Controls on the basin-scale distribution of hydraulic conductivity of superficial deposits: A case study from the Thames Basin, UK

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Abstract:

Controls on the basin-scale distribution of hydraulic conductivity of superficial deposits are assessed in the context of hydrological setting and basin evolution and are investigated using a case study from the Thames Basin, UK. A conceptual model of superficial deposits across the Thames Basin is used to define six lithostratigraphic classes of superficial deposits: pre-Anglian Clay-with-Flint deposits*;* pre-Anglian River Terrace Deposits associated with the ancestral River Thames and its tributaries; Tills formed during the Anglian glaciations; glacio-fluvial sand and gravel deposits formed during the Anglian; post-Anglian River Terrace Deposits associated with the modern day River Thames and tributaries; and post-Anglian alluvium associated with the modern day River Thames and tributaries. Hydraulic conductivity of the superficial deposits has been estimated from grain-size distribution data, originally collected for mineral resource assessments, using the Kozeny-Carmen methodology. Based on 6411 samples from 1416 boreholes, estimated hydraulic conductivity ranges from 0.2 to 5942 m day^{-1}, median and mean hydraulic conductivities are 1.67 and 26.72 m day^{-1} respectively, and the overall distribution of hydraulic conductivity values has a strong positive skew An apparent reduction in mean hydraulic conductivity with increasing age of the deposit is observed, particularly for the River Terrace Deposits. A reduction in maximum hydraulic conductivity at depths >10 m is also observed while the relationship between hydraulic conductivity and depth is controlled by the type of superficial deposit. At the catchment- to basin-scale, variation in hydraulic conductivity with depth may be explained with reference to both the deposit types and the age of the deposits. Where hydraulic conductivity is found to be intimately linked to the Quaternary evolution of the Basin, through contrasts in age and deposit type, permeability variations at the basin-scale may be constrained by applying a suitably refined conceptual model of the superficial deposits.

Superficial deposit (SD) aquifers can form a locally important component of water supply (Robins et al., 2002). However, because of their local and often heterogeneous nature, and due to difficulties in obtaining reliable field estimates of hydraulic conductivity from these usually poorly consolidated or unconsolidated deposits, groundwater resources in such aquifers can be problematic to characterise and quantify (MacDonald et al., 2012). Where they overly bedrock aquifers, SDs with relatively low hydraulic conductivity and storage can play an important role in protecting deeper groundwater resources by reducing groundwater vulnerability, but SDs with relatively high hydraulic conductivity and storage can themselves be at greater risk of pollution due to their proximity to sources of pollution (Jorgenson & Stockmarr, 2009; Griffiths et al., 2011). This is particularly so in urban areas where there is greater use of the shallow subsurface for infrastructure and a higher concentration of potentially polluting activities. SD aquifers can provide significant groundwater storage potential and may contribute to an increasingly important local component of exploitable groundwater resources (Price, 1996; MacDonald et al., 2005). They play a significant role in groundwater vulnerability assessments (Griffiths et al., 2011), and they are also increasingly the focus for implementation of sustainable drainage systems (Bonsor & Ó Dochartaigh, 2010) and may be considered for open-loop ground source heating and cooling systems (Birks et al., 2013). In addition, they can be associated with hazards such as localised groundwater flooding (Macdonald et al., 2012), the differential settlement of shallow unconsolidated deposits, and structural issues related to swell-shrink clays (Harrison et al. 2009). Consequently, there is a need to characterise better the hydraulic characteristics of SD aquifers, in particular the spatial distribution of hydraulic conductivity.

Compared with bedrock aquifers it is generally more difficult to characterise the hydraulic properties of SD aquifers. SDs are intrinsically heterogeneous over a range of scales and typically have discontinuous spatial distributions (McMillan et al., 2011), so it can be difficult to undertake standard field hydrogeological investigations, assess the representativeness of measurements made at a given observation borehole or retrieve representative samples for laboratory measurements. In addition it can be difficult to construct stable observation boreholes due to the unconsolidated nature of some SDs. Consequently, information on the hydraulic properties of SD aquifers derived from field or laboratory investigations is typically often limited and other approaches to characterising the hydraulic conductivity of SD aquifers have had to be adopted. In the absence of high-resolution field or laboratory-derived hydraulic conductivity data, hydraulic conductivity can be obtained from grain-size distribution (GSD) data. Numerous empirical formulae have been proposed to define relationships between hydraulic conductivity and grain-size distributions (e.g. Hazen, 1892; Kozeny, 1927; Carman, 1937, 1956; Shepherd, 1989), and, given suitable GSD data, the application of any of these empirical relationships can provide a comparatively quick and cost-effective means of deriving the relative hydraulic conductivity for superficial deposits. Hydraulic conductivity data derived from grain-size relationships has the added benefit over data obtained from site-specific hydraulic tests that if suitable grain-size data are available then estimates of hydraulic conductivity can be applied over a large number of sites so enabling regional or basin-scale comparative assessments to be undertaken.

Here a case study from the Thames Basin, UK, is presented that demonstrates how indirect information such as grain-size distributions can be used to systematically characterise variations in the hydraulic conductivity of SDs at the basin scale. In this case study, the importance of developing a conceptual model in order to analyse basin-scale variations in hydraulic characteristics of SD aquifers is emphasised. The conceptual model is based on considerations of both the stratigraphy and the lithological characteristics of the SDs. It has been used as a framework for analysis of hydraulic conductivity within and between the different SDs, and to investigate the possible role of hydrological setting and of aquifer and catchment evolution on hydraulic conductivity of SDs across the Thames Basin.

Basin-scale trends in hydraulic conductivity of SDs have been estimated by applying the empirical Kozeny-Carman equation (Bear, 1972; Odong, 2007), one of the most commonly applied empirical relationships to estimate hydraulic conductivity from GSD data. Note that this study is based on data-mining of an extensive, pre-existing GSD data set for the Thames Basin and the GSD dataset does not have associated hydraulic conductivity information or metadata. Consequently, given the uncertainties associated with empirical GSD-hydraulic conductivity relationships and the biases inherent in GSD data, the aims of the study are to i.) quantify the conceptual model using estimates of relative hydraulic conductivity for the different SDs; ii.) describe the variability in hydraulic conductivity with individual SDs; and iii.) characterise and explore the controls on spatial and depth variations in SD hydraulic conductivity across the Thames Basin. One way in which spatial variation in hydraulic conductivity has been investigated is by exploring similarities and differences in the distribution of SD hydraulic conductivity within three contrasting sub-catchments within the Thames Basin. These are the Upper Thames, the Loddon and the Lee sub-catchments.

The following section provides a brief background to the study area, outlining the geology and hydrogeology of the study area and presenting the conceptual model of the SDs in the Thames Basin. The grain size data and methods used to estimate hydraulic conductivity are then described. Grain-size data used in the study has been taken from the Industrial Mineral Resource Assessment Unit (IMAU) Sand and Gravel Database for the United Kingdom (British Geological Survey, 2014a). In the 1970s and early 1980s, the former IMAU of the BGS conducted several major surveys of the principal sand and gravel resource areas with the results being presented as Mineral Assessment Reports (MARs) (British Geological Survey, 2014a). The database contains a digital copy of grading data presented in the published reports along with some previously unpublished borehole records. The implications of using this grain-size dataset for estimating relative trends in SD hydraulic conductivity are considered prior to presenting the results. Controls on the distribution of estimated hydraulic conductivity at the basin-scale are discussed in terms of the evolution of the deposits and hydrological and hydrogeological processes that have acted on the SDs. The work is concluded with a discussion of the generic implications for using a linked conceptual model/empirical grain-size analysis approach to estimate relative hydraulic conductivity characteristics of SD aquifers.

The Thames Basin case study area

The Thames Basin, Figure 1, is located in the south east of the UK, and for the purposes of this study is defined by the Environment Agency's Thames River Basin District (Environment Agency, 2009). The source of the River Thames is in the Cotswolds, Gloucestershire. The length of the river down to Teddington Lock, in west London, is approximately 235 km, and the area of the Basin is about 16,100 km^2. Teddington Lock is the lowest flow gauging station on the River Thames and marks the non-tidal limit of the river. The mean flow at Teddington Lock is about 78 m^3 s^{-1} (Natural Environment Research Council, 2008). Mean annual rainfall varies across the Thames Basin from about 600 to 900 mm of which approximately 250 mm is effective (Bloomfield et al., 2009; 2011). Groundwater abstraction overall accounts for about 40 % and locally up to about 70 % of public water supply in the Basin, equivalent to ~2.25 million m^3 day^{-1}. This is derived largely from bedrock aquifers, predominantly the Cretaceous Chalk, though river terrace deposits (RTDs) in the Lower Thames valley are used for public supply.

The Thames Basin is underlain by a thick sequence of Mesozoic to Holocene deposits. Bedrock within the basin covers three broad zones based on geological structure the Midlands Shelf to the northwest; the London Platform in the central area; and the Wealden Basin to the south (Royse et al., 2012). Palaeogene to Holocene superficial deposits are found throughout the Thames Basin across all three of these structural zones. The basin has been subject to significant weathering, erosion, peri-glacial and glacial activity during the Pleistocene with the Quaternary deposits formed over approximately the last 1.65Ma (Gibbard, 1985, 1994; Bridgland 1994; Royse et al., 2012). As a result of these processes, discontinuous Quaternary deposits, principally river terrace deposits (RTDs), clay-with-flints (Klink et al., 1998) and tills, lie unconformably on a highly weathered and eroded bedrock surface which alternates between more permeable carbonate and siliclastic units and lower permeability mudstones. The influence of the Middle Pleistocene Anglian glaciation within part of the Thames Basin is evident from the localised covering of Till up to 40m thick and the presence of underlying buried channels of sub-glacial origin (Woodland, 1970; Gibbard, 1985, 1994; Bridgland 1994).

The RTDs occur along the corridor of the River Thames and its major tributaries and are generally underlain by mudstones such as the Oxford Clay and the London Clay Formations. The exception to this is the RTDs of the upper River Kennet catchment and the middle reaches of the River Thames which are primarily underlain by, and potentially in hydraulic continuity with, the Chalk aquifer (Allen et al., 1997), the principal aquifer in the Basin. Post-Anglian sand and gravel RTDs associated with the modern course of the River Thames and its tributaries are significant within the Basin and were laid down in a broad, braided river floodplain. These RTDs are generally up to 6m thick though isolated pockets in excess of 10m thick are present across the basin. The RTDs along the lower reaches of the Thames valley are thicker and occupy a wider floodplain than upstream sections. Progressively older river terraces occur at increasing distances from, and higher elevations above, the active river channel as a consequence of repeated cycles of terrace aggradation, and river downcutting in response to shifts in sediment supply and river discharge (Bridgland, 1994). Pre-Anglian RTDs and glacio-fluvial sand and gravel deposits associated with relict pre-glacial and glacial river channels occur at great distances from the modern day river network and in hill top locations (Ellison et al., 2004), and are particularly prevalent in the northeast of the Thames catchment along the course of the ancestral River Thames. Tills, formed during the Anglian glaciation, occur only in the northeastern area of the Thames catchment; the Tills occur contemporaneously with glacio-fluvial deposits and may overlie pre-Anglian RTDs (Sumbler 1996). The oldest SD in the catchment is the Clay-with-Flints (CWF) Formation, a *remanié* deposit resulting from the reworking of Palaeogene cover and dissolution of the underlying Chalk (Klink et al., 1998; Ellison et al., 2004), which partially covers the Chalk and Palaeogene interfluves and tends to be isolated from other SDs. The youngest SD is the alluvium which is found within the floodplain of the active river channel. The alluvium typically overlies the youngest post-Anglian RTD, which like the alluvium lies within the active floodplain.

Three sub-catchments with contrasting distributions of SDs, i.) the Upper Thames, ii.) the Loddon, and iii.) the Lee sub-catchments, are shown in Figure 1 and Table 1 summarises and contrasts the catchment characteristics of the Basin and sub-catchments. These sub-catchments have SDs of contrasting age and type and have been selected to enable comparison of differences in the hydraulic conductivity of SDs across the Basin. The Upper Thames sub-catchment stretches from the source of the River Thames near Cirencester, Gloucestershire to the River Thames just upstream of Oxford. Superficial deposits within the Upper Thames catchment are primarily comprised of post-Anglian RTDs associated with the River Thames. They are typically 3 to 4 m thick though thicknesses of up to 8 m are recorded (British Geological Survey, 2014b). With the exception of the River Windrush, RTDs are largely absent within the valleys of the Upper Thames tributaries and were not included within the IMAU assessment. A thin deposit of alluvium is present along some sections of the River Thames valley. The RTDs within the Upper Thames valley are primarily underlain by the Oxford Clay Formation, a low permeability unit designated by the environmental regulator as unproductive in terms of groundwater resource potential (British Geological Survey, 2014c).

The Loddon sub-catchment comprises the surface water catchment of the River Loddon and its tributaries. Superficial deposits within the Loddon catchment comprise post-Anglian RTDs associated with the main tributaries and the lower reaches of the River Loddon but are not so areally extensive compared with similar deposits in the Upper Thames. RTDs are largely absent along the smaller tributaries in the sub-catchment. Older (including pre-Anglian) river terraces and glacio-fluvial sand and gravels that are disconnected from the modern drainage network are present within the catchment, for example, close to the surface water divide. The SDs are typically up to 4 m thick though sections up to 8 m thick are common along the lower reaches of the River Loddon (British Geological Survey, 2014b). The bedrock geology within the catchment primarily comprises the London Clay Formation and overlying Eocene Sands of the Bagshot Formation and the Bracklesham Group.

The Lee sub-catchment comprises the surface water catchment of the River Lee and its tributaries. In contrast to the Upper Thames and Loddon sub-catchments, superficial deposits in the Lee sub-catchment are dominated by pre-Anglian RTDs associated with the ancestral River Thames; glaciofluvial deposits; and a thick covering of Till which partially obscure the underlying glacial sand and gravel deposits. CWF deposits are also present on the Chalk interfluves. The superficial deposits in the Lee catchment are underlain by the London Clay Formation, Lambeth Group and the Chalk Group.

Conceptual model of the Superficial Deposits

Based in the above observations, and for the purposes of the present study, the SDs within the Thames Basin have been classified into six broad lithostratigraphic groups, as shown in Figure 2 and defined as follows:

(a) pre-Anglian CWF deposits principally found along the crest of the Chiltern Hills and the North Downs*;*
(b) pre-Anglian River Terrace Deposits (preARTD) associated with the ancestral River Thames and its tributaries (Sumbler 1996);
(c) Tills formed by the Anglian ice sheet (Till) (Ellison et al., 2004), found primarily in the northern part of the Basin in the area of north and east Hertfordshire;
(d) glacio-fluvial sand and gravel deposits formed during the Anglian (GF), typically present along the dip slope of the Chilterns;
(e) post-Anglian RTDs (postARTD) associated with the modern day River Thames and tributaries;
(f) post-Anglian alluvium (Alluv)associated with the modern day River Thames and tributaries.

Figure 1 shows the spatial distribution of these SDs and Table 1 gives the percentages of each of the SDs present at outcrop across the Thames Basin and the three sub-catchments. Figure 2 shows a schematic cross-section of the relationship of the different SDs in the Basin with respect to elevation as a section from an active river channel through to the interfluves. A schematic litho-stratigraphic column is also given for reference in Figure 2.

Methods and the IMAU dataset

Background to estimating hydraulic conductivity from grain-size data

The hydraulic conductivity (*K*) of porous media varies according to the properties of the fluid passing through the media and the physical characteristics of the media (Vukovic & Soro, 1992). Estimates of the hydraulic conductivity of hydrogeological formations may be made by evaluating grain- and pore-size distribution, grain shape factors, specific surface, porosity and tortuosity of the media (Uma, 1989). A large number of theoretical and empirical formulae have been developed to derive *K* using these parameters, perhaps the most well-known and one of the earliest being the Hazen formula (Hazen, 1892). The empirical formula for hydraulic conductivity derived from GSD takes the standard form:

$$K = \frac{\rho g}{\mu} \text{ x } C \text{ x } f(n) \text{ x } d_e^2 \quad (1)$$

where ρ is the density of water, g is acceleration due to gravity, μ is the dynamic viscosity of water, *C* is a sorting coefficient, *f(n)* is porosity function and d_e is the effective grain size. Many of the empirical formulae subsequently published are a derivative of this standard formula with variations in the sorting coefficient and porosity functions to make allowance for the sediment type or geological environment under investigation, for example the Breyer, Kozeny-Carman and Slitcher formulae (Odong, 2007). In some instances additional functions are incorporated into the standard formulae to provide a better fit with observed hydraulic conductivity, such as the relative density of the sediment (MacDonald et al., 2012) and there are now many established formula in existence suitable for a variety of sediment types (Shepherd, 1989).

A recent review of these formulae across a broad range of sediment types suggests that *K* can be successfully estimated using GSD data (Odong, 2007; Vienken & Dietrich, 2011). While there is a good correlation between *K* derived from the empirical formula and *K* derived from other forms of hydraulic testing the mean *K* may differ by several orders of magnitude between the formulae (Vienken & Dietrich, 2011). Consequently, this has led to some researchers urging caution in the use and interpretation of hydraulic conductivity estimates based on empirical formulae. For example, Odong (2007) suggested that hydraulic conductivity estimates should only be used within their individual domains of applicability, and Vienken & Dietrich (2011) suggested that they should only be used when they can be validated by in-situ permeability testing using techniques with similar support volumes. However, it is not possible to validate individual estimates of hydraulic conductivity presented in this paper.

The results presented in this study are based on a data mining exercise, described in the following sections, where the data has been collected and analysed in an internally consistent manner, but where no corresponding field observations or measurements are available. As noted in the aims of the study, the purpose of this work is to provide an illustration of variations in hydraulic conductivity across the Thames Basin and to explore controls (such as age of deposits and present day depth) on the hydraulic conductivity of various SDs and to consider their implications for the development of quantitative conceptual models of the Basin. In order to achieve confidence in the observations the results are i.) presented and analysed in terms of data summaries for each of the SDs, or grouped or lumped SDs, i.e. using descriptions such as ranges and means for each cluster or region within the Basin; ii.) statistical tests are applied to compare these sub-populations, not individual observations, and iii.) summary statistics for the SDs and sub-populations of the modelled hydraulic conductivity data are compared qualitatively with previously published data for superficial deposits. So although individual observations have not been validated, the approach adopted is robust and fit for the purposes of the study. This pragmatic approach to the characterisation of hydraulic conductivity variations within the Basin is also consistent with the potential sampling biases in the underlying GSD data outlined in the following sections.

The IMAU grain-size data

The determination of GSD-derived hydraulic conductivity (K_{GSD}) for SDs across the Thames Basin ideally requires systematically collected grain-size distribution data obtained from representative sites over the full range of SDs present in the Basin. The GSD data used in the present study come from the Industrial Mineral Assessment Unit (IMAU) of the then Institute of Geological Sciences (now the British Geological Survey) (British Geological Survey, 2014a). During the 1970s and 1980s the IMAU completed an assessment of potential aggregate resources within the Thames Basin for which sieve analysis was undertaken and GSDs determined. The purpose of the IMAU investigation was to determine aggregate resource potential and so it is expected that there will be an inherent bias towards high permeability superficial deposits where the fraction of sand and/or gravel is potentially relatively high. This is reflected in the very limited number of samples from lower permeability units such as the CWF. Other known constraints on sampling are that aggregate resources less than 1 m in thickness or occurring at depths greater than 25 m below the surface were also not assessed by the IMAU. In addition, SDs where the ratio between overburden and resource exceeded 3:1 were excluded (Hopson, 1982).

Table 2 summarises the IMAU GSD data used in the study. Over 1440 boreholes were drilled by the IMAU in the Thames Basin: 167 within the Upper Thames sub-catchment; 213 within the Loddon sub-catchment; and 248 in the Lee sub-catchment. The boreholes are distributed across the SDs of the Thames Basin, but SDs within the lower reaches of the Thames catchment weren't sampled. Samples were sieved using 11 sieve sizes from $^{1}/_{16}$ mm – 64 mm (PLUS0630 – PLUS64) with the percentage of material retained recorded. In order to calculate the percentage passing the sieve sizes were converted into phi units, where grain size (mm) = $2^{-[\text{grain size (phi)}]}$. The phi scale of measurement is logarithmic and therefore a linear interpolation is used between the sieve sizes to determine the percentage grain size distribution. For the linear interpolation to be carried out it is necessary to add arbitrary markers to represent 0 % retained (128 mm) and 100 % retained ($^{1}/_{32}$ mm). In practice the grain sizes representing the 0 % retained and 100 % retained are generally unknown. The effective grain size is converted from phi units back to millimetres for use in the empirical formulae.

IMAU samples were typically collected at metre increments down a borehole. However, where the proportion of fines was high the sample was not sieved. Consequently, for areas where low permeability horizons predominate within the SDs K_{GSD} may be expected to be biased by the non-sampling of the fines. The extent to which the non-sampling of fines affects the derived K_{GSD} has been investigated by dividing the borehole depth by the total number of samples collected at each borehole. Where the proportion of fines is low and a sample is sieved every metre the ratio between the number of samples and the borehole depth approaches one. A sampling ratio of more than one indicates a degree of under sampling of fines. Approximately half of the boreholes within the Thames Basin have a ratio less than 1.25, while 80 % have a ratio less than two. In addition, there is a positive correlation between the sampling ratio and the depth to the top sample (correlation co-efficient 0.72; P value <0.05). From this it has inferred that broadly the under sampling of fines is due to the under sampling of lower permeability overburden rather than under sampling of finer-grained units within the sequence. Of the 278 boreholes with a sampling ratio greater than two, nearly two-thirds are located within the northern part of the Thames Basin (Table 2) where lower permeability glacial deposits are present and where the Lowestoft Till overburden appears to be greatest (up to 20 m).

Estimation of hydraulic conductivity

Hydraulic conductivity has been calculated using the Kozeny-Carman equation (Kozeny 1927 and later modified by Carmen (1937, 1956)(after Vukovic & Soro, 1992) as follows;

$$K_{GSD} = \left(\frac{\rho g}{\mu}\right)\left(\frac{d_m^2}{180}\right)\left[\frac{n^3}{(1-n)^2}\right], \text{ (Bear, 1972)} \quad (2)$$

where ρ is the density of water; g is acceleration due to gravity; μ is the dynamic viscosity; d_m is the effective grain size, and n is a measure of porosity that may be approximated using the grain-size distribution, where

$$n = 0.255\,(1 + 0.83^u) \quad (3)$$

and where u is the coefficient of uniformity which can be approximated from the GSD, where

$$u = \frac{d_{60}}{d_{10}} \quad (4)$$

The effective grain size (d_m) is taken to be the d_{10} (10 % cumulative passing grain-size) along with a sorting coefficient (C) of $8.3\text{x}10^{-3}$ to provide following Kozeny-Carmen formulation (Odong, 2007; Barahona-Palomo, et al., 2011) where hydraulic conductivity is expressed in metres per day;

$$K_{GSD} = 8.3x10^{-3}\left(\frac{\rho g}{\mu}\right)\left[\frac{n^3}{(1-n)^2}\right]d_{10}^2 \quad (5)$$

Whilst there are many empirical formula for deriving hydraulic conductivity from GSDs, the Kozeny-Carmen formulation has a number of advantages over other approaches. It is established in the literature as a good predictor of K_{GSD} applied to a variety of sediments (Odong, 2007; Barahona-

Palomo, et al., 2011) and it better accounts for porosity and specific surface (Carrier 2003; Vienken & Dietrich, 2011) acknowledging that the effects of packing and sorting are lost when using a disturbed sample for the GSD methodology.

The Kozeny-Carman equation is valid for laminar flow and therefore is not applicable for coarse grained deposits where the d_{10} exceeds 3 mm (Carrier, 2003). Of the sediment samples collected as part of the IMAU investigations only 0.2 % of the samples, across 59 boreholes, failed to meet this criterion, of which 24 boreholes are found within the Thames Basin and one lies within each of the Loddon and the Lee sub-catchments. These 24 samples that didn't meet this criterion were omitted from further analysis. Equally, it has been recommended that the Kozeny-Carman relationship should not be used for very fine materials where electrochemical reactions may occur between the grain particles and water (Carrier, 2003). Given the dominance of RTDs and GF deposits within the Thames Basin the Kozeny-Carman equation is not expected to be constrained by this limitation.

Analysis of the inferred hydraulic conductivity distributions

The hydraulic conductivity of SDs in the Thames Basin has been analysed in the context of the geological conceptual model (Figure 2). This requires each hydraulic conductivity estimate to be ascribed to one of the six SD classes. Since the IMAU study did not record detailed lithostratigraphic information for each sample, a number of assumptions have been made to enable samples to be put into the six SD classes. First, using the 12 figure grid reference for each IMAU sampling point, the outcrop lithology taken from the British Geological Survey digital 1:50 000 mapping of superficial deposits (DiGMapGB-50) in the Thames Basin was identified for each site. There are 122 SD lithostratigraphical units at the 1:50 000 scale mapping in the Thames Basin. The locations of IMAU boreholes fell within 59 of these lithostratigraphical units. These 59 lithostratigraphical units were reduced to 45 by removing units for which only one site was sampled and by removing units such as peat, head and loessic deposits which tend to have a more limited thickness and restricted spatial extent. Each of these 45 SD units was then associated with one of the six classes in the conceptual model and hence each site attributed to a SD class in the conceptual model. Using this approach, all samples within a borehole are attributed with the same lithology as the SD recorded at outcrop on the 1:50 000 map. Consequently, if the SD class changes with depth in a borehole then the deeper samples will be incorrectly classified. This is more likely be a problem where Till overlies PreARTDs or GF sands and gravels (Figure 2) e.g. in the Lee catchment but less of a problem for RTDs since they tend to form discrete terraces with minimal overlap. For samples attributed as Till in the northern part of the Thames Basin the depth of the top sample in these boreholes is on average 8.4 mbGL. From this, it has been inferred that using this approach it is likely that some or potentially many of the 945 samples classified as Till may in reality be samples from underlying GF sands and gravels and/or preARTDs. Consequently, although values of estimated hydraulic conductivity have been reported for the Till, the statistical analysis of the hydraulic conductivity distributions has been undertaken on grouped or lumped data for preARTDs, GF SDs and Till (Table 3b and Figure 3).

The hydraulic conductivity distributions have been quantified using standard statistical descriptors and methods, such as cumulative frequency plots and box and whisker plots where data have been grouped either in terms of the Basin or sub-catchments, as a function of SD types defined in the conceptual model (as described above) or as a function of depth. Non-parametric two-way Kolmogorov-Smirnov tests have been used to test the null hypothesis that pairs of grouped or lumped sub-populations are drawn from the same underlying population. (Note parametric tests for normality or log-normality were not applied since hydraulic conductivity measurements rarely conform to simple statistically regular distributions and the normalised frequency plots (Figure 3) clearly show that the distributions are not regular).

The depth of each of sample collected for sieve analysis was recorded by the IMAU, expressed as metres below ground surface, and K_{GSD} has been correlated with sample depth to examine the extent to which hydraulic conductivity varies as a function of burial depth of the deposit. In addition, an analysis has also been undertaken that characterises the variation in representative hydraulic conductivity with chronostratigraphic age of the SDs. The samples from the 45 SD classes were assigned to 12 age groups according to their minimum oxygen isotope stage (Sumbler, 1996). Oxygen isotope (δ^{18}O) ratios reflect global ice volumes and glacial events since seawater becomes enriched with δ^{18}O when water is lost to form ice-sheets. Oxygen isotopes therefore provide a stratigraphical framework for Quaternary events and may informally be correlated to climatic events, e.g. oxygen isotope stage 5e represents the interglacial equivalent to the Ipswichian climatostratigraphical stage (McMillan, 2011). As far as possible, the SD classes were ordered within each of the age groups based on the interval between their minimum and maximum oxygen isotope stage, where SDs with the shortest interval were presented first (Ellison, 2004; McMillan, 2011). Where the SD is undifferentiated on the BGS geological map e.g. '*River terrace deposits (undifferentiated)*' an age group of zero was assigned. Median K_{GSD} was then estimated for each of 45 SD classes and plotted as a histogram in descending order by age. The minimum and maximum isotope stage and K_{GSD} statistics for each of the 45 SD classes is presented in Appendix 1.

Results

Table 3 and Figure 3 summarise the estimated hydraulic conductivity (K_{GSD}) values for the SDs. There are 6411 estimates of hydraulic conductivity across the Thames Basin with a range of about 0.2 to 6000 m day^{-1}. The median and mean hydraulic conductivities are 1.67 and 26.72 m day^{-1} respectively and the overall distribution of hydraulic conductivity values has a strong positive skew. These values are consistent with the few previously published hydraulic conductivity data for SDs from the Thames Basin and for similar deposits elsewhere. Naylor (1974) reported values of hydraulic conductivity of floodplain river gravels of the middle Thames catchment in the range 4 to 2000 m day^{-1} and based on *in situ* falling head tests Dixon (2004) reported hydraulic conductivity of the sands and gravels in the River Thames floodplain in the area of Oxford in the range 100 and 1000 m day^{-1}. MacDonald et al (2012) reported on the *in situ* measurements of a similar series of fluvio-glacial deposits from Morayshire, where on, the basis of 38 observations, it was found that hydraulic conductivity ranged from 0.001 to >40 m day^{-1} with a mean of 5.1 m day^{-1} (MacDonald el al., 2012). This is a similar to the range and mean to the broadly equivalent preA/Till/GF combined unit of the present study. More generally, the values of hydraulic conductivity in Table 3 are consistent with book values for tills (1×10^{-9} to 0.1 m day^{-1}), sands (0.001 to 10 m day^{-1}) and gravels (1 to 1000 m day^{-1}), see for example Freeze and Cherry (Freeze and Cherry, Table 2.2, 1979).

The apparent truncation of the hydraulic conductivity distribution at about 0.2 m day^{-1} is consistent with a combination of the non-sampling of finer-grained lower conductivity units such as the CWF and Till deposits, and the non-sampling of some finer-grained units within sequences of mixed grain-size SDs. It is also consistent with censoring associated with the arbitrary grain-size marker of $^{1}/_{32}$ mm used to represent 100 % of material retained which gives rise to a minimum K_{GSD} of 0.16 m day^{-1}. In addition, there is also a censoring bias associated with the smallest sieve size used when collecting the grain size distribution data. A low percentage of material retained at the smallest sieve size ($^{1}/_{16}$ mm) indicates that finer particle fractions have not been properly accounted for and hence introduces a bias towards higher K_{GSD} values. In the Thames Basin the percentage of material retained at the smallest sieve size is 87 % on average, indicative of some bias. The apparent truncation combined with a positive skew to the distribution from a few high conductivity observations means that the normalised frequency plot of log-transformed hydraulic conductivity data (Figure 3) doesn’t conform to a simple log-normal distribution.

Table 3a presents results for the whole Thames Basin and also for the three sub-catchments. The median hydraulic conductivity values for the Lee, Upper Thames and Loddon sub-catchments are 1.09, 13.12 and 1.76 m day^{-1} respectively and the maximum hydraulic conductivity ranges from almost 3500 m day^{-1} in the Lee sub-catchment to less than 1000 m day^{-1} in the Upper Thames.

Differences in the form of the distribution of hydraulic conductivity between the sub-catchments are illustrated graphically in Figure 3. The log-normal probability plots and box and whisker plots show the hydraulic conductivity values for the Upper Thames to be systematically higher, less skewed and containing slightly lower maximum values than the other two sub-catchments.

Table 3b summarises the estimated hydraulic conductivity values for each of the SD classes defined by the conceptual model and for the class that combines hydraulic conductivity estimates for the preARTD, Till and GF deposits. Median hydraulic conductivity values range from 0.27 to 17.77 m day^{-1} and maximum values range over about four orders of magnitude from about 3 m day^{-1} to almost 6000 m day^{-1} for the CWF and the Alluvium respectively. The normal probability plots and box and whisker plots for the CWF, combined preARTDs/Till/GF deposits, the postARTDs and the Alluvium (Figure 3) show an overall pattern of increasing hydraulic conductivity from CWF to Alluvium. Results of non-parametric two-way Kolmogorov-Smirnov tests indicate that the distributions of hydraulic conductivity for each of these four groupings of SDs (i.e. CWF, combined preARTDs/Till/GF deposits, the postARTDs and the Alluvium) are independent at the 95 % confidence level.

It is inferred from these observations that differences in hydraulic conductivity distribution between sub-catchments reflect the relative differences in the type of SDs present in each sub-catchment. For example, the SDs in the Upper Thames catchment which have the highest mean hydraulic conductivity have a relatively high percentage of PostARTDs and Alluvium, whereas the Loddon and Lee catchments have a significant proportion of Till, PreARTDs and CWF SDs (Table 2).

To visualise spatial patterns in the hydraulic conductivity estimates the mean hydraulic conductivity of SDs has been estimated for each borehole across the Thames Basin and plotted as colour coded points for each of the SD classes on a map of the basin (Figure 4a). Corresponding maps for each of the sub-catchments are given in Figure 4b for the Loddon, Figure 4c for the Lee and Figure 4d for the Upper Thames. At the basin scale there is significant spatial variability in SD hydraulic conductivity. Generally higher values are observed within the Upper Thames catchment and along the course of the River Thames itself. High values are also observed along other tributaries to the river Thames. Away from the active river channel a reduction in K_{GSD} is observed. Less spatial coherence is seen within the Lee catchment.

Discussion

Hydraulic conductivity as a function of SD age and depth

It is inferred that hydraulic conductivity of the SDs in the Thames Basin is a function of age of the deposits, with younger deposits generally having higher hydraulic conductivity values (Figure 3). This is supported by box and whisker plots showing variation in the estimated hydraulic conductivity for 45 sub-classes of RTDs, GF deposits and CWF attributed to 12 groups according to their minimum oxygen isotope stage age (Ellison, 2004; McMillan, 2011) and plotted in descending order by age of the 45 SD sub-classes (Figure 5). Higher variability in hydraulic conductivity and comparatively high median hydraulic conductivity values, typically in the range 10 - 25 m day^{-1}, are observed for RTDs of minimum oxygen isotope stages one and two (postARTDs). However, median hydraulic conductivities for older RTDs (minimum oxygen isotope stage 12 and older) and glacial deposits have a median K_{GSD} typically less than 5 m day^{-1}. PreARTDs typically have a median K_{GSD} of less than 2 m day^{-1}. The Stanmore Gravel Formation (minimum oxygen isotope stage 82) which is located in the northeast part of the Thames catchment has comparatively wide ranging KGSD given its age. However the lithogenesis of the Stanmore Gravel Formation is uncertain with some suggestion that it may be a marine deposit associated with the Crag Group rather than a preARTD (Ellison et al, 2004); regardless of its origin, the lithology of the unit is described as a 'pebbly gravel', from which it is inferred that is likely to have a relatively high K_{GSD}. An equivalent reduction in average K_{GSD} with age is also apparent (Figure 5; Appendix 1) where RTDs of minimum oxygen isotope stages one and two (postARTDs) have far higher mean K_{GSD} than older RTDs. Exceptions to this are noted for two of the Thames terraces whose lithology is gravel-dominated.

Two observations are made with respect to the relationship between K_{GSD} and depth (Figure 6): firstly whether K_{GSD} varies with depth at the basin scale and secondly the degree of variability in the vertical K_{GSD} distribution within the different sub-catchments. It doesn't necessarily follow that trends in K_{GSD} with depth at the catchment- to basin-scale (Figure 6) will be observed at the local or borehole scale. There is, for example, evidence that the high mean K_{GSD} observed for the Stanmore Gravel Formation, Taplow Gravel Formation and Silchester Gravel Formation is skewed by high permeability horizons within their sequence as indicated by high max K_{GSD} values (Appendix 1). This bed-scale heterogeneity likely arised from small-scale channel features coupled to short-term changes in sediment loading or water supply with the effects restricted to individual river reaches (Maddy et al., 2001). Vertical heterogeneity in K_{GSD} at the bed scale may also be determined from the IMAU GSD dataset as samples were collected at metre intervals through the depth profile at each site. This level of assessment is not pertinent for the catchment-to-basin understanding being presented but would be an important consideration for detailed groundwater investigations.

At the basin scale, K_{GSD} values covering five orders of magnitude are observed at depths of 0-10 m, maximum K_{GSD} values are typically up to 1000 m day^{-1} while mean K_{GSD} is typically between 25 - 50 m day^{-1}. Below 10 m K_{GSD} values are lower and are more predictable, generally covering just three-orders of magnitude (0.2 – 50 m day^{-1}). A marginal increase in median K_{GSD} with depth is observed despite the reduced number of high K_{GSD} outliers. Sub-catchment variability in the K_{GSD} depth distribution is evident and is driven by the proportion of SD classes represented in each catchment. The SDs in the Upper Thames sub-catchment, dominated by RTDs and alluvium, are comparatively thin and therefore sampling depths are shallow, in the range of 0-10 m. In keeping with the basin scale K_{GSD}-depth relationship, K_{GSD} values in the Upper Thames catchment cover five orders of magnitude with comparatively high mean and median K_{GSD} values. High K_{GSD} values at shallow depths (<10 m) are also observed in the Loddon sub-catchment, though mean and median K_{GSD} values at these shallow depths are much lower than those of the Upper Thames sub-catchment. At depths >8 m K_{GSD} values in the Loddon catchment are very well constrained (K_{GSD} values <10 m day^{-1}). Contrasts in K_{GSD} between the Lee and Loddon sub-catchments, particularly at depths >10 m, are best explained with respect to the different SDs that dominate within each catchment. At these depths (>10 m) K_{GSD} values in the Loddon catchment do not exceed 10 m day^{-1} compared to the Lee catchment where K_{GSD} values up to about 50 m day^{-1} may be expected. The Loddon catchment is dominated by RTDs (Table 1), many of which are of minimum oxygen isotope stage 5 and older and hence have a lower mean and median K_{GSD} than younger RTDs (e.g. such as those found in the Upper Thames catchment) (Figure 5). In contrast SDs in the Lee catchment principally comprise Till and GF deposits. The suggestion that Till and GF deposits retain a higher K_{GSD} at depth compared to older RTDs is counter to the frequency distributions for the SD types presented in Figure 3. However, knowing that many sampling points classified as Till are in reality expected to be sampling underlying GF deposits and given that lenses and sheets of gravel are closely associated with Till (Sumbler, 1996), high K_{GSD} values at depth in a glaciated catchment, such as the Lee, may be expected. Sub-catchment assessment of K_{GSD} suggests that high K_{GSD} values observed at depths >10m in the Thames catchment are associated with Till and GF deposits and the very high K_{GSD} values observed at shallow depths (<10m) are associated with young (minimum oxygen isotope stage 1 and 2) RTDs.

Spatial variability in hydraulic conductivity

The spatial variability in K_{GSD} across the Thames Basin (Figure 4) appears to relate to the contrasting depositional environments of the SDs, which are intimately linked to the age of the SD (Figure 5) and the evolution of the hydrological regime operating on the Thames Basin through the Quaternary.

There is evidence of higher K_{GSD} in younger RTDs along the active river channel (minimum oxygen isotope stage 1 and 2) with decreasing K_{GSD} at increasing distances from the river. These observations may be explained within the context of progressive river terrace development. Within the active floodplain younger RTDs are expected to be in hydraulic connection with the river system

(Macdonald et al., 2012) they are subject to high groundwater fluxes and regular flood events which remove fines and serve to maintain and enhance a zone of high permeability within the fluvial deposits. As the river incises due to changes in river base level or sediment loading the older RTDs occupy a new position further away from the active river channel and at a higher elevation. Once these older RTDs are separated from the active river channel, through progressive terrace development, groundwater flux through the systems reduces and they become exposed to greater degradation through weathering causing clay-enrichment and a reduction in permeability. Bridgland (1994) for example notes that the Kesgrave Group was subject to pedogensis prior to the deposition of Anglian stage glacial deposits and there is evidence of soliflucted colluvium within terrace sequences.

Interglacial activity within the basin may also have a bearing on superficial permeability. There is a significant contrast in permeability of RTDs laid down prior to the deposition of GF sediments during the Ipswichian interglacial warm stage (Figure 5), and RTDs laid down after the Ipswichian interglacial stage deposits, which have a higher median K_{GSD}. Acknowledging the role of Quaternary processes in the development of superficial permeability trends, one might suggest that repeated exposure to cold and warm climatic cycles prior to the Ipswichian has also led to a reduction of K_{GSD} through degradation and clay enrichment of deposits by weathering, solifluction and alluviation processes (Ellison et al., 2004).

These processes may help explain the contrast in K_{GSD} between the RTDs of the Upper Thames catchment which have higher median K_{GSD} values and the Loddon catchment where K_{GSD} values are lower. While both catchments have comparable coverage of RTDS, the Loddon catchment has a greater proportion of older preARTDs and RTDs laid down prior to the Ipswichian Inter-glacial.

Lower and more variable K_{GSD} is observed across the Thames Basin where GF and Till deposits are present (Figure 4). While the boxplots of K_{GSD} for the SD types (Figure 3) suggest a comparable level of heterogeneity for the PostARTDs and the lumped PreARTD/Till/GF class, the spatial distribution of K_{GSD} (Figure 4) highlights apparent differences. The heterogeneity of the PreARTD/Till/GF deposits tends to occur at the intra-catchment scale while intra-catchment variability in K_{GSD} for postARTD is low but heterogeneity occurs at the basin scale. In keeping with this observation we notice that RTDs of equivalent age but deposited in different catchments, such as the Thatcham Gravel Formation and equivalent Taplow Gravel Formation or the Silchester Gravel Member and equivalent Black Park Gravel Member, do not necessarily have the same K_{GSD} trends (Appendix 1). This might suggest that catchment-scale depositional and hydrological setting and the lithological composition of the RTD exert more influence on K_{GSD} of RTDs than the basin-scale climatic and hydrological regime.

Wider application of the methodology and validation of the conceptual model

An approach to characterise basin-scale variability in SD permeability by combining grain-size data with a conceptual model of the SD distributions has been presented. The technique is advantageous in that it may be applied to large geographical areas relatively easily providing sufficient data exist and as long as there is adequate understanding of superficial geology. Using a conceptual model based on generic and commonly occurring SD types as defined by superficial mapping provides a methodology that may be applied within other catchments in the UK and elsewhere. Despite these advantages certain weaknesses of the methodology are acknowledged. The hydraulic conductivity data estimated using the Kozney-Carmen formula (Eqn. 5) have not been validated using field data (for example from slug or packer tests) as this data is not available, consequently, the confidence in individual observations is poorly constrained. Where such field data is available it should used, however, since the development and the conceptual model relies on statistical summaries of the hydraulic conductivity distributions for the SDs and as these are consistent with previously published field values, the approach outlined in the paper is thought to be fit for purpose. Other potential weaknesses in the approach are associated with sampling errors and biases. GSD methods sample disturbed sediments and therefore don't account for packing, sorting or layering (Uma et al., 1989) and the resulting estimated hydraulic conductivity values are non-directional. GSD formulae are generally less suitable for the characterisation of fine-grained deposits such as clays (Vukovic & Soro, 1992) which, in part, reflects the non-sampling of fine-grained horizons by the IMAU. However, this introduces a sampling bias and means that data for the CWF and Till deposits are more limited. Equally the Kozeny-Carmen formula is only valid for laminar flow and may only be applied if the d_{10} is <3 mm (Carrier 2003) which may preclude its use in certain environments where coarse-grained deposits dominate, such as glacial gravels. However, this was not found to be a problem in the Thames basin where the grain-size criterion was largely satisfied despite the presence of glacial gravels SDs. To reduce the effect of these limitations and in the absence of field-based hydraulic conductivity data to validate K_{GSD} it is essential to take account of the SD depositional environment through the application of a conceptual model and to apply relative K_{GSD} trends rather than extract absolute values. Application of empirical formulae for K_{GSD} which take account of the depositional setting and which incorporate additional functions for, e.g. porosity and specific surface will also reduce uncertainty in the prediction of hydraulic conductivity.

While the IMAU dataset offers the opportunity to characterise the 3D permeability depth profile a 2D spatial assessment was undertaken by preference by using a median K_{GSD} derived for each borehole location. Limitations of using a 2D map of the superficial cover to assign a SD class to each of the IMAU boreholes are recognised. As illustrated by the conceptual model (Figure 2) there are locations in the Thames Basin where SD mapped at surface is not representative of the SD sampled at depth by the IMAU project: this is especially true where Till overlies GF and PreARTDs. However, simple analysis of the K_{GSD} variations with depth (Figure 6) suggests that at the basin-scale the observations may be explained with reference to the SD types and the age of the SDs. Vertical variations in K_{GSD} are expected to be important at the local scale, however. If a 3D representation of the superficial geology were available to researchers it should be used in preference to reduce the uncertainty in assigning the K_{GSD} results to a SD class and to maximise the level of refinement in the conceptual model.

The initial classification of SDs from the conceptual understanding is a fundamental part of the methodology. Given the strong age-related influence on K_{GSD} seen in this study, where both the Anglian glaciation and the Ipswichian inter-glacial exert some control, it would be appropriate for researchers to consider age-related sub-classification of the SD types where ages or significant Quaternary events influencing the system can be defined.

At the basin-scale where K_{GSD} of SDs is intimately linked to the Quaternary evolution of the basin, (through contrasts in age and SD type), the spatial trends in relative K_{GSD} may readily be applied to large-scale process models where the permeability trends are constrained by a suitably refined conceptual model of the SDs.

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