

Hydrogeochemical indications of regional flow in the Lower Greensand aquifer of the London Basin

W. George Darling* and Melinda A. Lewis

British Geological Survey, Maclean Building, Wallingford, Oxon OX10 8BB, UK

*Correspondence wgd@bgs.ac.uk

Abstract: The Lower Greensand (LGS) forms the second most important aquifer in the London Basin but, being largely absent beneath the city itself, has received much less attention than the ubiquitous overlying Chalk aquifer. While the general directions of groundwater flow in the Chalk are well established, there has been much less certainty about flow in the LGS owing to regionally sparse borehole information. This study focuses on two hitherto uncertain aspects of the confined aquifer: the sources of recharge to the west-central London Basin around Slough, and the fate of LGS water where the aquifer thins out on the flank of the London Platform in the Gravesend–Medway–Sheppey area on the southern side of the basin. The application of hydrogeochemical techniques including environmental isotopes indicates that recharge to the Slough area is derived from the northern LGS outcrop, probably supplemented by downward leakage from the Chalk, while upward leakage from the LGS in North Kent is mixing with Chalk water to the extent that some Chalk boreholes on the Isle of Sheppey are abstracting high proportions of water with an LGS fingerprint. In doing so, this study demonstrates the value of re-examining previously published data from a fresh perspective.

The Lower Greensand (LGS) is an aquifer in which the downdip confined boreholes tend to be locally clustered (Allen et al. 1997), with large intervening areas devoid of opportunities to measure aquifer properties and hence arrive at an adequate understanding of regional groundwater flows. In such circumstances, hydrogeochemistry can have an important role to play, particularly through the use of environmental isotope tracers which can provide information on groundwater provenance and age.

Two areas of the LGS in the wider London Basin (Slough and North Kent) are currently rather poorly characterised in terms of what is occurring in the subsurface. In the Slough area the source of recharge has been under debate (e.g. Morgan-Jones 1985; Egerton 1994), while in North Kent the fate of natural discharge, though perhaps a less immediate issue, is nevertheless one which ideally should be factored into regional flow models.

Although the LGS may be something of a neglected aquifer compared to the overlying and more extensive Chalk, it has the advantage of locally producing good-quality, less-hard water

suitable for a range of light industrial uses including food processing and boiler feed water (Egerton, 1994). These properties help to explain why the LGS has been exploited in the Slough area since the early years of the 20th Century. Notwithstanding the high abstraction of ~11,000 m³/d (Egerton 1994), the aquifer remains fully artesian in Slough (Slough Heat & Power Ltd., pers. comm., September 2020), which raises questions about the source(s) of recharge. The LGS has only a relatively narrow and locally intermittent outcrop around the NW perimeter of the London Basin (Fig. 1), leading to suggestions (e.g. Egerton 1994) that the overlying Chalk Group could be contributing water, via leakage through the intervening aquitard formed by the low-permeability Gault Formation.

In North Kent, Evans et al. (1979) reported an approximately 15 km S–N downdip profile through the LGS showing increasing groundwater age, and inferred from this and water level contouring that the main flow must be diverted to the east where it would then ultimately discharge to the River Thames by upward leakage through overlying strata.

The fact these concepts have remained open to question for decades emphasises that relatively little is known about the hydrogeology of the LGS aquifer around the London Basin. The purpose of this paper is to examine both propositions with the aid of a mixture of new and legacy hydrogeochemical data, in which environmental isotope techniques play an important part.

Background

The Lower Greensand aquifer

The Lower Greensand Group was deposited around the edge of the London Platform, which lay above or just below sea level in the Lower Cretaceous (Middlemiss 1975). Therefore the LGS is largely absent beneath London itself, but is found in the west, south and NW of the wider London Basin (map - Fig. 1). The confined aquifer reaches a maximum thickness of ~70 m to the west of London, though its maximum depth of ~500 m is found to the SW owing to the asymmetric structure of the syncline forming the basin (see the cross-section A–B, Fig. 1).

Over much of its area, the LGS is confined beneath the Gault Formation (Upper Cretaceous), a clay typically 50–80 m thick and generally regarded as being an effective aquiclude preventing vertical recharge, where present, as beneath the Slough area. Hence the assumption is that recharge is mainly lateral and from the outcrop area. At the base of the LGS sequence, the Atherfield Clay Formation, typically 5–20 m thick along the south of the basin, provides a similar low-permeability seal. Lying between these two clay units are (from youngest to oldest) the Folkestone, Sandgate and Hythe formations. In the NW, the Woburn Sands Formation is considered to be age-equivalent to the upper LGS (Wonham and Elliott 1996), and here and in the Slough area, the LGS oversteps onto Jurassic rocks (mudstones at outcrop and limestones and sandstones, over Devonian sandstone at Slough).

The Folkestone Formation consists of generally poorly-cemented ferruginous sands and forms a good aquifer with a largely primary porosity. The Hythe Formation also forms a good aquifer but has more cementation and limestone bands especially to the east in Kent, to the extent that they have been exploited for building stone in some areas. Some fracture porosity would be expected in addition to their predominant intergranular porosity. On the evidence of differing hydraulic heads in the Folkestone and Hythe formations (IGS 1970), the intervening, thinner Sandgate Formation (fine sands, silts and silty clays) is considered to act as a leaky aquitard (Morgan-Jones 1985).

On the evidence of Middlemiss (1975) and Morgan-Jones (1985), southern outcrop or near-outcrop borehole sources are likely to be abstracting from the Hythe Formation but in the confined area around Slough, in terms of lithology and aquifer properties the LGS is regarded as most similar to the Folkestone Formation, as is the Woburn Sands Formation. However, according to Egerton (1994), hydraulic continuity between individual outcrops of the Woburn Sands and the main LGS in the Slough area remains to be demonstrated. In North Kent, the Hythe Formation thins rapidly north of its outcrop area (IGS 1970) but the Folkestone Formation generally extends as far north as the outcrop of the top of the Chalk, reaching the Thames estuary between Grays and Sheerness, and again east of Margate.

The LGS in the Slough area

Isotopic evidence

The first published account of radiocarbon dating applied to groundwater in the UK was focused on the LGS of the London Basin (Mather et al. 1973). Results were reported from eight sites along a transect from the Woburn Sands outcrop in the north to the Farnham area in the south (approximately the line A–B in Fig. 1), including two deep confined sites in Slough and Aldershot. From the data, it was clear that deep confined LGS groundwaters were old: given the uncertainties attached to ^{14}C -DIC dating, they were at or perhaps beyond the range of radiocarbon dating in groundwater (i.e. ≥ 30 ka in age). Tritium activities were also measured, but like radiocarbon they were at or below the detection limit, indicating that no significant post-1960 recharge had entered the aquifer locally. However, no measurements of the stable isotopes $\delta^{18}\text{O}$ or $\delta^2\text{H}$ appear to have been made. A later 1970s paper (Evans et al. 1979) added another result for Slough, again showing low ^{14}C and ^3H , but this time including stable isotopes which showed that the old water had a depleted composition, related to recharge under colder climatic conditions and consistent with its Pleistocene radiocarbon model age.

Further LGS environmental isotope data (^{14}C and stable isotopes) were obtained in the 1990s by the British Geological Survey. These covered approximately the same geographical range as Mather et al. (1973), but with a higher number of sites. The results confirmed Pleistocene recharge ages for deep groundwaters, and that they were depleted in stable isotopes (Darling et al. 1997).

For all the above studies, radiocarbon was measured by decay counting, necessitating the production of gram-size amounts of Ca or Sr carbonate by precipitation from 50–100 litres of water in order to provide enough material for analysis (e.g. Münnich 1968). The risk of contamination by modern atmospheric CO_2 during the precipitation step would always have been present, so in 2013 the sites from Slough to the southern outcrop were re-sampled by the British Geological Survey so that ^{14}C activities could be checked by AMS (accelerator mass spectrometry), which needs only 1-litre samples and does not require a precipitation stage (e.g. Plummer and Glynn 2004). These results are reported in Table 1.

Water level information

In the Slough area, the hydraulic head in the LGS is artesian at locations with surface elevations between 30 and 42 m above Ordnance Datum (AOD); up to 15 m above that of the Chalk (20–27 m AOD; BGS, 1984). However, further north where the Chalk outcrops around Dunstable, the water level in the Chalk is ~115 m AOD, and the head in the LGS is significantly lower at ~70 m AOD. The Chalk hydraulic gradient is therefore significantly steeper than that in the LGS, as expected when comparing fractured limestone and intergranular flow sandstone aquifers. Boreholes in Wooburn Green, 6 km N of Slough, have recorded water levels in the LGS at least 2 m above those of the Chalk. The intervening Gault Formation is ≥ 60 m thick everywhere in this area

The LGS in the North Kent area

Isotopic evidence

As part of early groundwater dating investigations in the UK, Evans et al. (1979) carried out an approximately S–N down-dip survey of four LGS sites extending from unconfined conditions at Ryarsh PS (water utility pumping station) to deep confinement at the then Bowaters (now Kimberly-Clark) paper mill near Gravesend, close to the northern limit of the LGS in Kent (map – Fig. 1). While they found a rise in water radiocarbon age with depth, the age gradient sharply increased between Northfleet PS and Bowaters. Combined with groundwater contours taken from the Hydrogeological Map of Kent (IGS, 1970), it was concluded that the main flow direction in the dominant Folkestone Formation must be easterly, towards eventual discharge into the Medway Estuary by way of upward leakage through the Gault and Chalk. This hypothesis was not pursued further at the time, but subsequently hydrochemical and, crucially, isotopic data have become available for the wider Medway–Sheppey area, from unrelated investigations into the response of coastal aquifers to Holocene sea-level rise (Edmunds et al. 2001) and the hydrogeology of the Chalk aquifer in North Kent (Adams 2008).

Water level information

In the area around the Isle of Sheppey, the hydraulic head in the LGS varies between about sea level and 10 m AOD, while that in the Chalk has been drawn down to between 10–80 m below OD due to abstraction exceeding recharge (IGS 1970). The head in the LGS is

therefore greater than that in the Chalk in this area, but further south where the Chalk is at outcrop the reverse is true. The Gault Formation clays are always in excess of ~60 m thick and extend further north across the London Platform than the underlying LGS. North of Aylesford (Kent) the Hythe Formation is absent (or clay-rich and not an aquifer), and the Folkestone Formation thins northwards from 55 m to 5 m thick at East Tilbury (Essex) and even less than this at Sheerness.

Sampling and analysis

Samples collected for this study were taken from pumping station and commercial boreholes in continuous or near-continuous production. Nevertheless, it was checked that parameters like pH, conductivity and dissolved oxygen had stabilised before sampling commenced.

Environmental isotope samples were collected in glass bottles: 28 mL for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ and 1 litre for ^{14}C . Stable isotopes were measured by isotope ratio mass spectrometry, while radiocarbon was measured by AMS.

Stable isotope analyses were carried out in the laboratories of the British Geological Survey at Keyworth, England, while ^{14}C was measured by the Radiocarbon Facility of the Natural Environment Research Council (NERC-RCF) at East Kilbride, Scotland.

Results and discussion

New LGS data

Results from the re-survey of LGS sites from Slough to the southern outcrop are reported in Table 1, which includes field parameters and environmental isotopes. Also reported are ^{14}C measurements from the same sites in 1992 (Darling et al. 1997). While decay-counting (1992 samples) may have had better precisions than AMS (2013 samples), it is apparent that deep confined sites at or near the ^{14}C detection limit usually give slightly lower values when measured by AMS. Younger age sites can vary a little either way; some of this variation over two decades may be 'real' (for example at Netley Mill which abstracts water of recent age

from the only wholly unconfined site considered here), but the main benefit of AMS measurement (beyond ease of sampling) would seem to be at low ^{14}C activities, though this is where radiocarbon dating becomes more uncertain because of the exponential nature of the decay curve. Nevertheless, it is clear that apparent groundwater age in the Slough area has continued to lie at or near the limit of ^{14}C groundwater dating (~30 ka) over the past 40 years of observation, from Mather et al. (1973) onwards, and by implication over the whole century of abstraction from the LGS.

Recharge to the LGS in the Slough area

The very steep age gradient from the southern outcrop to the Aldershot area led Mather et al. (1973) to conclude that any southerly recharge to Slough must be negligible, and that the only feasible source was the NW outcrop around the Woburn area (Fig. 1). In contrast, Morgan-Jones (1985) assumed that recharge to Slough was derived from the south, partly because the LGS outcrop area is greater (Fig. 1) but also because tritium was by then apparently present in deep confined boreholes in which Mather et al. (1973) had reported it to be at or below detection only a decade or so earlier. The implication was that if the thermonuclear ^3H peak of the mid-1960s had reached Aldershot and Slough, there must be active recharge from the southern outcrop (though no northern sites were included in the survey). Nonetheless, there must be considerable doubt over the validity of the 1985 tritium data, at least as measured in the deep confined boreholes at Aldershot and Slough, because an influx of even a small amount of modern water (by whatever route) should have led to a detectable rise in ^{14}C activity (e.g. Evans et al., 1979), which however has not been observed in four decades of measurement. A southerly source of recharge was also ruled out by Egerton (1994), though on hydrogeological grounds. Egerton's further doubt about hydraulic continuity between Slough and the Woburn Sands Formation outcrop area in the NW of the basin has been mentioned earlier.

One way of testing the source of recharge to Slough is to evaluate stable isotope data from across the LGS basin. It was observed by Darling et al. (2003) that owing to rain-out effects, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ composition of groundwater varies across the UK in a consistent way. The ~80 km separation between northern and southern LGS outcrops at the longitude of Slough (see cross-section, Fig. 1) should be enough to permit broad discrimination between recharge

from northerly or southerly sources. While this is potentially complicated for older groundwaters by depletion in isotopic values associated with colder conditions in the late Pleistocene, it was the conclusion of Darling et al. (2003) that the general direction of air-mass movements across the UK remained similar, so that the relative difference between north and south should be maintained.

Figure 2 plots $\delta^{18}\text{O}$ versus ^{14}C activity for waters from across the LGS at the approximate longitude of Slough. It is clear that samples appear to belong to ‘northern’ or ‘southern’ trends separated by $\sim 0.5\text{‰}$ in $\delta^{18}\text{O}$, the southerly appearing to terminate in the deepest part of the basin beneath the Aldershot area (Boxalls Lane and Tongham Moor PSs) while the northerly apparently terminates at Slough (Horlicks and Slough Estates boreholes). What happens flow-wise between Aldershot and Slough remains unclear owing to a lack of data, but it seems clear that little or no recharge to Slough can be coming from the southern LGS outcrop as there appears to be an intervening, very poorly-characterised saline water body (Egerton 1994).

However, while the apparent existence of a northerly flowpath does strongly suggest hydraulic continuity between outcrop and the deep confined aquifer, stable isotopes do not necessarily prove that recharge to the Slough area is sourced exclusively from the Woburn Sands Formation outcrop, since recharge to the much more extensive Chalk outcrop in the northern Chiltern Hills would have approximately the same isotopic composition as that to the Woburn Sands. Egerton’s (1994) contention that recharge to the Slough area must be largely derived from Chalk leakage was based on piezometric considerations, which ruled it out in the Slough area but not further north in the Chilterns. Such natural leakage might occur through the Gault Formation, and/or where faulting might have led to enhanced permeability or even direct contact between the Chalk and the LGS. A final hypothesis was that disused boreholes in the Slough area itself might provide a route for Chalk water to invade the LGS, albeit this was considered unlikely as LGS water quality at Slough has shown little change over the past 100 years (Egerton1994).

At first glance, stable isotopes appear to rule out a contribution by leakage from the unconfined Chalk to the confined LGS in the Chiltern Hills, because current $\delta^{18}\text{O}$ values of $\sim -7.3\text{‰}$ are too enriched compared to the LGS at Slough ($\sim -8.2\text{‰}$). However, given that the age of LGS water at Slough is at least 30 ka, leakage from a point say half-way towards

outcrop would have been in transit for ≥ 15 ka (not including any residence time in the Chalk and Gault Formation), and therefore would have had a more depleted late-Pleistocene isotopic composition matching that of the LGS. Even so, there are apparent hydrochemical differences, most obviously the higher Ca and HCO_3 concentrations in the Chalk, which appear to preclude the wholesale leakage of Chalk water into the LGS, certainly by the more direct forms of contact like faulting and borehole deficiencies.

However, one way to attempt a resolution of this question is a comparison of the low-radiocarbon LGS groundwaters from the Aldershot and Slough areas. As far as is known, there is little or no piezometric potential for Chalk water leakage into the southern LGS, so the average composition of the old waters from the Boxalls Lane and Tongham Moor PSs in Aldershot should provide a marker for hydrochemically-evolved, unmixed groundwater in the LGS of the western London Basin ('LGS evolved' in Fig. 3). It must be stressed that this is simply for purposes of geochemical comparison, and does not imply any flow connection between Aldershot and Slough.

Figure 3 takes data reported by Morgan Jones (1985) and Darling and Goody (2006) and cross-plots Cl against the other six major ions (Ca, Mg, Na, K, HCO_3 and SO_4) to seek evidence of mixing between the water types. Egerton (1994) had already noted the relatively high variability of groundwater quality in the potable Slough LGS boreholes (locations: see the final panel of Fig. 3) in the context of known saline, possibly connate waters from the wider area, and this appears to be reflected in the scatter of data points which cannot all be explained by simple binary mixing. Figure 3 shows ternary mixing fields constructed around the datapoints using BH SE8 (highest chloride) and 'LGS evolved' (old but not connate water from the LGS, see above) as end-members. A hypothetical third end-member is identified from the convergence of mixing lines from 'LGS evolved' via SE11 and from SE8 to contain all the other Slough datapoints. For most species the lines converge in the range 25–30 mg/L Cl, with coinciding concentrations shown in Fig. 3 as water 'X'. On this basis, water pumped from SE11 suggests an approximately two-thirds mixture of 'X' with 'LGS evolved' along a simple binary trend. Other boreholes produce ternary mixtures generally of rather less consistency, though SE10 for example tends to lie on or near the binary trend from SE8 to 'X'. Two additional plots, of the trace element F and the isotopic indicator $\delta^{13}\text{C-DIC}$, are also included in Fig. 3 and show mixing patterns similar to the major elements.

If water 'X' exists, could it be derived by downward leakage from the Chalk through the Gault Formation? To represent unmodified Chalk water prior to leakage through the Gault, Fig. 3 shows the composition of a water ('Chalk usz') considered to come from the deep Chalk unsaturated zone (data from Barracks Farm, W Berks, see Darling et al. 2012). This is a water with a high Mg/Ca ratio, low CFC and SF₆ concentrations, and a slightly higher δ¹³C-DIC value than is usual for the unconfined Chalk; all are signs that the water has resided at depth and not significantly exchanged with the more active upper 50 m of the saturated aquifer, for decades or longer. When 'X' is compared to this water, Fig. 3 shows indirectly that Na/Ca, Na/Cl and Mg/Ca are higher, while K/Na and F are lower – all evidence for ion exchange on clay minerals, corroborated by laboratory studies on Gault cores (Brightman et al. 1985). An accompanying rise in Cl would be expected (Alexander et al. 1987), while elevated SO₄ due to pyrite oxidation would also be typical. The resulting low-pH conditions during that process would favour the dissolution of carbonate minerals, typically present in the Gault (Forster et al. 1994), which would be consistent with the required rise in δ¹³C-DIC. With a good ionic balance and a calcite saturation index of ~ +0.4, the inferred composition of 'X' is certainly geochemically possible.

There are of course a number of assumptions accompanying the mixing hypothesis depicted in Fig. 3 (principally about the chosen end-member compositions and the extent of interaction with the Gault Formation), but the general agreement between different types of indicator suggests that Chalk groundwater could be making a contribution to the LGS aquifer at Slough, which would be in accordance with the views of Egerton (1994). Unfortunately the lack of LGS boreholes between the Dunstable-Luton area and Slough renders this process, if occurring, difficult to localise or quantify. Equally, a general lack of water quality data or sampling opportunities from SW of the inferred Slough–Stanwell isochlor (Fig. 3) makes difficult a better characterisation of the saline zone of the LGS lying between Windsor and Bracknell (Egerton 1994).

Discharge from the LGS in North Kent

A more detailed map of the Gravesend-Medway-Sheppey area, including the location of key boreholes, is provided in Fig. 4. To test the conjecture of Evans et al. (1979) referred to earlier, some way of differentiating between typical LGS and Chalk groundwaters is

necessary. Figure 5 shows a cross-plot of mNa/Ca versus $\delta^{13}\text{C}$ -DIC for sites in North Kent, together with background Chalk data from further west in the basin. Both these parameters can function as qualitative indicators of residence time: Na/Ca changing because of ion exchange (Ineson and Downing 1964), and $\delta^{13}\text{C}$ owing to carbonate dissolution-precipitation processes (Smith et al. 1976). The differing evolutionary paths of $\delta^{13}\text{C}$ prove a particularly effective way of differentiating between the two water types. Confined Chalk waters typically trend towards values of 0‰ owing to intense water-rock interaction with calcite of marine origin (Smith et al. 1976), whereas the relative paucity of carbonate in the LGS aquifer matrix (and some uncertainty over its source: Evans et al. 1979) means that $\delta^{13}\text{C}$ rarely exceeds -10% . A further check on the residence time aspect is provided by the ^{14}C activities shown in Fig. 4: these decline along both reaction paths.

The conclusion from Fig. 5 must be that at the time of sampling, the Chalk boreholes on the edge of the Medway estuary at Motney Hill, Sheppy Ltd, Co-Steel and Sheerness Port (locations in Fig. 4) were showing varying proportions of LGS leakage, with the last two likely to have been abstracting a high percentage. This would explain their anomalously depleted $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values, which are more negative than any values found in the Chalk of the central London Basin (Elliot et al. 1999) or elsewhere in North Kent, including the low- ^{14}C water from Hoath in the Herne Bay area (Edmunds et al. 2001).

The data therefore support the view of Evans et al. (1979) that the LGS aquifer must discharge by upward leakage against the edge of the London Platform beneath the Medway estuary. Such leakage could be promoted by intensive historical abstraction from the Chalk, but might also be evidence for faulting controlling the river's lower course, though this remains speculative. The absence of detectable LGS water in the Funton Brickworks borehole in the SE corner of the estuary implies that the LGS-Chalk mixing zone is relatively narrow (Figs 4 and 5).

From a hydrochemical perspective, unlike the ion-exchange and other water-rock interaction processes attributed to leakage from the Chalk through the Gault Formation in the case of recharge to Slough (see above), there would be less potential for upward leakage from the LGS to undergo significant hydrochemical modification in the Gault.

Whether this inferred LGS discharge to the Chalk ultimately reaches the Medway or Thames estuaries remains highly probable (Downing et al. 1987). Such leakage would presumably be most likely via Palaeogene sands where in direct contact with the riverbed, though transfer through the overlying London Clay Formation cannot wholly be ruled out. Certainly, at the time of sampling in the 1990s it is clear from the stable isotopic data that there was little or no pumping-induced seawater intrusion to the Chalk at Sheerness, implying the existence of a low-permeability barrier through which upward leakage under natural gradients is likely to be slow.

Hydrogeological context of implied flow through the Gault Formation

In both the Slough and North Kent areas, the hydrogeochemical evidence considered above suggests that significant water transfer can occur through the Gault. Yet the formation is traditionally regarded as a classic aquiclude: what hydrogeological factors could resolve this apparent contradiction?

Sedimentation and faulting

The considerable variations in thickness of the LGS can be explained either by deposition in drowned river valleys, or by tectonic control. Ruffell and Wignall (1990) show two fault zones (Woburn–Aspley, and extensions of the Wheatley–Dorchester and Abingdon faults), between the outcrop area of the Woburn Sands to the north and Slough, and conclude that sedimentation was controlled by faults rather than topography. Indeed, both Aldiss (2013) and Morgan et al. (2020) postulate that faulting around the London Basin is under-represented on geological maps. However, Ellison et al. (2018) do not show any major faults between the LGS outcrop to the north and Slough, and proven displacements of faults in surface strata rarely exceed ~25 m. Therefore it is unlikely that the 60+ metres of faulting required to juxtapose the Chalk and LGS occurs. Ellison et al. (2018) describe a series of faults that extend from SW London (Wimbledon–Streatham–Greenwich faults) to the NW corner of the Hoo Peninsula (Cliffe fault). However, there is again no evidence for large fault displacements in the post-Jurassic successions associated with the Cliffe fault.

Other potential routes for water movement

Egerton (1994) discussed the source of the LGS water at Slough, considering storage, flow downdip from outcrop and leakage from the overlying Chalk. If simply derived from storage,

it would have led to considerable drawdown, potentially 33 m at Slough Estates after 50 years abstraction at a mean rate of ~3400 Ml/yr. Flow from the outcrop area was also dismissed, owing to no visible effects on springs along the LGS outcrop. Hence Egerton (1994) inferred that the water pressure in the LGS at Slough was maintained by Chalk water flowing downdip from the area to the north, where the Chalk has a higher head than the LGS (see earlier). Assuming this area was 700 km² with an average head difference of 50 m across a 100 m combined thickness of Lower Chalk (Grey Chalk Subgroup) and Gault Formation with a mean hydraulic conductivity of 10⁻⁴ m/d, Darcy's law was used to calculate that 35,000 m³/d of Chalk water could reach the LGS. However, Egerton's hydraulic conductivity value for the Gault is high compared with that measured at Harwell (Oxon) of 8.3 x 10⁻¹² m/s (7.2 x 10⁻⁷ m/d) by Brightman et al. (1987). If this probably more realistic value of hydraulic conductivity is used for the basal 60 m of Gault in the succession, giving a hydraulic conductivity harmonic mean of 1.19 x 10⁻⁶ m/d, this volume is reduced to 416 m³/d.

Both these calculations assume the hydraulic gradient across the Gault Formation is the head difference between the Chalk and LGS divided by the thickness of the intervening Grey Chalk and Gault. However, the pressure/head in the Gault, and the difference between this and the aquifer formations above and below, are what will control water movement upwards or downwards through the Gault. Egerton (1994) also states that in the Thames valley, where the piezometric head is higher in the LGS than the Chalk, leakage in an upwards direction could occur from the LGS back into the Chalk.

Simple leakage around the edge of the London Platform would appear to be ruled out by the fact that the Gault Formation overlaps the LGS all the way around the basin perimeter. Similarly, it is unlikely that poorly-constructed boreholes have allowed mixing of waters from the two formations, as the number of boreholes penetrating both aquifers is small, and would probably have led to noticeable water quality changes over time.

Brightman et al. (1987) used data from a research borehole at Harwell (Oxon) to calculate the groundwater and solute fluxes across clays in the succession. They calculated cross-formational fluxes due to advective groundwater flow between the Gault Formation and LGS using the head gradient between the two formations and the hydraulic conductivity of the Gault. At Harwell, the hydraulic head gradient in the LGS is lower than that in the Gault and Chalk, with water moving downwards from the surface through them to a sink in the

Corallian Group. Alexander et al. (1987) modelled the transit times of water from the Chalk through the Gault, LGS and Kimmeridge Clay to the Corallian at Harwell to be of the order of 10^5 to 10^6 years.

Solutes are subject to different processes (dispersion and sorption, driven by differences in chemical potential) and do not necessarily move at the same speed as the groundwater. Diffusion occurs when the solute moves from zones of high to low concentration with the diffusive flux directly proportional to the concentration gradient, while osmosis between two bodies of water separated by a semi-permeable membrane allows the diffusion of solvent but not solute, with water flowing from regions of higher activity (lower concentrations of solute) to those of lower activity (higher solute concentrations). Osmotic flow therefore causes an increased difference in hydrostatic pressure across the semi-permeable membrane until equilibrium is reached whereby advective flow generated by the pressure difference is equal and opposite to the osmotically induced flow. If the Gault does not behave as a semi-permeable membrane, then only diffusion occurs and osmosis will not take place; if it behaves as an ideal semi-permeable membrane then only osmosis takes place and diffusion will not occur; and if it behaves as a non-ideal semi-permeable membrane there will be fluxes of both groundwater and solutes via diffusion and osmosis in opposite directions.

Therefore to estimate the movement of water and solutes across the Gault Formation requires information on both the mechanical (for advective flow) and chemical (for diffusion or osmosis) energy potentials. The parameters required are the head and hydraulic gradient, and chemical data; none of which are currently available for the Gault at either the Slough and area to the north or North Kent sites. Nevertheless, despite these qualifications and caveats, there seems little doubt from the hydrochemical data that LGS water in North Kent *does* leak upwards to the Chalk by some route, while the apparent Chalk 'fingerprint' on LGS water at Slough points to the reverse occurring.

Conclusions

Two areas of the Lower Greensand (LGS) aquifer in the London Basin have been investigated mainly using published hydrogeochemical information, but augmented by some new environmental isotope data. In both cases there was previously a degree of uncertainty:

in the case of Slough, over the source of recharge to the LGS in a zone of high abstraction; while in North Kent, over the fate of discharge from the aquifer under quasi-natural conditions.

A summary map of proposed LGS regional flows is provided in Fig. 6. Short, basically S–N flow paths to the Aldershot area contrast with a relatively long N–S flow path to Slough, probably augmented by leakage from the overlying Chalk aquifer. In Kent, there appears to be deviation of S–N flow to the east towards the Medway estuary.

In Slough, the persistence of artesian hydraulic heads over more than a century of abstraction has led to differing theories about the source(s) of recharge. The present study finds that recharge from the southern outcrop is unlikely on stable isotopic evidence. Hydrochemistry, on the other hand, appears to rule out recharge solely from the northern outcrop of the LGS, since it is shown that the observed compositions across the Slough wellfield can largely be explained by ternary mixing between water from the LGS, a residual more saline water, and drainage from the Chalk but hydrochemically modified, most likely by leakage through the intervening Gault Formation. The water presently abstracted at Slough has a late-Pleistocene stable isotope signature. Assuming continuing recharge to the system from the LGS and Chalk outcrops to the north, the current Pleistocene-Holocene boundary must lie somewhere up-dip in the LGS.

In North Kent, invasion of LGS water into the Chalk aquifer is apparently occurring in the Medway estuary area, reaching a maximum in the north at Sheerness on the Isle of Sheppey. As in the case of Slough, the Holocene-Pleistocene boundary must lie somewhere up-dip in the LGS, though unlike in the area N of Slough there may be more borehole potential to resolve its current position in the Medway area.

In both cases, it seems possible that under certain conditions of hydraulic head and perhaps lithology/structure, the Gault Formation may allow the passage of significant volumes of water between aquifers. However, it also raises further questions as to the exact mechanism(s) by which this transfer could happen, which would require further work including the measurement of hydraulic heads and water quality within the Gault.

Finally, in answering at least some of the long-standing questions about the LGS aquifer, this study has demonstrated the value of re-examining and combining legacy data from a variety of sources.

Acknowledgements The impetus behind this paper was The Hydrogeology of Sandstones conference organised by the Hydrogeological Group of the Geological Society of London. We thank the two referees for suggesting ways to improve the manuscript. The BGS radiocarbon data mentioned in the paper were obtained under NERC-RCF allocations 509/0992 and 1615.0312; our thanks go to Charlotte Bryant and Pauline Gulliver. This paper is published with the permission of the Director, British Geological Survey (UKRI).

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors

References

Adams, B. (editor). 2008. The Chalk aquifer of the North Downs. *British Geological Survey Research Report RR/08/02*, 60pp.

Aldiss D.T. 2013. Under-representation of faults on geological maps of the London region: reasons, consequences and solutions. *Proceedings of the Geologists' Association*, **124**, 929–945.

Alexander, J., Black, J.H. & Brightman, M.A. 1987. The role of low-permeability rocks in regional flow. In *Fluid Flow in Sedimentary Basins and Aquifers* (eds J.C. Goff and B.P.J. Williams), Geological Society, London, Special Publications, **34**, 173–183.

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

BGS (British Geological Survey). 1984. Hydrogeological map of the area between Cambridge and Maidenhead, 1:100,000.

Brightman, M.A., Alexander, J. & Gostelow, T.P. 1987. Groundwater movement through mudrock- measurement and interpretation. *British Geological Survey report FLPU 87-1*, 67pp.

Brightman, M.A., Bath, A.H., Cave, M.R. & Darling, W.G. 1985. Pore fluids from the argillaceous rocks of the Harwell region. *British Geological Survey Report FLPU-85-6*, 77pp.

Darling, W.G. & Goody, D.C. 2006. The hydrogeochemistry of methane: evidence from English groundwaters. *Chemical Geology*, **229**, 293–312.

Darling, W.G., Edmunds, W.M. & Smedley, P.L. 1997. Isotopic evidence for palaeowaters in the British Isles. *Applied Geochemistry*, **12**, 813–829.

Darling, W.G., Bath, A.H., & Talbot, J.C. 2003. The O and H stable isotope composition of freshwaters in the British Isles. 2, surface waters and groundwater. *Hydrology and Earth System Sciences*, **7**, 183–195.

Darling, W.G., Goody, D.C., Morris, B.L. & Peach, D.W. 2012. The hydrochemistry of a Chalk aquifer during recovery from drought. *Quarterly Journal of Engineering Geology and Hydrogeology*, **45**, 473–486.

Downing, R.A., Edmunds, W.M. & Gale, I.N. 1987. Regional groundwater flow in sedimentary basins in the UK. *Geological Society, London, Special Publications*, **34**, 105–125.

Edmunds, W.M., Buckley, D.K., Darling, W.G., Milne, C.J., Smedley, P.L. & Williams, A.T. 2001. Palaeowaters in the aquifers of the coastal regions of southern and eastern England. *Geological Society, London, Special Publications*, **189**, 71–92.

Egerton, R.H.L. 1994. Recharge of the Lower Greensand aquifer at Slough, England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **27** (Supplement), S57–S71.

Elliot, T., Andrews, J.N. & Edmunds, W.M. 1999. Hydrochemical trends, palaeorecharge and groundwater ages in the fissured Chalk aquifer of the London and Berkshire Basins, UK. *Applied Geochemistry*, **14**, 333–363.

Ellison, R., Schofield, D., Aldiss, D.T., Haslam, R., Lewis, M., O Dochartaigh, B., Bloomfield, J.P., Lee, J.R., Baptie, B., Shaw, R.P., Bide, T. & McEvoy, F.M. 2018. National geological screening : London and the Thames Valley. *British Geological Survey report CR/17/101N*, 82pp.

Evans, G.V., Otlet, R.L., Downing, R.A., Monkhouse, R.A. & Rae, G. 1979. Some problems in the interpretation of isotope measurements in United Kingdom aquifers. In *Isotope hydrology 1978*, IAEA, Vienna, 679–706.

Forster, A., Hobbs, P.R.N., Cripps, A.C., Entwisle, D.C., Fenwick, S.M.M., Raines, M.R., Jones, L.D., Self, S.J. & Meakin, J.L. 1994. Engineering geology of British rocks and soils: Gault Clay. *British Geological Survey report WN/94/31*, 76pp.

IGS (Institute of Geological Sciences). 1970. Hydrogeological map of Kent, 1:126720, 2 sheets.

Ineson, J. & Downing, R.A. 1964. Changes in the chemistry of groundwaters of the Chalk passing beneath argillaceous strata. *Bulletin of the Geological Survey of Great Britain*, **20**, 176–192.

- Mather, J.D., Gray, D.A., Allen, R.A. & Smith, D.B. 1973. Groundwater recharge in the Lower Greensand of the London Basin—results of tritium and carbon-14 determinations. *Quarterly Journal of Engineering Geology and Hydrogeology*, **6**, 141–152.
- Middlemiss, F.A. 1975. Studies in the sedimentation of the Lower Greensand of the Weald, 1875–1975: a review and commentary. *Proceedings of the Geologists' Association*, **86**, 457–473.
- Morgan, T., Ghail, R. & Lawrence, J. 2020. Major faulting in London: evidence for inherited basement faults in the London Basin. *Quarterly Journal of Engineering Geology and Hydrogeology*, doi.org/10.1144/qjegh2018-193.
- Morgan-Jones, M. 1985. The hydrogeochemistry of the Lower Greensand aquifers south of London, England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **18**, 443–458.
- Münnich, K.-O. 1968. Isotopen-Datierung von Grundwasser. *Naturwissenschaften* **55**, 158–163.
- Plummer, L.N. & Glynn, P.D. 2013. Radiocarbon Dating in groundwater systems. Chapter 4 in *Isotope Methods for Dating Old Groundwaters*, IAEA, Vienna, 33–73.
- Ruffell, A.H. & Wignall, P.B. 1990. Depositional trends in the Upper Jurassic-Lower Cretaceous of the northern margin of the Wessex Basin. *Proceedings of the Geologists' Association*, **101**, 279-288.
- Smith, D.B., Downing, R.A., Monkhouse, R.A., Otlet, R.L. & Pearson, F.J. 1976. The age of groundwater in the Chalk of the London Basin. *Water Resources Research*, **12**, 392–404.
- Wonham, J.P. & Elliott, T. 1996. High-resolution sequence stratigraphy of a mid-Cretaceous estuarine complex: the Woburn Sands of the Leighton Buzzard area, southern England. *Geological Society, London, Special Publications*, **103**, 41–62.

Table 1. *Environmental isotope data of groundwaters collected from Lower Greensand sources in 2013. Previous radiocarbon data from 1992 included for comparison. NGR – national grid reference, SEC – specific electrical conductivity, DIC – dissolved inorganic carbon, pmc – percent modern carbon.*

Site name	Code	NGR		Year of samp.	Temp °C	pH	SEC $\mu\text{S/cm}$	$\delta^{18}\text{O}$ ‰ VSMOW	$\delta^2\text{H}$	$^{14}\text{C-DIC}$ (2013)		$^{14}\text{C-DIC}$ (1992)	
		E	N							pmc value	±	pmc value	±
The Bourne PS	BR	484395	145594	2013	11.6	7.10	491	-6.90	-46.1	38.3	0.34	37.1	0.20
Tilford Meads PS	TL	487608	143642	2013	11.0	7.52	324	-6.89	-45.2	23.5	0.37	24.4	0.19
Tongham Moor PS	TN	488358	149435	2013	22.4	7.87	451	-7.46	-49.2	1.8	0.46	0.5	0.05
Boxalls Lane PS	BX	486438	149204	2013	21.7	7.91	544	-7.58	-50.8	<0.1	0.30	1.2	0.06
Mousehill PS	MS	493917	141690	2013	10.8	7.56	387	-6.90	-45.4	36.8	0.34	37.2	0.21
Netley Mill PS	NT	507918	147853	2013	11.2	6.46	239	-7.08	-45.8	77.3	0.37	72.5	0.40
Slough Est. No 7	SL	494641	181932	2013	17.3	7.89	673	-8.08	-54.2	<0.1	0.30	0.1	0.05
Horticks	HR	497300	180490	2013	17.7	7.82	549	-8.22	-56.0	<0.1	0.30	2.1	0.12

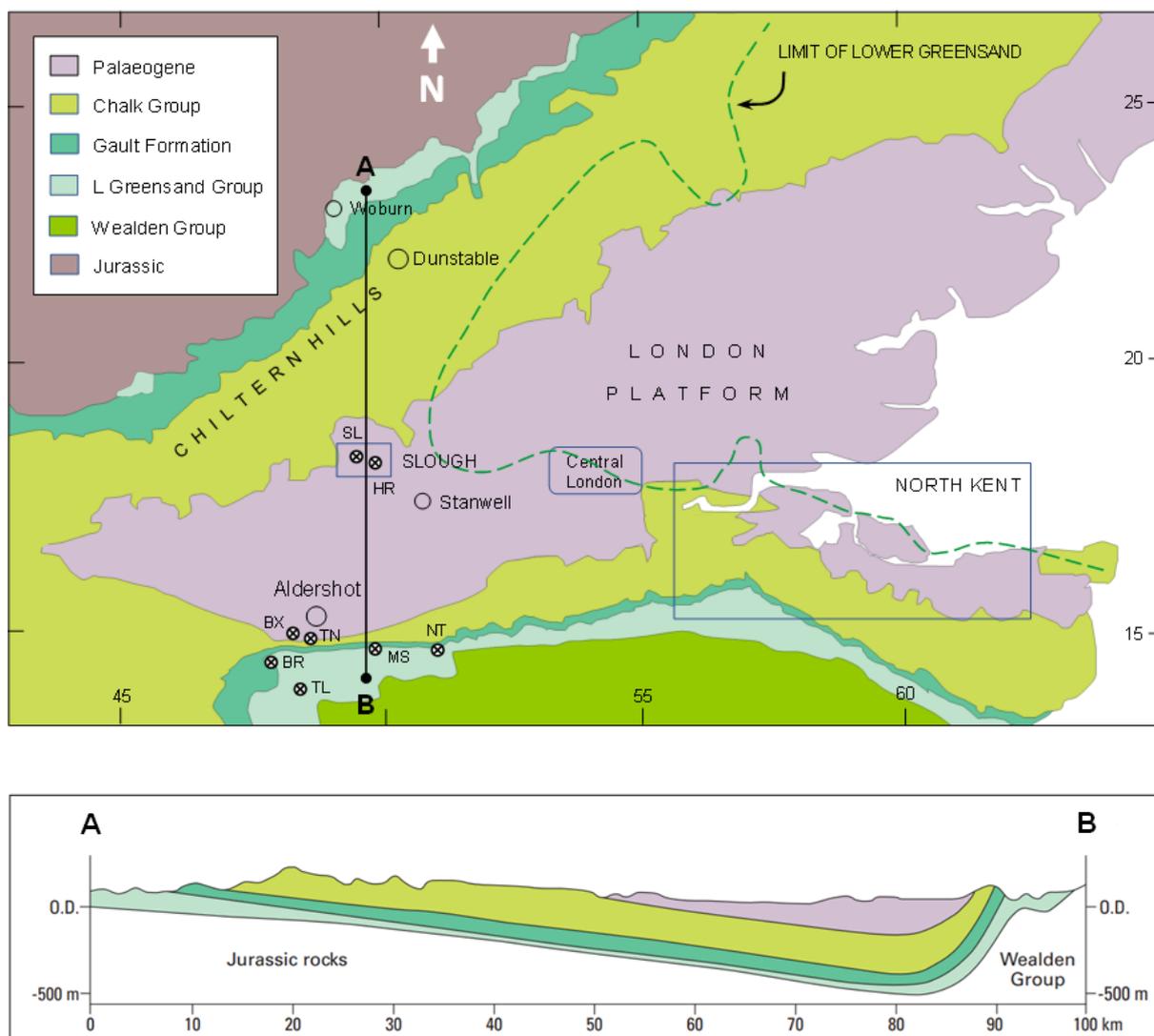


Fig. 1. Map showing the bedrock geology of the London Basin (50 km grid), with the two study areas of Slough and North Kent outlined. Also shown are the locations of LGS sites resampled for this study (refer to Table 1 for site details). The cross-section A–B demonstrates the asymmetric form of the basin. Contains British Geological Survey materials © UKRI 2021.

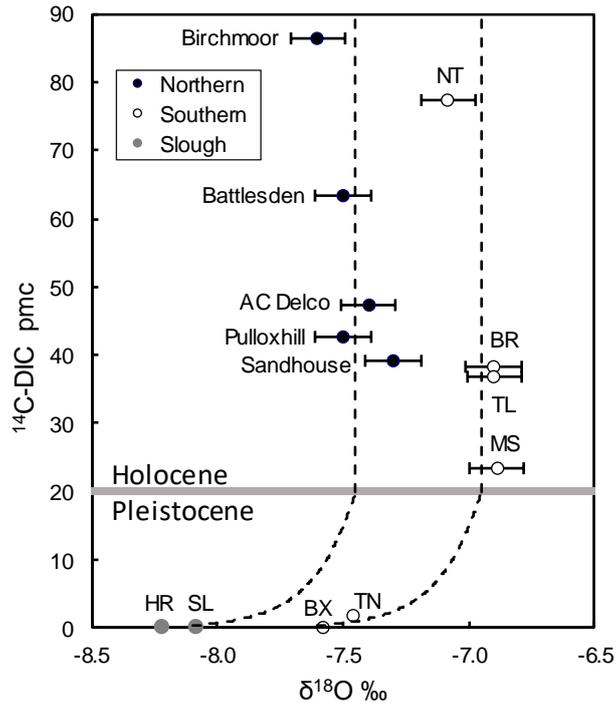


Fig. 2. The $\sim 0.5\text{‰}$ shift in $\delta^{18}\text{O}$ between groundwaters of the northern and southern flow paths into the LGS of the western London Basin, due to the rainout effect between the two recharge areas. The approximate position of the Pleistocene–Holocene boundary in terms of radiocarbon activity is indicated. Assuming the relative $\delta^{18}\text{O}$ shift still applies in the Pleistocene, groundwater at Slough appears to be recharged from the north. Northern site data from Darling et al. (1997), southern site data from Table 1 of this paper.

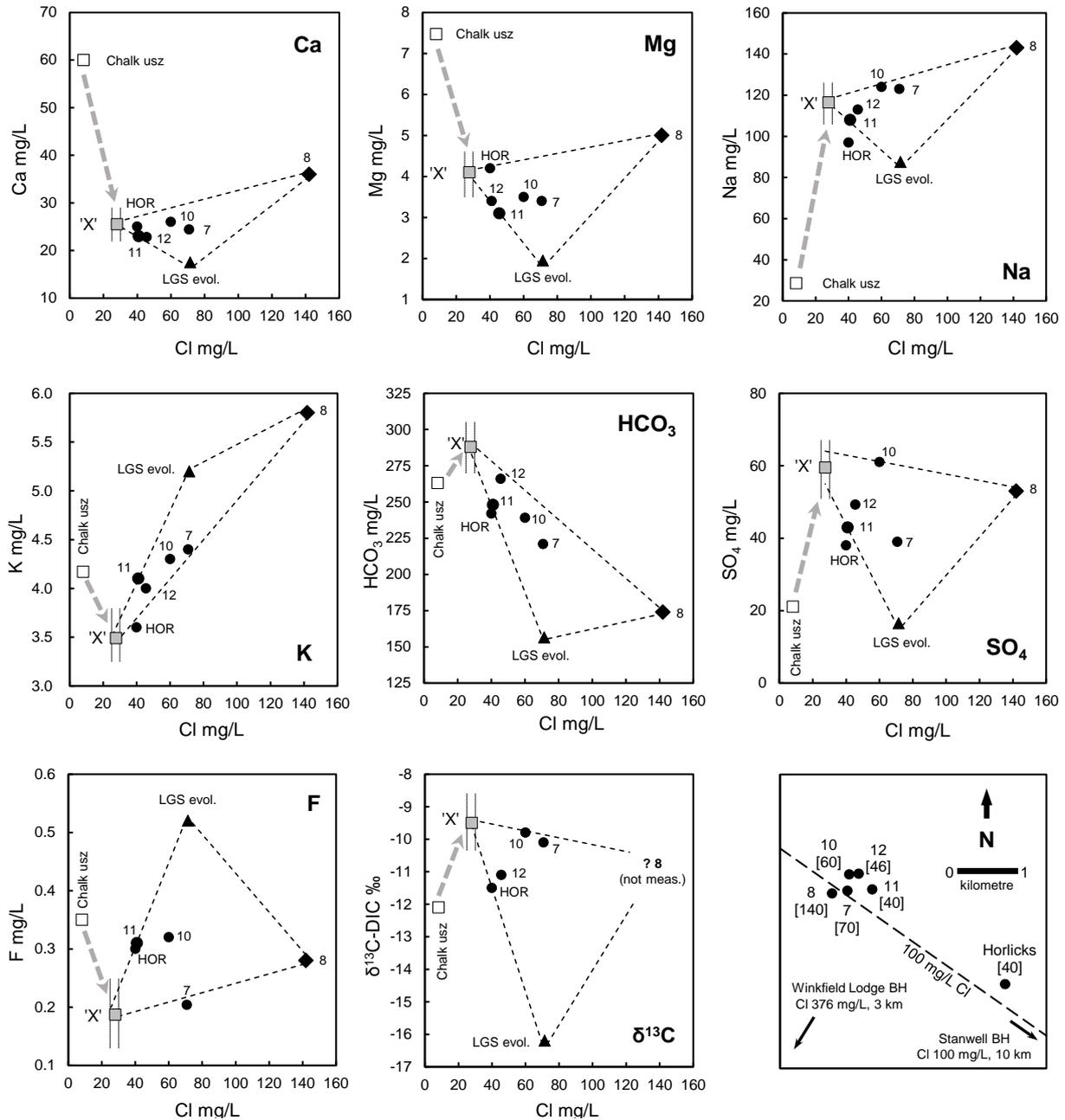


Fig. 3. Plots versus Cl of major ions plus F and $\delta^{13}\text{C-DIC}$ for Slough area borehole waters in relation to evolved LGS groundwater (see text). A ternary mixing field is identified, with water X as an end-member considered to be derived from Chalk unsaturated zone water ('usz') via reaction during leakage through the Gault Formation. Also included is a map of borehole locations, with Cl values in brackets and a tentative 100 mg/L isochlor line (see final panel). All numbered boreholes are prefixed by 'SE' (for Slough Estates) in the text. Data from Morgan-Jones (1985), Darling and Goody (2006) and Darling et al. (2012).

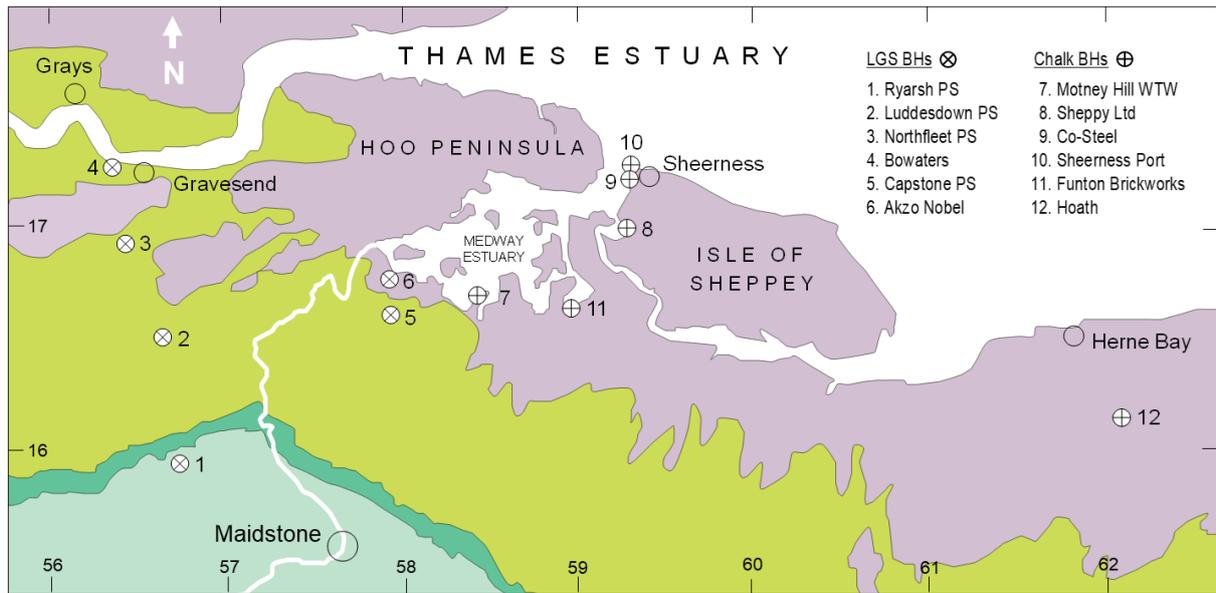


Fig. 4. Bedrock geological map of the North Kent area (10 km grid), showing the location of selected Chalk and LGS boreholes. Based on information in Evans et al. (1979), Edmunds et al. (2001) and Adams (2008). Refer to Fig.1 for geological legend. Contains British Geological Survey materials © UKRI 2021.

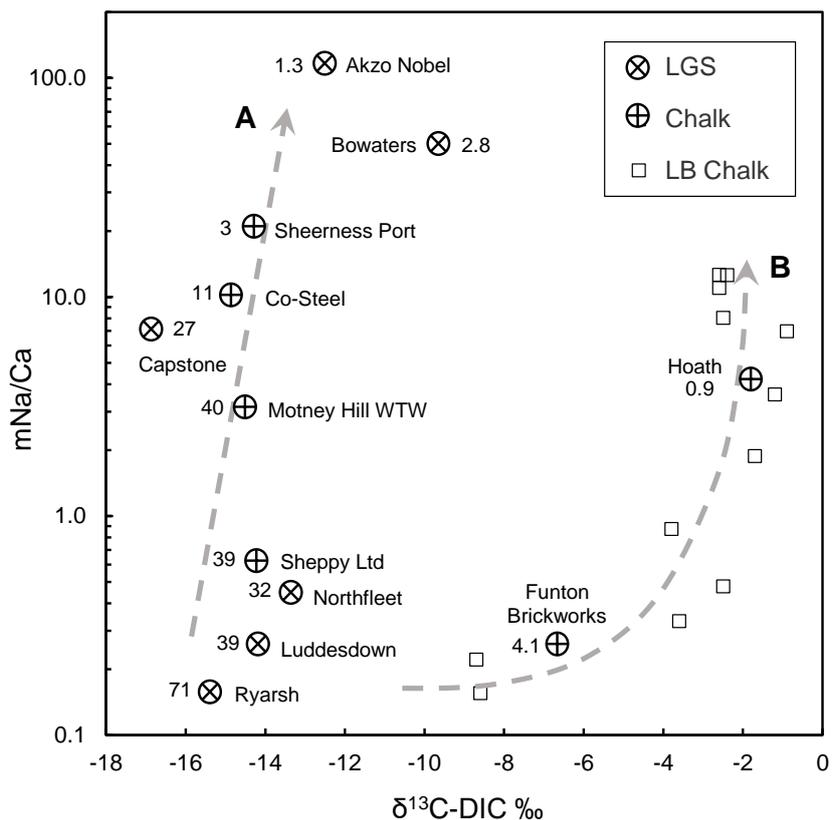


Fig. 5. Plot of mNa/Ca versus $\delta^{13}\text{C-DIC}$ for groundwaters in the general Medway region as a way of differentiating between LGS and Chalk groundwaters. Certain boreholes terminating in the Chalk appear to be abstracting a proportion of LGS water, assumed to be derived from upward leakage through the Gault Formation (path A). Unaffected Chalk groundwaters follow a different evolutionary trend (path B) typical of the confined Chalk aquifer beneath London ('LB Chalk'). The values attached to each site are ^{14}C activities in pmc (percent modern carbon). Data from Evans et al. (1979), Elliot et al. (1999), Edmunds et al., (2001) and Adams (2008).

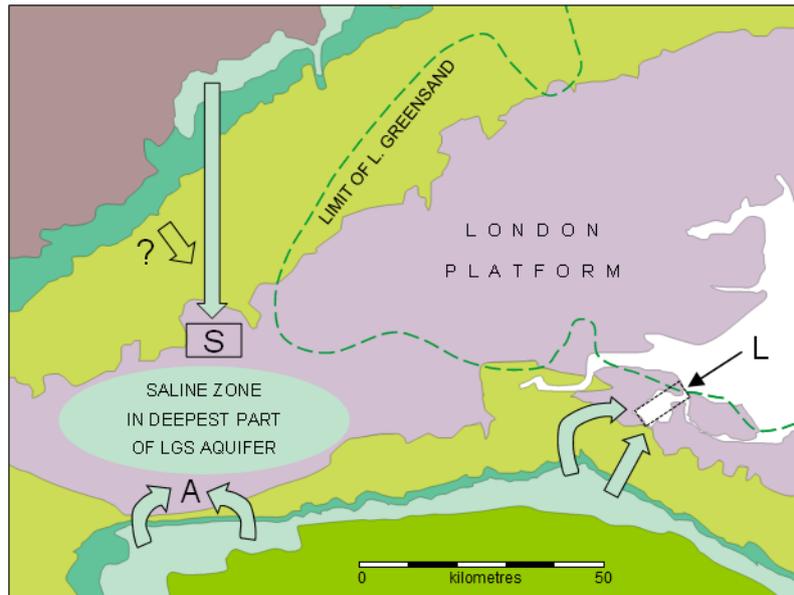


Fig. 6. Schematic map of regional flow in the LGS of the London Basin based on the findings of this study. Refer to Fig.1 for geological legend. A – Aldershot area, L – zone of LGS leakage into the Chalk aquifer, S – Slough area. Contains British Geological Survey materials © UKRI 2021.