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# Buried (drift-filled) hollows in London – a review of their location and key characteristics

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**Abstract:** This paper compiles new and existing information relating to features frequently referred to as drift-filled hollows located within London. The key aim of this paper is to update the article written by Berry (1979, 'Late Quaternary scour-hollows and related features in central London', *QJEG*, **12**, 9–29, https://doi.org/10.1144/GSL.QJEG.1979.012.01.03), producing a resource for both engineering projects and academic research. Fifty-four additional drift-filled hollows have been identified and their physical characteristics are tabulated where available information allows. A case study of the Nine Elms area is presented. The drift-filled hollows have been identified through examination and critical, quality assessment of historical borehole records, site investigation records, construction records and published articles. This enlarged dataset illustrates the high level of variability between features and, as a result, it is proposed that these features did not form due to a single process, but to differing processes.

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In 1979, the *Quarterly Journal of Engineering Geology* published a paper by Frank Berry of the Institute of Geological Sciences (now the British Geological Survey) titled 'Late Quaternary scour-hollows and related features in central London'. Despite its age, Berry's paper is still a common reference in geotechnical and engineering geological desk study reports for development projects in central London.

In the 40 years since the publication of this paper, the urban landscape of London has been transformed by mass high-rise developments and below-ground construction. These developments have, often inadvertently, uncovered a significant number of features similar to those described by Berry.

The near-surface geology of London was historically viewed as simple and predictable in engineering terms. The features first listed by Berry are a reasonably well-known exception to this view. Historically, these anomalies have been referred to as scour features, scour hollows, pingos, pingo scars and, more recently, as drift-filled hollows (DFHs).

In this paper we present an update to Berry's original work using a modern dataset and thus provide a renewed desk study resource. Furthermore, a case study for the Nine Elms area in Battersea is presented. An additional aim of the paper is to discourage the use of names for these features that suggest or imply a particular mode of formation.

Berry (1979) presented the first systematic study of these anomalies, identifying 28 features and attributed their formation to Quaternary fluvial scour. Subsequently, Hutchinson (1980, 1991) interpreted them as a combination of scour features and groundwater discharge features, with the latter possibly being the roots of periglacial open system pingos of possible Late Devensian age. Pingos are one type of ice-cored mounds (in addition to, for example, lithalsas, palsas etc.) found in areas with permafrost (cf. Mackay 1998).

More recently, DFH research has focused upon individual features identified mainly during site investigations for large-scale engineering projects (e.g. Newman 2009; Lee and Aldiss 2012; Bellhouse *et al.* 2015; Davis *et al.* 2018). Banks *et al.* (2015) developed this work to produce a hazard susceptibility map showing areas where DFHs were more likely to occur.

The significance of DFHs lies both within the engineering and scientific sectors. For geoscientists, the processes which lead to their formation and what the features can reveal about previous environments is still very much a topic of ongoing debate, for which further evidence-based research is required. For engineers, DFHs present anomalous, potentially unforeseen ground conditions with associated geotechnical hazards that must be identified and mitigated during the design and construction phases of a project.

Potential ground engineering design and construction hazards created by DFHs include, but are not limited to, unexpected differential settlement, a lack of groundwater cut-off, reduction in pile capacity, migration of contaminants from shallow to deep aquifers, pile bore and diaphragm wall collapse, tunnel face collapse and a high level of groundwater ingress into excavations. Many of these have safety implications as well as increasing costs to the client. The selection of appropriate construction techniques can also be problematic. These engineering hazards are compounded by the highly developed nature of London which often limits opportunities for extensive ground investigation – an issue that is further amplified by the features not currently being identifiable above ground due to a lack of surface expression.

## Geological setting

The London Basin is a post-Variscan sedimentary basin (Busby and Smith 2001) that is underlain by a block of Paleozoic rocks known as the London Platform. The DFHs described in this paper are mostly located within an asymmetrical synclinal structure that consists of a faulted fold of Cretaceous (chalk) and Paleogene strata (Thanet Formation up to the London Clay Formation) (Ellison *et al.* 2004). This geological sequence and structure created a confined aquifer system beneath the London Clay Formation ('London Clay'). The Seaford/Newhaven Chalk and Thanet Formation confined aquifer later became unconfined to the east of central London due to Quaternary uplift and erosion (Royse *et al.* 2012).

The Quaternary is principally represented by Pleistocene River Terrace Deposits (RTD) (Maidenhead and Lea formations; Bowen 1999) which form an upper unconfined aquifer. The DFHs themselves are understood to be anomalous depressions in the upper Cretaceous or Paleogene rockhead surface. These depressions are most frequently filled with Quaternary sediments, but some also contain Paleogene or Cretaceous sediments.

## Definitions and limitations

London, in this paper, is loosely defined as the area of confined or formerly confined lower aquifer (the Chalk and Thanet Formation) within the M25 motorway (Fig. 1).

The non-genetic term 'drift-filled hollow' (DFH) is used in this paper purely as a descriptive term. It does not imply any particular mode or modes of formation for the feature.

The use of 'drift' to describe the infill materials is preferred here because of its long-standing historical use to describe 'superficial' deposits of glacial, periglacial or Holocene origin and because it is free from any meaning related to possible modes of formation. However, it should be noted that 'drift' is not the only infilling material.

A DFH is here defined as an anomalous closed-form depression in the pre-Quaternary rockhead surface. 'Anomalous' is used instead of any fixed dimensional criteria and is relative to the surrounding local rockhead surface. This choice is born largely out of practicality. The term 'closed form' is used to exclude any continuous channel-like erosional features or rockhead steps within current or former Quaternary floodplains.

All features identified within this paper are grouped due to their anomalous depth to the local bedrock.

Any of the following individually or in combination are defined as 'disturbed' when considering DFH infill:

(1) disorganized contents – 'mélange' is used to refer to infill containing de-structured or brecciated remnants or mixtures of some or all of the Quaternary, Paleogene or older strata;
(2) disordered contents (e.g. London Clay above RTD);
(3) uplifted strata – strata beneath a DFH that are anomalously elevated. Any evidence of uplift must appear to be related to the closed form of the DFH;
(4) disturbed or unusually discontinuous strata below a DFH – as noted in (3), the disturbed strata arrangement must appear to be related to the closed form of the DFH.

Evidence of faulting in the underlying strata is, by itself, not sufficient to warrant a 'disturbed' classification, nor is the presence of naturally discontinuous strata (e.g. Lambeth Group sand channels).

Knowledge of the existence and the nature of almost all of the DFHs listed in this paper is based on data obtained from published journal articles, historical borehole records from the British Geological Survey's (BGS) GeoIndex tool (http://www.bgs.ac.uk/GeoIndex/2019), recent ground investigation borehole logs and

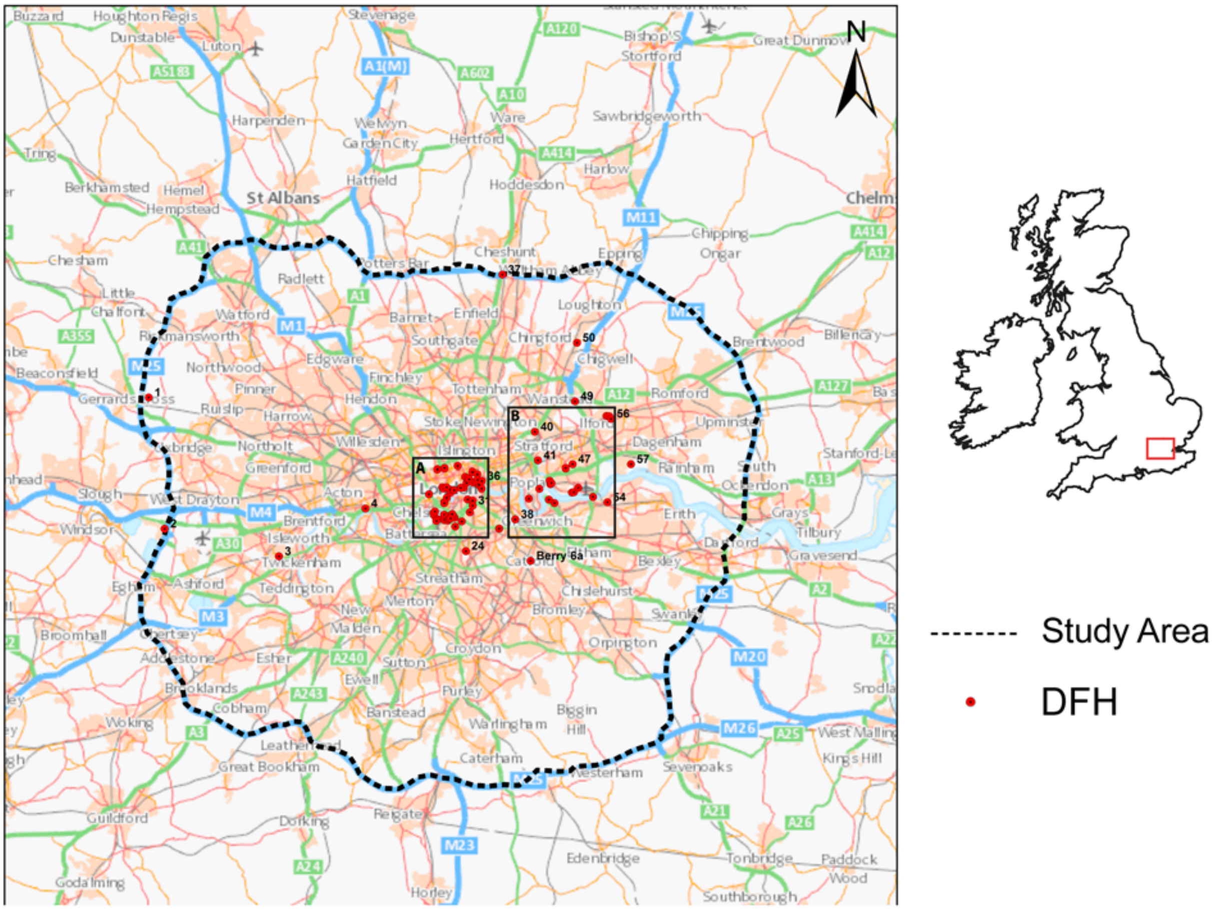


**Fig. 1.** Location of drift-filled hollow (DFH) features within the study area.

tunnelling or construction records. The reliability of the information provided in Table 1 is restricted by the quality of the primary data.

The identification method of the features documented within this paper has varied as stated above. However, the vast majority have been established through borehole exploration. An example cross-section is shown in Figure 2, illustrating an anomalous depth of infill to 17.5 m (depth from ground level) in comparison to the local level of London Clay at 8 m (depth from ground level). This illustrates how DFHs are identified through their anomalous depth to local bedrock.

Potential limitations to using boreholes, especially historical ones, for identifying DFHs include:

- difficulties in establishing the absolute ground level at the time of drilling relative to Ordnance Datum;
- historical, non-standardized soil descriptions that require retrospective interpretation;
- the tendency for older, non-standard records to try and fit the ground to the expected sequence when naming strata;
- a lack of knowledge of the adopted drilling techniques, the effect these techniques have on the samples retrieved and, in turn, interpretation for borehole logs;
- the limited number of boreholes and their often limited depths hinder identification and characterization of features;
- confidentiality issues often limit access to historical borehole data and ground investigation data;
- the tendency for ground investigation at urban sites to be constrained within development boundaries and within project design requirements, limiting the understanding of the full lateral extent of features.

This inevitably leads to difficulty in precisely defining DFH morphology and extent. As a result, the width, depth, elevation and strata data given in Table 1 are all apparent values that should be treated with an appropriate level of caution. It is likely that in almost all cases additional data would amend the implied DFH morphology to some extent. The data does, however, give an insight into the overall level of size and shape variability.

When considering the distribution of the identified DFHs, there is a significant geographical bias in the data due to the spatial variability in the types of development that have occurred. The majority of the nineteenth and twentieth century development in London comprises low-rise structures, which are typically founded above the water table in the RTD. Deeper modern boreholes are mostly associated with tunnelling projects, heavily loaded structures and structures with deep basements.

These factors mean that the extensive publicly available borehole archive for London is heavily biased towards finding the top of the RTD and shallow groundwater levels. Over much of London, deeper investigations have not been routinely carried out. As a result, many structures may well have been built without any knowledge of the deeper geology and its potential to contain DFHs.

## The drift-filled hollows

A total of 84 DFHs are listed in Table 1 with the following information, where available:

(1) name and number (1–84, ordered west to east);
(2) Ordnance Survey (OS) National Grid coordinates;
(3) estimated width;
(4) estimated depth below ground level;
(5) estimated elevation for the DFH base;
(6) strata at the base of the DFH;
(7) any evidence of uplift (‘uplift’ is the preferred term to diapir as it does not imply a formation process);
(8) any evidence of faulting;
(9) any evidence of ‘disturbed’ infill;
(10) information source (including a reference to a key BGS borehole if relevant); and
(11) any further relevant notes.

The locations of the DFHs are shown in Figures 1, 3 and 4.

Features are named and numbered from west to east. Any further sources of information on features, where available, have been noted. Any missing data in Table 1 are either unknown or confidential.

It is plausible that some adjacent features noted separately in Table 1 may be part of a single larger feature. This is due to ground investigations typically being restricted to development boundaries and can lead to data gaps between development sites. Where these gaps in the data exist, a connection between two neighbouring DFHs cannot be reliably established and therefore they must be recorded here as individual features.

Finally, DFHs which Berry (1979) identified have been included in Table 1. Where further information is now available or where errors have been recognized (e.g. Berry 3i where the depth of infill noted in the borehole cited is different to the borehole log itself), the relevant information has been updated with references noted. Berry’s nomenclature is unchanged.

## Physical characteristics

Figure 5 depicts several characteristics of DFHs shown in Table 1 as the percentage of features identified with each characteristic or whether it is unknown due to data restrictions. This illustrates the range of physical characteristics that DFHs can feature. In particular, it emphasizes both their variability and the unknowns associated with DFHs. The large proportion of unknowns is due to their variability, both between features and within a single feature, and the mode of understanding these features being through, most often, borehole exploration.

The limitations of boreholes for understanding the features of DFH are further demonstrated when grouping the characteristics of features within the dataset (Table 1 and Fig. 5). This is due to the analysis and grouping being based upon an interpretation of borehole and tunnelling logs, which in themselves are a mostly qualitative interpretation of a very small proportion of the subsurface.

These limitations of understanding are inherent and unavoidable at present due to the investigation techniques which have been undertaken on these features. Therefore, acknowledging the uncertainty and risk these features induce due to their variability is crucial. Likewise, it is essential to understand the constraints of the dataset caused by the restricted investigation. A primary example of this is the potential for the features’ infill to not solely contain superficial deposits, but also fragments of the surrounding bedrock deposits, as shown in Figures 6 and 7. Borehole spacing leads to the potential for bedrock within a feature’s infill to be missed or for the full extent of the bedrock clasts within the infill to be misunderstood. In turn, this would then be reported as a DFH within organized infill due to no bedrock recorded within the borehole log.

## Nine Elms

The Battersea and Nine Elms area south of the River Thames has an abundance of identified DFH features. For this reason, the elevation of the top of the London Clay was plotted between Vauxhall and Battersea (Fig. 8) to visualize its variability within the area.

This map was derived from 384 boreholes identified using the BGS GeoIndex tool and obtained from several individual site investigations. The borehole data were only included where there was a known Ordnance Datum, easting, northing and the top of London Clay was positively identified without query. The data were

**Table 1.** *Known drift-filled hollows (as of September 2019) and their associated characteristics*

| Feature name and number | Easting | Northing | Width (m) | Depth (m GL) | Base elevation (m OD) | Strata reached at base | Disturbed infill | Evidence of uplift | Evidence of faulting | Key BGS BHs (where available) | Source (where BGS is noted, from GeoIndex tool) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 – Slade Oak Lane | 502 319 | 188 685 | 40 | 40 | −37.5 | Chalk | Y | N | Y | | Gibbard *et al.* (1986) | |
| 2 – Bath Road | 503 782 | 176 576 | 55 | 32 | | LG | Y | Y | | | Simpson *et al.* (1989), Baker and James (1990), Banks *et al.* (2015) | Lambeth Group 12 m above the immediate local level. |
| 3 – Whitton | 514 361 | 174 030 | 400 × 150 | 30 | −16 | LC | N | | | | Staniforth *et al.* (1994), Newman (2009) | |
| 4 – Hammersmith A4 | 522 354 | 178 463 | | 30.05 | >−24.7 | | Y | | | | Confidential | Steep-sided feature trending NE–SW. |
| 5 – Hyde Park Corner | 528 240 | 179 780 | | 14.32 | −0.3 | LC | | | | TQ27NE33 & TQ27NE755 | BGS | Relatively undisturbed infill of layered clay, sand and into gravel before reaching the London Clay Fm. |
| 6 – Grosvenor Waterside | 528 640 | 178 040 | | 18 | −12.5 | LC | N | | | TQ27NE1564 | BGS | |
| Berry 1b | 528 739 | 177 812 | 3 | | −14.9 | LC | | | | | Berry (1979) | |
| 7 – Pimlico | 528 790 | 178 190 | 66 | | | LC | N | | Y | | Newman (2009) | |
| 8 – Battersea Power Station 2 | 528 923 | 177 310 | | 10 | 12 | LC | N | N | Y | | Battersea Power Station ground investigation | Smaller depression identified south of the larger Battersea Power Station feature. |
| Berry 1a (Battersea Power Station) | 528 940 | 177 511 | 200 × 125 | 36.2 | −27 | LC | N | N | | TQ27NE1606 | Edmunds (1931), Higginbottom and Fookes (1970), Berry (1979) | |
| 9 – Carburton Street | 529 024 | 182 052 | | 10–15 | | LG | Y | Y | Y | | Cox (1992) | Lambeth Group uplifted in relation to local level. |
| 10 – St James Square | 529 471 | 180 434 | | 15.2 | −2 | LC | Y | | Y | | Confidential | London Clay Fm. varies in depth across a short distance. Faulting is identified through the sharp vertical contact between the RTDs and the London Clay Fm. |
| Berry 1e | 529 487 | 177 506 | | 12.255 | −11.6 | LC | | | | TQ27NE625 | Berry (1979) | |
| Berry 1d (Battersea Gas Works) | 529 602 | 177 521 | | | −18.3 | LC | | | | TQ27NE154/B | Berry (1979) | |
| Berry 1d (Battersea Gas Works 2) | 529 602 | 177 521 | 170 × 60 | 28.8 | −17.6 | LC | | | | TQ27NE157/B | Berry (1979) | Feature 183 m NE from Berry 1d. |
| 11 – Dolphin Square (Thames) | 529 643 | 177 883 | >20 | | >−22 | | | | | | Confidential | |
| 12 – Elverton Street | 529 650 | 178 950 | | 15.9 | −11.3 | LC | | | | TQ27NE516 | BGS | |
| Berry 3a | 529 667 | 179 042 | 210 × 150 | 22.12 | −18.3 | U | N | | | TQ27NE230 | Berry (1979) | |
| 13 – Gower Street | 529 681 | 182 165 | 20 | 22 | | LG | Y | N | Y | | Cox (1992) | |
| 14 – Post Office Way | 529 683 | 177 372 | | 21.95 | −18.25 | LC | | | | TQ27NE154/B | BGS, Northern Line Extension | |
| Berry 1c | 529 806 | 177 605 | | | −31.7 | LG | Y | Y | | | Edmunds (1931), Berry (1979), BGS | Lambeth Group elevated by 6.1 m. Two features mentioned within the same paragraph of Berry (1979), possibly linked. |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 – Suffolk Street | 529 855 | 180 440 | | 13.72 | −2.64 | LC | Y | Y | | TQ28SE130 | BGS | |
| Berry 3b | 529 882 | 179 465 | 90 × 75 | 25 | −27.1 | LC | | | | TQ27NE387 | Berry (1979), BGS | |
| 16 – Ponton Road | 529 940 | 177 662 | 80 | 12.3 | −8 | LC | Y | | | | Confidential | Potentially an extension of Berry 1c (Meux's Brewery). |
| Berry 1f | 529 962 | 177 590 | | 15.24 | −11.58 | | | | | | Berry (1979) | |
| Berry 1g | 530 130 | 177 766 | | 30.5 | −27.4 | LG | Y | Y | Y | | Berry (1979), Banks *et al.* (2014) | Lambeth Group elevated 7.9 m. |
| Berry 3d | 530 139 | 180 217 | 46 | 10.8 | −12 | LC | N | | | TQ38SW1247 | Berry (1979) | |
| 17 – Wandsworth Road | 530 164 | 177 548 | | 13.6 | −9.8 | | | | | | Confidential | Elongated feature trending NE–SW. |
| Berry 3c | 530 233 | 179 943 | | | −19.5 | LC | Y | | | | Berry (1979) | |
| 18 – South Lambeth Road | 530 239 | 177 540 | | 11.6 | −7.3 | LC | N | | | TQ37NW1476 & TQ37NW1472 | BGS | |
| Berry 2e | 530 386 | 177 947 | | | −10.7 | LC | | N | | | Berry (1979) | |
| Berry 2d | 530 477 | 177 798 | 9 | | −17.7 | LC | Y | | | | Wakeling and Jennings (1976), Berry (1979) | |
| Berry 3e | 530 569 | 180 148 | 160 × 130 | | −27.1 | LC | N | N | | TQ38SW1282 | Berry (1979) | |
| Berry 2c | 530 612 | 177 606 | | 19 | −22.6 | LC | Y | | Y | TQ37NW456-7 | Berry (1979) | |
| Berry 2a | 530 668 | 176 788 | 500 | 21.8 | −16.1 | LG | Y | Y | | TQ37NW486-491 | Berry (1979), Banks *et al.* (2014) | |
| Berry 5a | 530 889 | 182 350 | 305 × 240 | 6 | 13.5 | LG | Y | | | TQ38SW1093 | Wakeling and Jennings (1976), Berry (1979), BGS | |
| 19 – Coin Street | 531 180 | 180 380 | | 15.73 | −11.25 | LC | N | | | TQ38SW2992 & TW38SW6 | BGS | |
| Berry 2b | 531 271 | 177 272 | 150 | 16.75 | −11.19 | LC | N | | | TQ37NW610 | Berry (1979), BGS | Berry (1979) borehole not available. Borehole reference provided here shows a cross-section of the DFH. The Berry paper states −10.2 m OD for the depth of the depression. The BGS borehole cited states −11.19 m OD (16.75 m depth). |
| Berry 3h | 531 456 | 180 383 | | | | LC | | | | | Berry (1979) | |
| 20 – Farringdon Street | 531 580 | 181 390 | 60 × 30 | 5.18 | 3.23 | LC | | | | TQ38SW525/B | BGS | |
| 21 – Brockwell | 531 654 | 174 519 | 100 | 11.8 | | LG | N | | | | Newman (2009) | |
| Berry 3f | 531 720 | 180 838 | 200 × 120 | 14.1 | −9.7 | LC | | | | TQ38SW762/H | Berry (1979), BGS | |
| 22 – Old Bailey | 531 792 | 181 289 | | 12.5 | −2 | LC | | | | TQ38SW2703 & TQ38SW2716 | BGS | Chalk gravel noted in the borehole logs. Feature trending NW–SE. |
| 23 – London Road | 531 821 | 179 300 | 150 × 60 | 13.05 | −9.75 | LC | N | | | TQ37NW1710 | BGS | Small feature. RTDs 3 m deeper than local level. |
| 24 – Ave Maria Lane | 531 940 | 181 177 | | 17.25 | −4.15 | LC | N | | | TQ38SW2741 | BGS | |
| 25 – Pasley Park | 532 010 | 178 110 | | 10.1 | −7.4 | LG | Y | Y | | TQ37NW2321 & TQ37NW2325 | BGS | Lambeth Group uplifted by 3–4 m. Full extent of feature is unknown. Trends NE–SW. |

*(continued)*

**Table 1.** *(Continued)*

| Feature name and number | Easting | Northing | Width (m) | Depth (m GL) | Base elevation (m OD) | Strata reached at base | Disturbed infill | Evidence of uplift | Evidence of faulting | Key BGS BHs (where available) | Source (where BGS is noted, from GeoIndex tool) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Berry 4a | 532 253 | 179 181 | 300 × 200 | | −19 | LG | | | | TQ37NW2432 | Berry (1979), BGS | |
| 26 – Barbican | 532 258 | 181 823 | | | | | | N | | | Baker (1885) | |
| 27 – Elephant and Castle | 532 270 | 179 195 | 300 | | −15 | LC | N | N | | TQ37NW2432 | BGS | Peat-filled depression underlain by alluvium. |
| 28 – Heygate Street | 532 280 | 178 730 | | 10.7 | −7.45 | LC | N | | | TQ37NW752 & TQ37NW753 | BGS | |
| 29 – Little Trinity Lane | 532 310 | 180 870 | | 8.7 | −4.9 | LC | | | | TQ38SW1943/A & TQ38SW1943/B | BGS | |
| 30 – Cannon Street | 532 571 | 180 986 | 15 × 11 | 21.03 | 32 | Chalk | Y | Y | Y | | Cox (1992) | Chalk 16 m above the immediate local level. |
| 31 – Moorgate | 532 703 | 181 638 | 70 | 11.9 | −10 | LC | N | N | N | | Crossrail, Davis *et al.* (2018) | |
| 32 – Cornhill | 532 747 | 181 102 | | 19.8 | | LC | | N | N | TQ38SW3074 | Bank Station desk study, Mott MacDonald, BGS | |
| Berry 3g | 532 840 | 180 629 | | 15.5 | −9.7 | LC | | | | TQ38SW787 | Berry (1979), BGS | |
| Berry 3i | 533 111 | 180 302 | 90 × 60 | 9.4 | −6 | LC | | | | TQ38SW1948 | Berry (1979) | Corrected from Berry (1979). |
| 33 – Lime Street | 533 132 | 181 001 | | 12.2 | 4.95 | LC | Y | N | Y | TQ38SW5178 | BGS | Extensive polishing of the London Clay Fm. |
| Berry 8a | 534 736 | 176 600 | | 18.6 | −11 | TS | | | Y | | Berry (1979), Banks *et al.* (2014) | |
| 34 – Great Cambridge Road (Waltham Cross) | 535 031 | 200 064 | | 28.6 | −5.26 | Chalk | | | | TL30SE136 | BGS | |
| 35 – New Cross | 536 216 | 181 638 | <250 × 100 | 16.6 | | TS | Y | Y | | TQ37NE1271 & TQ37NE1677 | BGS | A peat melange-filled depression with chalk pebbles/nodules noted in the fill. Chalk level is at −9 m OD. |
| 36 – Tiller Road | 537 473 | 179 364 | | 31 | −28.95 | Chalk | N | | | TQ37NE1452 | BGS, Jubilee Line extension ground investigation (1978) | Full extent unknown. Borehole ends in structureless chalk with fragments of intact chalk. |
| Berry 6a | 537 644 | 173 614 | 300 × 200 | 26.5 | −9.7 | LG | Y | Y | | TQ37SE747 | Berry (1979), BGS | The London Clay Fm./Lambeth Group boundary is elevated 12.2–15.2 m above the immediate local level. |
| 37 – Temple Mills Lane (Olympic Park) | 538 031 | 185 506 | 150 × 100 | 65 | −56 | Chalk | Y | Y | | TQ38NE1366 | Lee and Aldiss (2012), BGS | Chalk 20 m above the immediate local level. |
| 38 – Three Mill Lane (BGS Lea) | 538 316 | 182 858 | | 11.7 | −6.16 | LC | Y | | | TQ38SE2867 & TQ38SE1987 | BGS | |
| Berry 7a (Blackwall Tunnel) | 538 443 | 180 283 | 185 × 165 | 31.97 | −30.5 | Chalk | Y | Y | Y | TQ38SE110–113 & 140–141 | Berry (1979), BGS | The larger feature under the Thames. Chalk uplifted by 15 m. |
| Berry 7a (Blackwall Tunnel 2) | 538 443 | 180 283 | 50 | | −14 | LG | N | N | Y | TQ38SE110–113 & 140–141 | Berry (1979), BGS | The second smaller feature overlain by peat. |
| 39 – Bromley Park (Beckenham) | 538 869 | 170 277 | | 11 | 21.03 | Chalk | Y | Y | | TQ37SE540 & TQ37SE161 | Banks *et al.* (2014) | Chalk 20 m above the immediate local level. |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 – Board Street | 539 332 | 179 287 | | 18.2 | −17.1 | LG | | | | TQ37NE1470 | BGS, Jubilee Line extension ground investigation (1978) | |
| 41 – Limmo 2 | 539 388 | 181 034 | | 45 | −30 | LC | N | N | Y | | Crossrail | |
| Berry 7c | 539 462 | 180 705 | | 19.2 | −14.3 | LC | Y | Y | Y | TQ39498067 | Berry (1979), BGS | Chalk 15.3 m below immediate local level. |
| 42 – Limmo 1 | 539 566 | 180 820 | 450 | 24.8 | −20 | LC | N | N | Y | | Crossrail | |
| Berry 7b | 539 839 | 178 971 | | 18.97 | −16 | TS | N | | | TQ37NE1307/J | Berry (1979), TFL, BGS | Berry (1979) borehole not available in GeoIndex. |
| 43 – Jenkins Road West Ham | 540 886 | 182 153 | | 16.9 | −14.8 | LC | | | | TQ48SW408 & TQ48SW409 | BGS | |
| 44 – Greenway (Lee Tunnel) | 541 520 | 182 511 | | 75.5 | −67.09 | Chalk | Y | Y | Y | TQ48SW2085 | Bellhouse *et al.* (2015) | Chalk 20 m above the immediate local level and the Thanet Sand Fm. 10 m lower. |
| 45 – Wards Wharf Silvertown | 541 525 | 179 868 | | 18.5 | −15.24 | TS | | | | | Confidential | |
| 46 – Redbridge Station | 541 742 | 188 329 | | 3.8 | 5.57 | LC | LC | | | | TQ48NW220 | BGS |
| 47 – Albert Road (Berry Roding Buckhurst) | 541 926 | 193 749 | | >20 | | LC | N | Y | | | Discussed at the end of Berry (1979) | BH data confidential. Berry notes ‘diapiric’ movement of the chalk. The confidential boreholes only reach the top of the London Clay Fm. and there are no other publicly available deep boreholes in this location. |
| 48 – Hartmann Road | 542 044 | 180 377 | | 17.7 | −12.95 | TS | N | | | TQ48SW466 | BGS, Jubilee Line extension ground investigation (1978) | |
| 49 – North Woolwich on Thames | 543 408 | 179 535 | 400 × 200 | 20 | −10 | Chalk | N | N | Y | | Lenham *et al.* (2006) | |
| 50 – Crossrail Ilford Depot | 544 661 | 186 972 | | >25 | <−4 | LC | N | N | | | Crossrail | |
| 51 – Pettman Crescent | 544 746 | 179 037 | | 11 | −6.9 | TS | N | N | Y | TQ47NW401 | BGS, Jubilee Line extension ground investigation (1978) | |
| 52 – High Road, Ilford | 544 905 | 186 935 | | >11.5 | | LG | | | | | Confidential | |
| 53 – Green Lane Ilford | 545 083 | 186 708 | | | −16 | | N | | | | Confidential | |
| 54 – Renwick Road (Barking) | 546 928 | 182 507 | 100 | 45 | −39.46 | TS | Y | Y | Y | | Confidential | Chalk 15 m above the immediate local level. |

GL, ground level; LC, London Clay Fm.; LG, Lambeth Group; OD, Ordnance Datum; TS, Thanet Fm..

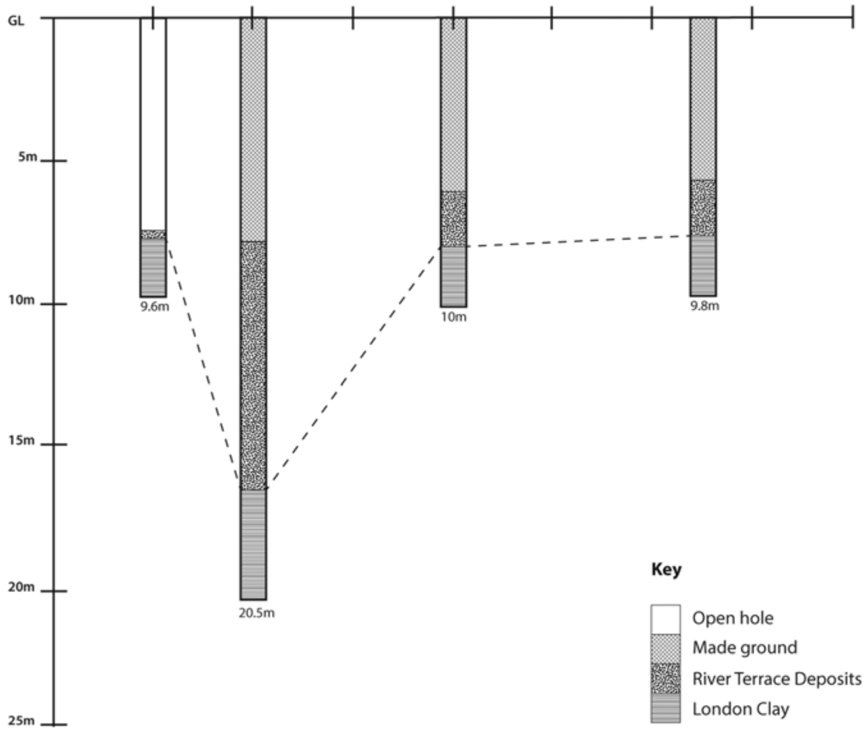


**Fig. 2.** A borehole cross-section of DFH '8 – Battersea Power Station 2'. The vertical scale is shown at 5 m and horizontal at 10 m. GL, ground level.


**Fig. 3.** Location of features within box A shown in Figure 1.

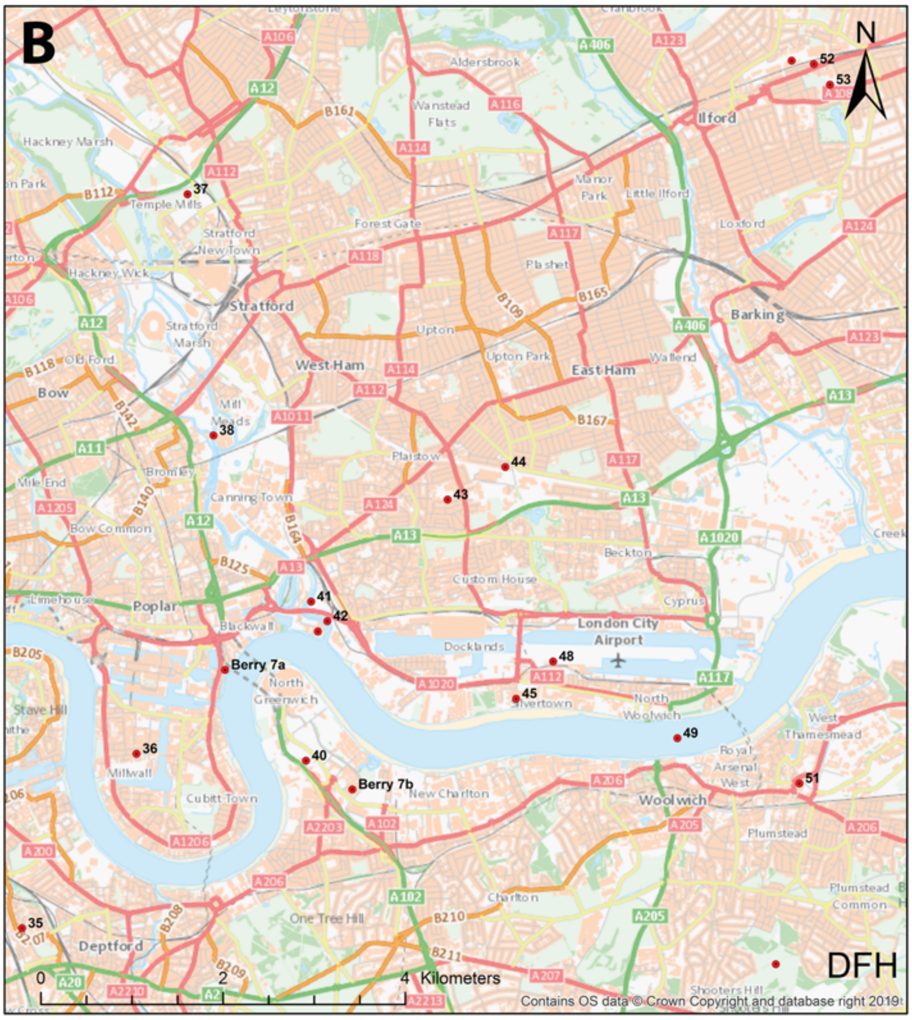


**Fig. 4.** Location of features within box B shown in Figure 1.

computed using ArcMap (Version 10.5.1) and interpolated using inverse distance weighted (IDW).

A number of points can be noted from Figure 8.

- The elevation of the upper surface of the London Clay is not constant and varies by more than 30 m across the mapped area. The consistently high area, shown at the south of the

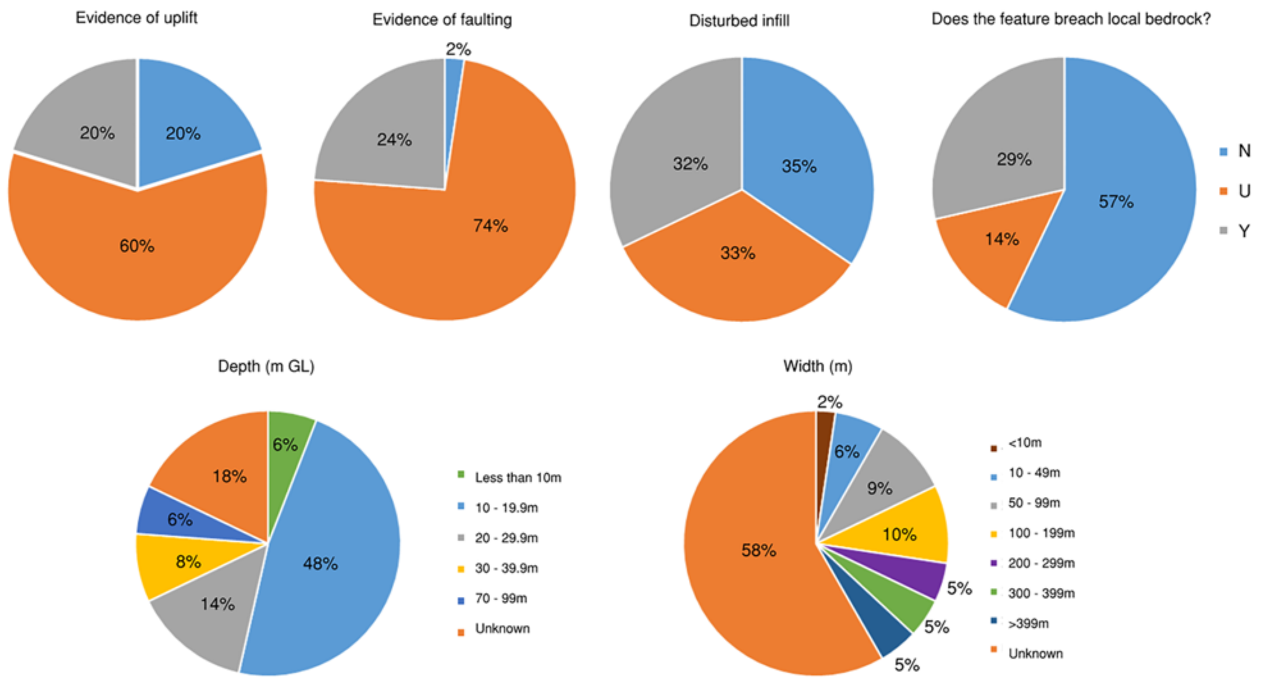


**Fig. 5.** Percentage of DFH with the physical characteristics identified within Table 1.

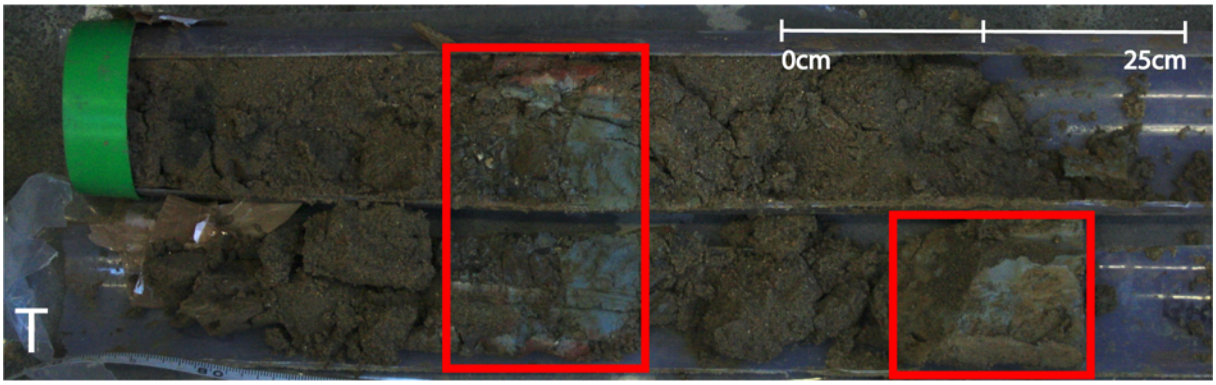


**Fig. 6.** Lambeth Group material identified within a borehole from central London; within DFH infill of otherwise silt and sand deposits. The Lambeth Group material located within this borehole is around 12 m above the local level and shown inside the red box. T indicates the top of the borehole.

map, is likely to reflect a buried erosional strath terrace formed during river downcutting.

- Even without the DFHs, the elevation of the top of the London Clay is variable, perhaps representing palaeochannel scour or deformation (potentially due to localized tectonic faulting or folding), or both.
- Individual, anomalous depressions are evident where detailed site investigations have taken place and the borehole information is available.
- The density of available data points varies spatially due to the nature of the development work and associated site investigations, so the features shown may not reflect the natural frequency of DFHs.
- The true deepest point of a DFH may fall outside of the area represented by data. As a result, the maximum depths shown may be underestimated.

## Discussion

The primary purpose of this paper is to present a resource by compiling existing and unpublished records of actual and potential DFHs to assist in desk studies for development and academic


**Fig. 7.** London Clay clast to left of glove, identified within the infill of a DFH mainly consisting of RTD-type superficial deposits.

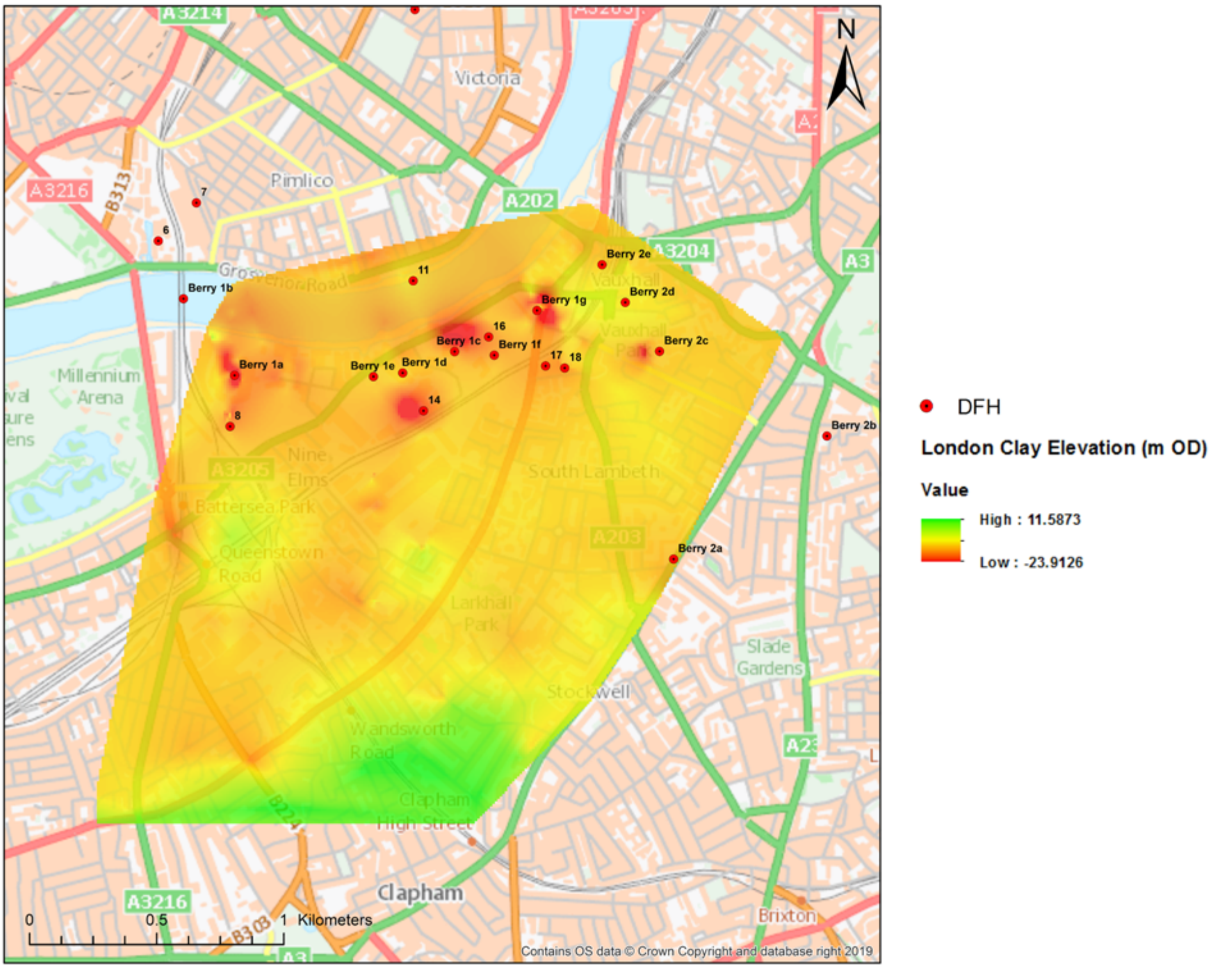


**Fig. 8.** The elevation of the top of the London Clay (m OD) across the Nine Elms area and the identified DFHs in the region.

research. The nomenclature used throughout this paper has been chosen to avoid implying any specific mode of formation.

It is evident from the information provided in Table 1 that each individual DFH varies in its size, shape, type of infill, degree of disturbance and their association with faulting and localized uplift. While each individual DFH varies in multiple characteristics, all features identified within this paper are grouped and thus termed 'drift-filled hollow' due to their anomalous depth to the local bedrock.

The extensive multi-phase sequence of Quaternary climate change and its associated uplift, erosion and deposition likely means the age of these features (formation and infilling) also varies in complex ways. Consequently, it is probable that many of the features had multiple and complex modes of formation and developmental processes which led to their current form.

The key to mitigating the hazards associated with these highly variable features is through well-informed and carefully planned ground investigation. If a possible DFH is identified, it should be investigated as a unique feature rather than assuming it shares characteristics with other DFHs.

While borehole surveys provide valuable information, it is impractical to expect site investigations to be able to fully explore the form of DFHs in this way, especially in a congested area such as central London. The use of geophysical methods is a potential method to inform and complement intrusive surveys and have been employed effectively elsewhere (Raines *et al.* 2015). Further research is required into the potential usage of this approach within central London due to noise, multiple electromagnetic sources, complex made ground and boundary restrictions.

Features not mentioned within this paper have been identified outside of the study area and within the Thames Valley (e.g. Hawkins 1952; Gibbard *et al.* 1986; Collins *et al.* 1996). These anomalies are outside the scope of this paper and are the focus of ongoing research. Nonetheless, their presence demonstrates the potential for DFHs to be abundant throughout the Thames Valley, and perhaps other areas such as the Hampshire Basin and Paris Basin due to similar geological, fluvial and climatic histories. However, the lack of data in these areas, compared to central London, makes the features more difficult to identify.

A final, and not insignificant issue is the availability of high-quality data. While some development projects have released site investigation data, much are still not publicly available. Until a process is found to allow these data to be released for general use, the detailed mitigation of risk will remain challenging and 'unforeseen' ground conditions will remain a significant risk.

Almost all the Crossrail ground investigation data are now available in AGS format through the BGS' Deposited Data Search webpage at: https://www.bgs.ac.uk/services/NGDC/dataDeposited.html. At the time of writing the coordinate system and datum these data use are specific to Transport for London.

## Conclusions

- This paper provides the locations of 84 DFHs from literature and other unpublished project experience for the London area. It also summarizes information regarding the basic characteristic features of each DFH as far as available data allow.

- The data sources are imperfect and the provided information should be treated with caution. Very careful and critical scrutiny of the available data is required. While additional data may change the detailed interpretation of individual DFHs, the available data are sufficient to provide an overview of the distribution of the known features, and their minimum extents.
- Borehole spacing, positioning and depth can lead to the features being missed or misinterpreted during the ground investigation phase. Once identified, high-quality, accurate logging is essential to understand the nature of the infill and the features extent. The use of geophysics is a potential method to understand the extent of irregular infill.
- The current known distribution of DFHs may, or may not be, an underestimation of their occurrence, as the type of data required to identify DFHs is biased towards particular areas. This is largely due to larger-scale engineering works and deeper excavation of the subsurface occurring more often within central London.
- Previous studies, together with the results for Nine Elms presented here, show that DFHs are individually highly variable and therefore the processes which led to their formation are likely to be complex and most likely multiphase. This paper provides a new catalogue of the known features for future research.

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