A Review of Karstic Potential and Groundwater Vulnerability of the Chalk Principal Aquifer in and around Markwells Wood, West Sussex.

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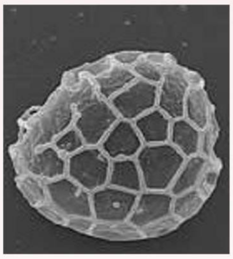

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EXECUTIVE SUMMARY & CONCLUSIONS

This review was commissioned by Markwells Wood Watch, a group of local residents concerned about plans by UK Oil & Gas Ltd (UKOG) to extract oil from a site within Markwells Wood, which is located close to the Hampshire border in West Sussex, and which falls within the South Downs National Park. Markwells Wood falls within the catchment area supplying groundwater to the Havant & Bedhampton springs, which form a large proportion of the water supplies of Portsmouth and the surrounding area, and which are one of the largest spring sources used for public water supply in the whole of England.

The review is predominantly a desk-based examination of published and unpublished literature relating to the occurrence and nature of groundwater resources in the Chalk of the South Downs. It has also reviewed topographic and geologic mapping; aerial photography and LIDAR data; and well and borehole records, and also records the findings of a site walkover survey conducted in January 2017.

The Chalk is a porous carbonate rock subject to dissolution by rainwater or surface water infiltrating and percolating through it. The dissolving power of infiltrating water works upon fractures and other planes of weakness within the rock, over time producing enlarged fissures and conduits, and in places certain landforms (e.g. stream sinks, dolines, caves) that reflect the dissolution of the rock. In general, soluble rocks that have been subject to this type of chemical weathering, and have developed to some extent the features mentioned above, are termed **'Karstic'.**

The Chalk is designated by the Environment Agency as a Principal Aquifer, meaning that it provides *"...significant quantities of water for people and may also sustain rivers, lakes and wetlands."* Indeed, the Chalk Principal Aquifer is the source of the majority of water supply to southern and south-eastern England. However, due to the high groundwater velocities (up to several kilometres per day) that frequently occur within flowing fractures, fissures and conduits, karstic groundwater supplies are among those most vulnerable to pollution.

This review has collated and synthesised a substantial body of literature relevant to:

- The general principles of karst formation within the Chalk Principal Aquifer of southern and eastern England;
- The potential karstic nature of the Chalk Principal Aquifer in the vicinity of Markwells Wood, West Sussex, and;
- The wider groundwater catchment supplying the Bedhampton & Havant springs of which Markwells Wood forms a part.

The review has proceeded from this examination of the likely and known factors influencing the degree of karstification within the wider Chalk Principal Aquifer, to the application of this knowledge of Chalk aquifer behaviour to local conditions at Markwells Wood. On this *a priori* basis it has been found that ***all of the geological and groundwater conditions required for karstification of the Chalk Principal Aquifer are in place at Markwells Wood.***

This is followed by a more detailed summary of site-specific geology and the presence of factors likely to influence the formation and existence of karstic features in the vicinity of Markwells Wood. Site-specific evidence of karstic features in and around the Markwells Wood area were determined from:

- A study of LIDAR and aerial photographic data;
- A site-walkover survey to correlate observations made from the LIDAR/aerial data with conditions on the ground;
- A study of local borehole and well records;
- Other records of local karst phenomena, particularly from groundwater tracing experiments and information arising during the Public Inquiry that upheld planning refusal for construction of the Hazleton landfill at the neighbouring village of Horndean.

The site-specific evidence acquired by these methods may be summarised as follows:

I) Dry valleys and other surface karst (dolines) are present within and nearby Markwells Wood. As surface karst is an expression of subsurface karst, subsurface karst in the area is expected to be well developed;

II) Subsurface karst (flowing features) are identified in a number of local boreholes;

III) There is an almost complete absence of surface water within the district, with the exception of 'Winterbournes' flowing in normally dry valleys during periods of unusually high groundwater recharge, thus indicating that all flow is concentrated in the subsurface;

IV) There is a correlation between the presence of karst dolines and the boundary between the Chalk Principal Aquifer and the overlying Clay-with-Flints deposits. This corroborates the same general findings in this regard from across the wider aquifer;

V) The dry valley immediately adjacent to the proposed UKOG oil exploration site is an upstream tributary of the dry valley system that passes through Rowlands Castle. These and other local dry valleys exhibit orientations mirroring known major NW/SE and NE/SW regional structural faulting within the Chalk;

VI) Tracer tests from Rowlands Castle prove groundwater velocities of up to 12.3 km/day and travel times to springs at Havant of approximately 9 hours, and;

VII) The loss of drilling fluid during the drilling of UKOG well MW1 through the Chalk beneath the water table at this site confirms karstic fissures and/or conduits directly beneath the site.

The weight of these observations, on the basis of multiple lines of evidence, suggest that karstic groundwater flow conditions, of potentially kilometres per hour, are present in the vicinity of the UKOG site at Markwells Wood.

On the other hand, there is little evidence to suggest that what takes 9 hours to travel from Rowlands Castle to Havant (a distance of 4.6 km), would take over 50 days to travel from the UKOG site to Rowlands Castle (a distance of less than 3.5 km). (50 days represents the outer limit of the Source Protection Zone 1 (SPZ1) boundary.)

Inspection of the existing SPZs delineated for the Chalk Principal Aquifer found that there is little argument to substantiate the boundaries of the current SPZ1 and SPZ2 divisions. The delineation of those zones appears to be based on incomplete mapping of surface karst features; a highly simplistic transmissivity distribution used for making basic contaminant transport calculations; and that those contaminant transport calculations were in any case inappropriately selected (they appear to be based on Darcy's Law rather than an understanding of fissure flow).

As an alternative, some crude estimations of potential groundwater travel times in the wider catchment are made on the basis of a number of proven connections between stream sinks and the Bedhampton & Havant springs. These suggest that travel times from the UKOG site at 8 km may be on the order of ten days, and that a 50 day travel time would correspond with a distance of between 10 and 11 km from the springs. This estimation is only based on a small amount of data and is necessarily to be treated with caution. However, this finding, and on the basis of the precautionary principal and other evidence presented above, there is considerable justification for the designation of the area around the UKOG site as within SPZ1 (that is, with travel times *from beneath the water table* of less than 50 days).

Additional groundwater vulnerability assessment, on the basis of the methodology of Edmonds (2008), is used to determine an Aquifer Vulnerability Rating beneath the UKOG site of between Moderate to Very High vulnerability, with High vulnerability established as the most likely rating using this method.

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1.0 INTRODUCTION

1.1 Background

Markwells Wood Watch are a group of local residents concerned about plans by UK Oil & Gas Ltd (UKOG) to extract oil from a site at Markwells Wood, West Sussex, located within the South Downs National Park. The planning application reference is as follows:

SDNP/16/04679/CM | *Appraisal and production of oil incorporating the drilling of one side track well from the existing well (for appraisal), three new hydrocarbon wells and one water injection well, and to allow the production of hydrocarbons from all four wells for a 20 year period.* | *Markwell's Wood-I Well Site, South Holt Farm, Dean Lane End, Forestside, Rowlands Castle, West Sussex.*

In particular, local residents and others are concerned regarding the lack of appreciation of the nature and importance of the Chalk principal aquifer underlying the site, as demonstrated by UKOG in their initial Groundwater Risk Assessment (Hydrock, 2016). This review has therefore been commissioned with the following aims and objectives:

1.2 Aims and objectives

This review has the broad aim to elucidate the hydrogeology of the district around Markwells Wood in West Sussex, paying particular attention to the potential for karst phenomena to be present and cataloguing any such identified. Within this review two principal objectives have been identified:

- To place the chalk hydrogeology of the Markwells Wood area in its wider context relative to chalk karst investigation findings elsewhere in West Sussex, Hampshire and the wider aquifer, and to draw parallels where appropriate between the site setting and similar settings elsewhere in/on the Chalk.

- To provide a clear assessment of the potential impact that karst phenomena in the Markwells Wood area are likely to have on strategic groundwater resources in the region, particularly in relation to the vulnerability of the Chalk Principal Aquifer to groundwater contamination.

This review is predominantly a desk-based examination of the following sources where available:

- Existing published literature, particularly relating to groundwater vulnerability and the mechanisms controlling the formation of karst within the English Chalk, and how these are relevant to Markwells Wood;
- Consultancy, water company & government reports relating to the hydrogeology of the area;
- British Geological Survey (BGS) mapping for the area;
- Aerial photography, topographic mapping and LIDAR data;

- Well and borehole records;
- Data relating to the current Source Protection Zone (SPZ);
- The current groundwater vulnerability map for the area;

The review also includes results from:

- A walk-over survey examining potential karstic features in the area;
- Liaison with the Environment Agency;
- An assessment of chalk groundwater vulnerability using the method of Edmonds (2008).

This report catalogues potential local karst phenomena and available literature on the subject, and may thus serve as a resource for the assistance of the local water company (Portsmouth Water), the Environment Agency, local people, and other interested parties.

1.3 Summary Site Description

The location of the UKOG site at Markwells Wood is located at approximately National Grid Reference (NGR) SU 758 132 and is shown on Figure 1 and Figure 2. The latter provides an aerial photograph of the wood and the surrounding area, showing also the local villages of Rowlands Castle and Horndean.

1.3.1 Topography

The northern margin of Markwells Wood is located on a north-westerly facing Chalk escarpment. The woodland continues to the south/south-east over the crest of the escarpment and is irregularly distributed down the predominantly south-easterly oriented dip slope. The elevation of the crest of the escarpment dips from approximately 160 metres abover Ordnance Datum (maOD) in the north-east, to approximately 110 maOD in the south-west, over a distance of approximately 2.2 km.

The south-easterly dipping slope of the Chalk between the crest of the escarpment and the UKOG site is incised by two minor dry valleys oriented approximately north-east to south-west. These join to form a larger dry valley some 650 m to the south-west of the UKOG site, at NGR SU 752 130. This dry valley itself forms a tributary to the larger north-south oriented dry valley to the west that runs through Finchdean and Rowlands Castle. The UKOG site is situated at an elevation of approximately 110 maOD and immediately adjacent to the base of the more southerly of the two minor dry valleys. The dry valleys are known colloquially as 'Lavants' or 'Winterbournes' and may become active surface water courses at times of high rainfall, typically during the winter (see Plates 1 & 2 for example). The relationship between dry valleys and Chalk karst will be discussed later in this report.

Plate 1. A Lavant or Winterbourne approximately 3 km north of Rowlands Castle and looking eastward across the valley to Markwells Wood. Date unknown.

Photograph courtesy of and copyright Joan Lee.

1.3.2 Land Use

Land use is predominantly arable agriculture with a significant proportion given over to woodland and forestry. There are some minor settlements and conurbations nearby, the nearest villages is West Marden 1.2 km east of the site, and the larger Rowlands Castle approximately 3.5 km to the south-west.

1.3.3 Climate

The South Downs are one of the sunniest and warmest parts of the UK, with average annual rainfall in the district reported as 844 mm by Jones & Robins (1999). Evapotranspiration averages 485 mm, allowing some 359 mm for recharging the Chalk Principal Aquifer. Average summer and winter temperatures are 16.1ºC and 5.5ºC (ibid). These values are now somewhat out of date, but offer a broad reflection of climatic situation.

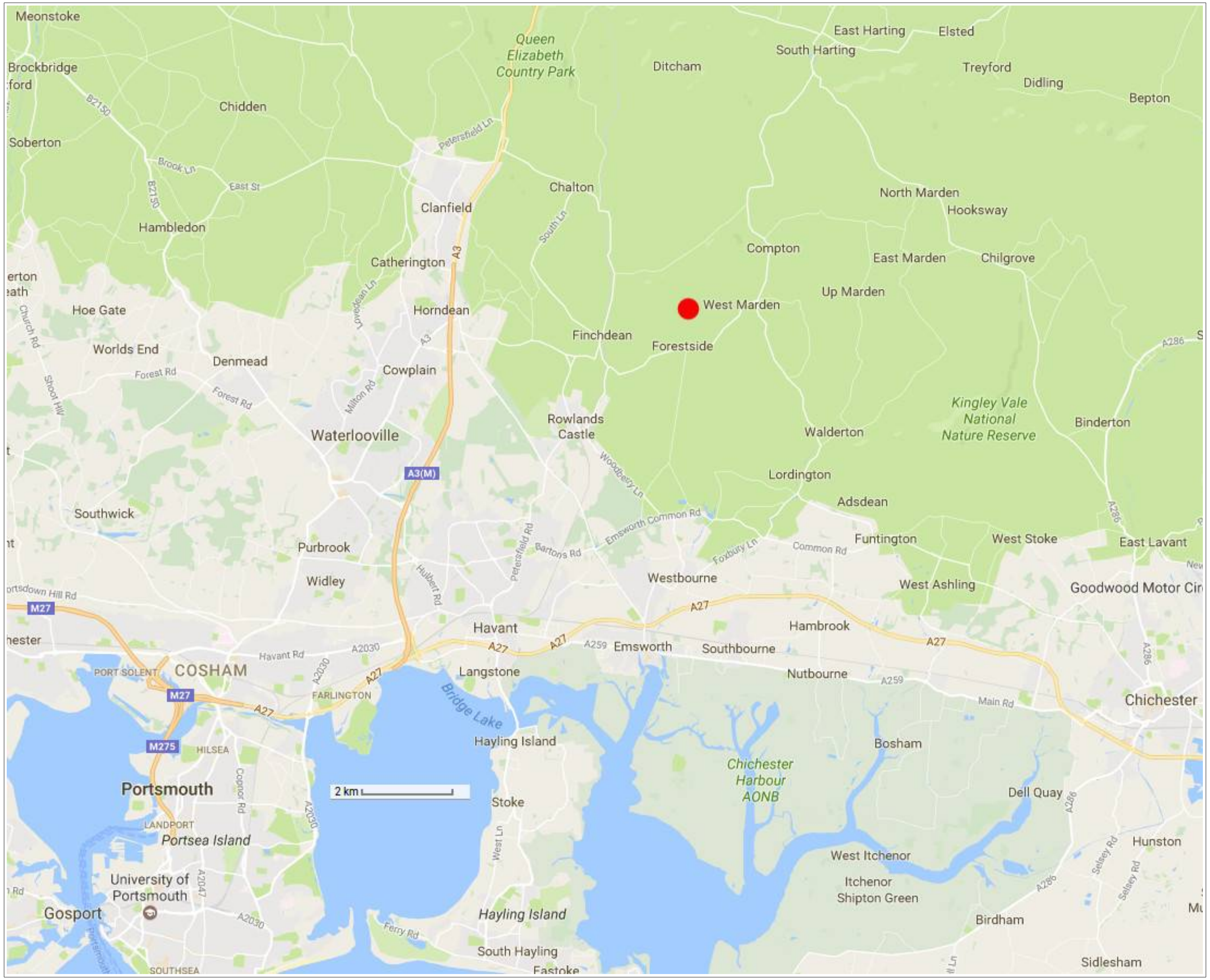

Figure 1. Location of Markwells Wood (in red) at ~1:120,000.

Figure 2. Aerial photograph of Markwells Wood and the surrounding area, showing the UKOG site in red and the local villages of Horndean and Rowlands Castle. Scale 1:30,000. Oriented northward.

2.0 SOURCES OF INFORMATION

The primary published and unpublished literature sources utilised in this review are given below:

- **Allen, D. J., Brewerton, L. J., Coleby, L. M., Gibbs, B. R., Lewis, M. A., MacDonald, A. M., Wagstaff, S. J. and Williams, A T. (1997).** The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report WD/97/34. 312pp. Environment Agency R&D Publication 8.*

- **Atkinson, T.C. & Smith, D, I. (1974)** Rapid groundwater flow in fissures in the Chalk: an example from south Hampshire. *Quarterly Journal of Engineering Geology. Vol. 7. 197 – 205.*

- **Barton, M.E., Cater, R. & Price, N.J. (undated).** The Chalk swallow holes of south-east Hampshire: Geological setting, groundwater hazards and fissure flow rates. *Unpublished report by Southampton University, Hampshire County Council and TBV Consultants.*

- **British Geological Survey (1998).** *Fareham. England & Wales Sheet 316. Solid and Drift Geology 1:50,000. (BGS, Keyworth, Nottingham).*

- **Edmonds, C.N. (1997).** Town & Country Planning Act 1990 - Appeal by Hughes Waste Management Ltd – Site at Hazleton Farm, Horndean. Proof of evidence of Dr Clive N. Edmonds (Engineering geologist / geomorphologist). *Unpublished Proof of Evidence to Public Inquiry / Planning Appeal reference Q1770/A/96/275529.*

- **Edmonds C.N. (2001).** Predicting Natural Cavities in Chalk. *In: Griffiths, J. S. (ed.) Land Surface Evaluation for Engineering Practice. Geological Society, London, Engineering Geology Special Publications, 18, 29–38. The Geological Society of London 2001.*

- **Edmonds, C.N. (2008).** Improved groundwater vulnerability mapping for the karstic chalk aquifer of south east England. *Engineering Geology 99 (2008) 95 – 108.*

- **Entec UK Limited (2006).** East Hampshire and Chichester Chalk Groundwater Conceptualisation Project. Phase 1 Data Synthesis - Conceptual Model and Water Balance. *(For Environment Agency, Southern Region.)*

- **Entec UK Limited (2007).** East Hampshire and Chichester Chalk Groundwater Conceptualisation Project. Phase 2A – Model Construction and Refinement. (*For Environment Agency, Southern Region.)*

- **Environment Agency, (1998).** Unpublished description of the derivation of the Bedhampton &

Havant springs Source Protection Zones. *(Provided as Appendix 3.)*

- **Environment Agency (2013).** *Groundwater protection: Principles & Practice (GP3).*
- **Hydrock (2016).** Proposed Markwells Wood Development: Groundwater Risk Assessment. *Final Report for UKOG (GB) Ltd.*
- **Jones, H.K. & Robins, N.S. (editors) (1999).** The Chalk aquifer of the South Downs. *Hydrogeological Report Series of the British Geological Survey.*
- **Jones, D.K.C. (1981).** Geomorphology of the British Isles: Southeast and Southern England. *London; Methuen.*
- **Maurice, L.D., Atkinson, T.C., Barker, J.A., Bloomfield, J.P., Farrant, A.R., and Williams, A.T. (2006).** Karstic behaviour of groundwater in the English Chalk. *Journal of Hydrology*. 330(1-2) 63-70.
- **Maurice, L. (2009).** Investigations of rapid groundwater flow and karst in Chalk. *Unpublished PhD thesis. University College London.*
- **Maurice, L., Atkinson, T.C., Barker, J.A., Williams, A.T. & Gallagher, A.J. (2012).** The nature and distribution of flowing features in a weakly karstified porous limestone aquifer. *Journal of Hydrology 438-439, 3-15.*
- **McDowell, P.W. (1975).** Detection of clay filled sinkholes in the chalk by geophysical methods. *Quarterly Journal of Engineering Geology 8, 303-310*
- **McDowell, P.W. (1996).** An assessment of the geohazards at the proposed Hazelton Farm landfill site at Horndean in Hampshire. *University of Portsmouth Enterprise Ltd – Ground Investigations Consultancy Unit.*
- **McDowell, P.W., Coulton, J., Edmonds, C.N. & Poulsom, A.J. (2008).** The nature, formation and engineering significance of sinkholes related to dissolution of chalk in SE Hampshire, England. *Quarterly Journal of Engineering Geology and Hydrogeology, 41, 1-12.*
- **Neve, A. (1997).** Town & Country Planning Act 1990 - Appeal by Hughes Waste Management Ltd – Site at Hazletone Farm, Horndean. Proof of evidence of Andy Neve (Technical Director, Portsmouth Water PLC). *Unpublished Proof of Evidence to Public Inquiry / Planning Appeal reference Q1770/A/96/275529.*
- **Price, M., 1987.** Fluid flow in the Chalk of England. *Geological Society Special Publication 34, 141-*

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- **Price, M., Downing, R.A., and Edmonds, W.M., (1993).** The Chalk as an aquifer. *In The hydrogeology of the Chalk of North-West Europe. Edited by Downing, R.A., Price, M., and Jones, G.P. 35-59*

- **Robins, N. S. & Dance, L. T. (2003).** A new conceptual groundwater flow system for the central South Downs aquifer. *Water and Environment Journal, 17: 111–116.*

- **Rust Environmental (1997).** *Proposed landfill site at Hazleton Farm, Horndean, Hants. Evaluation of risk to groundwater quality. Unpublished report to Public Inquiry / Planning Appeal reference Q1770/A/96/275529.*

- **Waltham, A.C. & Fookes, P.G. (2003).** Engineering classification of karst ground conditions. *Quarterly Journal of Engineering Geology & Hydrogeology. 36, pp. 101-118*

- **Younger, P.L. & Elliot, T. (1995).** Chalk fracture system characteristics: implications for flow and solute transport. *Quarterly Journal of Engineering Geology, 28, S39 – S50.*

3.0 INTRODUCTION TO THE HYDROGEOLOGY OF THE ENGLISH CHALK

3.1 Introduction

Markwells Wood is located on Chalk bedrock which is present either at the surface or, where some shallow superficial deposits (Clay-with-Flints) are present, at a depth typically not greater than 5 – 10 m. A summarising geological schematic is shown in Figure 3.

Very briefly, the Chalk consists of a sequence of sedimentary rocks of Cretaceous age, laid down as submarine deposits between 100 and 65.5 million years ago. The Chalk is now a porous and predominantly carbonate rock subject to dissolution by rainwater or surface water infiltrating and percolating through it. The dissolving power of infiltrating water (recharge) works upon fractures and other planes of weakness within the rock, over time producing enlarged fissures and conduits, and in places certain types of surface landform that reflect the dissolution of the rock (e.g. stream sinks, dolines, conduits, caves). In general, soluble rocks that have been subject to this type of chemical weathering, and developed features such as those mentioned, are termed '**Karstic**'.

There is a sizeable body of literature regarding this topic and only an extremely truncated introduction will be given here in order to inform more site-specific information. No claims to originality are made for the work presented in this review, much of which is derived verbatim from the following texts in particular:

- **Jones, H.K. & Robins, N.S. (editors) (1999).** The Chalk aquifer of the South Downs. *Hydrogeological Report Series of the British Geological Survey.*

- **Allen, D. J., Brewerton, L. J., Coleby, L. M., Gibbs, B. R., Lewis, M. A., MacDonald, A. M., Wagstaff, S. J. and Williams, A T. (1997).** The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report WD/97/34. 312pp. Environment Agency R&D Publication 8.*

- ***Maurice, L. (2009).*** *Investigations of rapid groundwater flow and karst in Chalk. Unpublished PhD thesis. University College London.*

These three texts together provide a comprehensive overview of the literature and conceptual understanding of the Chalk Principal Aquifer, and the reader is referred to them for further information and references. Regarding wider review of karst, the following is a classic text on the subject and provides an accessible and detailed introduction:

- **Ford, D.C., and Williams, P. (2007).** Karst hydrogeology and geomorphology. *John Wiley and Sons Ltd. 2nd ed. 562 pp.*

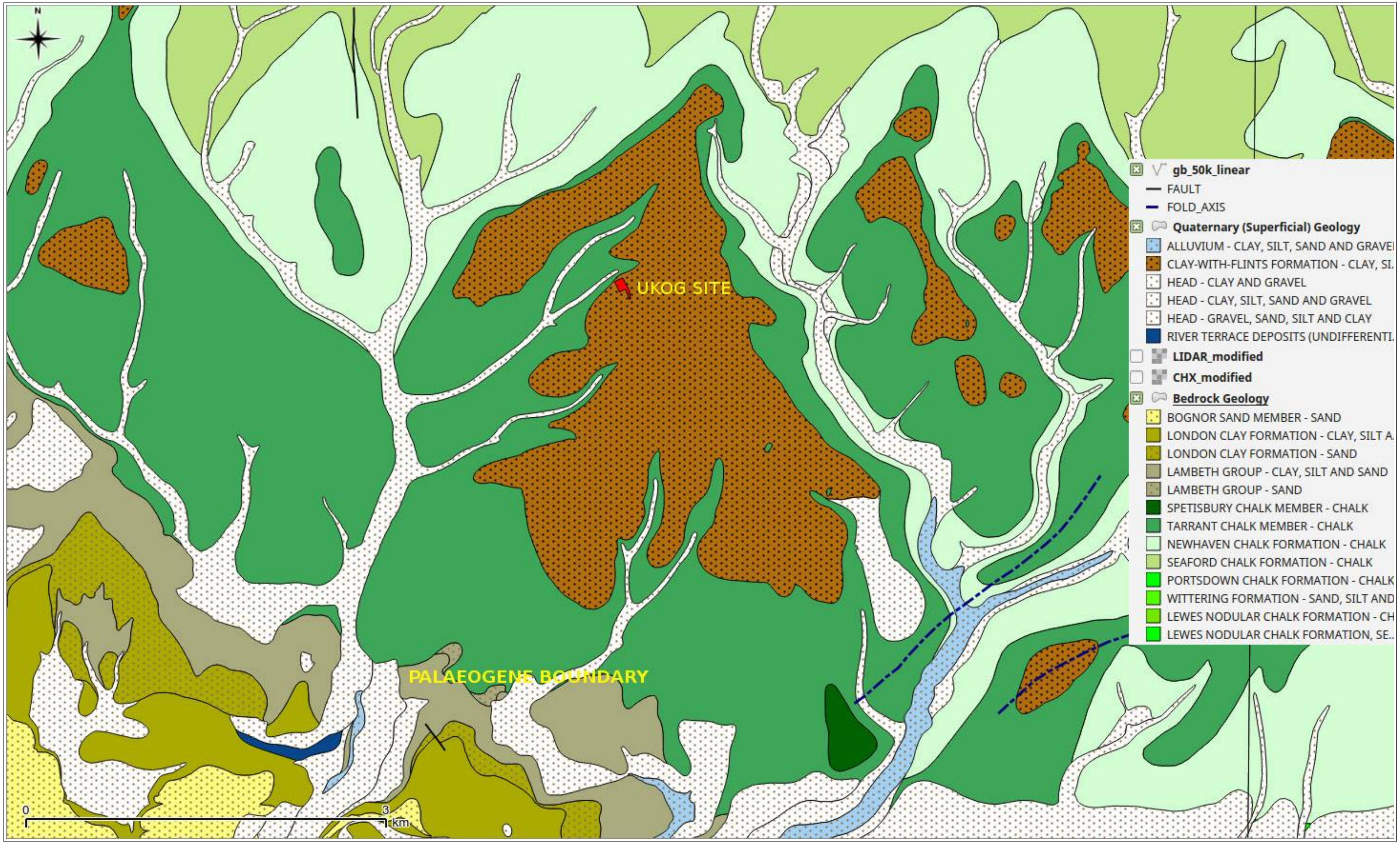

Figure 3. Geological map of the area around Markwells Wood, showing solid (bedrock) and superficial (Quaternary) geology. Scale ~ 1:30,000.

(Licence No. 2011/3PDL/xxxxxx British Geological Survey © NERC.)

3.2 The Chalk Principal Aquifer

3.2.1 Groundwater Flow

Maurice *et al* (2012) conceptualise groundwater flow within the Chalk as taking place *“...through a hierarchy of different types of void…”* for which they use the overarching term 'flowing features'. They continue:

> *“These flowing features have generally increasing permeability from unmodified fractures to fissures, tubules, conduits and caves. Fissures are defined... as fractures that have been enlarged by solutional processes, but retain the broadly planar geometry of unmodified fractures... Tubules are small cylindrical voids of 1 to 50 mm diameter… Conduits are larger solutional voids, often tubular, sometimes rectangular in cross-section...and caves are voids that are large enough to enter.”*

3.2.2 Porosity & Water Storage

The vast mass (or matrix) of native rock, within which this network of flowing features is situated, is characterised by typically high levels of porosity (approaching 45% by volume in places, although may be as low as 15%), but with a very low intrinsic permeability, because individual pore sizes are relatively tiny (on the order of 0.1 to 1.0 micrometer). The majority of the water stored within the aquifer is within the matrix, but this is tightly held by the capillary action of the pores. The majority of storage that actually contributes to groundwater flow is therefore within the fracture and fissure network, and this is thought to comprise about 1% of the aquifer by volume.

3.2.3 Chalk Composition & Fracture Spacing

The Chalk has a variable composition that includes flint bands, hard beds, soft beds and marl beds (with high clay content). Together with physical (tectonic and other) stresses, these factors exert variable controls on groundwater flow due to differences in intrinsic permeability, in the propensity to fracture, and the tendency to develop or influence the development of flowing features. A number of studies have been made regarding fracture spacing in the Chalk (e.g. Younger & Elliot, 1995), and spacings of 0.1 to 1.0 m are considered typical in the main part of the aquifer (see Jones & Robins (1999) for more detail).

3.2.4 Groundwater Levels & the Unsaturated Zone

Generally speaking, groundwater levels are highest in January and February, and lowest toward the end of the summer in August and September. The depth of the unsaturated zone from the surface varies depending on location, with valleys (including dry valleys) having the thinnest unsaturated zones. The higher interfluvial areas between the valleys (contrarily named 'Downs') may have unsaturated zone thicknesses over 100 m in places. At Markwells Wood, the closest water level measurement indicates a depth to water table (in

February 1988) of ~12 m (at Old Idsworth Farm at approximately NGR SU 749 143). This is located in the upper reaches of a dry valley. Hydrock (2006) estimate a depth to water table of 55 mbgl (metres below ground level) at the UKOG site. These values are highly seasonally dependent and groundwater level fluctuations may be tens of metres throughout the year.

3.2.5 Permeability Distribution

Regarding the most productive part of the aquifer, Jones & Robins (1999) note that:

> *"The majority of groundwater flow generally occurs within 50 m of the water table, through dissolution-enhanced fractures. Some smaller flows, however, have been found at depth (down to 140 m), especially close to the coast."*
>
> pg. 50

It is also noted that the highest borehole yields are usually located within or close to river or dry valleys, although borehole yields are dependent upon encountering flowing features within the ground. For this reason boreholes may exhibit a wide range of transmissivity, which is a measure of the degree of permeability of the rock (technically the hydraulic conductivity by the depth of the aquifer). However, it should be noted that transmissivity (and storage coefficients) are dependent upon water level (Allen *et al,* 1997), as a greater saturated thickness is likely to engage more flowing features, and thus improve borehole yields. Transmissivity in the Chalk may vary between almost nothing and several thousand m^2/day.

3.3 Palaeogene & Quaternary deposits overlying the Chalk

At Markwells Wood, the Cretaceous Chalk is unconformably overlain by the heavily weathered residue of more recently deposited (Palaeogene) marine clays. As mentioned, this deposit is known as the 'Clay-with-Flints'.

3.3.1 Reading Formation (Lambeth Group, Palaeogene)

Approximately 4 km to the south of the UKOG site, approaching Rowlands Castle, Stubbermere and Aldsworth, the intact boundary of the Palaeogene clays is present, consisting mostly of the Reading Formation, overlain yet further to the south in places by London Clay. Together these units form the local expression of the Lambeth Group, and are labelled as such in Figure 3. Jones and Robins (1999):

> *"The Reading Formation has a maximum thickness of 40 m… It comprises mostly brightly mottled red, brown and greenish grey clays, which overlie a basal… sandy or loamy unit... Other bodies of fine-grained sand occur locally within the clays, and lignite or fossil wood is found near the base of the formation.*

The Reading Formation of Sussex generally behaves as an aquiclude[1], confining groundwater in the Chalk aquifer, although local sandy beds may give rise to chalk water springs. A common feature around the margins of the Reading Formation outcrop on the Chalk is the development of swallow holes, where acid runoff comes into contact with the chalk to create large solution features. The Reading Formation is also believed to be the in-situ parent material from which the Clay-with-Flints has developed on the Chalk dip slopes."

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3.3.2 Clay-with-Flints (Quaternary)

Jones & Robins (1999) again provide a useful summary of the Clay-with-Flints deposits as it relates to the underlying Chalk aquifer:

"The deposits are stiff, yellowish and reddish brown clays with fresh and broken, weathered flint nodules resulting from the in-situ weathering of the Reading Formation over long periods. The latter rests on a sub-Palaeogene erosion surface cut on the Chalk dip slope of the South Downs and it has been demonstrated that the Clay-with-Flints rests on the extension of this surface beyond the present outcrops of unaltered Reading Formation... A thin basal part of the deposit, comprising fox-red clay with unworn corticed flint nodules, is believed to result from solution of the Chalk and translocation of clay minerals... The upper and major part of the deposit represents the altered residuum of the Reading Formation. Solution pipes in the Chalk occur beneath the Clay-with-Flints around the margins of its outcrops.

The tenacious nature of the clay component of the Clay-with-Flints suggests that it forms an impermeable capping to the Chalk. However, in practice, soil cracks, plant roots and the junctions of clay and flints provide pathways for the migration of water to depths of at least 2 m, and it is best to regard the Clay-with-Flints as semi-permeable rather than impermeable. The deposit is highly dissected and less than 5 m thick over much of the South Downs, and the small remaining patches have little effect on retarding infiltration."

pg. 12

3.3.3 Head Deposits (Quaternary)

Head deposits are shown as the sinuous dotted white areas shown on Figure 3. These deposits occupy the topographic lows at the bases of the dry valleys within the area of Markwells Wood, and are described in the BGS lexicon of rock units as comprising

"...gravel, sand and clay depending on upslope source and distance from source. Poorly sorted and poorly stratified deposits formed mostly by solifluction and/or hillwash and soil creep."

1 An aquiclude is a relatively impermeable deposit, hindering the infiltration of water.

Immediately west and north of Markwells Wood these sands, gravels and clays are derived predominantly from the local Clay-with-Flints deposits and consist of weathered chalk and flint rubble, clays, silts, sands and gravels.

3.4 Chalk Karst

3.4.1 The Influence of the Palaeogene Cover

As alluded to above, the presence of a clay cover, in both its relatively unaltered (Reading Formation; London Clay) and highly weathered (Clay-with-Flints) aspects, plays an important role with respect to the formation of karst within the Chalk.

This relationship has been most closely studied in the Pang and Lambourne catchments in Berkshire, approximately 50 km to the north-west of Markwells Wood (Maurice *et al,* 2006; Maurice, 2009; Maurice *et al*, 2012). Here the situation is broadly analogous to that in the South Downs, with southerly dipping Chalk in the upper parts of the catchments becoming confined beneath Palaeogene clays to the south, with a mantle of Clay-with-Flints in patchy deposits to the north of the Chalk/Palaeogene boundary.

The degree of karst development in the Chalk in this setting is strongly correlated with distance from the Palaeogene boundary. It is associated with runoff and recharge channelled off of, and through, Palaeogene and Clay-with-Flints deposits. As the Palaeogene and Clay-with-Flints deposits are of typically low permeability, rainwater tends to concentrate in surface streams prior to flowing onto the underlying and topographically lower Chalk. Higher permeability silt, sand and gravel lenses within the clays can also concentrate recharge passing vertically through them. Clays and clay soils above the Chalk leads to the formation of acidic recharging soil water, and hence greater aggressivity (dissolving power) of waters arising on the Palaeogene / Clay-with-Flints than on the Chalk outcrop.

Jones & Robins (1999) state that a significant unconformity exists between the top of the Chalk and the base of the Palaeogene, and that this represents a *"….a long period of uplift, flexuring and erosion."* This uplift, folding and weathering is believed to have resulted in considerable development of karst at the time, which later became buried beneath the subsequently deposited Palaeogene clays, and preserved in the form of 'Palaeokarst' (McDowell, 1996; Jones, 1981). Where the Palaeogene has been eroded, so too has much of the surface of the Chalk, together with the ancient karstification. Where the Palaeogene is still present, there has been less opportunity for erosion of the surface and near-surface palaeokarst, and hence there is a greater occurrence of karst features than on the Chalk where it is without clay cover.

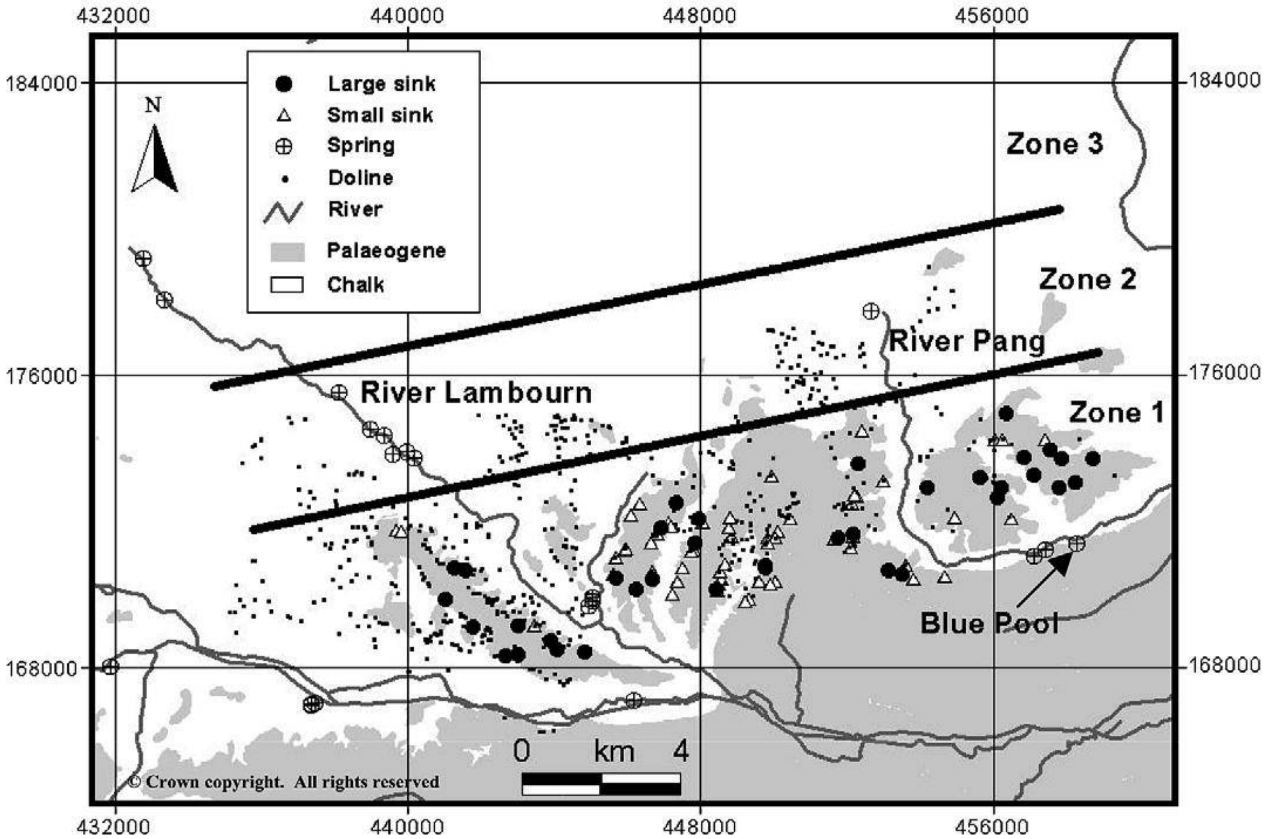
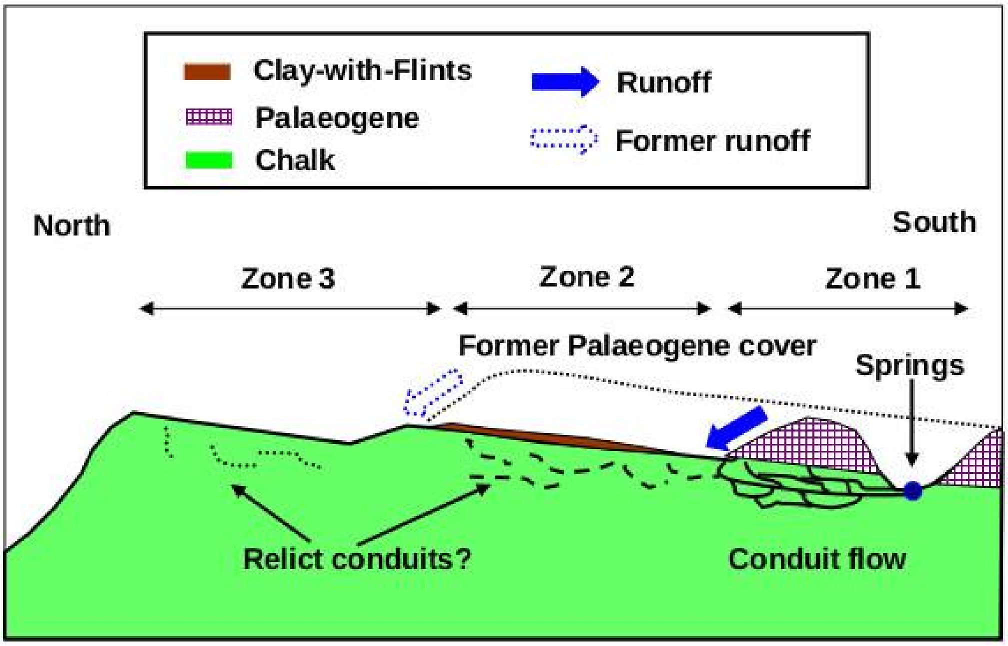


Figure 4. Zones of karst development in the Chalk and their relation to the Palaeogene boundary, as determined for the Pang and Lambourne catchments, Berkshire (after Maurice *et al,* 2006).



Figures 5. Schematic North-South cross-section through the South Downs showing the relation between karstic development within the Chalk and the presence of overlying Palaeogene and Clay-with-Flints deposits (after Maurice, 2009).

In addition to the existence of palaeokarst, periglacial[2] conditions prevailed during much later Quaternary[3] glacial periods, and particularly during the Anglian glaciation which advanced the furthest south of any of the UK Quaternary glaciations. Under such conditions karst surface features may also be associated with freeze-thaw action and other periglacial processes weathering the ground.

Modern-day runoff from and through the intact Palaeogene cover is thought to exploit and enhance the palaeokarst and the more recent Quaternary karst, and continues to develop new karstification.

This situation is summarised in Figures 4 and 5, where Maurice *et al* (2006) identify three distinct zones of karstification, as follows):

- Zone 1 is on the boundary of the present day Palaeogene cover with the underlying Chalk and is characterised by frequent stream sinks, dolines and dry valleys;

- Zone 2 represents areas which were formerly Zone 1 areas and where erosion has left only the weathered remnants of the Palaeogene clays in places (i.e. the Clay-with-Flints) above the Chalk. Karst formation is still active; dry valleys and dolines are present but no stream sinks;

- Zone 3, which has had the majority of surface karst removed by erosion.

(NB It is important that these karst zones are not confused with Source Protection Zones – see Section 5.0.)

<u>3.4.2 Surface Karst in Karst Zone 2: Dolines and Dry Valleys</u>

3.4.2.1 Dolines

Dolines studied in the Pang & Lambourne catchments were recorded at up to 10 m deep and from 1 to 30 m in diameter. Maurice (2009) illustrates an example of one of the larger dolines in the Lambourne catchment, reproduced here as Plate 2.

> *"Many hundreds of dolines were recorded in Zones 1 and 2 where the Chalk is overlain by the Lambeth Group or Clay-with-Flints…the majority of natural dolines are likely to be subsidence dolines formed by suffosion. Most dolines are on high ground between valleys, but a few are within dry valley features suggesting that they may be relict stream sinks."*

Maurice (2009) pg. 160

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2 Periglacial conditions refers to a harsh, cold climate in the proximal zone of the ice sheets, but remaining unglaciated.

3 The Quaternary refers to the last ~2.5 million years of Earth's history, and is characterised by the cyclical growth and decay of continental ice sheets.

There are a number of formation mechanisms for dolines (Figure 6), but the *majority* (i.e. not all but most) of those associated with Clay-with-Flints or Palaeogene deposits are probably subsidence dolines formed by suffosion (bottom right on Figure 6). The process of suffosion is one in which sediments fall or are washed down vertical dissolutional features in the underlying karst rock (Ford & Williams, 2007).

Plate 2. A doline in the Lambourne catchment (from Maurice (2009).

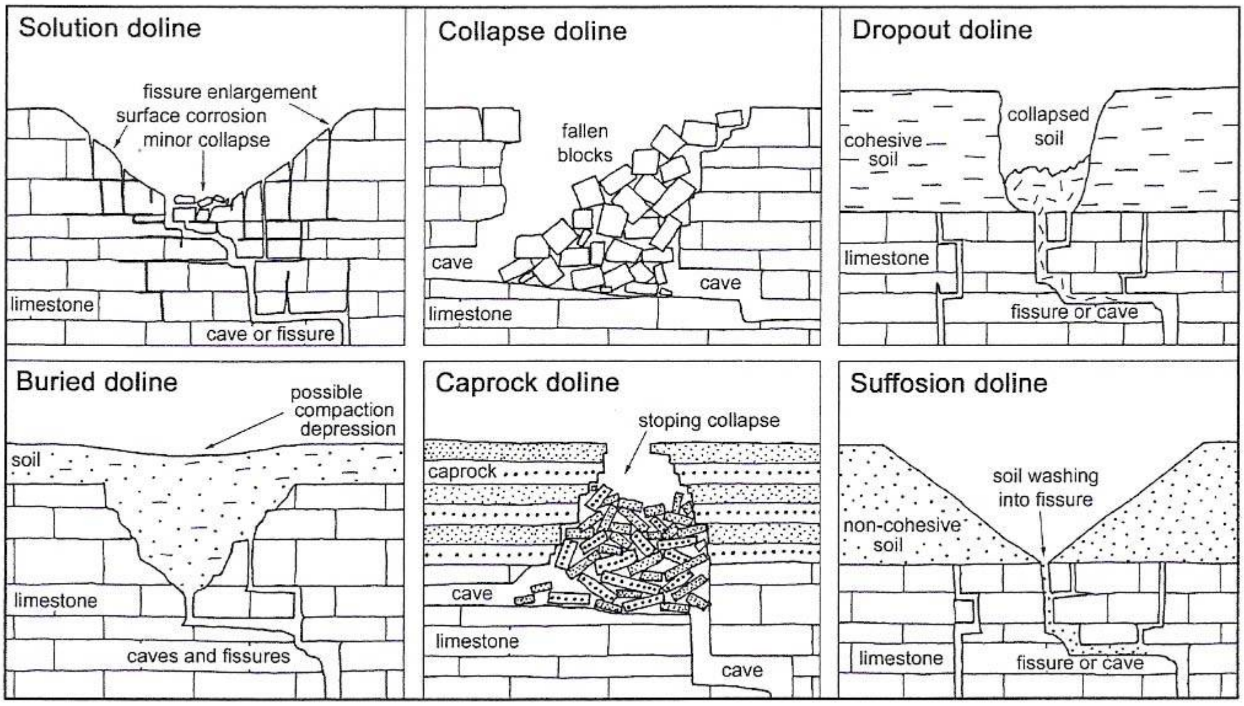

Figure 6. Mechanisms of doline formation (from Waltham & Fookes, 2003)

*(Please note that the term 'sink hole' strictly only applies to those dolines formed by collapse processes – i.e. those labelled 'Collapse doline', 'Dropout doline' and 'Caprock doline' on Figure 6. A 'swallow hole' is regarded here as equivalent **only** to a doline where it receives flowing surface water, and is referred to by the specific term 'stream sink' in this report.)*

Maurice (2009) states that:

> *"Dolines may be palaeokarst features that are not currently functionally karstic. However...their presence implies that there is or has been a fully connected flowpath between the doline and the aquifer discharge point (Williams, 2004). This can occur across the full spectrum of karst scales but it implies that there is a connected network of fractures of sufficient size to transport solute and/or sediment through the aquifer."*

pg. 62

It must be noted that across much of the South Downs and elsewhere on the Chalk, extraction pits dug for marl, chalk, sands, gravels, brickearths and flint are features that may be mistaken with or for dolines. This will be discussed further in relation to pits and hollows located in and around Markwells Wood, but in brief it appears possible to recognise three types of ground depression in this area:

I) Dolines

II) Human-dug pits without much evidence of a doline (although any such may have been obliterated by workings)

III Dolines seemingly later worked by people

Extraction pits may well exploit existing dolines or other natural depressions as these, by virtue of their origin, may contain more highly weathered chalks and clays, easier to extract (in the case of chalk) and possibly of greater purity, uniformity or quality (in the case of clays, sands and gravels). Where the parent clays have been entirely eroded, dolines may form outliers of weathered clays surrounded by Chalk (McDowell, 1975). Similarly, they may form inliers of more readily accessible chalk in areas of predominantly clay materials at the surface.

3.4.2.2 Dry Valleys

The position of dry valleys in the Chalk is influenced by folding and fracturing of the rock. The orientation of dry valleys is considered to be strongly controlled by large scale NW/SE and NE/SW trending fault systems affecting the Chalk across the whole of southern England. McDowell *et al* (2008) provide a summary of the evidence relating to structural influence on dry valleys, but their predominant orientations in these directions are clearly shown on Figure 7.

Dry valley formation is considered to have originated through a further three main processes acting upon the faulted Chalk (Jones & Robins, 1999):

1. Normal fluvial erosion processes at times when sea level was much higher[4].

2. Fluvial erosion and periglacial weathering during glacial periods, when the near-surface ground would have been permanently frozen throughout the year.

3. Karst dissolution processes concentrated in topographic lows.

Maurice (2009) states:

> *"...as major river valleys are downcut, the water table is lowered and new conduits and fissures develop at lower levels resulting in networks of fissures and conduits that previously fed springs (and hence rivers) becoming inactive. ...C.C Fagg[5] suggested that karstic spring head recession resulted in chalk valleys becoming dry, and that inactive swallow holes and springs in dry valleys have been obscured by recent periglacial features."* *pg.71*

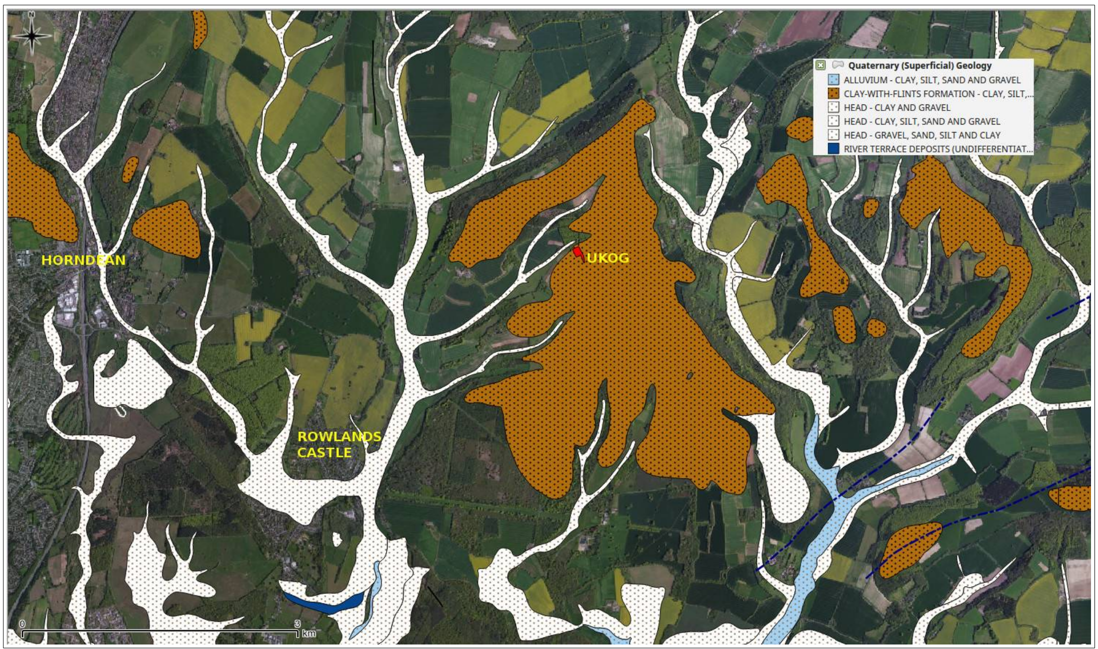

Figure 7. The distribution of Head deposits within dry valleys in the Markwells Wood area, showing also the distribution of Clay-with-Flints deposits.

(Licence No. 2011/3PDL/xxxxxx British Geological Survey © NERC.)

4 e.g. during the Calabrian marine transgression during the Palaeogene, when sea levels were 180 m higher than they are today (Jones & Robins; 1999)

5 Fagg , C C. 1923. The recession of the Chalk escarpment and the development of Chalk valleys in the regional survey area. Proceedings and Transactions of the Croydon Natural History Science Society, Vol. 9, 93–112.

In any case, it is widely recognised that the transmissivity of the Chalk Principal Aquifer tends to be greatest in the river and dry valleys as the networks of flowing features are most strongly developed at these localities. As mentioned in Section 3.3.4, dry valleys also typically contain Head deposits, which are stony, sandy clays and clayey gravels derived from Clay-with-Flints and chalk that have been transported by solifluction (soil creep) processes to the topographic lows (i.e. the dry valleys). This may also be seen clearly with reference to Figure 7, which shows the distribution of Head (and therefore dry valleys) in the Markwells Wood area. The large dry valley to west of the UKOG site is shown in Plate 1 during 'Winterbourne' conditions of high water table and activated surface flow.

3.4.3 Subsurface Karst Development in Karst Zones 1, 2 & 3.

Amongst the central findings of Maurice's (2009) doctoral research are included the following statements:

> *"... fissure and conduit development does occur at considerable depths in the aquifer and that fissures and conduits are present in the saturated zone of* (Karst) *Zones 2 and 3. Some of these features may be relict features that were initiated in the past by stream sinks providing aggressive point recharge to the Chalk."*

pg. 414 (present authors addition underlined)

> *"Small-scale karst conduits and fissures probably occur more frequently in the Chalk than was previously thought, and results of SBDTs[6] suggest that they are common in Zones 2 and 3 where there is less surface karst as well as in Zone 1 where there is a high density of surface karst. "*

pg. 419

Her research findings were also presented in Maurice *et al* (2012), including data on the density of flowing features recorded by CCTV and geophysical logging from boreholes across the Pang & Lambourne catchments. Those data are reproduced here in summary form in Table 1.

Karst Zone	River valley	Major dry valley	Interfluve and minor dry valley	All
1	0.25 ± 0.09	-	0.26 ± 0.28	0.25 ± 0.07
2	-	0.26 ± 0.32	0.14 ± 0.10	0.18 ± 0.09
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

Table 1. The density of flowing features per metre, with 95% confidence limits, in different karst and topographical settings in the Pang & Lambourne catchments. Those with no confidence limits are for a single borehole. After Maurice *et al* (2012).

6 Single Borehole Dilution Test – a type of experiment that monitors the dilution of an introduced tracer (usually common salt) over time within a borehole.

4.0 KARST POTENTIAL OF THE CHALK IN AND AROUND MARKWELLS WOOD

This section of the review will now apply a number of different methods to characterising the karst potential of the Markwells Wood area:

4.1 Karst potential by analogy with previously studied areas

Due to its location with respect to the Palaeogene boundary and Clay-with-Flints deposits, Markwells Wood clearly falls within Karst Zone 2 under the scheme of categorisation developed by Maurice *et al* (2006). Thus, ***all of the geological and groundwater conditions required for karstification of the Chalk Principal Aquifer are in place at Markwells Wood.***

By analogy with the Pang & Lambourne catchments, we might *a priori* expect to find:

- Dissolutional development of fractures to form fissures, tubules and small conduits. (Section 3.2.1)
- Flowing features beneath the water table with a potential average density of 0.18 (±0.09) flowing features per metre. This implies one flowing feature every 5.55 metres on average. In interfluvial and minor dry valley areas (combined) this spacing increases to 0.14 (±0.10) flowing features per metre, or a 7.14 m spacing between flowing features (after Table 1).
- Common doline formation indicating potential for "...*a fully connected flowpath between the doline and the aquifer discharge point."* (Section 3.4.2.1)
- Dry (under-drained) valleys with high transmissivity. (Section 3.4.2.2)
- A lack of stream sinks.

Of these there is obvious evidence for common doline formation, dry valleys, and a lack of stream sinks. This review continues with an examination of that evidence, and also identifies additional evidence for the presence of flowing features within the Chalk Principal Aquifer, principally from local borehole logs.

4.2 The Regional Distribution of Dry Valleys

The distribution of surface water courses in the region of south Hampshire and West Sussex is shown on Figure 8.

It is obvious from the figure that the area of Markwells Wood (the red spot) is characterised by an almost complete lack of surface water courses. As karst systems infiltrate almost all water to the subsurface, the density of the surface river network may be used as a proxy for the degree of karstification of the hydrological system. Conversely, those areas to the north and south where the river network density increases significantly, fall outside of the carbonate rock areas, and reflect the fact that there is no karstification at the surface in those areas (personal communication between Emily Mott of Markwells Wood Watch, and Andreas Hartmann of the Dept. of Hydrology at the University of Freiburg, Germany).

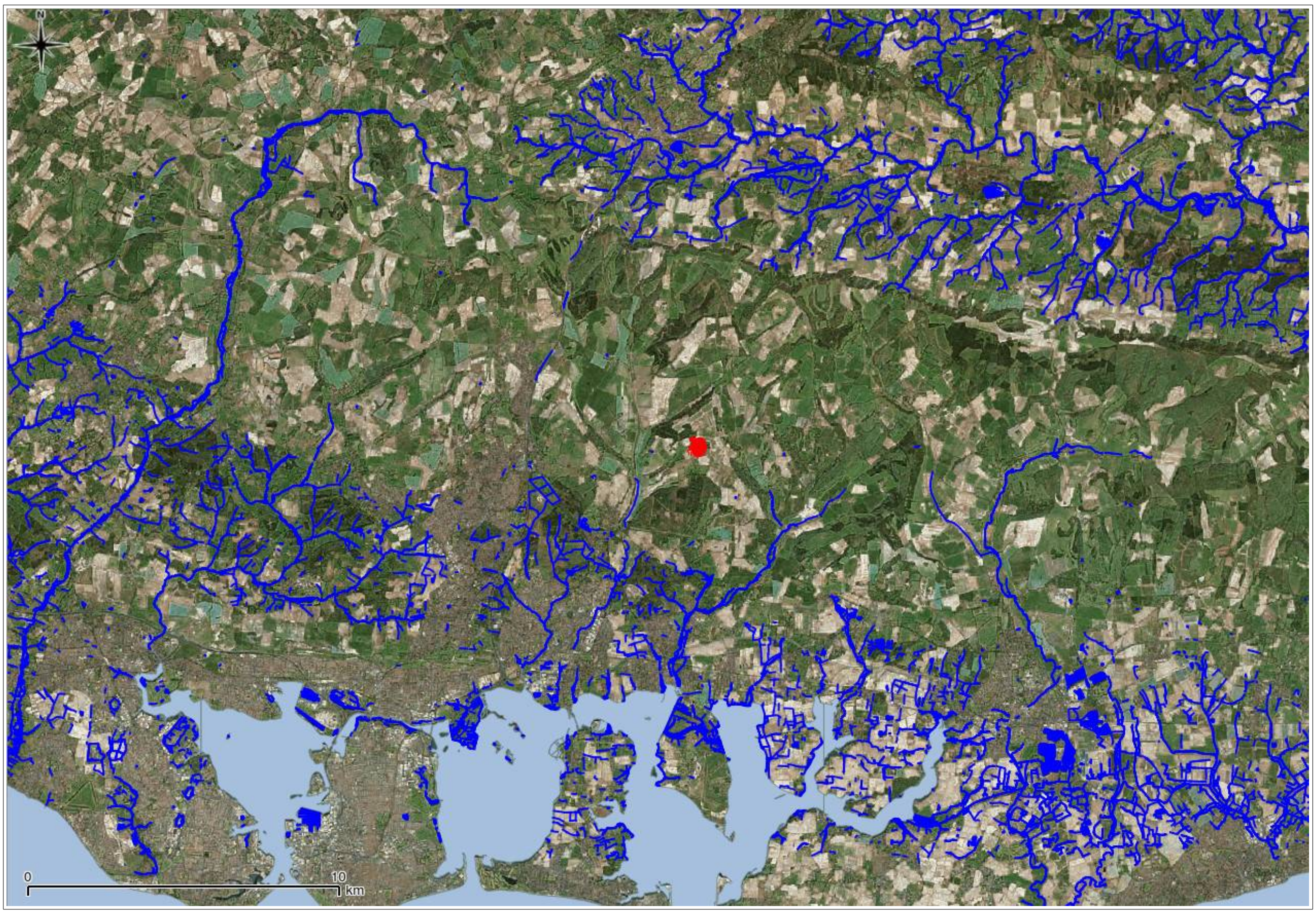

Figure 8. The distribution of surface drainage across southern Hampshire and West Sussex. UKOG site denoted by a red spot.

4.3 Dolines within the Markwells Wood area

4.3.1 The Hazleton (Horndean) Landfill Public Inquiry

Horndean is approximately 5 km to the west of Markwells Wood and falls within Karst Zone 1, as it is located on the edge of the Palaeogene boundary (see Figures 2 & 3, which are at the same scale). However, an extensive Public Inquiry was held to examine evidence associated with an appeal against a planning decision to refuse (no pun intended) a proposed landfill at Horndean. A considerable amount of evidence relating to the Inquiry is retained by the Environment Agency and was examined by the present author at their Chichester offices on 25th January 2017.

As part of his Proof of Evidence to the Inquiry, McDowell (1996) gives a series of examples and photographic evidence of local doline morphology in the Horndean area. Edmonds (1997) also discusses the formation and nature of these dolines in some detail. Earlier work by Atkinson & Smith (1974) reported groundwater velocities of over 2 km/day from stream sinks at Horndean, and additional details were provided to the Inquiry of the water tracing experiments undertaken. Further evidence was supplied by Neve (1997), the then Technical Director of Portsmouth Water, regarding the significance of any impact to the Bedhampton & Havant springs, and by Rust Environmental (1997) also regarding risks to groundwater.

A number of consultants were employed by the Appellant to submit evidence demonstrating that there were no significant karst-related hazards in the area of the landfill. On various grounds the flaws in this evidence were made clear, particularly with regard to shortcomings in the ground investigation and monitoring that had been undertaken to demonstrate a lack of karst, especially where such features may be small yet capable of transmitting large volumes of contamination. It was concluded by the Inquiry that there was indeed significant potential for any groundwater contamination arising at the site to be transported, at rapid speeds and with minimal attenuation, to the critical water supplies of the Bedhampton & Havant springs, which at that time supplied drinking water to over 200,000 people.

4.3.2 LIDAR Data & Site Walkover Survey

12 km^2 LIDAR[7] data (Copyright Fugro Geospatial and South Downs National Park Authority) for the Markwells Wood area were kindly provided by the South Downs National Park Authority. These data were used to identify numerous potentially karstic features within the immediate vicinity of the UKOG well site, and in the broader Markwells Wood area. Some examples are shown in Figure 9 to demonstrate the three types of surface hollow or depression identified (i.e. dolines, dolines later excavated by humans, and pits potentially of human origin only). A subset of these features were visited in the field on 24th and 25th January 2017. Field notes regarding the appearance of the features are provided in Appendix 1, and are indexed to the series of Photographs provided in Appendix 2.

The apparent doline marked 'A' in Figure 9 is situated approximately 500 m to the north of the UKOG site, about 40 m from the base of a minor dry valley. This doline was photographed on 25th January 2017 (Plate 3) during a site walkover survey. It is a uniform oval shape, approximately 50 m along the long axis by ~25 m on the shorter. The depth was not recorded in the field although appears to be on the order of 2 to 4 m. It bears a close resemblance to the Lambourne catchment doline shown in Plate 2. It is not possible to completely exclude the possibility that this is a feature of human origin, but it does not appear to show signs of working, at least not in the more clear sense as shown by the hollows that have been labelled 'Pits' on Figure 9.

7 LIDAR is a high-resolution ground surface mapping technique.

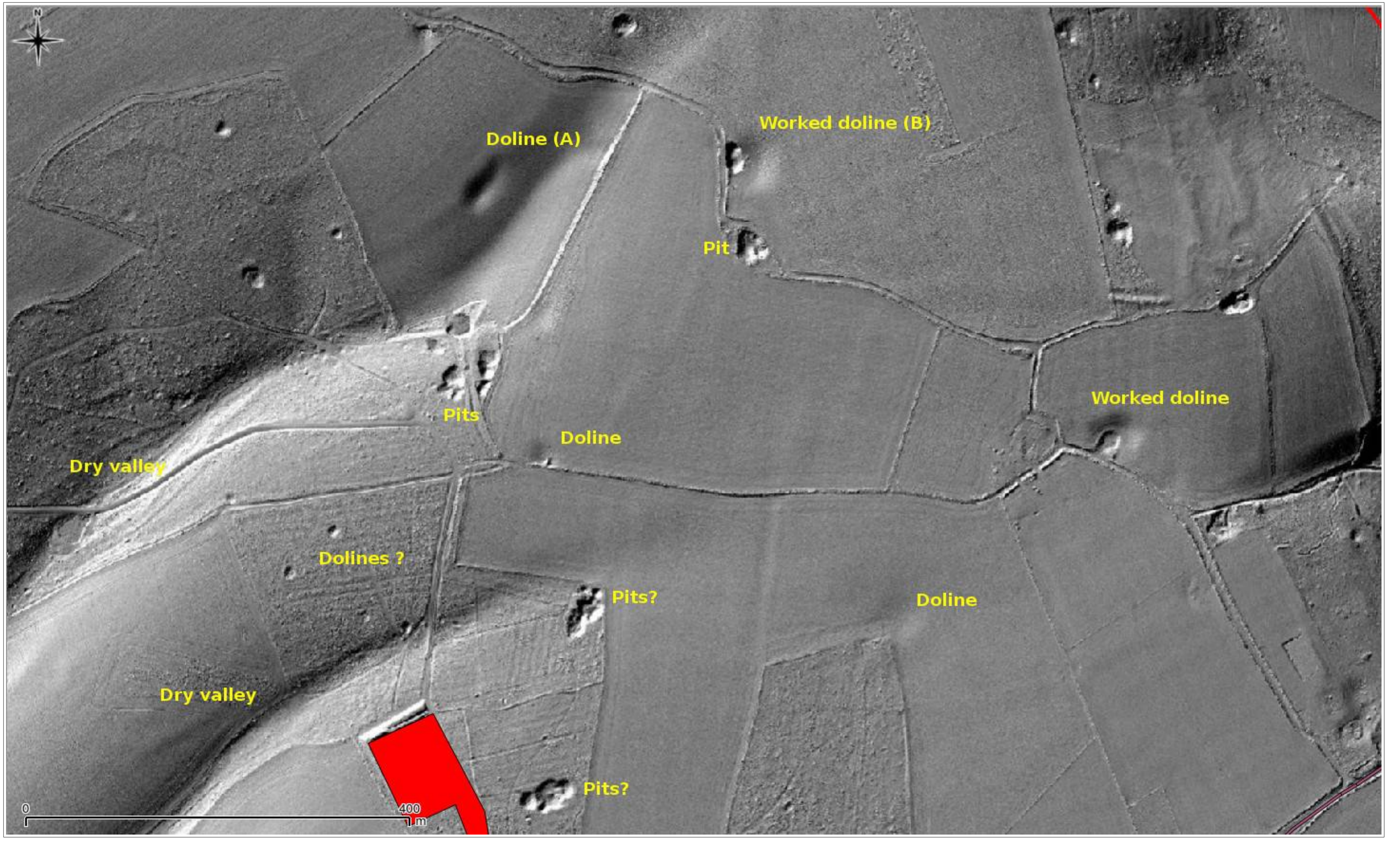

Figure 9. Annotated LIDAR image showing apparent dolines, worked dolines, and pits of human origin. Photographs of A & B are provided in Plates 3 & 4 respectively. UKOG site in red. (Copyright Fugro Geospatial and South Downs National Park Authority.)

Plate 3. An apparent doline, marked as 'Doline 'A'' on Figure 9. It has an obviously similar morphology to the Lambourne catchment doline shown in Plate 2.

Plate 4. A deeper, more steeply-sided pit located within a much wider depression. Marked as 'B' on Figure 9.

The 'Worked doline' labelled 'B' in Figure 9 is shown on Plate 4. Here the trees are situated within the worked pit, which has steep-sided edges, but which can be clearly seen to occupy a depression in the landscape.

It is notable that only 1 out 32 potential dolines visited in the field contained standing water, indicating a lack of clay fill and rapid infiltration (site visit made in January 2017 so during winter recharge conditions).

4.3.3 Correlation between Potential Dolines and Clay-with-Flints Deposits

For the reasons given in Section 3.4.2.1 regarding the potential commonalities between dolines and human-dug pits, all surface depressions, whether clearly excavated by humans or not, have been classified as potential dolines for the purpose of this exercise. 190 potential dolines were identified using this method. By exlcuding all depressions that show any obvious sign of human excavation, 27 features were identified. The results of overlaying the Quaternary Head and Clay-with-Flints geology with the locations of identified potential surface karst features are shown in Figure 10. From this diagram it can be seen that :

- A large majority of potential karst features are located on or immediately adjacent to the Clay-with-Flints deposits (approximately 170 out of 190 (~90%)).
- On the Chalk to the north-west and to the east of the Clay-with-Flints there are virtually no potentially karstic features identified.
- There is a linear band of over 25 features along the northern boundary of the Clay-with-Flints.
- There is a linear band of over 30 features along the eastern boundary of the Clay-with-Flints.
- There is also a concentration of over 50 potential karstic features along the Clay-with-Flints boundary where it surrounds the dry valleys to the immediate north, west and south-west of the UKOG site.
- There are approximately 30 features situated on the Clay-with-Flints but away from the boundary with the Chalk (~16%)

No statistical analysis has been undertaken on the relationship between the occurrence of potential karst features and distance from the Chalk / Clay-with-Flints boundary so it is not at this point possible to state categorically the degree of correlation between the two phenomena. However, it does seem that the Chalk / Clay-with-Flints boundary may be a logical place to make extractions, as clay could be brought onto the chalk for soil improvement or perhaps brick making, and the chalk (or chalk marl) would be excavated for liming/marling on the Clay-with-Flints or other acidic Palaeogene soils. Nonetheless, there is nothing to indicate that a hollow being worked precludes its origin as a doline, but rather there is a possibility that karst processes may concentrate economically favourable deposits (Section 3.4.2.1).

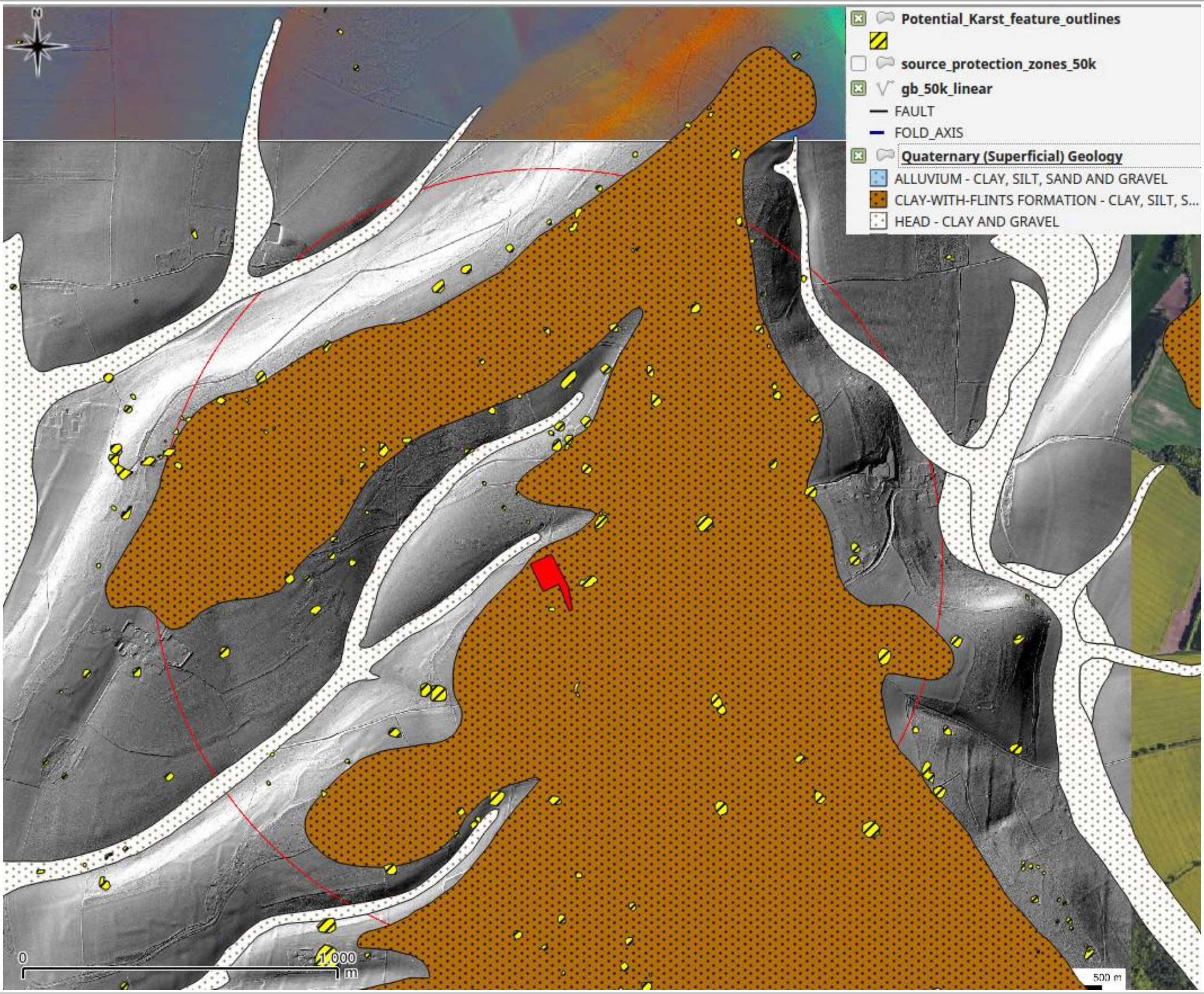

Figure 10. Overlap of potential karstic features with Clay-with-Flints deposits.

(Contains LIDAR data Copyright Fugro Geospatial and South Downs National Park Authority, and Geological data under Licence No. 2011/3PDL/xxxxxx British Geological Survey © NERC.)

4.4 Karstic features identified in local boreholes and wells

Using the BGS online borehole scans viewer[8] 18 groundwater boreholes and wells are recorded within 2.5 km of the UKOG site. All of them are drilled or dug into the Chalk Principal Aquifer.

The majority of these boreholes and wells were drilled or dug prior to 1945 and most have no logs associated with their construction; usually just a series of recorded water levels, if that. However, three of the boreholes do have additional information relating to fissures or to pumping tests used to establish the performance of the aquifer at those localities:

- West Marden Hall, at NGR SU 76880 13560, 1.4 km east of the UKOG site. A fissure is recorded at 216 ft depth (~66 mbgl), and the borehole was terminated at 217 ft depth. Presumably, encountering

8 http://mapapps.bgs.ac.uk/geologyofbritain/home.html accessed 5th February 2017.

this fissure meant that the well could supply the required amount of water. A pumping test for the borehole recorded a yield of 500 gallons per hour (~0.63 L/s), but this may simply reflect either the required amount or the capacity of the pump. (The BGS Reference for this well is SU71SE9.)

- Old Idsworth Farm, at NGR 74900 14300, 1.4 km north-west of the UKOG site. There are no well construction / logging details for this well, but it was pump-tested in February 1988. The results of the test are interesting as the pumping rate was 1.7 L/s (1350 gallons per hour) and lasted for 2 hours, but it did not change the water level in the well by even 1 cm (!). This indicates that the well is rapidly supplied by fissure flow. Some additional information indicated that the transmissive zone is above 35 mbgl; i.e. at relatively shallow depth. (The BGS Reference for this well is SU71SW80.)

- Compton Farm, at NGR SU 77750 14800, 2.4 km north-east of the UKOG site. A fissure is recorded at 192 ft depth (~58.5 mbgl) and a heading (adit) was driven off at this level. The well was terminated at 201 ft, presumably as the heading was sufficiently productive at the fissure above. The yield for this well is recorded at 2000 gallons per hour (~2.5 L/s or 216,000 L/day); again this may simply reflect the required amount or the capacity of the pump. (The BGS Reference for this well is SU71SE4.)

All three of these boreholes are either equally far or further away from the Chalk/Palaeogene boundary than the UKOG site, and all three are situated adjacent to or within a dry valley. In other words, all three of these boreholes, with either recorded flowing features or strong evidence thereof, are in an analogous situation to the site at Markwells Wood.

In addition to the above, drilling fluid losses occurred during drilling of the UKOG MW1 well at depths of 131 to 231 metres below ground level and deeper (Hydrock, 2016). This appears relatively deep karst development within the Chalk, and may reflect relict or palaeokarst developed during periods of lower water tables, potentially during the Anglian or Devensian glaciations when sea level was over 100 m lower than at present. At this depth in the aquifer flow paths are potentially longer between recharge and discharge points, and groundwater velocities may be slower. This may explain why no exceptional increase in turbidity was recorded at the Bedhampron & Havant springs (although Hydrock (2016) do not present any data for scrutiny). However, it should be borne in mind that most boreholes within the Chalk are drilled for water supply purposes and once sufficient fissures have been encountered the need for deeper drilling disappears; thus there is considerably less information available regarding conditions deeper within the Chalk.

5.0 GROUNDWATER VULNERABILITY AND PROTECTION

5.1 Relevant Legislation

The Water Resources Act 1991, and the Water Framework Directive (200/60/EC) are the primary guiding legislation for the protection of water bodies in England. Within this general scheme various categories of groundwater protection are defined. The two most relevant are I) Protection of water intended for human consumption, and II) Protection of water with relation to infrastructure developments.

5.1.1 Protection of Water Intended for Human Consumption

There are two components to DEFRA's approach to the protection of water intended for human consumption (Environment Agency, 2013):

- Aquifer designation
- Source Protection Zones

The Chalk is designated a Principal Aquifer due to its strategic national and regional importance for water supply. This means it is regarded as having the greatest level of sensitivity of any designation (Table 2).

In addition, individual water supplies within the aquifer (e.g. the Bedhampton & Havant springs) are characterised by the area that supplies them, divided into different Source Protection Zones (SPZs), with three SPZs of increasing sensitivity (Table 2).

Aquifer designation	↑	Within an SPZ
Principal aquifer		SPZ1
Secondary aquifer		SPZ2
Unproductive strata	Increasing sensitivity	SPZ3

Table 2. General groundwater protection hierarchy (from Environment Agency, 2013).

The Environment Agency (2013) (pg. 61) note that:

> *"SPZs are not statutory. However, SPZ1 has been noted in statutory guidance as the minimum area under the former Groundwater Directive that is identified for the protection of drinking water. SPZs are also recognised within the Environmental Permitting Regulations (EPR) as a zone where certain activities cannot take place (for example, in certain standard rule permits)."*

And define SPZs as follows (Environment Agency (2013):

- ***SPZ1*** *inner protection zone – defined as the* ***50-day travel time*** *from any point below the water table to the abstraction source. This zone has a minimum radius of 50 metres. SPZ1 represents the immediate area around a borehole where remediation of pollution is unlikely to be achievable within available timescales, such as in less than 50 days.*

- ***SPZ2*** *outer protection zone – defined by a* ***400-day travel time*** *from a point below the water table. This zone has a minimum radius of 250 or 500 metres around the abstraction source, depending on the size of the abstraction.*

- ***SPZ3*** *source catchment protection zone – defined as the area around an abstraction source within which* ***all groundwater*** *recharge is presumed to be discharged at the abstraction source.*

5.1.2 Protection of Water with relation to Infrastructure Developments

Environment Agency Position Statement C7 - Oil and conventional gas exploration and extraction (Environment Agency (2013, pg.) states:

> *"We will object to such hydrocarbon exploration, extraction infrastructure or activity within SPZ1. Outside SPZ1, we will also object when the activity would have an unacceptable effect on groundwater.*
>
> *Where development does proceed, we expect BAT[9] to protect groundwater to be applied where any associated drilling or operation of the boreholes passes through a groundwater resource. Elsewhere, established good practice for pollution prevention should be followed.*
>
> *Where such activities already exist we will work with operators to assess and if necessary mitigate the risks. We will object to any redevelopment scheme involving retention of oil exploration, extraction infrastructure or activity within SPZ1 unless there are substantial mitigating factors."*

It appears debatable whether the development at the UKOG site is of a 'conventional' or 'unconventional' nature, although this is beyond the scope of the current review.

5.2 Source Protection Zones (SPZs) at Markwells Wood

Figure 11 shows the SPZs currently defined for the Bedhampton & Havant springs. Please note that the SPZs are defined on the basis of supposed groundwater travel times beneath the water table as per Section 5.1.1. The pale hatched areas marked as 'SPZ1 – 3 (Groundwater activity only)' refer to the area generally

9 Best Available Technique

protected at the surface by Palaeogene clays away from the boundary with the underlying Chalk, and is only used for regulating subsurface activities.

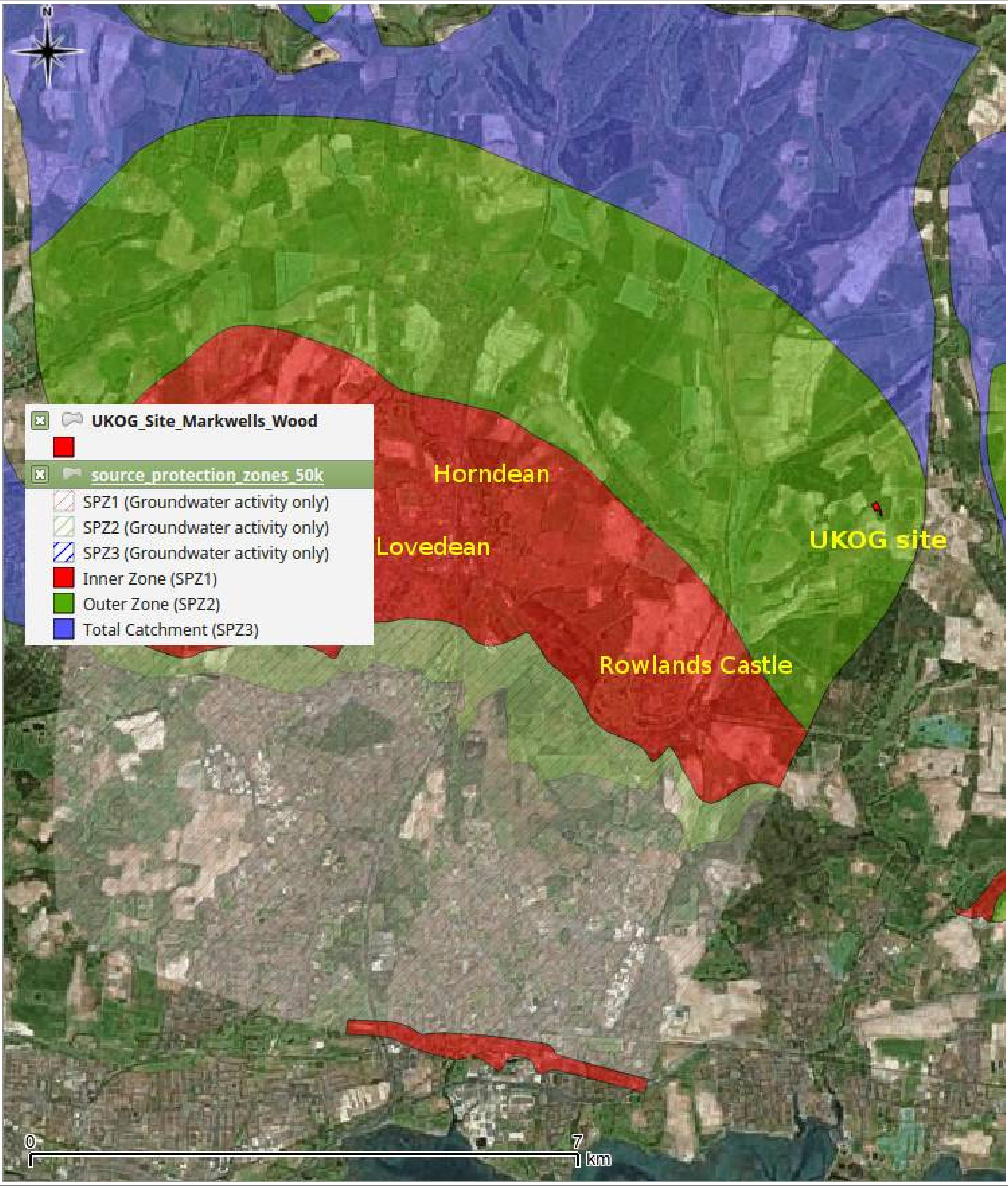

Figure 11. Source Protection Zones around the Havant & Bedhampton Springs, showing the UKOG site at Markwells Wood falling within SPZ2. Contains Environment Agency information © Environment Agency and/or database right.

As currently defined, the UKOG site falls within SPZ2, or in other words, is estimated to have a groundwater travel time of between 51 and 400 days to the springs (Figure 11). However, it is important to note that the boundary between the SPZ1 and SPZ2 areas was defined on the basis of karst mapping (dolines in particular) that occurred during the Hazleton Landfill Inquiry (Environment Agency, 1998; please see Appendix 3 for this document). The doline mapping undertaken by Rust Environmental (1997) for that Public Inquiry was limited only to the area immediately around Horndean, and did not examine the Chalk further afield. This is illustrated by their figure (Map 1 given in Appendix 3) which shows a preponderance of dolines between Eastings 70 and 72 and Northings 11 and 13 – namely the area in and around Horndean. It thus appears that the derivation of SPZ2 is partly a function of the effort spent mapping dolines in that area, and not a function of their actual distribution across the wider catchment.

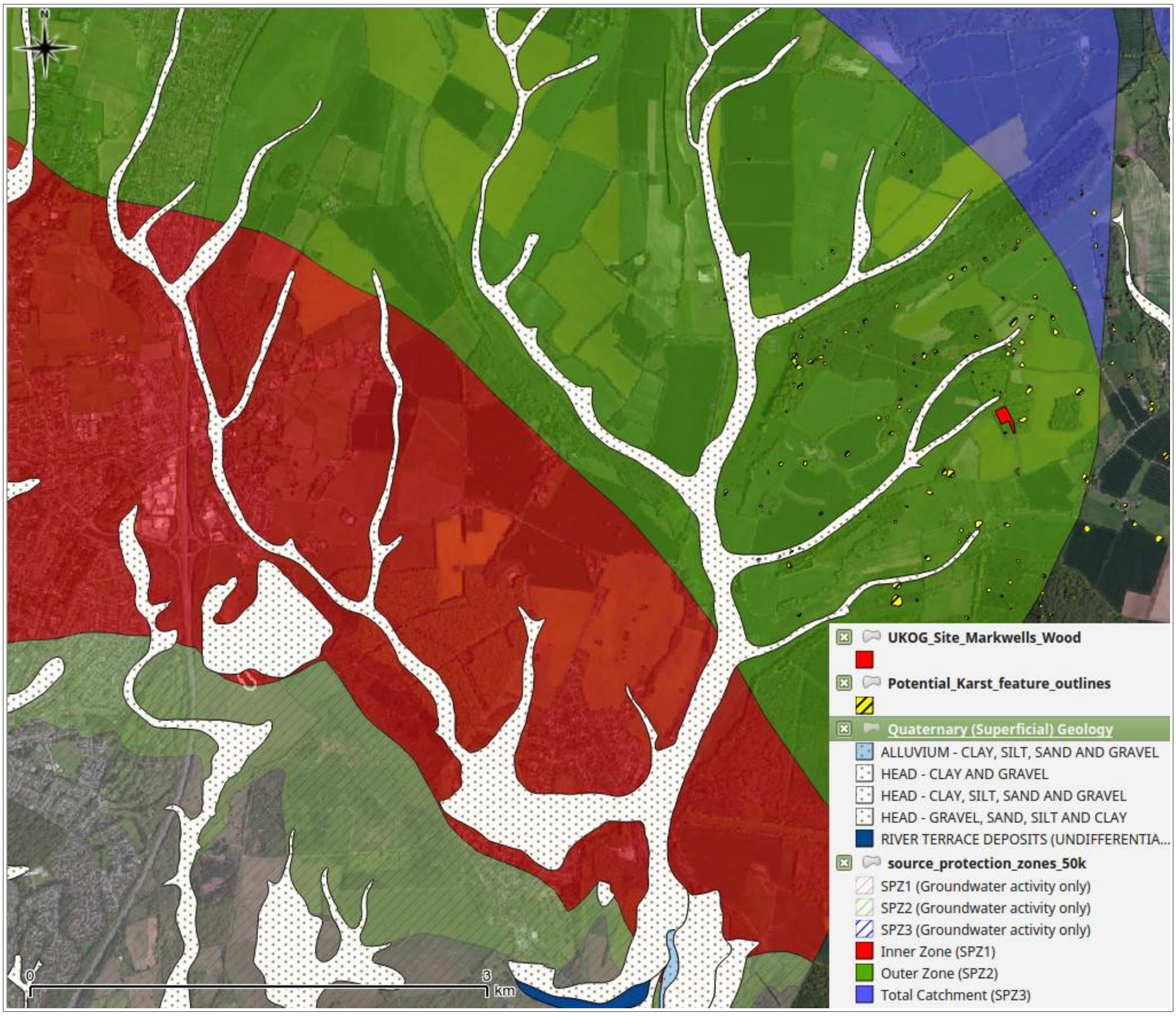

Figure 12. Relationship (or lack thereof) between SPZ distribution and likely areas of high and low transmissivity as defined by dry valleys. Contains Environment Agency information © Environment Agency and/or database right and geological data under Licence No. 2011/3PDL/xxxxxx British Geological Survey © NERC.)

Appendix 3 shows that the derivation of the SPZs has taken no account for variations in aquifer transmissivity between interfluves and dry valleys. If this had been done, one would expect to find the shapes of the SPZs correlated to some extent with the positions of the dry valleys, which they are not (Figure 12). Indeed, the SPZs have been calculated on the basis of distance from the dolines incompletely mapped along the edge of the Chalk / Palaeogene boundary as shown in Map 1 of Environment Agency (1998) and provided in Appendix 3.

Those distances are given as 1,500 m for SPZ1, and 4,500 m for SPZ2. Although it is not transparent from the description provided, these distances appear to have been calculated on the basis of a highly simplistic transmissivity distribution used for making basic contaminant transport calculations; and that those contaminant transport calculations were in any case inappropriately selected (they appear to be based on Darcy's Law rather than an understanding of channelled fissure flow).

It is also worth noting that the areas with Clay-with-Flints deposits (i.e. correlating with the Karst Zone 2 of Maurice *et al* (2006)) have been largely included within SPZ1 the north-west and north-east of Horndean, but have been completely excluded from SPZ1 in the area of Markwells Wood. Hence there is a somewhat inconsistent treatment of essentially the same geology.

5.3 Groundwater Velocities within the Chalk Principal Aquifer supplying the Bedhampton & Havant springs

The UKOG site is situated immediately adjacent to the base of a minor dry valley forming part of a system of dry valleys that exhibit known high-velocity groundwater connections to the Bedhampton and Havant springs (Figure 7).

The BGS webpage[10] about those springs (accessed 5th February 2017) provides groundwater velocity data from a number of groundwater tracer tests[11] that have been conducted in the area, and which are reproduced here in Table 3.

These experiments have repeatedly and conclusively demonstrated that groundwater velocities within the Chalk upstream of the Bedhampton & Havant springs may be as high as several kilometres per day. The results from four different experiments indicate a range of groundwater velocities between 0.6 and 12.3 km/day. One experiment resulted in no detection of the tracer.

The experiment from Rowlands Castle that resulted in a calculated groundwater velocity of 12.3 km/day implies a travel time over the intervening 4.6 km between the injection and sampling locations of just under 9 hours.

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10 http://bgs.ac.uk/research/groundwater/about/karstAquifers/bedhamptonHavantSprings.html

11 Experiments in which dyes or other substances are introduced to the groundwater system at an injection site, and monitored for at locations potentially supplied by the injection site.

Injection site and number	Detection site	Distance (km)	Velocity (km/day)	Reference
Hazleton Wood/Horndean #32	Bedhampton Havant	5.8 6	2.6 2.1	Atkinson and Smith (1974)
Lovedean #26	Bedhampton Havant	6.3 6.6	2.7 3.2	Barton et al.
Rowlands Castle #39	Bedhampton Havant	4.8 4.6	10.5 12.3	Barton et al.
Horndean #41	Bedhampton Havant	5.8 5.7	9.1 4	Barton et al.
Lovedean #13	Lovedean Well	0.9	0.6	Barton et al.
Rowlands Castle #40	Not detected			Barton et al.

Table 3. Groundwater tracer test results to the Bedhampton & Havant springs.

Given the evidence for karst formation and flowing features within the Chalk in the vicinity of the UKOG site presented in Section 5, there is nothing to support the contention that what takes 9 hours to travel from Rowlands Castle to Havant (a distance of 4.6 km), would take over 50 days to travel from the UKOG site to Rowlands Castle (a distance of less than 3.5 km).

Barton et al (undated) do however provide a graph plotting straight-line distance vs. travel time for various groundwater tracer tests to the Bedhampton & Havant springs, and which is reproduced here as Figure 13.

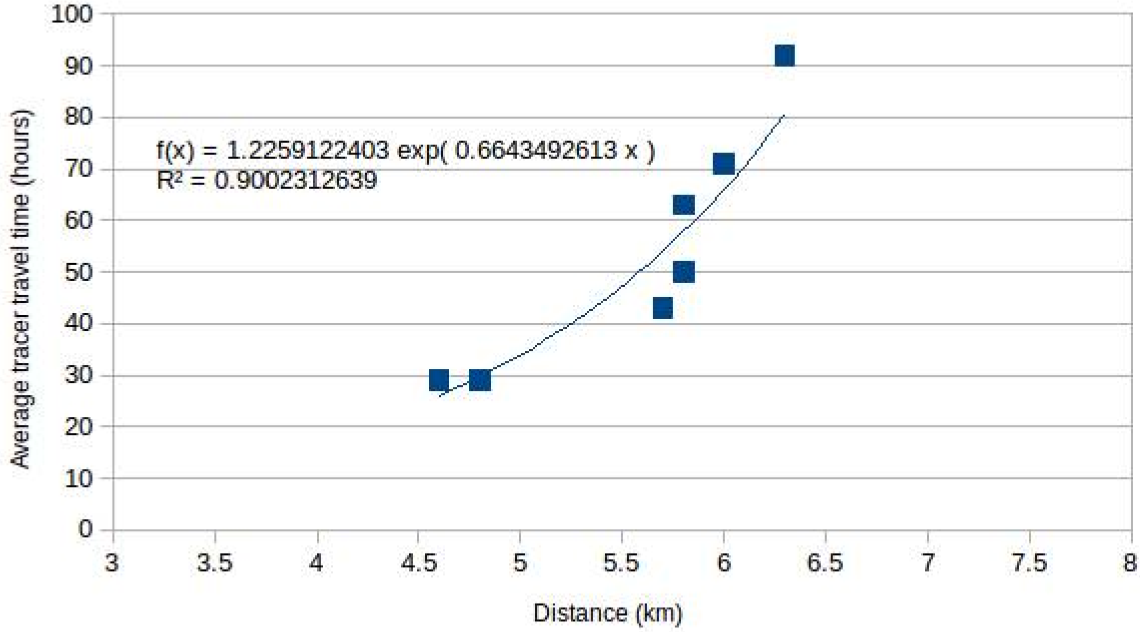

Figure 13. Travel time in hours vs. distance travelled for 8 groundwater tracing connections.

On this basis an exponential trend has been fitted to these data and may be used to predict travel times from further afield in the catchment. The trend fits the data with a coefficient of determination of 0.9, which represents a close fit (1.0 would be a perfect fit; 0.0 would represent no correlation). This relationship may be used to crudely suggest travel times from further afield in the catchment, as given in Table 4.

Distance (km)	Time (hours)	Time (days)
7	128.3	5.3
8	249.3	10.4
9	484.4	20.2
10	941.2	39.2
11	1829.0	76.2
12	3554.2	148.1
13	6906.6	287.8
14	13421.0	559.2
15	26080.0	1086.7

Table 4. Calculated tracer transport times against distance on the basis of 8 proven groundwater connections.

The UKOG site is situated 8 km straight line distance from the Bedhampton & Havant springs, suggesting a travel time of 10.4 days, and the 50 day travel time is located at some distance over 10 km from the springs. However, this system is very crude and only based on data from between 4.6 and 6.6 km distance from the springs. A linearl relationship may be more appropriate fitted to the data over 5.5 km, for example. The relationship would need to be improved by more groundwater tracer data from further afield in the catchment before substantial weight could be placed upon it, although it is useful here in the context of other findings. It is worth noting that the reason for a lack of tracer test data from Karst Zone 2 is the lack of stream sinks that facilitate tracer injection into the aquifer, and not due to a lack of high-velocity groundwater flow.

5.4 Groundwater Vulnerability Scoring using the Method of Edmonds (2008)

Edmonds (2008) presents a methodology for additional *a priori* classification of groundwater vulnerability in the karstic Chalk aquifer of southern and eastern England. This is based on work presented in Edmonds (2001). He cites the major influential factors influencing karst development as follows:

Major factors:

- Chalk lithostratigraphy
- Presence of Tertiary and Quaternary cover deposits

Moderate factors:

- Water table level relative to Chalk surface elevation
- Patterns of topographical relief and surface water drainage / subsurface groundwater infiltration
- Present and former surface water drainage paths

Minor factors:

- Impact of glacial erosion and deposition

He combines these into a classification and scoring system. Applying this system to the UKOG site at Markwells Wood gives the following results (please refer to Edmonds (2008) for details of the methodology):

I) Overlying deposits score, O = Q1 + Q2 + Q3, where:

Q1 = Quaternary deposit only present = 6
Q2 = Clay-with-Flints present = 3
Q3 = Quaternary deposit feathering margin = 2

Score for O = 11

II) Concentration of flow score, C

Category 1 (Model 1), Terrain unit either 1 or 2.

If Terrain unit is 1 (slope), then C = 6
If Terrain unit is 2 (valley floor) , then C = 20

Score for C should probably be somewhere between 6 and 20.

III) Karst network development score, K = L + P + W, where:

L = White Chalk Group = 20
P = Palaeo surface water drainage paths = 0
W = Water table level conditions = 10

Score for K = 30

IV) Final Aquifer Vulnerability Rating (AVR)

AVR = (O+K) x C

For Terrain unit 1, AVR = 246 = Moderate vulnerability
For Terrain unit 2, AVR = 820 = Very high vulnerability

As the drilling pad itself sits on the slope approximately 50 m from the valley floor, Terrain unit 1 is strictly the more appropriate. However, the site is much closer to the valley floor than to the centre of the interfluve, and dolines are apparent throughout the area, so taking those factors into account might result in a score somewhere between the two of these AVRs. Taking the mean gives a classification of High vulnerability. Nonetheless, even a Moderate vulnerability score is significant in terms of the proposed development.

6.0 SUMMARY & CONCLUSIONS

This review has collated and synthesised a substantial body of literature relevant to:

- The general principles of karst formation within the Chalk Principal Aquifer of southern and eastern England;
- The potential karstic nature of the Chalk Principal Aquifer in the vicinity of Markwells Wood, West Sussex, and;
- The wider groundwater catchment supplying the Bedhampton & Havant springs of which Markwells Wood forms a part.

The review has proceeded from an examination of the likely and known factors influencing the degree of karstification within the Chalk Principal Aquifer, to the application of this wider general knowledge of Chalk aquifer behaviour to local conditions at Markwells Wood. On this *a priori* basis it has been found that ***all of the geological and groundwater conditions required for karstification of the Chalk Principal Aquifer are in place at Markwells Wood.***

Further to this approach, site-specific evidence of karstic features in and around the Markwells Wood area were determined from:

- A study of LIDAR and aerial photographic data;
- A site-walkover survey to correlate observations made from the LIDAR/aerial data with conditions on the ground;
- A study of local borehole and well records;
- Other records of local karst phenomena, particularly from groundwater tracing experiments and information arising during the Public Inquiry that upheld planning refusal for construction of the Hazleton landfill at the neighbouring village of Horndean.

In brief, the site-specific evidence acquired by these methods may be summarised as follows:

I) Dry valleys and other surface karst (dolines) are present within and nearby Markwells Wood. As surface karst is an expression of subsurface karst, subsurface karst in the area is expected to be well developed;

II) Subsurface karst (flowing features) are identified in a number of local boreholes;

III) There is an almost complete absence of surface water within the district, with the exception of 'Winterbournes' flowing in normally dry valleys during periods of unusually high groundwater recharge, thus indicating that all flow is concentrated in the subsurface;

IV) There is a correlation between the presence of karst dolines and the boundary between the Chalk Principal Aquifer and the overlying Clay-with-Flints deposits (and which corroborates the same general findings in this regard from across the wider aquifer);

V) The dry valley immediately adjacent to the proposed UKOG oil exploration site is an upstream tributary of the dry valley system that passes through Rowlands Castle. These and other local dry valleys exhibit orientations reflecting major NW/SE and NE/SW regional structural faulting within the Chalk;

VI) Tracer tests from Rowlands Castle prove groundwater velocities of up to 12.3 km/day and travel times to springs at Havant of approximately 9 hours, and;

VII) The loss of drilling fluid during the drilling of UKOG well MW1 through the Chalk beneath the water table at this site confirms karstic fissures and/or conduits directly beneath the site.

The weight of these observations, on the basis of multiple lines of evidence, suggest that karstic groundwater flow conditions, of potentially kilometres per hour, are likely to be present in the vicinity of the UKOG site at Markwells Wood.

On the other hand, there is little evidence to suggest that what takes 9 hours to travel from Rowlands Castle to Havant (a distance of 4.6 km), would take over 50 days to travel from the UKOG site to Rowlands Castle (a distance of less than 3.5 km). (50 days representing the outer limit of the Source Protection Zone 1 (SPZ1) boundary.)

Further inspection of the existing Source Protection Zones delineated for the Chalk Principal Aquifer found that there is little argument to substantiate the boundaries of the current SPZ1 and SPZ2 divisions. The delineation of those zones appears to be based on incomplete mapping; a highly simplistic transmissivity distribution used for making basic contaminant transport calculations; and that those contaminant transport calculations were in any case inappropriately selected (they appear to be based on Darcy's Law rather than an understanding of fissure flow).

As an alternative, some crude estimations of potential groundwater travel times in the wider catchment are made on the basis of a number of proven connections between stream sinks and the Bedhampton & Havant springs. These suggest that travel times from the UKOG site at 8 km may be on the order of ten days, and that a 50 day travel time would correspond with a distance of between 10 and 11 km from the springs. This estimation is only based on a small amount of data and is necessarily to be treated with caution. However, this finding, and on the basis of the precautionary principal and other evidence presented above, there is considerable justification for the designation of the area around the UKOG site as within SPZ1 (that is, with travel times *from beneath the water table* of less than 50 days).

Additional groundwater vulnerability assessment, on the basis of the methodology of Edmonds (2008), is used to determine an Aquifer Vulnerability Rating beneath the UKOG site of between Moderate to Very High vulnerability, with High vulnerability established as the most likely rating using this method.

APPENDICES

The Appendices are available for download from the following web addresses:

Appendix 1 – Field Data and Photographic Index

https://www.dropbox.com/sh/jstj45esqjbmhgc/AADY_f0TSGZB3MS9eEYbduXya?dl=0

(Please note that grid references are password protected.)

Appendix 2 – Photographs

https://www.dropbox.com/sh/99l1t0q5wvvn743/AACM6zHThtUJu_psrHNiz6bba?dl=0

Appendix 3 – Environment Agency (1998) description of derivation of SPZs for the Bedhampton & Havant springs.

https://www.dropbox.com/sh/q3r5x2r7e6c310b/AAAnRZRGIvfYuXvgt9HFpxh5a?dl=0

A copy of this report may be downloaded from:

https://www.dropbox.com/sh/6kht4nkxs1jrsxy/AABYdHdh7EHHtr0HiKCkCqcoa?dl=0