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Anomalous buried hollows in London: development of a hazard susceptibility map

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Abstract: Engineering works carried out in central London over many decades have revealed a number of buried hollows that exhibit curious characteristics. Some extend deep into the bedrock geology and are in-filled with disturbed superficial deposits and reworked bedrock. Others are contained within the superficial deposits. They can be up to 500 m wide and more than 60 m in depth. As the infill material often has different behavioural characteristics from the surrounding deposits failure to identify them during an initial site investigation can prove costly. This paper considers their common characteristics and describes the method used to develop a buried hollow hazard susceptibility map. This map provides planners with a broader awareness of the potential location of difficult ground conditions associated with them, thereby reducing the potential for unforeseen ground conditions through effective site investigation design. The paper continues with a discussion of some of the likely processes associated with their formation, which are attributed to cryogenic processes, and concludes with potential future research directions.

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This paper presents a new British Geological Survey (BGS) geographic information system (GIS)-hosted hazard susceptibility map for naturally occurring, buried (sediment-filled) hollows in London that are commonly referred to as 'drift-filled hollows' or 'rockhead anomalies' in the literature. Here they are referred to as 'buried hollows'. Characteristically, these anomalous features comprise zones of disturbed ground that are buried beneath and extend up into the superficial cover. The method behind the GIS map layer is described, along with its limitations and potential applications, including the implications for process understanding with respect to the buried hollows.

A number of the buried hollows found in central London (Fig. 1) are associated with deep zones of disturbance in the bedrock geology (London Clay Formation, Lambeth Group and in a few cases the White Chalk Subgroup of the London Basin; see Tables 1 and 2 and Fig. 2). Usually they have asymmetric, funnel-shaped forms and are typically 15–25 m deep, but locally the zone of disturbance or 'root' of the features may be considerably deeper; for example, up to 33 m in Battersea and over 60 m in Blackwall (Ellison *et al*. 2004). They are normally buried beneath, and partially in-filled with, sands and sandy gravels of probable Devensian age. Sediment fill is of silt to boulder grade material, predominantly comprising flint gravel, but with bedrock (Chalk, Lambeth Group or London Clay) injections, diapirs or mélange recorded in some instances (Berry 1979; Lee & Aldiss 2011). An associated bulging of the underlying strata has also been observed at some locations (Berry 1979; Ellison *et al*. 2004). Further information on the characteristics of the documented buried hollows is summarized in the Appendix. The buried hollows can be subdivided between those that are underlain by London Clay and those with roots that extend below the London Clay (Appendix, Tables A1 and A2 respectively). However, absence of proven connectivity may be due to the nature of the site investigation and should not be taken as proof of absence of connectivity between the near surface and the Chalk.

Where buried hollows have been encountered in central London, they are primarily found beneath the Kempton Park Gravel Member, a Thames river terrace (Table 2). To interpret Table 2 it should be noted that several changes have been made to the geological nomenclature over time. For example, continuing work on the River Terrace Deposits, which reflects their value in the interpretation of palaeoclimate and landscape evolution (Gibbard 1985; Bridgland 1994), has resulted in refinement of some of the river terrace names and their correlations (Table 2). Similarly, the Basal Beds is a general term that has been applied to the Thanet Sand and Upnor formations, which overlie the Chalk and are generally in hydraulic continuity with it. The Chalk and overlying Thanet and Upnor formations form one of the most important aquifers in the UK. It is confined in Central London by the Lower Mottled Clay or the Lower Shelly Clay of the Lambeth Group and the London Clay Formation of the Thames Group.

Given the urban setting, the opportunities for detailed description are rare. Where more detailed site investigations have been carried out they are often of a sensitive nature and are ordinarily unpublished or confidential. Broadly, the features are characterized by considerable ground disturbance; they are generally 90–475 m wide (Berry 1979) and are steep-sided, with slopes generally in excess of 20°. Features that penetrate the London Clay Formation commonly include an association with a thick zone of bedrock mélange, which may comprise bedrock from the London Clay Formation, the Lambeth Group and the Thanet Formation or less commonly the Chalk Group (Appendix, Table A2). The bedrock strata are commonly elevated above the surrounding bedrock boundary (Ellison *et al*. 2004) and blocks and fragments of chalk that have migrated towards the surface have locally been uplifted by up to 20 m (e.g. 15 m at Blackwall). Where the London Clay Formation has not been completely penetrated or it has perhaps sealed itself, the hollows are generally filled with gravels, which are interbedded with sands and commonly clays, and the deposits may be largely saturated, giving rise to a loss of strength in the bedrock as well as the superficial deposits (Appendix, Table A1). It should also be noted that a number of the latter may not be fully characterized (i.e. the base has not yet been established).

Various mechanisms, reflecting different settings and form, have been proposed for the formation of buried hollows and the process understanding remains equivocal. Historically, because of their

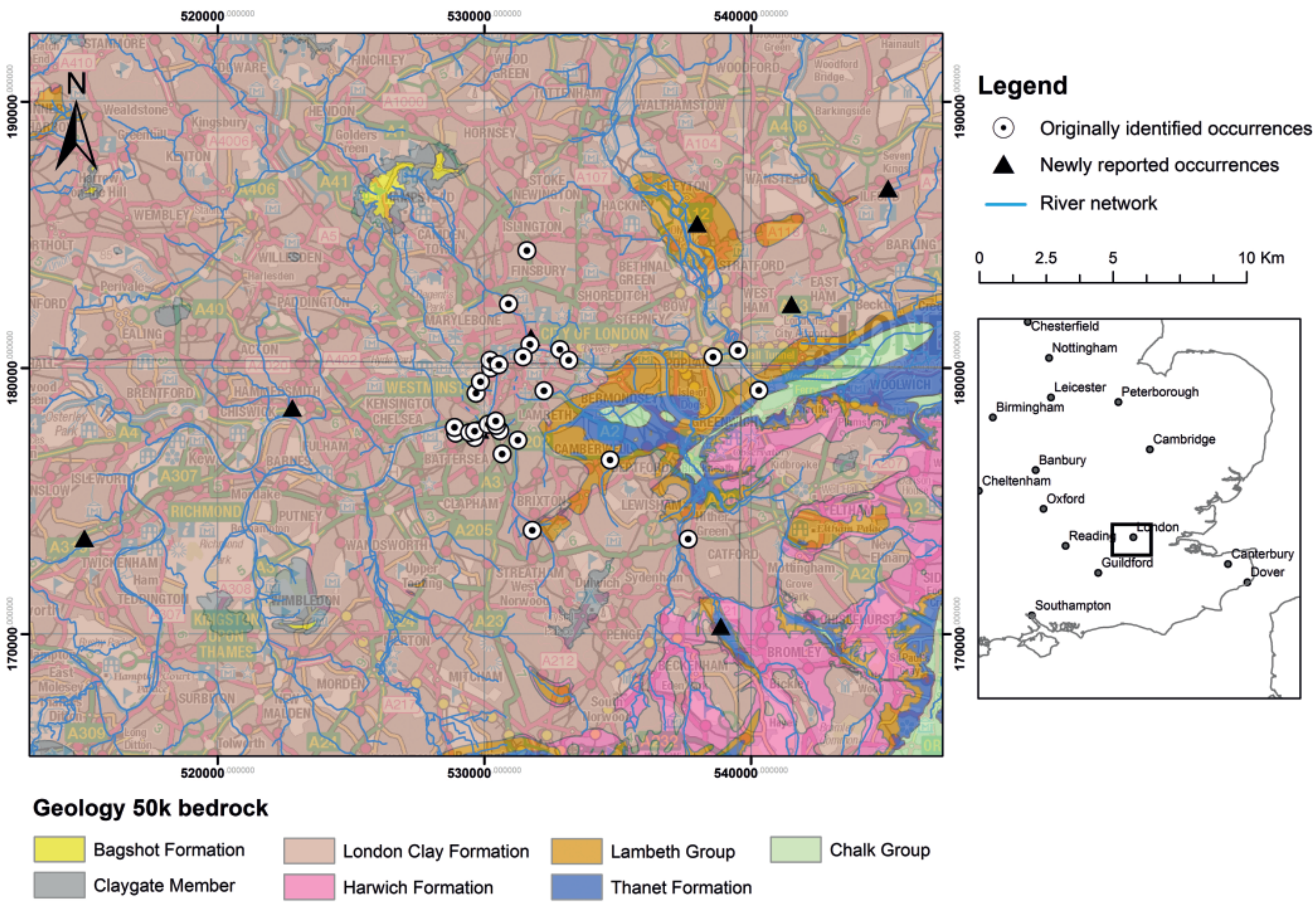

Fig. 1. Location of the originally identified and newly reported occurrences of buried hollows in central London. The underlying bedrock geology (1:50000) is shown along with the modern river drainage network. BGS©NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2014. Lost rivers of London reproduced from Barton (1992).

Table 1. *Geological succession of the research area (adapted from Sumbler 1996 and Ellison et al. 2004)*

System	Series	Group	Principal deposits
Quaternary (see Table 2)	Holocene		Alluvium, hillwash, tufa, peat, coastal and estuarine sand and mud
	Pleistocene		River terrace sand and gravel (Kempton Park Gravel Member, Taplow Gravel Member, Lynch Hill Gravel Member, Boyn Hill Gravel Member, Black Park Gravel Member and pre-diversionary river terrace deposits of the Kesgrave catchment subgroup) till, glacial sand and gravel, slope deposits, clay with flints
Palaeogene		Thames	Marine muds, including London Clay and Harwich Formations
		Lambeth	Reading Formation (Upper Mottled Clay and Lower Mottled Clay members)
			Woolwich Formation (Upper Shelly Clay, Laminated Beds and Lower Shelly Clay members)
			Upnor Formation
			Thanet Sand Formation
Cretaceous	Upper Chalk	Chalk	Newhaven Chalk Formation
			Seaford Chalk Formation
			Lewes Chalk Formation

distribution and association with channels, often near the mouths of tributaries to the main river, they have been referred to as scour hollows or drift-filled hollows (Berry 1979). This interpretation assumes that they formed during the growth and decay of permafrost. More recently, they have been interpreted as the scars of hydraulic pingos that were fed by artesian water (Hutchinson 1980, 1991). Pingos are periglacial ice mounds developed in areas of permafrost or discontinuous permafrost (Gurney 1998). They have two main genetic forms: (1) hydrostatic (closed) pingos where an isolated lens of unfrozen water-laden sediments, such as a sub-channel talik, provides the source of water for the growth of the pingos' ice-core; (2) hydraulic (open) pingos where sub-permafrost or intra-permafrost groundwater flow, which is recharged from areas of discontinuous permafrost, sustains the pingo ice growth (Mackay 1985).

Hutchinson (1980, 1991) identified a number of common geological and hydrogeological characteristics associated with the distribution of the hollows. These can be summarized as follows.

(1) They are commonly situated in valleys, close to the valley floor.

(2) They are usually associated with the feather edge of the London Clay (less than 35 m in thickness).

(3) Artesian groundwater conditions (based on the distribution of the maximum historical groundwater levels; Simpson *et al.* 1989). However, as noted by Hutchinson (1991) the actual uplift

Table 2. *Quaternary correlation chart for the Middle and Lower Thames (adapted from McMillan et al. 2011)*

Epoch, British/ European Stage and approximate correlation with Marine Isotope Stage (cold even and warm odd numbers)			Middle Thames	Lea Valley
Holocene		1	**Thames Catchments Subgroup** **Maidenhead Formation** Alluvium	Thames Catchments Subgroup **Maidenhead Formation** Alluvium Floodplain Gravel Bed
Late Pleistocene	Devensian/ Weichsalian	Loch Lomond Stadial (2-1)	Shepperton Gravel Member	Lea Valley Member
		Windermere Interstadial (2)		
		Dimlington Stadial (2)	Kempton Park Gravel Member (terrace 1)	Lea Valley Arctic Bed
		3		Langley Silt Member (Brickearth) Enfield Silt Member (Brickearth)
		4		
		5d-a		
	Ipswichian/ Eemian (5e)			Highbury Member Waterhall Farm Member
Mid Pleistocene	6		Kempton Park Gravel Member (part) Taplow Gravel Member (terrace 2)	Leytonstone Member Stamford Hill Member
	7			
	8		Taplow Gravel Member (part) Hackney Gravel Formation (terrace 3) Lynch Hill Gravel Member (terrace 4)	
	9			
	10		Lynch Hill Gravel Member (part) Boyn Hill Gravel Member (terrace 5)	
	Hoxnian/ Holsteinian (11)			
	Anglian/ Elsterian (12)		Boyn Hill Gravel Member (part) Black Park Gravel Member (terrace 6)	**Lowestoft Formation** Hoddeston Member
			Kesgrave Catchment Subgroup of the Dunwich Group Colchester Formation Winter Hill Gravel Member	
Early Pleistocene	?61-13		**Sudbury Formation** Gerrards Cross Gravel Member Beaconsfield Gravel Member Chorleywood Gravel Member Westland Green Gravel Member Satwell Gravel Member Stoke Row Member	
	103 to ?62		**Stanmore Gravel Formation**	
Miocene to Early Pleistocene				

pressures required to generate uplift of the Lambeth Group were considerably higher than the Historic Maximum Value (HMV). Higher artesian pressures could result from both melt water recharge and the relative lowering of base level.

(4) Unloading of the overburden material (by scouring) may have facilitated pore water pressure breaching of the London Clay.

It was Hutchinson's assertion that, if valid, it may be possible to use such observations to define areas in London where these features are most likely to occur. Drawing upon the empirical evidence that underlies Hutchinson's work and capturing the buried hollows that are underlain by, or penetrate, the London Clay, the aim of the BGS project was to generate a susceptibility map. The work combines a series of geological, geomorphological and hydrogeological factors within a GIS for central London to define zones where further anomalous buried hollows are considered most likely to occur.

Development of the hazard susceptibility map

A number of researchers have presented maps of the location of the buried hollows in central London, most notably Berry (1979), Hutchinson (1980) and Simpson *et al*. (1989). There were 31 occurrences from these publications. A further nine features were identified from information provided to the BGS from third-party site investigations (Fig. 1). Summary information for each of the identified features is provided in the Appendix. Based on the work of Hutchinson (1980, 1991) a series of 'contributory factors' relating to the geological and hydrogeological setting of the hollows were developed to constrain their likely distribution, with the intersection of these rules providing areas where these features are most likely to be encountered. The rules for the component layers were developed within a GIS (Table 3) and were defined using the original set of 31 buried hollows. The nine more recently reported features were used to start validating the map. The contributory factors are described in more detail below.

Contributory factor 1: artesian groundwater levels

Hutchinson (1980) suggested that the buried hollow features developed as hydraulic pingos in the London Clay Formation deriving

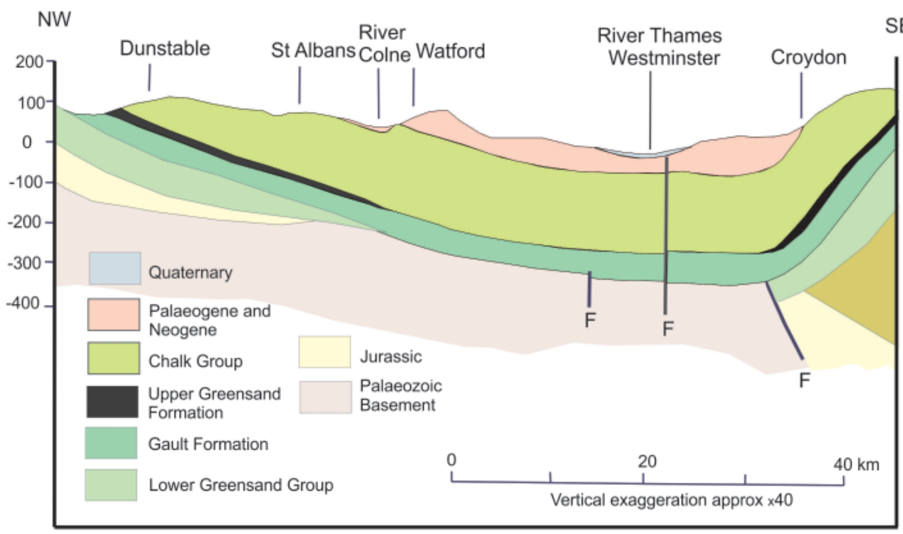

Fig. 2. Schematic, simplified geological cross-section, oriented NW–SE through the London Basin. Major faults are indicated (F); other faults (Fig. 4) are not shown (Royse *et al*. 2012, fig. 3).

their water source from the chalk aquifer, which was artesian (i.e. groundwater head exceeds ground elevation) with the potential to supply groundwater to the surface via a pathway such as a pipe or root. The association of the buried hollows with the feather edge of the London Clay Formation where the chalk confining layer is thinner further suggested to Hutchinson (1980, 1991) that these features are associated with zones of former artesian groundwater conditions. The occurrence of bedrock diapirs in several of the hollows (Berry 1979) is also indicative of excess pore water pressures. Although it is not yet possible to determine what the pore pressures were when the hollows were formed, historical groundwater pressures are known and have been used as an approximation. Maximum groundwater level data for the Lower London Tertiary units and the Chalk aquifers dating from the early 1800s, prior to major groundwater exploitation, were compiled by the former Water Resources Board (1972). Using these groundwater level data, in combination with ground elevation data, an approximation of former artesian conditions has been made (Water Resources Board 1972). The resultant map of artesian groundwater flow has been geo-referenced and digitized to form a layer within the GIS (Fig. 3). The zone of former artesian groundwater conditions forms one of the rules within the susceptibility map (Fig. 3).

Contributory factor 2: London Clay (thickness <35 m)

The thickness of the London Clay Formation is important in that it provides the confining layer for artesian groundwater pressures and regulates pore pressure release. Hutchinson (1980) suggested that where it is reduced to less than 35 m in thickness pore pressures were sufficient to breach the confining effect of the London Clay Formation and allow a restricted supply of water to surface. A 3D bedrock geology model for areas of central London has been developed by the BGS using borehole lithological records, geological surface line work and a digital terrain model (Ford *et al*. 2008). The model is based on over 6700 line-km of correlated cross-sections providing a level of detail equivalent to 1:50000 scale mapping (Ford *et al*. 2010). Surfaces for all of the main bedrock units have been created within the model including the London Clay Formation. The modelled thickness of the London Clay was exported from the 3D geological model into the GIS as a raster surface. Areas where the modelled thickness of the London Clay Formation is less than 35 m form one of the layers incorporated within the map in combination with components of the Lambeth Group (Fig. 3).

Distribution of clay units within the Lambeth Group

The value of 35 m assigned by Hutchinson (1980, 1991) to the confining thickness of the London Clay Formation was derived empirically using information on known occurrences of buried hollows. However, four of these features occur where the London Clay Formation is absent. Where juxtaposed against the London Clay Formation, cohesive units of the Lambeth Group may also contribute to the confining process. This being so, it was considered that the distribution and thickness of these clay-rich units should be accounted for in the hazard susceptibility map. Reviewing the lithological sequence of the Lambeth Group (Table 1) we suggest that the Lower Shelly Clays, the Upper and Lower Mottled Beds and locally the Laminated Beds have sufficient clay content to support pore pressures. The subsurface distribution of the Lambeth Group subunits has been investigated previously and is presented within the geological memoir for London (Ellison *et al*. 2004). Additional revisions to the Lambeth group subdivisions have been undertaken more recently by the BGS and the distribution of these units is available as geospatial vector data in digital shapefile format for use within the GIS. The shapefiles for the Upper Mottled Clay and Lower Mottled Clay of the Reading Formation and for the Lower Mottled Clay, where it is mainly clay, were derived from the geological memoir for London (Ellison *et al*. 2004). Shapefiles for the Laminated Beds and the Lower Shelly Clays were derived using borehole records held by the BGS. The intersection of the boundaries of these units provides a zone where clay facies dominate within the Lambeth Group sequence. This zone has been combined with the extent of the London Clay Formation, where it is less than 35 m thick, to form a layer within our hazard susceptibility map (Fig. 3).

Additional factor 3: Kempton Park Gravel Member

Hutchinson (1991) noted that the buried hollows occur beneath the Late Quaternary Thames terraces. This is represented by the Kempton Park Gravel Member, which has been defined using the BGS 1:10000 and 1:50000 digital geological map (DIGMapGB10; DIGMapGB50) and forms one of the criteria used to define the hazard susceptibility map (Fig. 3). The digital geological maps provide a 2D expression of superficial deposits present at ground surface and as such there are sections where alluvium or loessic derived deposits such as the Langley Silt Member are mapped at surface in part obscuring river terrace deposits at depth. The

Table 3. *Geological and hydrogeological factors contributing to the GIS layer*

Rule	Justification	GIS layer
(1) Within areas of former artesian groundwater conditions	Potential source of groundwater close to ground surface, under an upward hydraulic gradient	Zone of historical maximum artesian groundwater conditions
(2) Beneath the Kempton Park Gravel Member	Empirical association of buried hollows with the Kempton Park Gravel Member	Distribution of the Kempton Park Gravel Member with BGS digital geological map (1:50000)
(3) Where the London Clay Formation is less than 35 m thick or where the London Clay is absent but the Lambeth Group is clay-rich	At the feather edge of the London Clay Formation and Lambeth Group where it forms a thin confining layer there is greatest potential for it having been breached by elevated pore water pressures. Where breached there is the potential for hydraulic connection between deeper groundwater and the ground surface	Zone where the London Clay Formation is less than 35 m thick combined with areas where clay-rich units in the Lambeth Group are present

subsurface extent of the Kempton Park Gravel Member is undefined in some areas, particularly along the lower sections of the River Thames downstream of the River Lee where the river terrace deposits are concealed by a significant thickness of Holocene floodplain deposits and made ground, and the subcrop of the various river terraces has not been mapped. In this instance, the extent of the alluvium downstream of the River Lee has been used as a proxy for the likely extent of the sub-alluvial Kempton Park Gravel Member. It is acknowledged that sub-alluvial Shepperton Gravels will also be included within the Kempton Park Member layer; this is expected to be the case only downstream of the River Lee.

In summary, three contributory factors (rules; Table 3) constrain the environment within which anomalous buried hollows are most likely to occur, with the intersection of these rules defining the zones of our hazard susceptibility map. Based on the characteristics of the buried hollows currently identified and on an assessment of information regarding the geological processes leading to their formation it is anticipated that further occurrences of these hollows are most likely when all three rules are satisfied. However, through interrogation of the existing buried hollows it is known that in some cases these features develop when some of the rules are not satisfied. To account for this two zones are indicated on the map (Fig. 5): zone A, where all three of the rules are satisfied and a high susceptibility to buried hollows is assumed; zone B, where any two of the three rules are satisfied and susceptibility to buried hollows is considered to be moderate. Of the 31 original occurrences of buried hollows 65% occur within zone A, and 19% within zone B (Table 4). Four of the buried hollows occur outside the hazard susceptibility zones and one occurs outside the map area.

Advisory factors

In addition to the three contributory factors used to define the hazard susceptibility map there are two hydrogeological characteristics that are pertinent to the distribution of the buried hollows, but that have not been used explicitly in the development of the hazard susceptibility map. First, quantitative assessment of faults has not been included in the hazard mapping exercise. Faults within the Chalk Group and overlying geological strata (Fig. 4) offer the potential to provide groundwater pathways that overcome confining pressure and reach shallow deposits to facilitate buried hollow development. Subsequent to Hutchinson's publications de Freitas (2009) described the linear pattern of the river network (lost and current rivers) and related it to faulting. A qualitative assessment of the role of faulting in hollow formation has been made and is considered relevant to the discussion on the process of formation of the hollows. Second, there is evidence to associate the buried hollows with modern river networks and the gravel deposits of former river channels, but this has not been included in the development of the map. Berry (1979) used this association as the basis for his classification of these features (Appendix). He undertook detailed examination of the bedform of the alluvium and noted the correlation of the hollows with channels. A number of the buried hollows correspond closely to the outer part of the meanders in the Holocene alluvium associated with the current course of the River Thames (features 1a–1g, 3a–3e (albeit an earlier course), and 7a and 7b of the Appendix). Despite the empirical association of buried hollows with the river drainage network its use within the hazard susceptibility map is not justified. The modern river network represents the Holocene catchment drainage system and does not necessarily reflect the cold-climate drainage network in operation when the hollows most probably formed during the late Devensian.

Buried hollows that fall outside the GIS layer

There are four isolated hollows that do not lie within zone A or B of the hazard susceptibility map (Fig. 5; Table 5). Therefore it was necessary to assess whether the hydrogeological criteria (Table 3) should be extended, or whether these features fall outside the characteristics of the majority of the buried hollows, thereby indicating that these occurrences result from different processes to those that fall within the hazard susceptibility map. Evaluation of the four occurrences (Table 5) reveals that two of the features (8a and 11a) are coincident with the Streatham Fault (Fig. 4), suggestive of a hydraulic connection between the deeper chalk aquifer and the shallow river terraces. Three (5a, 8a and 11a) are located within the valleys of former rivers in London (Barton 1992), a local point of groundwater discharge that might be associated with scour processes. The review also suggests that there are isolated hollow occurrences that do not occur near a fault or within modern river valleys, indicating that they may result from a different mode of formation. The possibility that these features are associated with unmapped faults (Aldiss 2013), such as strike-slip faults (dextral shear associated with the Variscan orogeny; de Freitas 2009) that have not been identified in the 3D modelling of the geology, should also be considered.

Limitations of the hazard susceptibility map

The high percentage of originally identified buried hollows occurring within zones A and B of the hazard susceptibility map (84%) implies a high level of confidence in the GIS map layer. However, there are limitations relating to the approach used to derive the map that should be considered.

- The process of formation of the buried hollows is equivocal (see discussion) and different processes may have acted to produce several different types of buried hollow. The distinction between different forms of hollow is not explicitly taken into account in the development of the hazard susceptibility map (e.g. penetrating or not penetrating the London Clay; Tables A1 and A2), because the absence of a proven connection through the London Clay Formation is not necessarily proof of there not being a connection. The hydrogeological criteria and derived GIS rules may

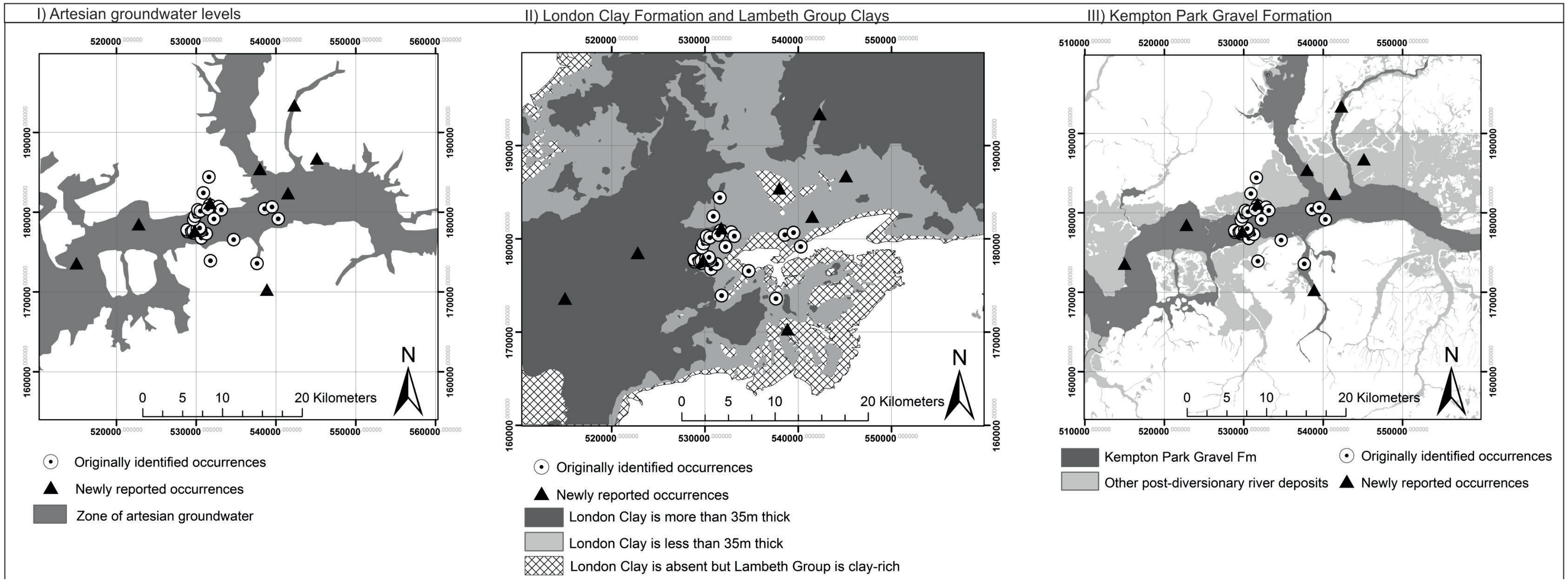

Fig. 3. Factors contributing to the susceptibility map. BGS©NERC. Zone of artesian groundwater © Environment Agency copyright and/or database rights 2012. All rights reserved. Lost rivers of London reproduced from Barton (1992).

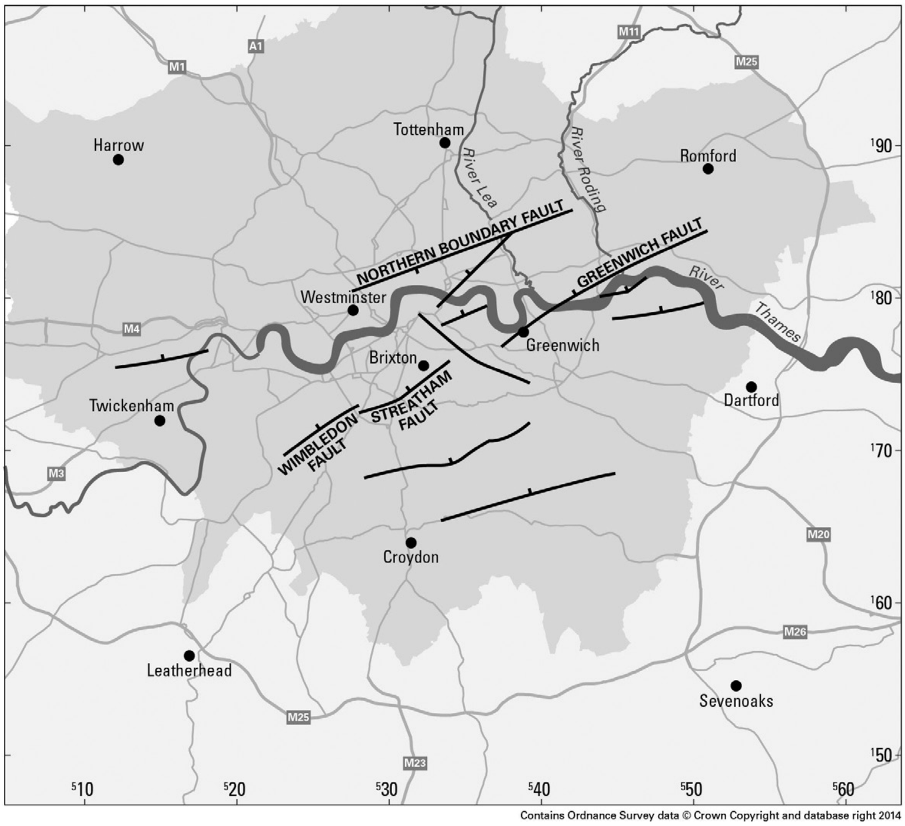

Fig. 4. Mapped faults. BGS©NERC.

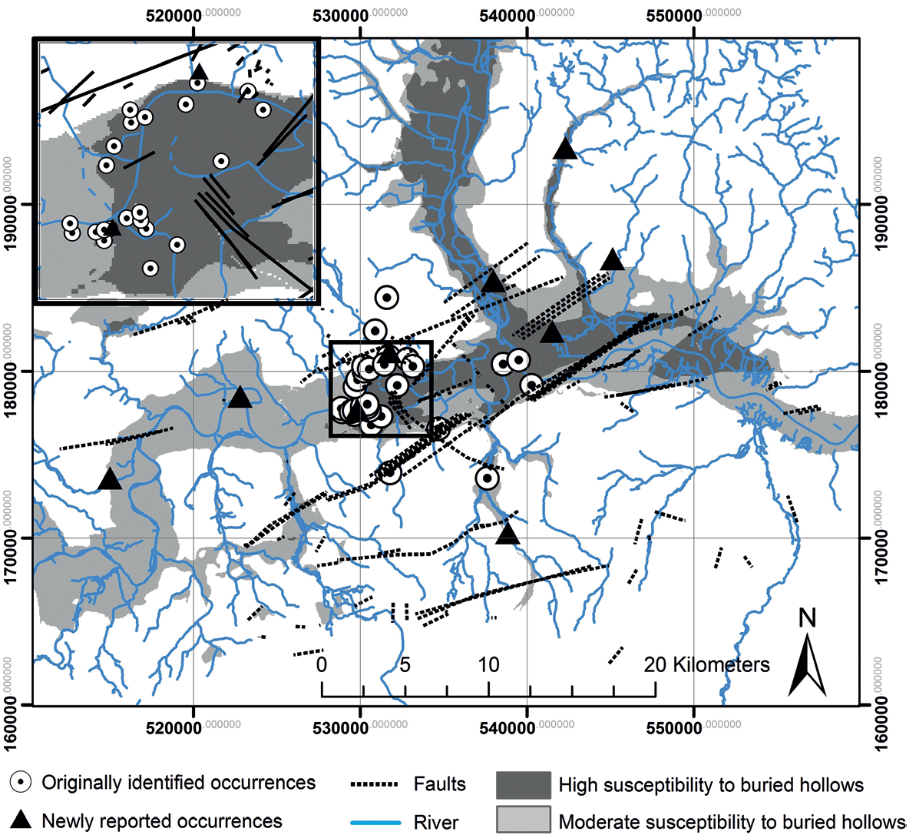

Fig. 5. Zoned hazard susceptibility map. BGS©NERC. Contains OS Open data ©Crown Copyright and database rights 2014. Lost rivers of London reproduced from Barton (1992).

therefore be appropriate for some, but not necessarily all, buried hollows present within the study area.

- The method of Hutchinson (1980, 1991) and our consequential susceptibility map were defined using 31 occurrences of buried hollows in central London. The majority (22) of these are clustered within a small area (just 30 km^2) between Battersea and Charing Cross. By definition there is an increased likelihood that the cluster of hollows will share the same hydrogeological setting, which introduces bias to the defined hydrogeological criteria. Although we are mindful of the potential bias, the occurrence of buried hollows within zone A, but beyond the cluster, would

Table 4. *Number of originally identified buried hollow features that occur within the hazard susceptibility zones*

Location	Number of occurrences	%
Zone A	20	65
Zone B	6	19
Outside zones A and B	4	13
Outside map area	1	3

suggest that the hydrogeological criteria may be applied appropriately over the wider area.

- The buried hollows, which are revealed only by deep excavations or deep site investigation boreholes, are most likely to be discovered in areas of London subject to major development. Thus, the location of known features is directly related to the extent of development within central London. This may contribute to spatial bias in the dataset. Much of the recent development in London has occurred within younger, low-lying river terraces such as the Kempton Park Gravel Member. Buried hollows may also be associated with older river terraces but they remain undiscovered. There is currently insufficient empirical evidence to warrant the inclusion of other river terraces in the hazard susceptibility map.
- The spatial extent of the derived hazard susceptibility map is limited by the coverage of data used to derive the GIS layers. The zone of artesian groundwater levels *c*. 1800 is available only for central London. Similarly, the 3D geological model of London from which the thickness of the London Clay Formation was derived is currently available only for the Lower Thames Valley.
- It is questionable whether the combined thickness of the Lambeth Group clay units alone would have been sufficient to confine pore pressures. However, within central London, areas where clay dominates within the Lambeth Group largely coincide with areas where a thickness of London Clay is present and so this is an issue only along the feather edge of the Lambeth Group.
- The area defined by the Kempton Park Gravel Member is largely overlain by the area defined by the probable historical artesian groundwater conditions, potentially leading to double-counting within the hazard susceptibility map. This occurs because river terraces develop within river valleys and artesian groundwater conditions are more likely to occur in valley floor locations at the groundwater discharge points. There are, however, areas that fall within the zone of former artesian groundwater conditions but not within the area of the Kempton Park Gravel layer and vice versa.

Limitations of the map and uncertainties with the adopted approach may be reconciled through appropriate validation of the map. To this end a number of more recently reported occurrences of buried hollows, revealed subsequent to the work of Hutchinson (1980, 1991), have been compared with the hazard susceptibility map to justify or otherwise the geological and hydrogeological criteria selected. Nine features have been identified for this purpose: Twickenham, Nine Elms, Hammersmith, Ludgate Hill, Illford, Beckenham, Roding Valley, Newham and Stratford. These buried hollows offer a less-clustered dataset than the originally reported occurrences. The locations of the 'recently identified' hollows have been compared with the hazard susceptibility map (Table 6). Of the nine reported occurrences, six occur within zone A or B of the hazard susceptibility map and a further two lie within 200 m of zone B.

Discussion: implications for process understanding

Application of the susceptibility map to development

The susceptibility map is likely to be of use to ground engineers and engineering geologists at the Phase 1, desk study stage of ground investigation for proposed development in London and for hydrogeologists seeking to identify potential contaminant migration pathways. The value of this susceptibility layer lies in the opportunity for planners, developers, consultants and ground engineers to have a regional awareness of the likelihood of these features. This may lead to more effective site investigation design and reduce the likelihood of unforeseen ground conditions. Buried hollows form zones of contrasting ground conditions for civil engineering projects (Higginbottom & Fookes 1970; Berry 1979; Hutchinson 1991; Lenham *et al*. 2006; Paul 2009). More specifically, a number of examples of buried hollows causing significant disruption to engineering have been reported in the literature (Higginbottom & Fookes 1970; Anonymous 1984; Hutchinson 1991; Strange *et al*. 1998; Lenham *et al*. 2006; Paul 2009). The disruption ranges from differential settlement of foundations to excessive local settlement and stability problems within excavations and tunnels with the inevitable consequences of unforeseen ground conditions. There is also a potential for these features to form preferential pathways for contaminants. Clearly, there is a significantly greater likelihood of hydraulic connectivity with the Chalk where the structures penetrate the London Clay (Appendix, Table A2).

With respect to building foundations the occurrence of buried hollows necessitates appropriate consideration of foundation type and depth based on the potential for differential settlement. If encountered, the buried hollows will affect any provision for groundwater control, and the disturbance and greater variability in the strata may necessitate protection of concrete from attack by sulphate or more acidic ground conditions. The implications for tunnelling are particularly significant in that the hollows may escape detection at the ground surface and give rise to significant and unforeseen changes in ground condition at depth. In particular, revisions may have to be made to methods of support and groundwater control. The potential connectivity of the superficial deposits

Table 5. *Buried hollows that fall outside hazard susceptibility zones A and B*

Hollow	Criteria not met	Evaluation
5a, Greys Inn	Not within the zone of artesian groundwater levels; not overlain by Kempton Park Gravel	Located within the valley of the former River Fleet (Barton 1992) and overlain by Hackney Gravel Formation
8a, Peckham	Not overlain by Kempton Park Gravel; London Clay Formation and Lambeth Group Clays are absent	Associated with the Streatham Fault; within 200 m of the mapped extent of the Kempton Park Gravel; along the valley of the former Peck stream (Barton 1992)
10a, Highbury Corner	Not within the zone of artesian groundwater levels; not overlain by Kempton Park Gravel	'Dry' sand encountered; not within close proximity to river channel or mapped fault
11a, Tulse Hill	Not within the zone of artesian groundwater levels; not overlain by Kempton Park Gravel	Associated with the Streatham Fault; Lambeth Group is locally uplifted; within 200 m of the former river Effra

Table 6. *Number of newly reported in-filled hollow features that occur within the hazard susceptibility zones*

Location	Number
Zone A	4
Zone B	2
Outside zones A and B	3
Outside map area	0

with the underlying Chalk aquifer that results from the formation of the anomalous ground conditions presents a hydrogeological challenge in terms of the potential for contaminant migration as a consequence of under-drainage. The detail of the likely engineering impacts varies with the form and setting of the buried hollows.

Application of the susceptibility map to process understanding

The map has research value by providing an opportunity to interrogate the GIS-hosted information to further understanding of how these features formed. Although we have adopted the criteria of Hutchinson (1980, 1991), further interpretation of the assumptions is necessary to provide a better understanding of the processes forming these features. Two key processes have previously been associated with the formation of the buried hollows: scouring (Berry 1979) and open pingo formation (Hutchinson 1980). Here, we consider a broader range of hypotheses. The processes have been considered in the context of both the hydrogeological criteria defined above and observations derived from the literature. There are a number of common characteristics of the features (Fig. 6) that have informed this discussion, as follows.

(1) The buried hollows fall into two groups: those underlain by the London Clay Formation and those with roots that penetrate the London Clay Formation (Appendix).

(2) The buried hollows appear to be associated with known and predicted areas of upwelling (artesian conditions) and there is evidence to suggest that faulting or dominant jointing may contribute to this. Of the 31 buried hollows originally identified, nine lie within 500 m of a mapped (major) fault and a further six lie within 1000 m of one. However, to date BGS mapping has focused on the faults that can be traced through unexposed ground because they juxtapose different rock formations along much of their outcrop (Aldiss 2013; Royse 2010; Fig. 4) and it is suspected that faults are under-represented by current mapping (Aldiss 2013). The preferred orientations (NE–SW and NW–SE) for the long axes of the buried hollows that are shown in the Appendix suggest that the morphology of the buried hollows may be aligned with faults or dominant joints. The former corresponds to the major fault set orientation of the area (as evident from the 1:250000 scale map). There is also a visual correlation of the orientations with the nearest mapped fault sets, thereby suggesting a correlation with dominant joint sets (if not faulting) in the Chalk. Faulting in the London Basin appears complex, possibly dominated by strike-slip faulting (de Freitas 2009) that has not been integrated in the 3D modelling, albeit that the structure of the London Basin has not been fully resolved. Local complexity is exemplified in the Farringdon area (Aldiss 2013). It has been noted that a number of channel reaches are parallel to the trend of dominant faults, but it has also been argued (de Freitas 2009) that faults in the London Basin can be deduced from river patterns, possibly as a consequence of movement on faults owing to the Quaternary forebulge and crustal down-warping in front of the major glacial advances.

(3) There is a clear affinity with the Kempton Park Gravel Terrace.

(4) Some of the buried hollows incorporate large-scale ground deformations, including vertically injected masses of chalk breccia and putty chalk; uplifted Palaeogene strata, and involutions of Palaeogene and River Terrace gravels. The vertical movement suggests excess water pressures at depth with a steep pressure gradient to the surface. The condition of the chalk suggests that it is likely that the material was frozen and saturated, or oversaturated as it approached the ground surface. Once movement had ceased the excess water pressure would have drained and this would have been associated with settlement.

(5) Many of the hollows are associated with the Holocene river network (Berry 1979).

As described below, with some consideration of the limitations, there are a number of processes that might lead to some of the characteristics that are described above.

Scouring

The association of a number of the buried hollows with the Thames and its tributaries supports an interpretation of these features as scour hollows, formed as a consequence of fluvial or glacio-fluvial processes. River scour can occur in a number of fluvial settings; for example, junction scour (i.e. scouring at the confluence of a tributary river with the main channel; Ginsberg & Perillo 1999), flood scour and vortex scour (Mlynarczyk & Rotnicki 1989; Hutchinson 1991), which may be associated with meanders (Mlynarczyk & Rotnicki 1989). It has been reported that scour depth in this situation is often between three and five times the depth of the confluent channels (Kjerfve *et al*. 1979; Rice *et al*. 2008). It has also been shown that scour depth increases at higher discharge angles and discharge ratios (Rice *et al*. 2008). The relative bed elevation (tributary to main channel) also influences the potential for scouring. In this model of hollow formation scouring would be most likely during the periods of climatic amelioration when groundwater tables were at a relatively low level (owing to lower sea levels), while surface water discharges were increasing and permafrost was wasting. Elevated pore pressures would result in a reduction in strength of some of the deposits, rendering them vulnerable to erosion. A related explanation might be discontinuous gully formation, whereby permafrost provides cohesion for bed sediments, which are seasonally eroded along channel forms (discontinuous gullies of Rose *et al*. 1980) at times of peak discharge without a proportionate increase in sediment supply. This explanation would result in more elongate (of the order of 2 km in length), possibly open-ended forms to the buried hollows.

The correlation between hollows and the Holocene river network inferred by Berry (1979) indicates that a stream-related hydrological process (e.g. scouring; Ginsberg & Perillo 1999) associated with the higher energy environment of the outside of meanders is associated with the buried hollows that are underlain by the London Clay Formation. However, scour hollows generally form at much shallower angles than have been recorded for a number of these features (Tables A1 and A2); albeit that this might be a facet of the metastability brought about by permafrost followed by rapid sediment filling providing support to the feature. It is also plausible that pre-existing scour hollows influenced the subsequent alignment of the river channels. Scouring does not explain the bedrock disturbance associated with the deeper features.

Dissolution

Acknowledging that the area is underlain by the White Chalk Subgroup, consideration has been given to Chalk dissolution (Gibbard 1985), which might result in hollow formation but would not account for many of the associated features. For example, the upward warping of bedrock boundaries adjacent to a number of the buried hollows (Tables A1 and A2) would point to processes other than chalk dissolution as the triggering process for the buried hollows. Only one of the 31 published examples (7c; Table A1) is

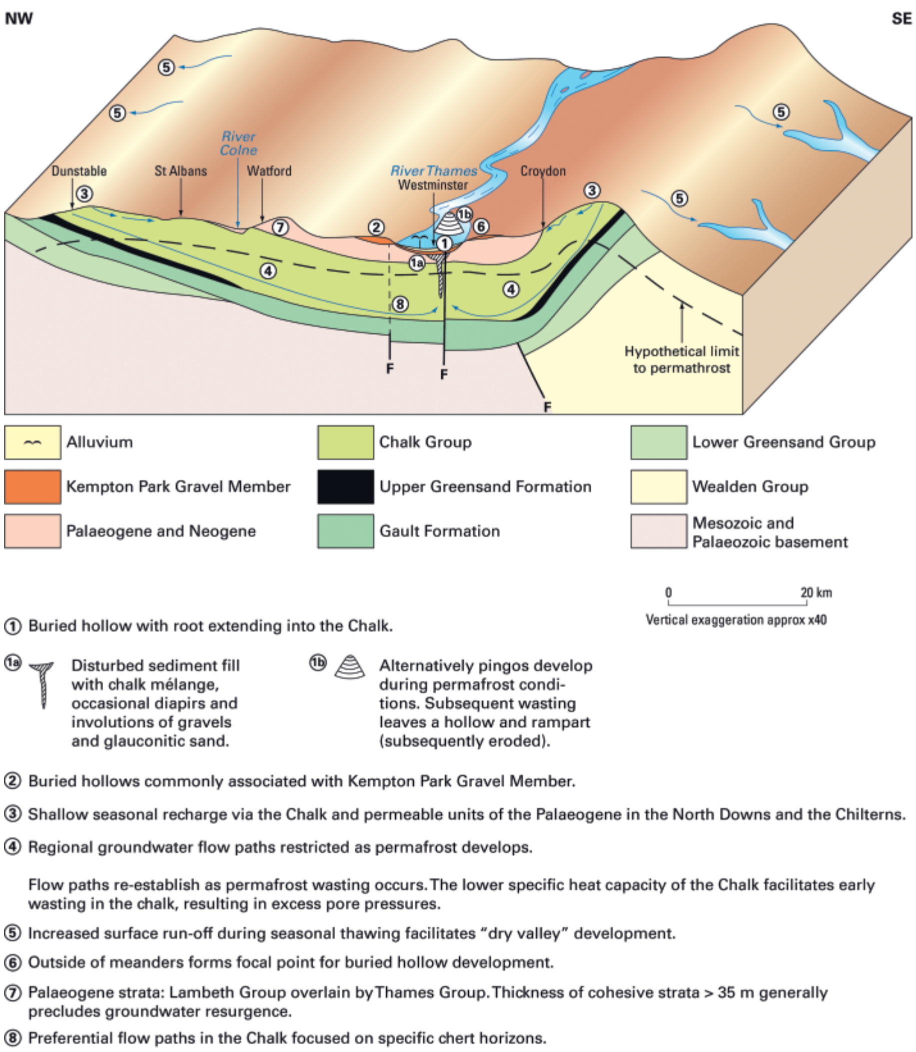

Fig. 6. Conceptual model to show the context of the buried hollow in London.

known to be underlain by a depression in the Chalk surface (Hutchinson 1991). Locally, chalk dissolution may be a trigger for ground disturbance (e.g. Thorez *et al*. 1971), but this is considered to be a different process that tends to be associated with doline or pipe formation at the feather edge of the cover deposits (e.g. McDowall *et al*. 2008).

Valley bulging

Valley bulges (Hutchinson 1991) are relict periglacial features. They occur in England south of the former glacial limits and are most closely associated with valley settings where rapid incision of valleys through competent into underlying, less competent argillaceous strata initiates lateral displacement of the argillaceous strata towards the valley. Descriptions of some of the buried hollows do include reference to local bulging of the bedrock strata (1c, 2a, 6a and 9a; Table A2) and where this is associated with the scour hollows a comparable process, guided by remnant permafrost and excess pore pressures, might be envisaged. However, in at least five cases the features penetrated the London Clay, and the underlying Lambeth Group lithologies are intruded 6–12 m upwards. This apparent diapirism indicates a more sudden and differential release of excess pore pressure than would be associated with bulging.

Frost heave

Frost heave or bedrock heave (jacking) has been reported in frozen ground. This is characterized by the uplift of frost-wedged blocks, with uplift being facilitated by the pressure generated by free water freezing in joints (Dionne 1983; Worsley 2007), but it tends to be a near-surface phenomenon and would not account for the scale of disruption noted in many of the buried hollows.

Ice wedges

Ice wedges have been classified as both permafrost and thermokarst features. Ice wedges develop in the active layer (upper layer of the permafrost that thaws seasonally; Ballantyne & Harris 1994). They comprise vertical wedge-shaped intrusions extending to the permafrost and form as a consequence of contraction and tensile failure of the rock or sediment during cooling, with subsequent seasonal enlargement as ice and sediment accumulate within the crack, thereby preventing closure. Ice wedges propagate downwards, with seasonal growth of ice within cracks extending upwards and then collapsing during seasonal melting, causing up-tilted beds to sag downwards. Pidwirny (2006) described how beaded channels develop in periglacial regions when streams pass over networks of ice wedges and the thermal properties of the flowing water cause the ice wedges to melt, producing pools. Although downward entrainment of sediment (in particular gravels) has been observed in cores from the buried hollows associated with bedrock disturbance, the overall geometry and scale of the buried hollows suggest that a different process was in operation for hollow formation.

Thermokarst processes

Thermokarst processes might account for some of the features associated with the buried hollows, in particular the deformation of the sediments that fill the hollows and the bedrock diapirs. Periglacial phenomena are dominated by frost heave (the accumulation of segregation ice owing to the negative pore pressure generated at the freezing front) and thaw consolidation (the self-consolidation that occurs as thawing of the dilated ground takes place). This sediment deformation can be compared with soft sediment deformation structures that result from the warming of frozen ground and have been studied in the western Canadian Arctic (Murton & French 1993; Murton 2001). More specifically, thermokarst involutions in glacial deposits form by loading and buoyancy or by water escape during the degradation of ice-rich permafrost (Murton & French 1993), but this is at a smaller scale than the extent of bedrock disturbance associated with the buried hollows. Similar processes might account for the downward migration of flint pebbles and glauconitic sand (derived from the Palaeogene strata). Similarly, bedrock diapirism can result from the melting of segregation ice, as in an example to the south of Liepzig, Germany (Péwé 1995) where diapirs of lignite (100 m long, by 15 m wide and 10 m high) are thought to have been emplaced as segregation ice melted.

Ground ice relicts

Hutchinson (1980) interpreted the buried hollows as relict pingo scars, possibly associated with river scouring. This implies specific characteristics with respect to their structure and the interpretation of the palaeoenvironmental conditions at the time of formation. Pingos are intrapermafrost features; the term originates from an Inuit word applied to the conical hills in the Mackenzie Delta area of the Northwest Territories of Canada and its use to describe the ice-cored mounds of this area has been attributed to Porsild (1938). Where they are active they are significant positive features in the landscape, because they are ice-cored hills that are typically conical and can form and persist only in permafrost regions (e.g. Mackenzie Delta, Canada; Mackay 1998). Examples in the Arctic range from 3 to 70 m in height and from 30 to 600 m in diameter (Hutchinson 1991). Long-term studies of active pingos in the Northwest Territories of Canada have been documented by Mackay (1962, 1979, 1985, 1988). Shorter term studies have also been carried out in Alaska (Holmes *et al*. 1968), Greenland (Christiansen 1995; Scholz & Baumann 1997; Gurney 1998), the Tibetan Plateau (Wu *et al*. 2004, 2005) Spitsbergen (Yoshikawa & Harada 1995) and Svalbard (Ross *et al*. 2007). Classified by Hutchinson (1991) as groundwater discharge features, pingos form as a consequence of the freezing of water, which moves under a pressure gradient to the site of the pingo. As previously noted, they fall within two classes: hydraulic (open system, formed under an upward hydraulic gradient) and hydrostatic (closed system, formed under a downward hydraulic gradient and typically forming in drained lake bottoms; Mackay 1998). In some cases faults or dominant joints provide routes for groundwater; for example, in Spitsbergen (Yoshikawa & Harada 1995), Alaska (Holmes *et al*. 1968); West Greenland (Scholz & Baumann 1997) and the Tibetan Plateau (Wu *et al*. 2004, 2005). Ground-ice driven uplift and cracking of the surface soil and sediment leads to instability on the oversteepened sides. As pingos become inactive and waste, they generally do so from the top down, and the positive features become collapse features, leaving a circular or oval rampart often containing a pond or marshy area (Mackay 1988).

Other types of cryogenic mound, such as seasonal frost mounds, lithalsas (Calmels *et al*. 2008) or mineral palsas (Worsley *et al*. 1995) and organic palsas (Pissart 2000), that leave similar remnant features at a range of scales (up to about 100 m long and 40 m deep) have been described in the literature and probably form a continuum with pingos (Worsley *et al*. 1995). The key difference between mineral palsas (lithalsas) and organic palsas is the nature of the host soil (that of mineral palsas comprising mineral soil, albeit possibly capped with organic soil, whereas that of palsas is organic soil). They are associated with discontinuous permafrost, in contrast to pingos, which form as true permafrost features. Mineral palsas and palsas also differ from pingos in forming mounds of segregation ice by cryosuction rather than being supplied by groundwater pressure. Both pingos and palsas commonly form in clusters, but palsas commonly occur at a higher density and commonly coalesce. It is considered unlikely that these types of cryogenic mound would account for the significant depth of disturbance associated with the buried hollows.

Relict ground ice scars have been described elsewhere in the literature; the typical morphological evidence of Pleistocene pingos comprises circular or oval depressions of 25–250 m in diameter with ramparts, generally occurring in clusters (Ballantyne & Harris 1994). The root of the scar typically comprises disturbed sediment. Pingo scars are commonly associated with springs, and on slopes they tend to be elongated downslope (Ballantyne & Harris 1994). They occur in a variety of sediments, often located on plains, valley floors and lower valley sides where groundwater seepage takes place. The depth of the basin left by the pingo depends on the size of the ice core and the amount of material that is relocated to the margins through mass wasting while the pingo remains active. They are usually, but not always, ramparted. The central depression of pingo scars is usually infilled by clays and silts and/or organic debris and peat, possibly with free water (Hutchinson 1991). Despite the range of formational processes associated with different types of cryogenic mound the morphologies of the remnant features are comparable, rendering process discrimination from relict scars difficult. Documented British examples include ground ice scars in Wales (situated both north and south of the Late Devensian ice-sheet in west and mid-Wales), East Anglia, the Whicham Valley (Cumbria), the Isle of Man and Ireland (Bryant & Carpenter 1987). These remnants are progressively being destroyed, particularly as a consequence of anthropogenic modification (Hutchinson 1991), so that descriptions in the literature (e.g. Ballantyne & Harris 1994) are increasingly valuable. Hutchinson (1980, 1991) interpreted the hollows in London as relict open (hydraulic) pingo systems located where the London Clay wedges out against the Deptford pericline, which brings Chalk and Lower Tertiary aquifers to the surface, to form sites of artesian groundwater flow.

The maintenance of artesian pressures for sufficient duration for pingo growth would have required recharge to the aquifer either within a region of discontinuous permafrost (talik) or via unfrozen sub-channel taliks and the presence of an unfrozen recharge zone for the Chalk is speculative. The permafrost cap might reduce aquifer recharge and there is evidence for increased runoff in the region during cold stages (Cheetham 1980; Collins *et al*. 1996). The depth of permafrost within the London Basin during the Quaternary is not well defined (Hutchinson & Thomas-Betts 1990; Murton & Lautridou 2003), but a depth of permafrost of about 105 m is implicit in the study by Hutchinson (1991). Within the central parts of the London Basin, the Chalk is largely confined by a thickness of Palaeocene Sands, the Lambeth Group and the London Clay Formation. For groundwater to travel to the zone of pingo development a pathway through the confining layers would be required. Hutchinson (1980) proposed that an unfrozen root or pipe feature might be sufficient to provide this pathway. Faults offer a plausible alternative, particularly where there are known structural controls on groundwater upwelling. The strong negative pore pressure exerted by the growing ice would be sufficient to generate the disturbance that has been recorded in the buried hollows and this observation has been used by Hutchinson (1991) to support the concept of pingo formation.

There are features of the buried hollows that do not match the normally observed criteria for pingo scars; in particular, the absence of associated ramparts. Given that many of these features are associated with the river valleys it is possible that any ramparts have been eroded. A further consideration is that of relative sea level. It has been speculated that sea level was *c*. 30 m below the current levels at the time of the Devensian glaciation. Evidence for this comes from the occurrence of some 35 m of alluvium in the area of Canvey Island, and it would appear that this is not considered in the calculations of Hutchinson (1991) of the required piezometric levels for pingo formation. A final issue with the hypothesis that the buried hollows are depressions formed by the thawing of the pingo ice core is that this segregated ice is typically found near the surface, with a roughly planar basal surface (Mackay 1998). On melting, this would leave a relatively shallow and flat-bottomed feature.

Dual-process models

Hutchinson (1991) noted that the observational evidence points to a dual process of scour reducing overburden pressure and facilitating cracking of the London Clay Formation and thereby pore pressure release, albeit that there are some scour hollows that are not associated with diapirs (Appendix) and less commonly diapirs that are not associated with scour features (Berry 1979). In this scenario the scouring might be penecontemporaneous, as a consequence of the increased discharge associated with ameliorating climatic conditions and while low sea-level conditions prevailed. Alternatively, sediment that is already disturbed by diapirism might naturally form a focus for subsequent scouring. Segregation ice may have facilitated soft sediment deformation and diapirism, and the influence of artesian pore water pressure is implicit in the depth to which the disturbances occur and the potential for sediment injection. It has also been suggested that the diapiric intrusion of the underlying Lambeth Group into the London Clay beneath the buried hollows reflected zones of particularly high artesian pressure and possible weakening of the London Clay Formation and the Lambeth Group by freezing and thawing. Building on this, an alternative hypothesis to that of relict pingos is that the hollows are thermokarst features (Fig. 6). Further to the characteristic traits of thermokarst that are associated with the buried hollows and described above, it has been noted that a number of the buried hollows exhibit preferred orientations (NE–SW and NW–SE) of their long axes, which correspond to dominant fault orientations (Belayneh *et al*. 2007; Mortimore *et al*. 2011). Permafrost wasting might allow the release of pore pressures, possibly via faults or dominant joints such that they formed groundwater discharge points as permafrost melting occurred. Permafrost wasting might also be associated with channel beading (Pidwirny 2006). This hypothesis would not require the formation of pingos and might be associated with neotectonic movement on faults or dominant joints as permafrost wasting took place (de Freitas 2009). Such movement may have contributed to the thaw process. This hypothesis would also be in keeping with the apparent focus of artesian pressures on the bedrock low.

Differential wasting of ground ice as a consequence of differences in the thermal conductivity and diffusivity of the Chalk and overlying clays might also be significant. The specific heat capacity of Chalk is likely to be of the order of 0.18 kcal kg^{-1} °C^{-1}, whereas that of sandy clay is 0.33 kcal kg^{-1} °C^{-1} and that of quartz sand is 0.19 kcal kg^{-1} °C^{-1} (Engineering Toolbox, undated, http://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html). This suggests that the Chalk would be prone to permafrost wasting earlier than the overlying cohesive deposits. The Chalk thermal conductivity and diffusivity are likely to be higher than thoseof the clays (e.g. Busby *et al*. 2011). If significant, this too might facilitate earlier more rapid wasting in the recharge zone (North Downs and Chilterns) than in the basin, thereby increasing the artesian groundwater pressures. Fluvial sediments in nearby Chalk catchments show a very abrupt reduction in stream power and increased dominance by groundwater-controlled flow at the end of the last cold stage (Collins *et al*. 2006), which may reflect this process. Additionally and as a consequence of sea-level lowering, karstification of the Chalk (Mortimore *et al*. 2011), which is commonly focused on the boundary between specific flint bands and the chalk, might form a focus for groundwater flow to the recharge zones.

It is likely to be more than coincidental that the majority of the buried hollows fall within the footprint of a single graben bounded by the Northern Boundary Fault to the north and the Streatham and Greenwich faults to the south, where the Chalk is downthrown by some 50 m (Fig. 4; Royse 2010). The Chalk within this zone is expected to be highly deformed with a greater propensity for fracturing and faulting than may be elicited from current mapping activities. With indications that the Greenwich and Streatham faults and branches of the Northern Boundary Fault (Fig. 4) act as barriers to groundwater flow (Environment Agency 2013) an area of preferential groundwater discharge for buried hollow development may have developed within this faulted zone and may explain the clustering of buried hollows locally.

Conclusion

There are a number of examples of significant disruption resulting from the occurrence of buried hollows that have been reported in the literature (Higginbottom & Fookes 1970; Hutchinson 1991; Strange *et al*. 1998; Lenham *et al*. 2006; Paul 2009), which range from differential settlement of foundations to excessive local settlement and stability problems both in excavations and in tunnels with all the inevitable consequence of unforeseen ground conditions. There is also potential for buried hollows to form preferential pathways for contaminant migration. The benefits that the hazard susceptibility map that has been presented might bring in terms of ensuring adequate investigation in this area of Central London, where any overrun on projects is at considerable cost, are obvious. Interrogations of the layers that have been used to formulate the map have raised a number of additional questions regarding the genesis of the hollows. These have been summarized in Figure 6.

The associations demonstrated in the GIS layer are insufficient to verify or discard the processes associated with the formation of the buried hollows. Additional hypotheses for their formation that might also be considered have been presented. The occurrence of diapirs in areas beyond the area of known scour features suggests the occurrence of more extensive segregation ice within the permafrost zone and an alternative hypothesis is that permafrost wasting might allow the release of pore pressures, possibly via faults or dominant joints such that they formed groundwater discharge points as permafrost melting occurred and might be associated with neotectonic movement on faults or dominant joints as permafrost wasting took place.

Stratigraphical relationships are important in developing the understanding of the age and likely formational environment associated with the buried hollows. It has been suggested that terrace incision takes place at the warming limb of the climatic cycle (Bridgland *et al*. 2004) or alternatively during the cold (periglacial) phase of the climate cycle (Murton & Belshaw 2011). The latter would suggest that the hollows are associated with permafrost conditions. Of the 31 original occurrences 26 occur beneath the Kempton Park Gravel Member, which indicates that the hollows are of Devensian age or older. The remaining hollows are overlain by the Hackney Gravel Member (Wolstonian age), Shepperton Gravel Member (late Devensian age), Boyn Hill Gravel Member (Hoxnian–Wolstonian age) and interglacial lacustrine deposits, evidence that these features have occurred more than once during the Quaternary period.

Detailed lithological and tectonic descriptions (Phillips & Lee 2011) of buried hollows, as core becomes available, are necessary to further process understanding. Where possible, these should be based on high-quality coring, supplemented by geophysics as an approach to recording all new occurrences to further the 3D understanding of these features. Detailed description should contribute to understanding the processes associated with the sediment movement and likely extent of frozen ground at the time of formation (e.g. any shearing and the degree of roundness of the entrained clasts). Lee & Aldiss (2011) have adopted a lithofacies approach to core logging of ground disturbed by buried hollows. If adopted, these approaches will also provide the detail required to assess the extent of upward bedrock migration. In some cases downward migration of flint pebbles and glauconitic sand (derived from the Palaeogene strata; Aldiss, pers. comm.) also occurs. Through developing the process understanding it should be possible to further refine the hazard susceptibility associated with these features. Permafrost modelling would be a good way to test the hypotheses that have been presented.

Appendix

Table A1. *Characteristics of the documented buried hollows underlain by London Clay*

National Grid reference	Strata affected; characteristics of the disturbance	Level (m OD) of base of hollow or disturbance and basal strata	Plan dimensions and orientation of long axis	Classification	Reference
28928 77547	London Clay overlain by loamy sand laminated with blue or brown clay and subordinate gravel, capped by gravel and alluvium enclosing peat	−27 m; London Clay	N–S axis of combined hollows	Scour hollow; two depressions within a curvilinear depression, association with former meander in the lower floodplain of the alluvial deposits	1a of Berry (1979)
28880 77761	River Terrace Deposits extending down into the London Clay	−14.9 m; London Clay		Scour hollow	1b of Berry (1979)
2948 7752		−11.6 m		Scour hollow	1e, Battersea Gas Works of Berry (1979)
31261 77285		−10.2 m in London Clay	≥150 m	Scour hollow	2b, Brixton Road of Berry (1979)
30430 78002	Softened London Clay	−10.7 m; London Clay		Scour hollow	2e, Victoria Line, Vauxhall Station of Berry (1979)
30214 80285	Well-stratified basal gravel overlain by soft fine-grained alluvium capped by black mud, black clay or dark-coloured clay	−12 m; London Clay	Minimum 46 m; limits not fully known	Scour hollow	3d, Whitehall Place, Board of Agriculture Building of Berry (1979)
31714 80880		−9.7 m	200 m × 120 m E–W, parallel to channel	Scour hollow	3f, Blackfriars, Fleet of Berry (1979)
32833 80690		−9.7 m	Parallel to the channel	Scour hollow	3g, London Bridge, Walbrook of Berry (1979)
31452 80404		Minor hollow; London Clay		Upstream tip of a scour hollow	3h, Hatfields, Waterloo and City Railway of Berry (1979)
39517 80650	Stratified sand and gravel	Below −16 m; Lambeth Group		Scour hollow	7b, East Greenwich Gas Works of Berry (1979)
40291 79154	Fault? Chalk 15.3 m below local trends	Below −14.3 m; Thanet Sand Formation		Scour hollow	7c, Lee River–Thames junction of Berry (1979)
34715 76541	Slumped fill	Below −11 m; Thanet Sand Formation	Influenced by faulting (Berry 1979)	Scour hollow	8a, Peckham hollow
31600 84400	Dry sand encountered			Scour hollow	10a, Highbury Corner (Simpson *et al*. 1989)

Table A2. *Characteristics of the documented buried hollows with roots that extend below the London Clay*

National Grid reference	Strata affected; characteristics of the disturbance	Level (m OD) of base of hollow or disturbance and basal strata	Plan dimensions and orientation of long axis	Classification	Reference
29761 77642	Drift deposits comprise gravel with subordinate sand, clay and clay-bound pebbles. Boundary between London Clay and Lambeth Group elevated by 6.1 m	−29.6 m or deeper; Lambeth Group. In a second hole −27.7 or −31.7 m		Scour hollow	1c, Mieux Brewery of Berry (1979)
29642 77380	Up to 5 m of fine-grained, soft, silty, clays and sands with thin clay partings over gravel- and sand-filled hollow. Deposits coarsen downwards. Clay fragments towards the base	−17.6 m	170 m × 60 m; NE–SW	Scour hollow	1d, Battersea Gas Works of Berry (1979)
2965 7762		−24 m (Simpson *et al*. 1989)		Scour hollow	1f, Mieux Brewery of Berry (1979)
30142 77880	London Clay–Lambeth Group boundary elevated by 7.9 m	−27.4 m; Claystone	Linear NE–SW; asymmetric, steep cliff in London Clay on northern side	Scour hollow	1g, Market Tower, New Covent Garden of Berry (1979)
30666 76761	Drift to −15.2 m OD (12.2 m lower than the local trend). Borehole TQ 37NW/490 revealed drift in contact with 4.9 m of mottled clays and fine silts and sands, interpreted as Reading Beds at −16.1 to −21 m OD and 9–12 m above the local trend of the London Clay–Lambeth Group boundary	−16 m; London Clay	Possibly NNW–SSE, of the order of 500 m	Scour hollow with two additional hollows encountered during tunnelling works	2a, Clapham Road, South Lambeth, (Berry 1979)
30571 77642	London Clay. Lower part of fill slipped and recumbently folded beds of sand, within a gravelly matrix	−22.6 m; London Clay		Scour hollow	2c, Victoria Line, Vauxhall Park of Berry (1979)
30452 77833	Fill of sands, sandy gravel and sandy clay forming two descending cone-shaped masses of sand and sandy gravel separated by a vertical wall of London Clay	−17.7 m; London Clay	*c*. 9 m across	Scour hollow	2d, Victoria Line, Lawn Lane, Vauxhall Grove of Berry (1979)
29690 79047	Fill of dense gravels that are stratified and interbedded with thick strata of more sandy material. Base of the soft alluvium and sands overlying the hollow is slightly higher than adjacent levels	−18.3 m; London Clay	210 m × 150 m; NW–SE	Scour hollow	3a, Horseferry Road of Berry (1979)
29857 79476	Lenticular mass of apparently well-stratified silty clays, silts and sandy strata below normal levels and resting on thinner gravels and stony sands	Lower than −27.1 m; London Clay	90 m × 75 m; NW–SE	Scour hollow, squarer in plan form	3b, Board of Trade, Abbey House, Victoria Street of Berry (1979)
30238 79999	Fill of redeposited London Clay interbedded with sand and gravel	−19.5 m; London Clay	NE–SW	Scour hollow	3c, Ministry of Defence (Whitehall No. 1), Richmond Terrace of Berry (1979)
30547 80119	Gravel with interbedded sands	−27.1 m; London Clay	160 m × 130 m; NE–SW	Scour hollow	3e, Bakerloo Line, Hungerford Bridge of Berry (1979)
33166 80285	Basal sand with pebbles and clay laminae overlain by coarse and finer gravels	−11 m	60–90 m		3i, Hayes Wharf of Berry (1979)
32238 79142	Gravels and sands overlain by Alluvium, including up to 5.5 m of peat	Below −19.5 m; Lambeth Group	In excess of 300 × 200 m; WNW–ESE	Scour hollow	4a, Southwark, Rockingham Street of Berry (1979)
30904 82404*	Lambeth Group clays. Two lobes of the hollow with differing fill	Below −20 m; Lambeth Group	305 m; NE–SW	Scour hollow	5a, Gray's Inn Road, Calthorpe Street of Berry (1979)
37641 73568	Rise of 12.2–15.2 m in the boundary between the London Clay and the Lambeth Group. Hollow filled with cobbles and gravel with subordinate sand and clay lenses	−9.7 m; Lambeth Group	200 × 300 m; NNE–SSW	Scour hollow	6a, Catford, Lewisham Town Hall of Berry (1979)
38583 80409	Scour hollows filled with slipped Pleistocene gravels and sands over finer-grained deposits	−29.3 m; Lambeth Group sands	185 m features within an overall feature of at least 165 m; NE–SW	Scour hollow	7a, Blackwall Tunnels of Berry (1979)
04100 77900	Lambeth Group uplifted by *c*. 12 m			Scour hollow	9a, Three Valleys Water Tunnel, Thorney (Simpson *et al*. 1989)
31800 73900	Basal Sands in vertical feature	Boyn Hill Terrace			11a, Tulse Hill, Lambeth (Simpson *et al*. 1989)

*Associated with higher level of the terrace.

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