category have generally been carried out in the Chalk of southern England, while the second category of tests has a more widespread geographical distribution.

'Karstic' tracer tests

Subsurface karstic-type flow has been investigated at several sites in the Chalk by means of tracer tests, some of the most prominent examples of which are given below.

One of the best known sites of swallow hole activity in the Chalk is at Water End in Hertfordshire, where the Mimmshall Brook, a headwater of the River Colne, disappears at certain times of the year into a swallow hole complex. The swallow holes are located at the edge of the boundary between the Chalk and Eocene cover. Three tracer tests, carried out in 1927, 1928 and 1932 using fluorescein dye, showed that water recharging the swallow holes travelled northeast towards the River Lea Catchment. Tracers entering the swallow holes were detected in a series of springs and wells up to 16 km from the swallow holes. The breakthrough times gave flow velocities ranging up to 5.5 km/d, with tracers being detected over a thirty-degree arc from the swallow holes (Harold 1937). The velocities between the swallow holes and a particular detection point in the Lea Valley varied by up to 37% between tests, and the fastest route also varied between tests. A test carried out in 1935 in swallow holes at South Mimms (3.5 km to the southwest of Water End) also showed flows towards the Lea Valley over distances up to 19 km, with velocities ranging up to 3.2 km/d.

There are several implications of this work. It showed that rapid (several kilometres per day) natural flows can occur in the Chalk in the Water End - Lea Valley area over distances of about 15 to 20 kilometres. The conduit system through which flow occurs is complex, and the individual pathlines followed by flow are not constant and probably vary with water level. The system of conduits through which the flow occurs is widespread, as is shown by the dispersion of the detected tracer along a section of the Lea Valley several kilometres in length.

Bacteriological examination of groundwater samples taken from the Lea Valley in 1935-36 showed a strong correlation between rainfall and the level of bacteria (Harold 1937). The increase in bacteria numbers coincided with periods when streamflows known to contain bacteria entered the swallow holes at North and South Mimms. Given the connection between the swallow holes and the sampling points in the Lea Valley, this suggested that particles of bacterial size could travel rapidly through fractures in this area of Chalk.

Atkinson and Smith (1974) reported a tracer experiment in the Havant-Bedhampton area. Here swallow holes occur near to the northern margins of the Eocene outcrop, with groundwater flows occurring in Upper Chalk. Rhodamine WT dye was pumped into a swallow hole for three days. The travel time to its emergence at the Bedhampton spring (a distance of 5.75 km) was 62.5 hours, corresponding to a velocity of 2.2 km/d (peak concentration). From calculations involving the quantities of flow and the hydraulic gradient Atkinson suggested that the fracture was the equivalent of a pipe 0.74 m in diameter (although in reality several features would probably be involved). Price (1987) suggested that in an ideal case (a plane parallel fracture with no roughness or channelling) a fracture of only 4.5 mm width, and with a transmissivity of 5000 m^2/d could carry the observed flow.

Banks *et al.* (1995) reported a tracer test in Berkshire between a swallow hole and a spring 4.7 km away (both less than 1 km from the Chalk/Eocene boundary) which gave the highest velocities yet observed in the Chalk - 5.8 km/d for peak concentration and 6.8 km/d for breakthrough. The authors suggest that little attenuation occurred as the tracer moved from the sinkhole to the spring. By using Price's (1987) method the authors calculated that a single fracture of width 5.4 mm could theoretically be sufficient to represent the fracture system.

The pollution of a well at Addington, Croydon led to a series of tracer tests being carried out in the early 1900's (Richards and Brinckner 1908) to establish whether a waste disposal site located in a depression 3.2 km from the well could be the source. The well is close (around 1 km) to the edge of Palaeogene cover, with local deposits of clay-with-flints. Four tests were carried out, two by washing salt into the depression, and two using bacteria. All tests showed a connection between the depression and the well, with breakthrough times giving velocities of between 2.6 and 3.4 km/d for the salt, and 1.0 to 1.1 km/d for the bacteria. The well collected water from headings and an interesting observation was that only certain fractures produced flow with significant chloride, indicating discrete flow routes within the fracture system.

'Non-karstic' tracer tests

The above tracer tests, and others, show that fast preferential flow routes (or karstic flows) do occur in the Chalk and are commonly associated with the proximity of Palaeogene cover. However, what is not known is how common such behaviour is. Are these special cases on which interest has been focused because of obvious features such as sinking streams and resurgences, or do they represent only the most obvious examples of a more widespread phenomenon?

In southern England there are few examples of tracer tests carried out in the Chalk that are unconnected with obvious karstic features.

A tracer experiment was undertaken at the M1/M25 motorway intersection and was reported by Price *et al.* (1992). This area is close to the Chalk/Palaeogene boundary and karstic features are common, but the studies were carried out in soakaways that were apparently unassociated with karstic features. Tracer studies carried out in soakaways at the motorway intersection showed that some tracer travelled rapidly to a pumping station (a distance of 3 km), with maximum recorded velocities in excess of 2.4 km/d, but tracer recovery was very low, and it was thought that significant amounts were moving through fine fractures.

At Arish Mell in the Lulworth area of Dorset a tracer experiment was carried out between a borehole, 400 m inland from the coast, and coastal springs (Alexander 1981). Dye injected into the borehole arrived at the coastal springs, giving a sharp peak after four days (implying a velocity for the peak of 0.1 km/d). The shape of the peak and the high hydraulic conductivity implied by a locally low hydraulic gradient were taken to suggest karstic flow in the area.

A number of tracer tests have been undertaken in East Anglia by researchers of the University of East Anglia. These are chiefly borehole dilution tests, or radial tests from an injection borehole to a pumped borehole (e.g. Ward 1989, Kachi 1987). The main conclusion of the extensive testing and modelling carried out by Ward was that the flow was dominated by microfractures with a range of sizes, rather than by a few discrete high permeability conduits.

A tracer test at Kilham in North Yorkshire suggested flow velocities along a 3.1 km section of the Broachdale Valley of 0.28 - 0.44 km/d which in turn implies a network of interconnected fractures extending over several kilometres (Ward and Williams 1995). Very few tracer tests from the northern Chalk province are reported in the literature.

In summary, the tracer test data support the contention that there can be rapid flow in the Chalk, particularly in southern England and particularly close to Palaeogene cover. Tracer information is, at present, insufficient to suggest whether rapid flows may occur away from such cover. In East Anglia, available tracer information does not support the existence of rapid flow through well-developed conduit systems. Further north a test at Kilham in Yorkshire did indicate rapid flows.

Caves

Speleologists have long recognised and explored one aspect of the karstic nature of the Chalk (e.g. Reeve 1976, 1977, 1981, 1982, Proctor 1984, Fogg 1984, Lowe 1992). Explorable caves are seen in the Chalk at many locations (e.g. Sussex, Devon, Kent), mostly around the coast. Although some are of marine origin, a large proportion are connected to palaeo-solution features of fresh water origin. Often, these caves are now dry, but some extend down into the saturated zone where they are less easily explored.

One such cave system has been identified and examined at Beachy Head (Reeve 1981). The cave system is developed along a series of faults and joints and although generally sub-horizontal, has occasional vertical steps. The retreat of the cliff line at Beachy Head intersected and exposed the system allowing the cave to be examined (Figure 2). The main cave is several hundreds of metres long and has been followed until it becomes filled with water. A tabular flint layer appears to be associated with the cave development and was observed to be followed by the caves (including vertical displacements). It is possible that the perturbation in groundwater flow caused by the presence of the flint layer initiated the dissolution and enlargement of the fractures, which were then further enlarged by the concentration of flow through the fractures. As the caves are now mainly above the water table they may have developed when water levels were higher during interglacial periods of the Devensian period.

Chalk boreholes pumping sand

Chalk boreholes in southern England have been known to pump sand. In one such borehole in the South Downs sand was found within large, solution-enhanced bedding plane fractures to a depth of 70 m below the ground surface (Southern Science 1992). Groundwater flow induced by abstraction disturbs the sand within the fractures and transports it into the borehole. The origin of sand and gravel in bedding plane fractures can be identified from cliff sections: in cliff sections in France (Dieppe West, Beauville, Tilleul Plage) overlying sands and gravels have been washed down large subvertical solution pipes and deposited in horizontal bedding planes. The fractures are observed to have significant solution enhancement. Similar features are observed throughout the Chalk in England; e.g. in cliff sections along the south coast and also excavations in Caversham (Robinson, V personal communication).

Therefore, the presence of sand and gravel in Chalk boreholes may indicate the presence of large solution features in the surrounding Chalk (see Figure 3). In addition, sand and gravel may be present in solution pipes that provide access for aggressive recharge deep into the Chalk and solution enhancement of bedding plane fractures.

Adits

Extensive adit systems were built in different parts of the Chalk aquifer during the second half of the 19th century and the early part of the 20th century. The notes made during their construction are extremely interesting and useful for understanding the aquifer properties of the Chalk. During construction, engineers often estimated the location and flow from individual fractures. Unfortunately, many of the construction details have been lost over the years and little documentary records now exist, apart from the Brighton water supply (Mustchin 1974). This adit system extends for many kilometres and is generally located between -10 and +10 m OD. The yield of each adit is recorded as coming from a limited number of fractures - possibly as few as one every 30 to 50 m - each having large inflows (up to 50 l/s). This information implies that at this particular depth in the Brighton area, there exist widely spaced subvertical fractures with substantial groundwater flow.

The information is highly subjective, however, and depends on what the original engineer thought constituted a productive fracture. Also adits can be deep therefore the majority of groundwater flow may occur in a fracture network above the adit with only a few vertical fractures extending to the adit. Nevertheless, if studied and mapped carefully, adits can provide additional insight into the behaviour of the aquifer not available from boreholes. Boreholes can only give information on horizontal and sub-horizontal fractures; since adits and tunnels are horizontal, information can be gained on the distribution and yield of sub-vertical fractures.

Water levels

Significantly different water levels are often recorded in Chalk boreholes in close proximity. This change in rest water-level is often due to boreholes intersecting different fracture sets that are not necessarily connected. In addition water level variations during pumping tests can also indicate the presence of discrete fracture sets: pumping can rapidly affect water-levels in a borehole or spring several kilometres away but have little significant effect on much closer boreholes. Examples of these phenomena are observed throughout the Chalk, e.g. Swanbourne Lake, South Downs (Southern Science 1994) and South Dorset (Alexander 1981, Houston *et al* 1986). Such effects could be attributed to discrete, highly directional fracture zones that allow rapid flow.

Some boreholes respond quickly to rainfall. Water-levels can be observed to rise rapidly in some areas of the Chalk within a matter of days following heavy rainfall (Institute of Hydrology and British Geological Survey 1996). One reason for such behaviour is rapid by-pass flow through the unsaturated zone connecting to a fracture network within the aquifer. This behaviour, which gives rise to “flashy” hydrographs is a common features in aquifers that are thought of as karst (European Commission 1995).

The Chichester Flood

In early January 1994, Chichester was subjected to severe flooding that lasted for nearly a month (Taylor 1995, Posford Duvivier 1994). Groundwater played a significant role in this episode. Groundwater levels were low at the end of the 1993 recession but during the early part of the winter the area received above average rainfall, with about 350 mm falling in approximately 6 weeks - 40% of which fell in just six days (Taylor 1995). Groundwater levels rose extremely rapidly and springs appeared throughout the catchment. Consequently, flow within the River Lavant increased rapidly and the resulting flood caused much damage around the Lavant Valley and in the City of Chichester.

In analysing groundwater-level data from the Chilgrove borehole, Posford Duvivier (1994) identified a critical level within the Chalk aquifer. Once water-levels exceeded this level, river flows in the area increased markedly. It appears that the capacity for the Chalk aquifer to store significant quantities of recharge - and therefore buffer the intense rainfall - had been overcome and the catchment underwent a significant change, becoming 'flashy'. It has been suggested that this critical level corresponds to a zone of highly permeable Chalk that provides a rapid flow path connecting groundwater in the interfluves to springs within the valley (Taylor 1995). Packer testing (National Rivers Authority 1993) in the area corroborates this theory by showing the existence of high permeability within the unsaturated zone (see Figure 4).

Surface Drainage

The nature of streams and rivers on the Chalk outcrop is also indicative of a karstic aquifer. In an unpublished study, the National Rivers Authority, Wessex Region recorded flow during 2 seasons in 10 winterbournes throughout the Chalk of Wessex and Dorset (Stanton, W. personal communication). Each winterbourne (i.e. the seasonally flowing upper reaches of streams) dried up in different, but well defined stages with small springs and swallow holes defining the start and end points of each stage. Some winterbournes had reaches high up the valley that flowed almost continuously throughout the year, while reaches downstream dried up quickly. Such disappearance and re-emergence of streams implies that a discrete network of fractures is present in the valley bottom.

Surface drainage on the Chalk outcrop is poorly developed. The dendritic river patterns that are seen on most other geological formations are not observed; instead the valley patterns tend to be orthogonal, possibly defined by the fracture directions (e.g. see Figure 5). The lack of surface drainage illustrates the high permeability of Chalk strata - most water flows through the catchment as groundwater. Rapid groundwater flow can also result in groundwater flowing across surface catchment boundaries, e.g. the Alre in Hampshire (Giles and Lowings 1990), the Frome valley and Lulworth Cove in Dorset (Houston *et al* 1986).

Geomorphological features

There is significant geomorphological evidence of surface dissolution features on the Chalk outcrop (e.g. Fagg 1958, Docherty 1971, West and Dumbleton 1972, Sperling *et al.* 1977, Edmonds 1983, Goudie 1990). Dolines, solution pipes and swallow holes are all observed in the Chalk. Although the regional frequency of these features is apparently lower than in other limestones, locally the frequency can be comparable. The highest density is found in Dorset (e.g. >150 per km^2 at Puddletown Heath) with other important areas within the Chilterns, Pewsey area, Kent Downs, and the Surrey and West Kent Downs (Figure 6). The lowest density areas are the Salisbury Plain and Yorkshire and Lincolnshire (Edmonds 1983). Swallow holes and dolines are found both on recharge areas (i.e. interfluves) and discharge areas (i.e. valleys). In addition, the surface of the Chalk where overlain by some sort of cover, has undulations quite similar to the clints and grykes observed in harder limestones (as in the Carboniferous Limestone). These can be exposed in quarries and excavations (e.g. West and Dumbleton 1972). It appears that the Chalk is too soft to maintain them at outcrop.

Active swallow holes are also observed in the Chalk. For example, a tributary of the River Colne flows down a series of swallow holes at Water End in Hertfordshire and re-emerges in a different catchment (Harold 1937). At a series of swallow holes in Little Bedwyn, Berkshire [SU 306 650] surface water streams were observed to flow through the bottom of the swallow holes, directly into the Chalk: the recharge rate into the Chalk would require a well developed fracture system to accommodate the water. Swallow holes have also been identified in the bed of the River Mole in Kent (Fagg 1958) where river water was observed to mix freely with groundwater through a series of swallow holes and springs.

There is little information on the distribution of active swallow holes throughout the Chalk outcrop. Since swallow holes are often active for only a few weeks in the year, it is difficult to distinguish them from dolines and collapse features. The link between surface karstic features and rapid groundwater flow is uncertain. Further investigations, perhaps small excavations or tracer tests, would help bridge the knowledge gap.

Indicator bacteria

Escherichca (E) coli bacteria, which are indicators of faecal contamination, have been detected in untreated water from boreholes where the unsaturated zone of the Chalk is several metres thick (in some cases in excess of 30 m thick). The survival time of these indicator bacteria in either the unsaturated or saturated zones of the Chalk is not known, but times reported in the literature are generally of the order of four days to four weeks, depending on the environmental conditions (Lewis *et al.* 1980). *E coli* are too large to enter the pores in the Chalk and therefore cannot reach the water table by a piston flow mechanism through the unsaturated zone matrix. This implies that bacteria must travel through fractures, especially those enlarged by solution. Therefore, the presence of these bacteria can be taken as an indicator of rapid groundwater flow from the ground surface, through the unsaturated zone and the aquifer, to the borehole. However, although the indicator bacteria are widespread, they are not universal, therefore it is possible for karstic flow to exist in the vicinity of a borehole but for no bacteria to be detected.

In a study of the occurrence of indicator bacteria in abstraction boreholes, groundwater samples taken in the vicinity of the Palaeogene deposits contained indicator bacteria more frequently than groundwater sampled at a distance from the Palaeogene deposits (Figure 7). Indicator bacteria were detected in four out of five boreholes situated within one kilometre of the Palaeogene cover but in only two out of five boreholes where the Palaeogene cover is greater than one kilometre distant. This implies that the bacteria were transported more easily through the Chalk in the vicinity of the Palaeogene cover and, therefore, that rapid groundwater flow, particularly in the unsaturated zone, may be common near the Palaeogene deposits.

Emerging patterns

From the evidence given above, it is apparent that the Chalk exhibits many karst-like features and associated rapid groundwater flow. Geomorphologists have noted various surface expressions of karst on the Chalk outcrop. Limited data from the saturated zone show the importance of discrete, solution enhanced fractures with channelled, rapid, groundwater flow. From the above evidence, various patterns begin to emerge: in particular, rapid groundwater flow in the Chalk of southern England is generally associated with cover, often Palaeogene cover, and to a lesser extent with valleys. These are examined below.

Palaeogene deposits or other forms of cover

Surface expressions of karst - dolines, solution pipes and swallow holes - have long been associated with cover. The high density of dolines found in South Dorset, for example are formed beneath Palaeogene cover (Sperling *et al.* 1977); dolines and swallow holes in the Chilterns are formed beneath both Palaeogene deposits and clay-with-flints (Edmonds 1983). Figure 8 illustrates the distribution of the clay-with-flints in southern England. Areas with little clay-with-flints cover (Salisbury Plain, South Downs) also have fewer surface karst features (cf Figure 6). Although there has been little work - apart from occasional tracer tests in swallow holes - directly linking rapid groundwater flow with surface karst, much of the evidence for rapid groundwater flow is from areas on the Chalk outcrop close to Palaeogene deposits, the same area that surface karst is most evident.

All of the rapid flows proved by the tracer studies in southern England discussed above have been in catchments with, or close to Palaeogene deposits; i.e. Water End, Bedhampton, Addington and Arish Mell. The sand observed in solution pipes and fractures deep within the aquifer also had its origin from deposits overlying the Chalk. This suggests that these solution features developed at a time when the Chalk was overlain by Palaeogene deposits. This cover has subsequently been removed by erosion.

Perhaps the most convincing evidence of the link between cover and rapid subsurface groundwater flow is from a study of indicator bacteria in untreated groundwater samples. The occurrence of these bacteria in groundwater samples is correlated to the presence of Palaeogene deposits (Figure 7). It has already been suggested that the presence of bacteria in groundwater samples is an indicator of rapid flow, particularly in the unsaturated zone since the bacteria must have travelled from the ground surface to the borehole in a matter of weeks. Unlike the tracer tests above, this evidence is not biased by being taken from visible karst features - the samples were taken from boreholes throughout a large area.

Many transmissivity data are available for the same area as the indicator bacteria. There was no correlation found between high transmissivity and distance from the Palaeogene deposits. Also, sites with high transmissivity did not necessarily have a high frequency of indicator bacteria in untreated samples. The occurrence of bacteria (and therefore rapid groundwater flow) therefore may be predicted more accurately by the distance from Palaeogene deposits, than by the measured transmissivity value. This can be explained by returning to the pumping test. Often pumping tests are carried out when water levels are low, to estimate the available resources. Pumping tests do not test the unsaturated zone and also integrate the effect of individual fractures. Transmissivity calculated from pumping tests is therefore not a good indicator of the possibility of rapid groundwater flow.

Several factors could account for the high degree of solution activity associated with cover:

1. Soils associated with Palaeogene deposits and clay-with-flints tend to be quite acidic (Edmunds *et al* 1992).

2. Chalk soils are generally permeable, but those associated with cover can be quite clayey and therefore concentrate runoff to discrete points.

3. As recharge drains through the cover, it remains undersaturated with respect to calcite, thus

allowing the acidic recharge to reach the Chalk surface.

In summary, whatever the mechanism, rapid groundwater flow appears to be correlated with cover. Most evidence highlights the important role of the Palaeogene deposits; more work will need to be undertaken to find out if, like surface karst features, rapid groundwater flow is associated to the same degree with other forms of cover.

Valleys

There is evidence, albeit rather limited, that suggests rapid groundwater flow may also be found in major valleys. Some of the tracer tests, although close to Palaeogene deposits were also in major valleys: e.g. the Blue Pool in the River Pang (Banks *et al* 1995) and the Water End swallow holes in Hertfordshire (Harold 1937). Also, the large number of swallow holes found in the bed of the River Mole have formed because of the presence of the river (Fagg 1958). .

The distinct pattern observed in the ephemeral sections of the Wessex chalk streams indirectly suggests the presence of swallow holes and springs in valleys. Discrete features, such as individual springs and sinks in the river bed, are probably responsible for the streams drying up in distinct stages. Below the stream bed there may be a series of fractures joining the springs and sinks, although no direct evidence exists for this. Although not part of the evidence presented above, geophysical borehole logging in valleys often highlights a high degree of fracturing at the top of the Chalk (e.g. Owen and Robinson 1978); where this is connected to the ground surface by dissolution features, rapid groundwater flow could occur between ground surface and borehole.

Chalk valley bottoms have undergone a complex evolution and any number or combination of factors may be responsible for the development of rapid groundwater flow features. For example, periglaciation (Younger 1989), high historic rainfall, changes in sea level, and the tectonic history may all have contributed to the development of valleys and high permeability zones within the valley.

These valley 'karst' type features may also be developed in today's environment. Surface water flowing within streams has different chemistry from the groundwater; mixing with groundwater perturbs the chemistry and can produce water with a higher dissolution potential. This aggressive water coupled with the high flux through the valleys and the dynamics of surface water flow could produce sink holes and springs in stream beds, possibly linked with conduits (Figure 9). Docherty (1971), when reviewing the work of Fagg in the Mole Gap, suggested that such karstic features might exist in many valleys that used to contain flowing streams, although the surface expressions might now be concealed by cover deposits.

There is presently not as much evidence for rapid groundwater flow in valleys as there is close to Palaeogene cover. Direct study of valley bottoms for surface karst features, possibly below cover, would help to establish the significance of rapid flow. Tracer tests could be used to help prove the existence of rapid links between valley bottoms and the underlying aquifer.

Conclusions

Evidence for rapid groundwater flow is mainly qualitative with tracer tests being the only quantitative method of gaining data. Taking all the various strands of evidence together, however, allows the hydrogeologist a slightly different view of the Chalk aquifer. The potential for rapid groundwater flow in the Chalk may be widespread, but rapid flow might only occur infrequently, when the features are saturated. There is a large amount of evidence that suggests rapid groundwater flow is more frequent close to Palaeogene deposits. Other forms of cover, surface karstic features, and valley bottoms may also be associated with rapid groundwater flow, but further investigation is needed to establish a definite link. Examining the Chalk aquifer with tools other than the pumping test might expose more of the karstic nature of the Chalk aquifer; for example interdisciplinary geomorphological studies, packer tests, tracer tests and examination of adits and tunnels would provide valuable additional hydrogeological data.

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Figures

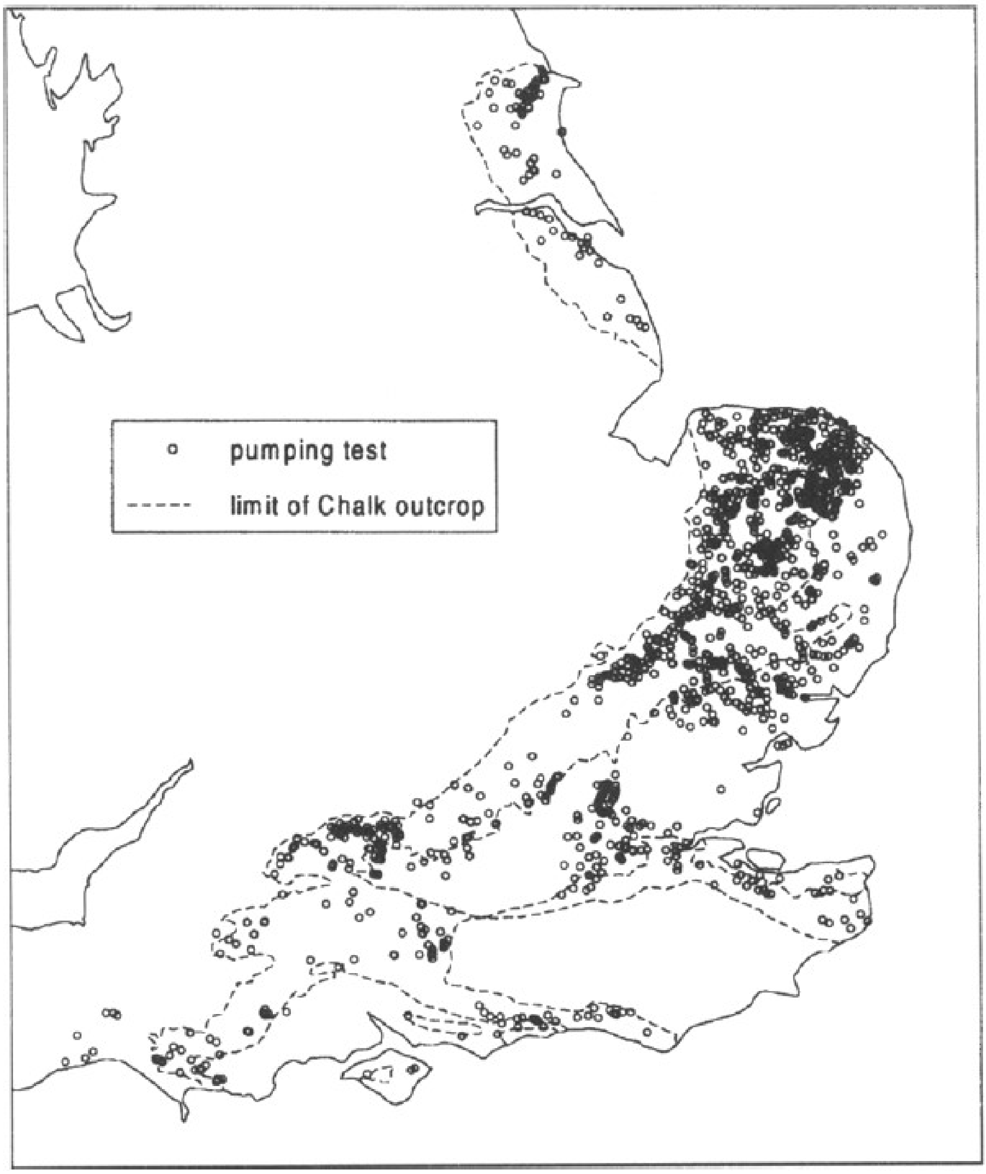

Figure 1 The distribution of pumping test data for the Chalk of England (data from Allen *et al* 1997).

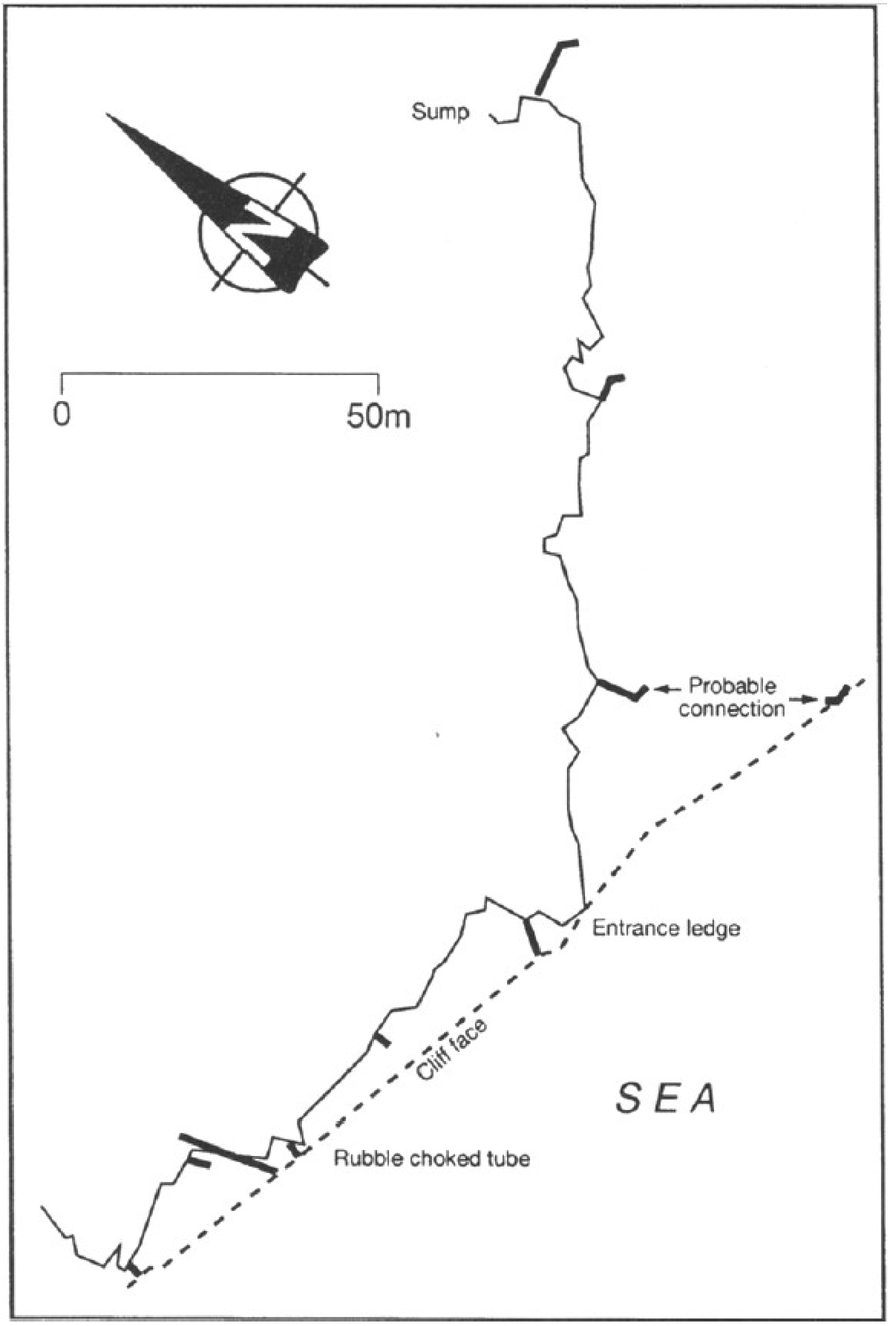

Figure 2 A sketch map of the Beachy Head chalk cave (after Reeve 1981).

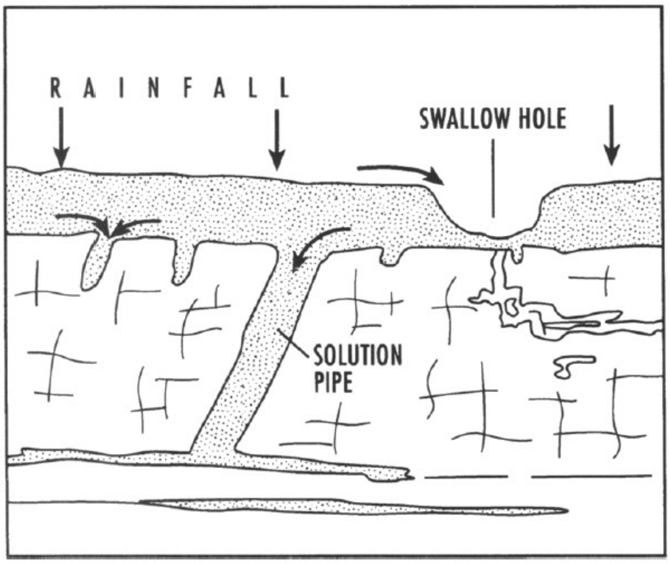

Figure 3 A cross section through the Chalk aquifer where overlain by thin cover (from Allen *et al.* 1997). Dissolution features can develop which lead to rapid groundwater flow and also the infilling of sediment.

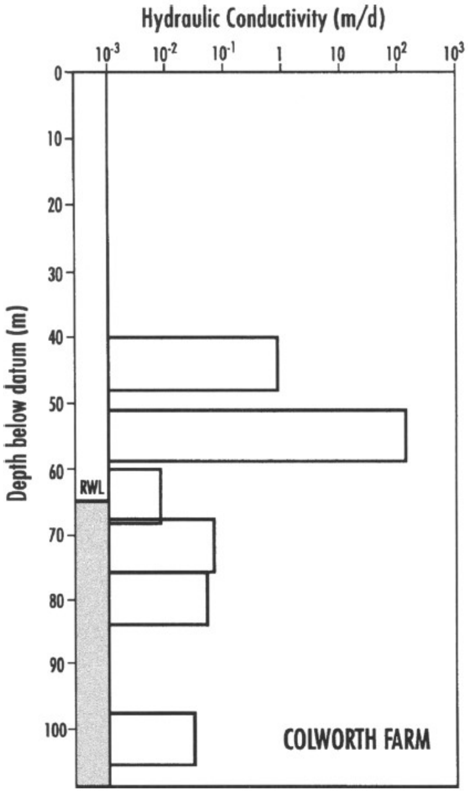

Figure 4 The permeability distribution from a packer test undertaken at Colworth Farm borehole, situated on an interfluve in the South Downs (from Allen *et al.* in press: data from National Rivers Authority 1993).

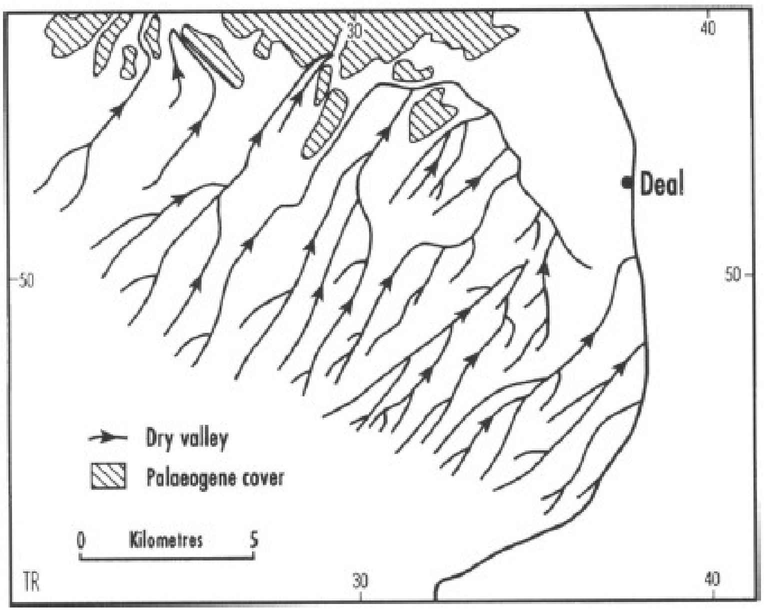

Figure 5 Distribution of dry valleys within the Chalk of the Dover/Deal area (after Allen *et al*. 1997)

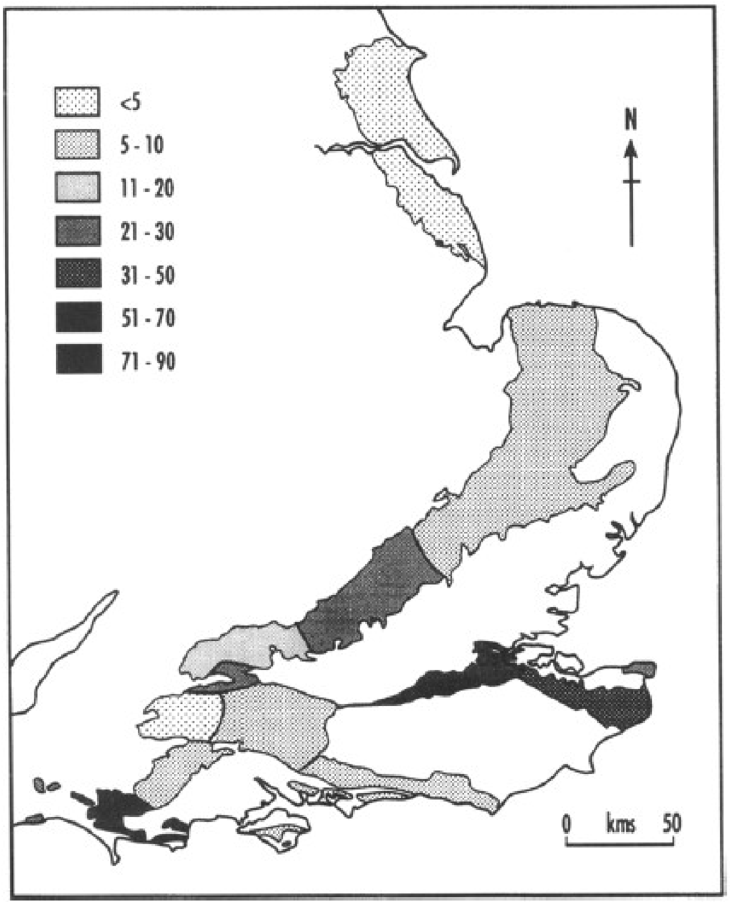

Figure 6 The apparent frequency of dolines per 100 km^2 on the Chalk outcrop (based on Edmonds 1983, taken from Allen *et al.* 1997).

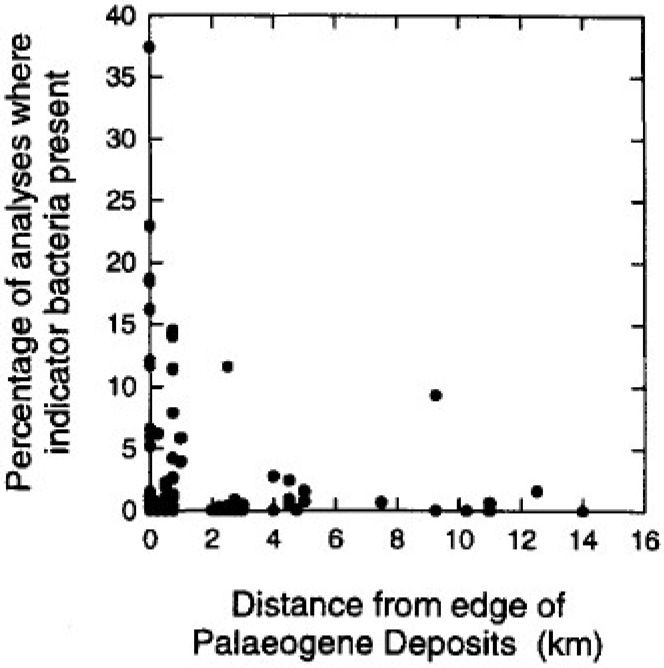

Figure 7 Frequency of groundwater samples in southern England showing indicator bacteria related to the distance from Palaeogene deposits.

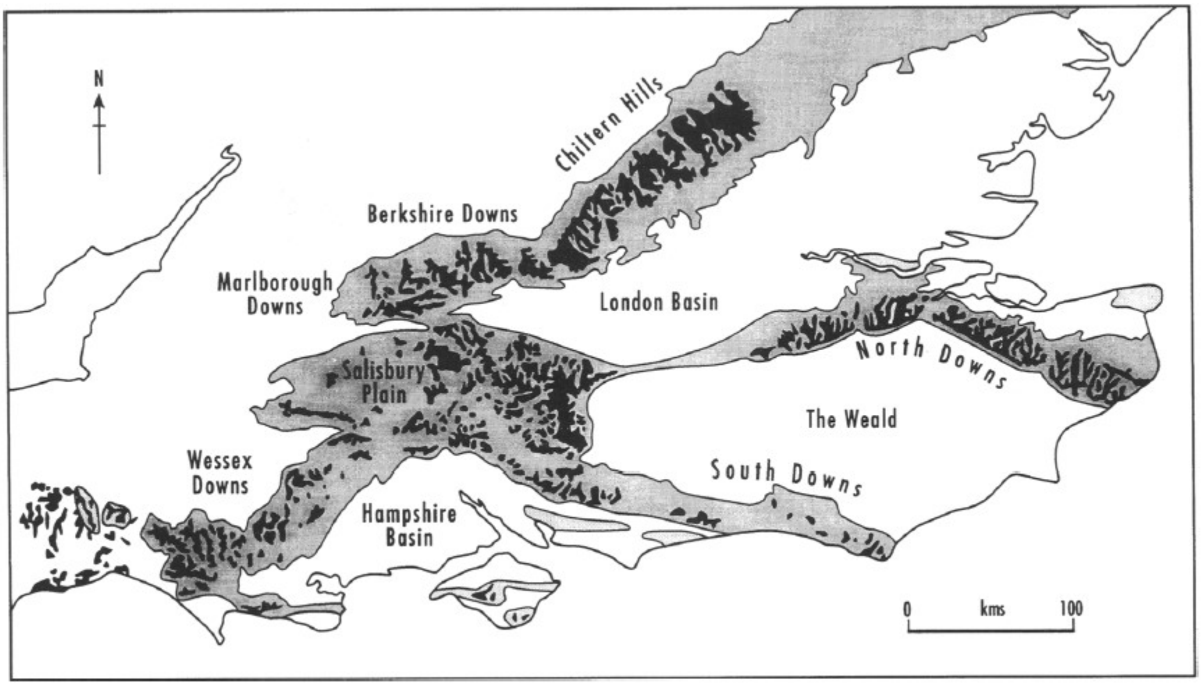

Figure 8 The distribution of clay-with-flints on the Chalk outcrop of southern England (based on Goudie 1990, taken from Allen *et al.* 1997).

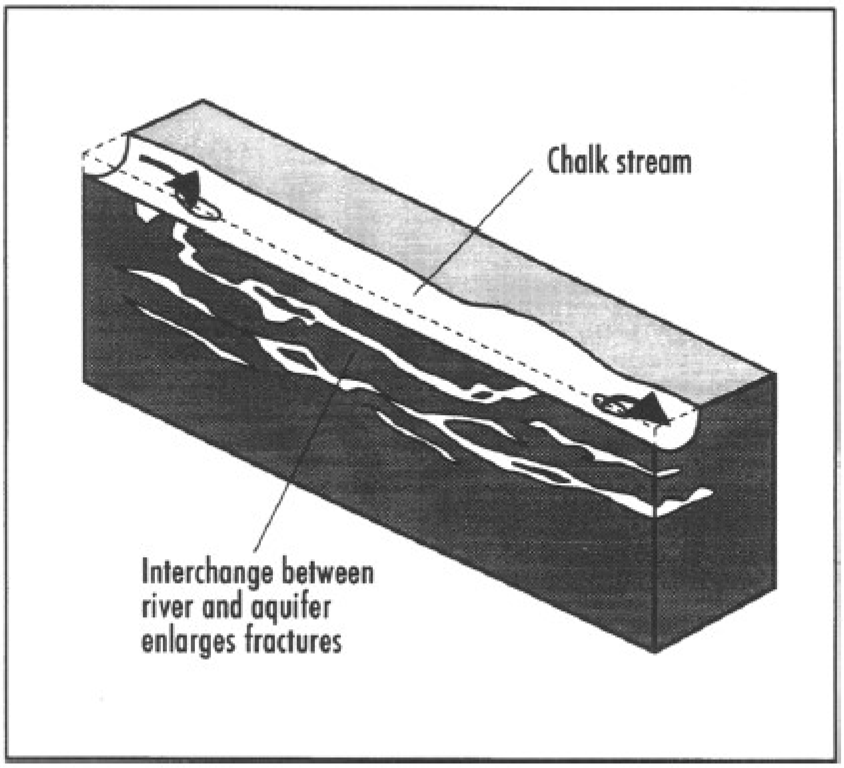

Figure 9 The development of discrete dissolution enhanced fractures beneath chalk streams